Framework for effective automobile operations using cold spray technology

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A research dissertation submitted to the Faculty of Engineering and Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Engineering.

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Date: **09.05.2019**

DECLARATION

I hereby declare that this dissertation is my own unaided work unless where stated otherwise. This dissertation is being submitted for the degree of Master of Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before either individually or jointly, for any course requirement, examination or degree at this or any other tertiary education institution;

Signature:…………………………. Date: 09.05.2019

ACKNOWLEDGEMENTS

I would like to express my sincerest gratitude to Prof I. Botef for his unwavering support, guidance, encouragement and more importantly for inspiring and challenging me throughout this journey.

I would also like to acknowledge and thank the academic and administrative staff of University of the Witwatersrand’s School of Mechanical, Industrial and Aeronautical Engineering for their support and guidance through the programme.

To BMW South Africa, I will remain indebted to you for granting me the opportunity to further my studies. I am humbled and eternally grateful. It is also of outmost importance to note that the opinions, arguments, suggestions and conclusions contained in this dissertation are that of the author and not the company.

To my mentor Phindile Ndimande, colleague Joseph Mampana and friends in academia Alert Mncube, Prince Mulenga, Kenny Mabunda, Simelane Khaya and Muhammed Dangoor, I am grateful for their encouragement, for continuously reminding me of where my priorities lie and sharing their postgraduate studies experiences with me. You all inspire me to be a better person.

I wish to thank my mother Evah, my father Solomon, my siblings (Khutso, Kopano and Quintus) for their love and being my greatest support system at all times.

Finally, to the great man above, God, words cannot begin to describe how grateful I am for this opportunity and everyone you have placed in my way throughout this journey.

ABSTRACT

Cold spray technology is an additive manufacturing technology characterised by small particles being deposited onto a substrate at high velocity using a supersonic gas jet. It has been shown to provide quality coatings for repairs, dimensional restoration, corrosion protection and fabrication of components in different industries. Cold spray technology does not induce any thermal stress on the substrate, thus ensuring the material properties of the substrate are conserved. This advantage has enabled deposition on unconventional materials such as ceramics, polymers and composites as well as metals such as aluminium and magnesium, which are critical to the automotive industry. Traditional coating and repair processes have not been able to adequately coat these materials without introducing deleterious defects onto the substrate. As a result, parts are required to be replaced at a considerable cost with longer lead times. Cold spray technology enables the recovery of these units in production, thus ensuring plant throughputs are attained.

The automotive industry's quest for Greener solutions that increase production, economies of scale and global penetration motivates the adoption of such technologies. Cold spray technology does not emit any harmful greenhouse gases and diminishes all emissions associated with the primary extraction of minerals and vehicle production. Furthermore, the industry has a growing demand for lightweight vehicles to achieve fuel efficiency and better emission control. The ability of cold spray technology's to coat unconventional materials enables substitution of traditional cast iron and mild steel with lightweight alternatives such as magnesium and aluminium. Development of new materials with advanced properties and functionalities means cold spray coatings can grow existing profit avenues and open new ones for the automotive industry. The technology enables on-demand, on-time delivery of components that match customer demands and customisation through additive manufacturing.

In this dissertation, different cold spray technology research and development opportunities are reviewed and consideration of their efficient operations within the South African automotive industry is established and evaluated. The findings demonstrate the ability of cold spray technology to fabricate, protect and rework different substrates critical to the automotive industry. Based on the findings, it is suggested that the industry foster collaborative efforts within and out of the industry.

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LIST OF ACRONYMS

AL-Aluminium
AM –Additive manufacturing
AHSS - Advanced high strength steel
APDP- Automotive Production and Development Programme
CGDS –Cold gas dynamic spray
CGI - Compacted Graphite cast iron
CPU –Cost per unit
CU-Copper
CNC – computerized numerical control
DTI – Department of Trade and Industry
DPR- Direct pass rate
DMD - direct deposition method
GDP- Gross domestic product
HAZ - Heat affected zone
HSS - High strength steel
HVOF -High velocity oxy-fuel spraying
HVPC - High velocity particle consolidation
IPAP - Industrial Policy Action Plan
LT –Lead time
MIDP- Motor Industry Development Program
Mg- Magnesium
OEM –Original equipment manufacturer
OFHC - Oxygen-free-high-conductivity
Si - Silicon
SPD - Supersonic particle/powder deposition
SLS- Selective laser sintering
SMD –Surface mount device
TPU -Time per unit
UNFCCC - United Nations Framework Convention on Climate Change
ZAR – South African rand
Zn-Zinc

1. INTRODUCTION

Cold spray technology, as described by Villafuerte (2015), is a process characterised by small spray particles (5-50 µm) being deposited onto a substrate using a supersonic gas jet at high velocity (300-1200 m/s). The solid deposition takes place at a temperature lower than the melting point of the feedstock material, thus ensuring no melting occurs. In contrast to other thermal processes, cold spray technology does not introduce any thermal stress for deposition that may result in deleterious defects such as oxidization, grain growth, stress and possible material failure, amongst many others disadvantages (Villafuerte, 2015; H. Singh, Khosla, Sidhu, Kalsi & Karthikeyan, 2018). The advantages of cold spray permits deposition on unconventional materials, such as temperature-sensitive nanocrystalline, and amorphous materials as well as oxygen-sensitive materials, such as titanium, aluminium and copper (Sova, Grigoriev, Okunkova & Smurov, 2013).

These recent developments in surface engineering have opened new opportunities for material substitution from traditional cast iron and mild steel to aluminium, magnesium and titanium (Mallick, 2012;Moridi, Hassani-Gangaraj, Guagliano & Dao, 2014). Alternative lightweight materials assist with the reduction of emissions and fuel use, which contributes positively to the overall life cycle of the product and production system. Unstable and competitive materials and product prices have also added to the pressure as original equipment manufacturers (OEMs) are forced to consider unconventional materials (Miller, Zhuang, Ottema, Wittebrood, & De Smet, 2000).

The rise of advances in cold spray technology over the past decade has increased its potential for adoption for various applications in different industries such as medicine, aerospace, petrochemical, and the automotive and electronics industries (Champagne, 2007). The introduction of the technology diminishes existing challenges in the automotive industry, such as costly production losses incurred through process time, corrosion, wear and dimensional irregularities. Production losses affect the production line's productivity through high lead times (LT), low direct pass rate (DPR), high time per unit (TPU), cost per unit (CPU) and rework time as employees and resources need to be dedicated for reworking or the units are scrapped completely from the production line. The adoption of cold spray technology presents an opportunity to further compound downstream losses such as material failure and corrosion in aftersales that gravely impact an OEM’s warranty. An urgent need exists for enabling technologies that support current and future industry changes, attain production throughputs to meet demand, and establish production efficiencies to leverage the scale of economics. Cold spray technology is envisaged as a great tool for meeting these challenges and an enabler for attaining production efficiency in the automotive industry. In this document, a useful framework for critically reviewing issues in research and development through which the automotive industry can establish efficient operations is outlined and evaluated.

1.1 Research Background

Cold spray technology has had much notable success in research and development; however, it is faintly implemented in certain industries such as the automotive industry. The technology has challenges and limitations, such as its inability to produce metal components using additive manufacturing (Additive manufacturing for automotive, 2015). However, other aspects of additive manufacturing such as plastic components production, coatings using different substrates are possible. A second challenge is the high investment necessary for implementation, which has put a halt on its adoption, particularly in developing countries such as South Africa. Nonetheless, in contrast to its thermal technology counterparts, cold spray technology presents an opportunity to produce lightweight porous structures that are given metallic features and finishes through consecutive coatings.

The South African automotive industry seeks to increase its production locally and globally to accommodate the rise in demand from the market. Initiatives such as the Automotive Production Development Programme (APDP) and Industrial Policy Action Plan (IPAP) initiated and led by the Department of Trade and Industry (DTI) are examples of programmes created to facilitate such changes in demand and supply (ASCCI, 2017). Despite the increase in investment from government, private organisations and investors, such as the R6.0 billion from BMW, R1.7 billion from Toyota and R2.5 billion from Ford between the years 2016-2017, the industry still faces greater challenges to accommodate the changes necessary for the fourth industrial revolution (Davies, 2016). The fourth industrial revolution is the fusion of the physical, digital and biological systems and how they interact with each other. It includes, but is not limited to, artificial intelligence, automation and smart machinery and quantum sequencing. By creating “Smart factories”, the revolution will change the value chain, i.e. the interaction of the virtual and physical systems of manufacturing. This allows for product customisation, flexibility and shorter lead times (Schwab, 2016). Some of these challenges local OEM face with regards to the revolution includes the local automotive industry's readiness for technological advancements, material changes and the necessary skills to implement those technical and material changes.

Conventional materials such as cast iron and steel have been compatible with traditional coating processes such as high velocity oxy-fuel spraying (HVOF), electric wire arc and plasma spraying. However, these traditional processes have not been able to adequately coat non-conventional lightweight materials such as nanostructures, composites and other alloys because of the heat introduced to the process (Champagne, 2007). Traditional processes introduce deleterious defects to the substrate, thus degrading its quality. This has limited material substitution because of the properties necessary for successful substitution for different components and their requirements. For example, the powertrain operates at elevated temperatures and in abrasive conditions. This makes it necessary to ensure that internal and external damages are prevented in the design and production stage. Materials eligible for substitution must be able to withstand aggressive environmental conditions with increased strength and hardness. Magnesium has not been eligible for the substitution because it is susceptible to corrosion (Hengyong, Yandouzi, Lu, MacDonald & Bertrand, 2012). The demand for lightweight vehicles supports the adoption of technologies that enable the development of materials with advanced properties and functionalities such as cold spray.

The growth and development of the transportation industry and society welcomes a new set of problems such as noise pollution and congestion in the cities as well as climate change and the catastrophic events that signal global warming (Hannon, McKerracher, Orlandi & Ramkumar, 2016). The transport industry as one of the highest contributors to greenhouse gas emissions and thus climate change; it is one industry in dire need of change (UNFCCC, 2008). This has forced key decision makers to support the adoption of environmentally friendlier systems, designs and technologies for the automotive industry.

On time delivery has become increasingly important as the automotive industry has grown more customer centric over the years. The industry thrives off customisation and on-demand supply (Hannon et al., 2016). OEMs are challenged with maximising warehouse space usage, controlling lineside inventory in production plants and ensuring nimble production periods for timeous delivery. The technology's ability to tailor-make products on demand cuts off transportation times, expensive packaging and storage space.

1.2 Research Justification

There are various grounds to pursue this research; the most prominent is the urgent need to achieve stability and effective operations within the automotive industry and its transition into the fourth industrial revolution. From the literature, it has been shown that cold spray provides coatings of superior quality compared to conventional spray coatings. Besides its technical ability, the technology presents opportunities for the automotive industry to better position itself and improve its readiness to engage with the fourth industrial revolution.

With this in mind, the following have become a necessity for effective operations:

- Establishment of efficient production systems with low to zero losses, or the integration of technologies that assist in recovering defective units on and off the production line, such as rework technologies (Gram, 2013; Kleine, 2015).
- Optimisation of material use on the production line through reduction of waste.
- Reduction of emissions in production systems (industry) and thus the adoption of Green technologies (UNFCCC, 2008; Kilchenstein & Champagne, 2013).
- Adoption of inherently safer and Green vehicle designs (Knight, 2011).
- Delivery of components on time that match customer demands and customisation that can be achieved through additive manufacturing (Giffi & Gangula, 2014; Additive manufacturing for automotive, 2015; Pathak & Saha, 2017).
- Adaption of processes and technologies to existing industry production lines as justifiable investment costs (Singh, Sidhi & Kalsi, 2012).
- Develop of coating technologies that support both conventional and unconventional material for application on existing and new commercial products (Mallick, 2012; Moridi et al., 2014).
- Achievement of cost effective technology for all of the above (Pelsoci, 2015).

The focus of this research will be on the South African automotive industry; however, the research can be adapted to other countries because it will also consider a global view and market. At the time of writing, the proposed technology was not being used in South Africa on an industrial scale. The intention of this research is to interrogate the efficacy of using this technology in the South African market with the view of increasing local penetration and production economies.

1.3 Research Problem

The South African automotive industry's vision to increase local and global penetration and engage in the fourth industrial revolution has put unprecedented pressure on local OEMs. As the leading country in the automotive industry in the sub-Saharan region, it also needs to ensure it fully embraces technological innovation, upskilling initiatives and marketing changes to remain relevant and competitive within the global market. The following challenges outlined below pose a threat to the industry's readiness for the fourth industrial revolution and the vision of the South African automotive industry producing more vehicles locally and thus the jobs the industry provides.

1.3.1 Material composition

Prior to the 1970s, vehicles were constructed out of cast iron and mild steel. Besides the desirable physical properties of these materials, the cost and availability justified the use (Mallick, 2012). In recent years, greater emphasis has been put on fuel efficiency and improved emission control. Manufacturers have started to consider unconventional lightweight materials to reduce the vehicle weight. The inclusion of these unconventional materials requires a review of their chemical and physical properties as well as the production process, handling and techniques. Most of these lightweight materials such as aluminium, magnesium, composites and carbon fibres have been limited in automotive application because they do not meet the industry requirements in one or more ways, such as reduced strength, increased susceptibility to corrosion, and low heat and electrical conductivity (Moridi et al., 2014).

Conventional thermal spray processes have not been able to adequately support the substitution for cast iron and steel because the heat source causes deleterious defects. Challenges with respect to price increases, scarcity and the volumes needed for mass production have made it even more important to ensure efficient use of these resources (Milleret al., 2000; Musfirah & Jaharah, 2012). The industry therefore needs technologies that support the coating of unconventional lightweight materials and the reworking of defective parts. There is also a need for coating technologies that facilitate the development of new or enhanced materials with advanced properties and functionalities.

1.3.2 Production

Units and body panels (single parts) can be scrapped for various reasons, such as mis-machined parts and dimensional irregularities, which could lead to the body being completely disqualified on the production line. The value of a scrapped car (unit) or a part depends on many factors including the value of the materials and amount of work already invested in it, e.g., unrecoverable materials such the cost of the metal sheets, paint and assembled hang-on parts. The value can easily rise with an even larger or complex production line and thus threaten production targets such as volume, direct pass rate, etc. These losses can cost companies millions in reworking/reprocessing, which is, in essence, means “double-handling,” loss of inventory and idling time that could be translated into value added production time. With the recent increases in the cost of materials, utilities and labour in South Africa, industries face an urgent and even bigger challenge to avoid any losses in their production processes (Gram, 2013).

1.3.3 Supplier and delivery

In recent times, OEMs have been challenged to produce vehicles with shorter waiting times to customers. The demand for shorter waiting times becomes a challenge with the use of a monopolised global supplier network. The waiting period for the customer can easily rise with production challenges such as defects and parts shortages, unavailability of customised options, transportation challenges, political clashes and natural disasters. An OEM’s efficiency is now measured not only in terms of the product quality but also the turn-around time between ordering a vehicle to delivery. Technologies that enable on-demand supply have become a necessity. These will also push the industry to invest in such initiatives because they facilitate job creation within individual countries.

With all these factors in mind, the predicament in the industry is the inability of existing conventional technologies to support the fabricating, reworking and coating of parts on the production line, after sales, and in the field because they are not compatible with the materials of interest. Cold spray technology does not use any thermal input to substrate, thus providing coatings that are hard, corrosion resistant and oxide free with no grain growth. The adoption of cold spray technology within the automotive industry has been hindered by various factors such as high investment costs that cannot be justified for small plants, job shops or OEMs in developing countries. Furthermore, the unavailability of standards on the public front and the limited range of materials eligible for coating has been an impediment to the adoption of the technology. Notwithstanding its challenges, the adoption of cold spray technology would be beneficial because it has been shown to adequately support materials of interest to the automotive industry for reworking, prototyping and additive manufacturing.

1.4 Research Question and Hypotheses

The intention in this research is to analyse numerous coating and surface-related issues in the automotive industry in pursuit of establishing a framework for the effective operation of cold spray technology by addressing the following research question:

Are there cold spray research and development opportunities which, after consideration, could lead to an enhanced cold spray technology application in the automotive industry and more efficient automotive operations?

The argument is that cold spray technology can be used to achieve efficient operations within the automotive industry through some of the services and applications it offers. However, in light of its limitations, cold spray technology is not ready to replace any of the thermal processes. It complements current thermal technologies and facilitates introduction of quality coatings and additive manufacturing that none of the existing thermal technologies have been able to provide. With this in mind, the intention is to provide solutions where other thermal technologies fall short. Some of the technology's research and developments which will be interrogated with the intention of establishing efficient operations are outlined below;

In order to answer the research question, the following research hypotheses will be addressed:

*H*1: Cold spray technology is envisaged as a suitable tool for remediation of otherwise unserviceable magnesium components critical to the automotive operations.

*H*2**:** Cold spray technology is envisaged as a suitable tool for remediation of otherwise unserviceable aluminium components critical to the automotive operations.

*H*3: Cold spray technology is an additive manufacturing technology that will assist the automotive industry achieve efficiency.

*H*4: Investment in education can help with the identification and implementation of cold spray technology and thus help towards achieving effective operations in the automotive industry.

*H*5**:** Cold spray technology is a Green technology that stands to reduce emissions in the automotive industry currently and going into the future.

*H*6: Proper implementation of cold spray technology would complement current conventional thermal spray systems and help towards ensuring efficient operations.

1.5 Delimitation of Scope

The research has the following limitations; in other words, it will not cover the following aspects:

- The history of how the technology was conceptualised to its realisation.
- Patents and copyrights and their roles in the automotive industry.
- Cold spray technology's advantages that are not closely related to the automotive industry
- The body shop of the automotive manufacturer in question that does not include the press shop.
- The entire scope/spectrum of eligible materials; only a few materials of interest that are applicable to the automotive industry are reviewed.
- The fabrication of the materials, e.g., magnesium alloys, porous structures and nanostructures.
- The life cycle of the vehicle and cost benefit analysis will not be conducted in this dissertation however it will be reviewed from literature studies.
- The research does not take the practical and experimental approach of showing the effectiveness of the technology as a coating method for different substrates and considering specific feedstock materials and parameters.

1.6 Source of Data and Methodologies

The sources of data for the literature review included reputable and published papers, books, journals, automotive blogs, documented conference proceedings, consultants and their companies and expert reviews. Different approaches to validate the applicability of the data such as comparison of the proposed framework to tried and tested frameworks of a similar nature were used. The methodology followed in this research to identify relevant research topics, formulate hypotheses, test the hypotheses and critique the results are outlined in greater detail in Chapter 3 (Methodology and Validation).

1.7 Contributions

The shift from the third to the fourth industrial revolution has introduced a great deal of instability into the automotive industry. The need for efficient, Green and cost-effective ways of producing and reworking vehicles and their associated parts in the market is imperative. There is also an urgent need to produce high performance vehicles that are environmentally cleaner and fuel efficient. These factors attest to the necessity of exploring cold spray technology adoption in the automotive industry.

This research is one of the very few to review the application of cold spray technology in the automotive industry. It focuses on various issues associated with the automotive business, environment, products and production that are deemed important to establish efficient cold spray operations within the automotive industry. It also incorporates arguments on how the technology fits into the automotive industry’s future and thus the fourth industrial revolution. However, it does not take the practical and experimental approach of showing the effectiveness of the technology as a coating method for different substrates and considering specific feedstock materials and parameters. Furthermore, the research also takes a different outlook on how this technology, which encompasses aspects of the fourth industrial revolutions, brings about job creation and improves the South African automotive sector. This is particularly important in a job creation economies where there is the fear of erosion of jobs with the introduction of automation and elements of the fourth industrial revolution.

1.8 Definitions

Important terminology used in the context of the research is outlined below, further definitions and acronyms are outlined in the Appendix A: Glossary and List of Acronyms respectively;

Assembly – this section of the plant is responsible for trimming the body with all the interior components and adding on the exterior, such as bumpers. It is also responsible for the insertion of the mechanical and electronic wires and devices in the vehicle, including the powertrain, wheels, and front and rear window shields.

Bodyshop – where the pressed metal sheets (panels or hang-on parts) are assembled.

Coating – layering a substance (natural or synthetic) over the surface of another material that is to be shielded from environment or to be provided with decorative properties (Singh et.al 2018).

Cold gas dynamic spray (CGDS) – often referred to as *cold spray technology (CS*); CGDS is a solid-state process characterised by small spray particles (5-50 µm) being deposited onto the substrate using a supersonic gas jet at high velocity (300-1200 m/s). The solid deposition takes place at a temperature lower than the melting point of the feedstock material, thus ensuring no melting of the substrate occurs (Villafuerte, 2015).

Component – (1) synonymous to part (small metal sheets which will be assembled to make a vehicle). In other contexts, (2) it means a functional unit in the vehicle, made of several parts such as an engine block or transmission housing.

Future of mobility – related to fourth industrial revolution, it means a broader view of what the future holds for the industry and is driven by social trends, legislation and technological advancements. Its core principles also fit directly into the fourth industrial revolution, for example, connectivity, fuel-efficient automobiles and autonomy, etc.

OEM – original equipment manufacturer; it includes both the cold spray suppliers and automotive manufacturers such as Audi, BMW, Mercedes Benz, Volkswagen, etc.

Life cycle analysis (LCA) – A consistent methodology for evaluating environmental performance of various product systems. The system boundary of LCA is from cradle to gate as applied to a wide range of products systems including cars and trucks. (Sullivan, Kelly & E*gowainy, 2018)*

Monocoque- or structural skin – *outer* skin performs the dual role of the body surface and structure (Crolla, 2009)

Paint shop – this is the metal sheets' preparation location where the metal is washed and an E-coat is applied. It includes drying, wax and sealing, and the actual paint applications section of the plant.

Sub-assemblies – section of a production plant where a unit is constructed separately to be fitted into a larger unit within the same production section.

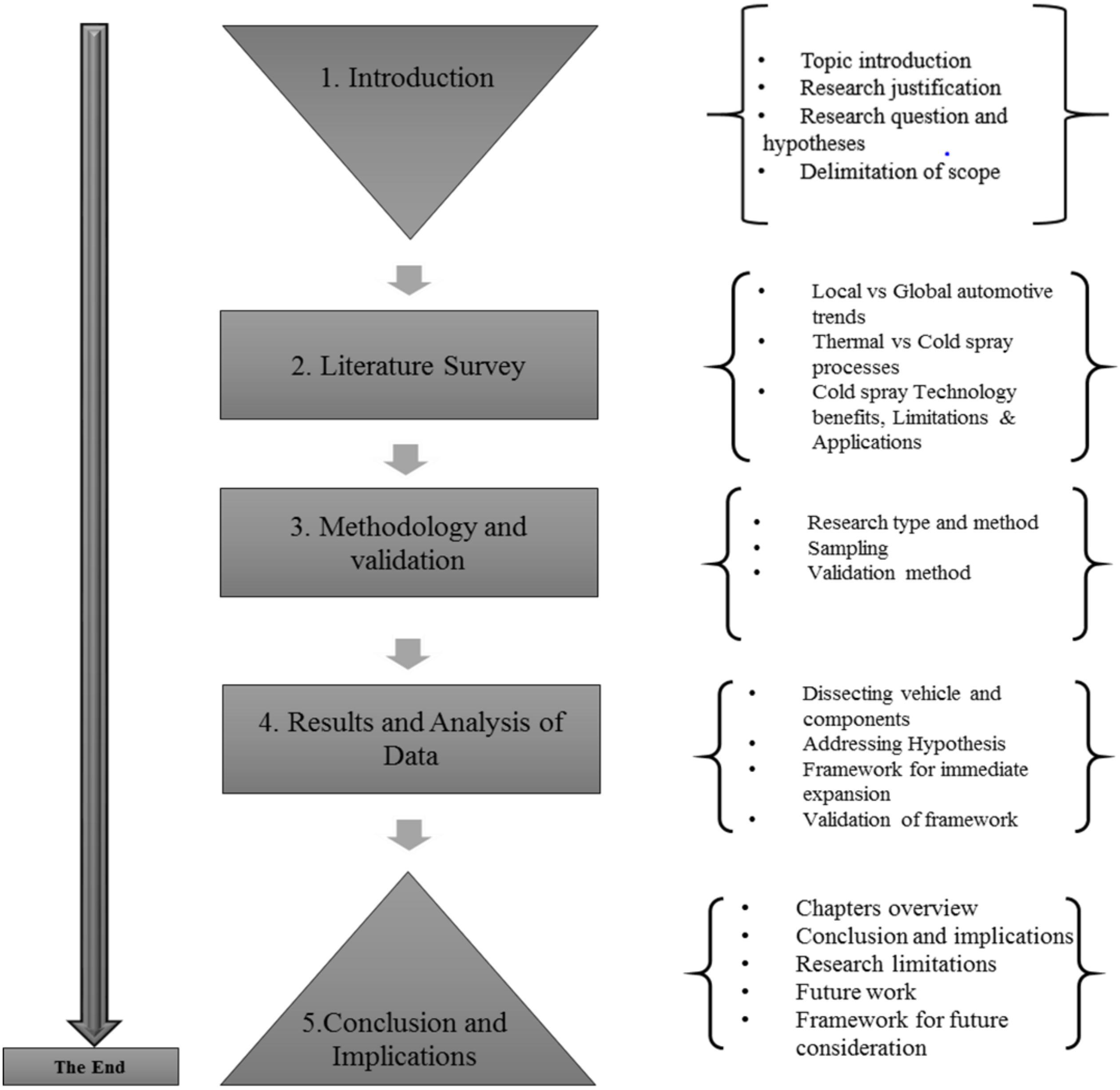
SUMA – often referred to as supermarkets, it is the parts pulled from the warehouse and organised into a lineside mini-warehouse.

Unit – single car or vehicle.

1.9 Outline of Dissertation

The dissertation consists of five chapters including the introductory chapter as illustrated in the figure. Each chapter is a standalone section as it briefly introduces its objective, addresses objective in the main body and concludes its findings at the end of the chapter. The figure also illustrates briefly what each chapter covers.

Figure 1: Organisation of dissertation chapters



In the first chapter, the topic, scope of coverage, angle and goal of the research is introduced. Chapter 2 is a literature review of the current trends and challenges for mobility in the automotive industry in South Africa and globally. It further incorporates the current status and future aspirations of the automotive industry, briefly highlighting the advancements necessary in both cold spray technology and its current limitations .It further highlights the materials of interest that have been found compatible with cold spray and some of its uses in different industries including the automotive industry.

The research methodology and validation process is outlined in Chapter 3. Chapter 4 presents the research results and an evaluation of the proposed framework by applying the validation process**.** The results are also critically reviewed and discussed in Chapter 4. The research report is concluded with an analysis of the findings and their implications and limitations in Chapter 5. The final chapter also includes a section outlining recommendations for the industry and future research.

1.10 Conclusion

From this chapter, it is apparent that production losses kill productivity and thus business. It is the small events (losses) that impede a production line's productivity, particularly if taken for granted or considered part of the process (Lichtenberg, 2017). Companies lose fortunes in production defects through time, volume and resources. The clear and urgent need for cost effective and Green technologies that support the use of unconventional materials for improved fuel efficiency and emission control in the production of vehicles has been shown. Cold spray technology is a believed to be a viable option for the automotive industry because of its reported superior coatings and manufacturing advantages. The intention of this research is to interrogate the efficacy of using cold spray technology in the South African automotive industry with the view of increasing local and global penetration and production economies.

2. LITERATURE SURVEY

In the following chapter, the relevant literature about the automotive industry and cold spray technology will be reviewed. First, insight into the current state and trends in the local and global automotive industry is provided with particular focus on how these challenges are linked to the need for new emerging technologies such as cold spray technology. The different thermal spray technologies are then introduced and compared. Finally, cold spray technology, its process, setup, materials, benefits and limitations are covered.

2.1 Overview of the Local and Global Automotive Industry

2.1.1 Trends and challenges of the global automotive industry

The global automotive industry has grown dramatically over the years and will be subject to change over the next decade in pursuit of its transformation and transition into the fourth industrial revolution. The changes that are required for the transition and transformation has subjected the market to a lot of disruptions, volatility, uncertainty, complexity and instability such as unpredictable market models and diverse range of customer needs. One of the industry's biggest challenges particularly with respect to enabling technologies is the absence of rare-skill sets and competencies that have not been developed in the labour force over the years across the globe (Sarasini, Karlstrom & Sanden, 2014). This has presented automakers with the challenge to consider new technologies and upskill their employees with the necessary competencies. Developing countries are the most affected by rare-skill shortages; they also lack infrastructure and readily available investment.

The fourth industrial revolution has also pushed automakers to form strategic alliances to achieve common goals, such as the reported collaboration between Renault and Nissan to develop "zero emission transportation" (Sarasini et al., 2014), and similarly BMW has partnered with INTEL, MobiEye and Delphi to develop systems for autonomous driving (BMW Group, 2016). These types of collaboration are examples of a network strategy designed to assist and fast track development and access to new and existing knowledge relevant for innovation, which could potentially boost competitive advantage.

In pursuit of achieving effective operations, it is imperative to gauge and comprehend the current state and future direction of the industry. The automotive industry is currently driven and focused on the fourth industrial revolution, which is often termed the "**digital revolution**." It is a fusion of physical, digital and biological systems with aspects of the third industrial revolution. Some of the spheres or areas of coverage include connectivity and digitalisation, lightweight vehicles, artificial intelligence, and highly intelligent and automated production systems. With these developments in mind, production lines will soon need less forepersons and general workers but highly skilled specialists, which attests to the industry's need to develop special skills promptly (Sarian, 2014; Additive manufacturing for automotive, 2015). A study conducted by Breunig, Kelly, Mathis and Wee (2016) revealed that only 30 percent of the technology suppliers and 16 percent of manufacturers have an overall strategy of what the transition into the fourth industrial revolution requires of them. Cold spray technology is not only envisaged as a key technology instrumental for the transition from the third to the fourth industrial revolution in production through material substitution and mis-machined parts reworks but also in supply chain and additive manufacturing of parts. Its ability to influence multiple areas of the automotive industry makes it a technology of great interest; however, it is still not implemented in developing countries such as South Africa.

New trends in the market have shown how Millennials do not have an urge to own vehicles; this can be seen from plummeting figures for cars targeted at younger markets such as the Ford Fiesta, BMW 1 series and Mercedes Benz A-class. Moreover, Millennials who purchase vehicles do not purchase new automobiles but pre-owned vehicles (Deloitte University Press, 2017). With the decline in the purchase of new vehicles, there will be a greater need for maintenance and servicing of existing vehicles in the market. Moreover, more entrepreneurs are investing in providing fleet transport services such as Car-Sharing, Metered taxis and Uber. So, while there is still a market for automobiles, an emerging market is for aftersales services, panel beaters and job shops. These trends are more prominent in the United States of America and Europe as opposed to South Africa. However, as affordability becomes a concern due to the worsening economic climate, South Africans will follow suit because fuel prices and interest rates for vehicle financing are also expected to increase dramatically. Cold spray technology as a rework, reproduction and additive manufacturing technology would be able to support this market and its demands.

2.1.2 Trends and challenges of the local automotive industry

The automotive and components industry in South Africa comprises vehicle manufacturers such as Mercedes Benz, BMW, Nissan, Ford, Mazda, General Motors, Renault, Volkswagen and Toyota, just to name a few. All of these manufacturers have production plants in South Africa, alongside component manufacturers such as Bloxwich, Corning, Arvin Exhaust and Senior Flexonics (South Africa Info, 2016).

Some of the challenges that the South African automotive industry faces include the complete ownership of automotive manufacturing companies. For example, most OEMs locally are subsidiaries not affiliates. The holding OEM's research and development hubs are based offshore. The local OEMs (subsidiaries) are often the last to become involved in the rollout of the training, development and latest technology implementation. For example, the fourth industrial revolution requires the development of rare-skill sets. South Africa remains disadvantaged in this regard as specialists are developed offshore and deployed to South Africa to assist in the integration of systems. There is no homegrown development of these rare-skill sets, and more importantly, the industry and higher education system have a huge skills gap. As such, the larger proportion of the population working for the OEMs remain disadvantaged in terms of skills and technology. For example, at the time of print, the cold spray research lab at the University of the Witwatersrand in Johannesburg is the only such facility in Africa.

South Africa harbours the most developed automotive industry and economy in Sub-Saharan Africa; therefore the challenges do not only affect South Africa but also the Sub-Saharan African region as well. The automotive industry is one of the largest manufacturing sectors in the South African economy, contributing on average 7.2 % to the GDP in 2015 and creating over 30 000 jobs countrywide (ASCCI, 2017). This attests to the importance of the survival, growth and success of the industry to the country and continent. Most of the vehicles assembled locally are for export markets such as Japan, the United States of America and Europe.

In 2011, the Motor Industry Development Program (MIDP), in conjunction with the Automotive Production and Development Programme (APDP), launched an initiative aimed at improving logistics, supplier development, localisation, incubation, technology and skills development locally. According to South Africa Info (2016), it was only in 2013 that the APDP was successfully implemented. It has a vision to expand local production by increasing export production to at least 1.2 million vehicles per annum by 2020. These programmes are aimed at bridging the skills gap, bringing in both business and foreign investment, and more importantly, opening doors for the automotive industry in particular.

Trading and labour policies adopted in developing countries such as South Africa have assisted in the facilitation of rare-skills transfer; however, with respect to the rate at which the fourth industrial revolution requires the industry to progress, this could still not be enough. Evaluating the integration of emerging technologies into current systems in the automotive industry and their role in the transition into the fourth industrial revolution has thus become of great importance in establishing competitive businesses locally that is aligned with the global market.

2.2 Thermal Spray Technologies: Overview

Thermal spray is a set of established industrial methods of refurbishing or surfacing a substrate. It is a family of processes that are adaptable, cost-effective and versatile through which substrates made of polymers, composites, cermet, ceramics, metals and metal alloys can be coated for protection against corrosion, wear, abrasion, high temperature, chemicals and erosion (Villafuerte, 2014; TSS Thermal Spray Technology, 2016). Substrates can also be coated for functional supports, for decoration, for repairs or to modify the existing structure. One of this technology's outstanding feature is its ability to repair worn out parts to their original state and give coated substrates superior properties.

Thermal spraying equipment differs from one technology to another. It can be done through powder feeds or wires. Other feeds are blends of different powder feeds which is preferred because the final coating has superior characteristics to the individual feeds methods. The morphology, size, preparation and density of the feeds is out of the scope of coverage of this work. Included in the next section is an overview comparison of the five thermal spray processes. Appendix B briefly reviews each process individually.

The market for thermal spray has grown to an estimated US$6.5 billion, which translates to ZAR88.65 billion with the market exchange rate at the time of writing. The European and North American markets have been the world leaders in thermal spray technology development and application. Leading industries include the aerospace and industrial gas turbine industries.

Traditional markets such as the automotive industry have predominantly used these technologies in the energy, steel and semiconductor/electronic sectors. Industries growth trends worldwide have also led to the adoption of these technologies, particularly in thriving economies such as China where there is spike in the emergence and expansion of traditional industries (TSS Thermal Spray Technology, 2016).

2.2.1 Comparison of thermal spray processes

The different types of thermal spray processes include but are not limited to flame spraying, wire arc spraying, plasma spraying, high velocity Oxy-fuel spraying and cold spraying.

These different thermal spray processes have different flame temperatures. As such, for each of these processes, there is a restricted range of materials (substrates) that can be coated. Important aspects to consider for coating formation is the particle melting and substrate melting points and the deformation temperatures for each thermal spray process, which contributes to the quality of the coating. Once the substrate is identified, the choice of the process will depend on the properties of the substrate, the ultimate use of the substrate, and its final desired properties, costs, and time (Marrocco, 2008). The important parameters for coating formation such as gas type and temperature, nozzle and gun design, substrate choice, etc., are not covered in this research.

Conventional thermal spray processes such as wire arc, flame arc and plasma spraying are largely based on the principle of melting feedstock material for application of protective coatings. The quality of these coatings depends on the rate at which feed particles melt. In contrast, HVOF does not need the feed particles to be completely melted for application; however, a certain amount of heat is still necessary to ensure partial melting. The use of heat in these processes introduces deleterious defects to the substrate; as a result, it has limited the expansion of the coatings onto other materials such as ceramics. Cold spray technology uses kinetic energy (particle velocity) to ensure coating formation. The temperature of the carrier gas is lower than the melting point temperature of the coating particle material. As a result of the low temperatures used in cold spray coatings, the microstructure of the substrate is preserved. The coating does not have any deleterious defects associates with the use of heat such as oxidation, phase transformations or residual stress, just to name a few (Marrocco, 2008).

Other significant differences between cold spray and other conventional thermal spray processes are as follows (Marrocco, 2008; Ghelichi & Guagliano, 2009; ASM Thermal Spray Society, 2013; Hofsajer & Botef, 2013; Villafuerte, 2014).

- Absence of heat in the process has allowed for the coating of oxygen-sensitive materials such as titanium and copper.
- Grain growth formation of brittle and undesirable phases, which are common in conventional processes, have allowed for the coating of nanophase/nanostructured substrates, composites and other metals that have previously not been possible to coat.
- Thicker coatings (even free-standing) for dissimilar materials.
- Coating processes can take place with minimal surface preparation as compared to conventional processes; as such, it avoids the use of chemicals and saves time.
- Absence of high-temperature gas jets and explosive gases such as acetylene, hydrogen, propane, propylene increases operational safety.
- High deposition rates relative to conventional processes make it favourable for robust operations.

Based on these process advantages, it is clear that cold spray technology offers superior coatings that also enable coatings of unconventional materials. The following sections outline what cold spray is and a detailed overview of its benefits, limitations, and materials in current automotive industry practices.

2.3 Cold Spray Technology

Cold spray technology is a relatively new coating process that falls under the “thermal spray technologies” umbrella (TST: Engineered Coating Solutions, 2016). Various names have been used in industry for cold spray technology such as cold gas-dynamic spray method, kinetic metallization, kinetic spraying, high velocity powder deposition or high velocity particle consolidation (HVPC), and supersonic particle/powder deposition (SPD) (Joining-Lab, 2012); it is important to note that the principle remains the same.

The subsequent subsections of this chapter review the literature of cold spray technology. The technology’s history and development are outlined in Appendix C. In this section, the process description, uses as an additive technology, benefits and limitations, and current practises of the technology will be covered.

2.3.1 Process description

The principle of cold spray is a high velocity supersonic gas jet (300 to 1200 m/s) that is used to accelerate small powder particles (5-50 µm) towards a substrate where a coating is formed upon impact (Papyrin, Kosarev, Klinkov, Alkhimo & Fomin, 2006). The term “cold spray” has been used to describe the process because both the temperature of the powder-laden gas jet and the temperature of the powder material are low enough to prevent phase change or stress in the deposit or substrate (Joining-Lab, 2012).The velocity of the particles needs to be above critical velocity before particles plastically deform and adhere to the substrate (Karthikeyan, 2004).

A typical cold spray system consists of a gas delivery system, gas heater, powder feeder/hopper, nozzle/spray gun, control console and a substrate. The process can take different configurations, namely, “low pressure or high pressure” systems. The difference between the two systems is the point where the compressed gas is introduced into the system and nature of the gas. This is clearly depicted in Figures 1 and 2 below.

Figure 2: High-pressure cold spray system

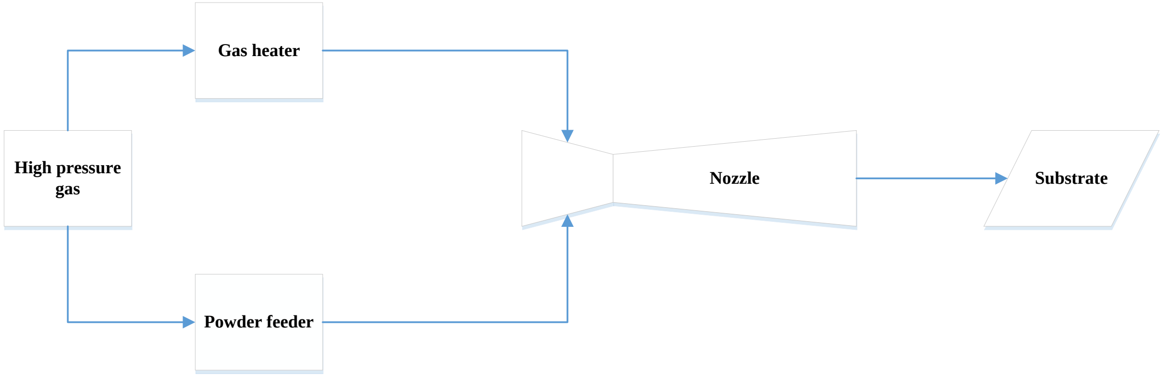


Figure 2 above shows a high- pressure system where the main gas stream and the powder stream are both introduced into the inlet of the nozzle. This configuration is said to be commonly used in stationary cold spray systems (Joining-lab, 2012) (Joining-Lab, 2012). Compressed high-pressure gas and low molecular weight gases such as helium 15-40 bars are also said to be common to such systems.

Figure 3: Low-pressure cold spray system

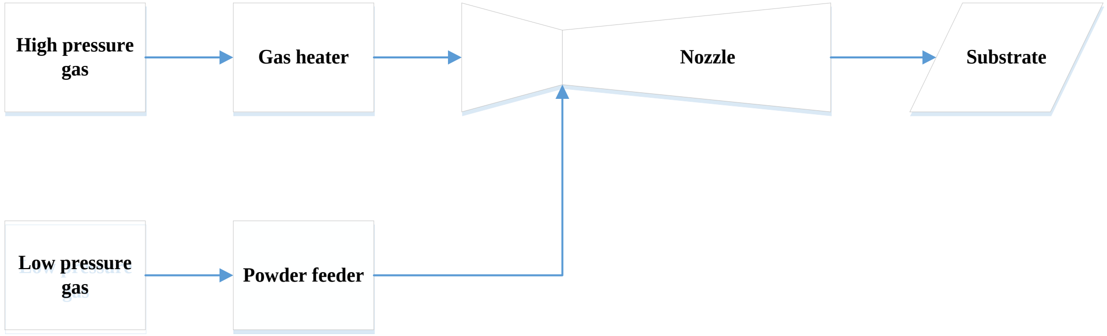


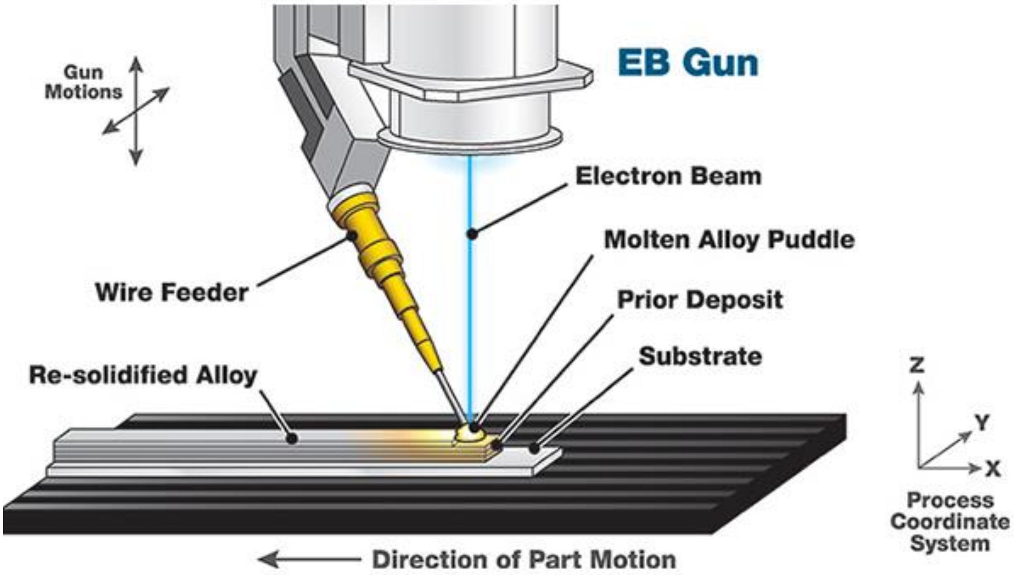
Figure 3 above a system where a low-pressure gas is used to transport the powder particles in the powder feeder to the nozzle. The powder stream is injected into the nozzle at a point where the gas has expanded to low pressure (Joining-Lab, 2012). This process is commonly used for portable cold spray systems. Readily available low-pressure air can be used for this system, but nitrogen is a good option. Nitrogen is readily available (found in abundance) and it is inert. Though it might be costly on an industrial scale, alternatives such as onsite nitrogen gas –generating machines can be cost effective.

The use of the low temperatures in cold spray technology makes it suitable for heat sensitive materials such as nanophase, amorphous materials, and oxygen-sensitive materials like aluminium, copper and titanium as well as phase sensitive materials such as carbide composites (Karthikeyan, 2004).

2.3.2 Cold spray as an additive manufacturing technology

Cold spray technology can be adapted for use as an additive manufacturing process. Additive manufacturing, also known as rapid form manufacturing, is a freeform fabrication of components using the layer-to-layer approach as shown in Figure 3. It allows for the creation of single components with minimal steps where the time and cost of manufacturing are not a factor of component complexity. The process can create geometrically complex components without much challenges (Sova et al., 2013; Villafuerte, 2014).

Figure 4: Illustration of additive manufacturing concept using a wired-feed electron beam system (Kerns, 2016)



Current additive manufacturing methods such selective laser melting (SLM), selective laser sintering (SLS), and direct metal deposition (DMD) still require intermediate binding, additional process steps and use of heat for feedstock material melting (Sova et al., 2013). These limit their application with certain materials such as oxygen and temperature-sensitive materials. These technologies have been successfully used for coating and fabrication of moulds, polymers and other metals. The use of cold spray assists in fostering certain desirable characteristics in these products, such as giving polymers heat transfer properties through coating the substrate with metallic feeds.

Cold spray technology is able to form multi-layered depositions on different substrates because deposition occurs in a solid state. This makes certain that the substrate's microstructure is not altered and its desirable properties are preserved. This kind of deposition has been a limitation in SLM technology. Cold spray technology can also be used for mixed feeds coatings, which have exhibited superior coatings properties as compared to single feeds. An example of these is coatings of Co-Cr +316 L stainless steel, which has higher and better mechanical properties and corrosion resistance than does pure 316L deposits (Sova et al., 2013). Cold spray technology presents many technical benefits to surface and coatings processes, but it has limitations also.

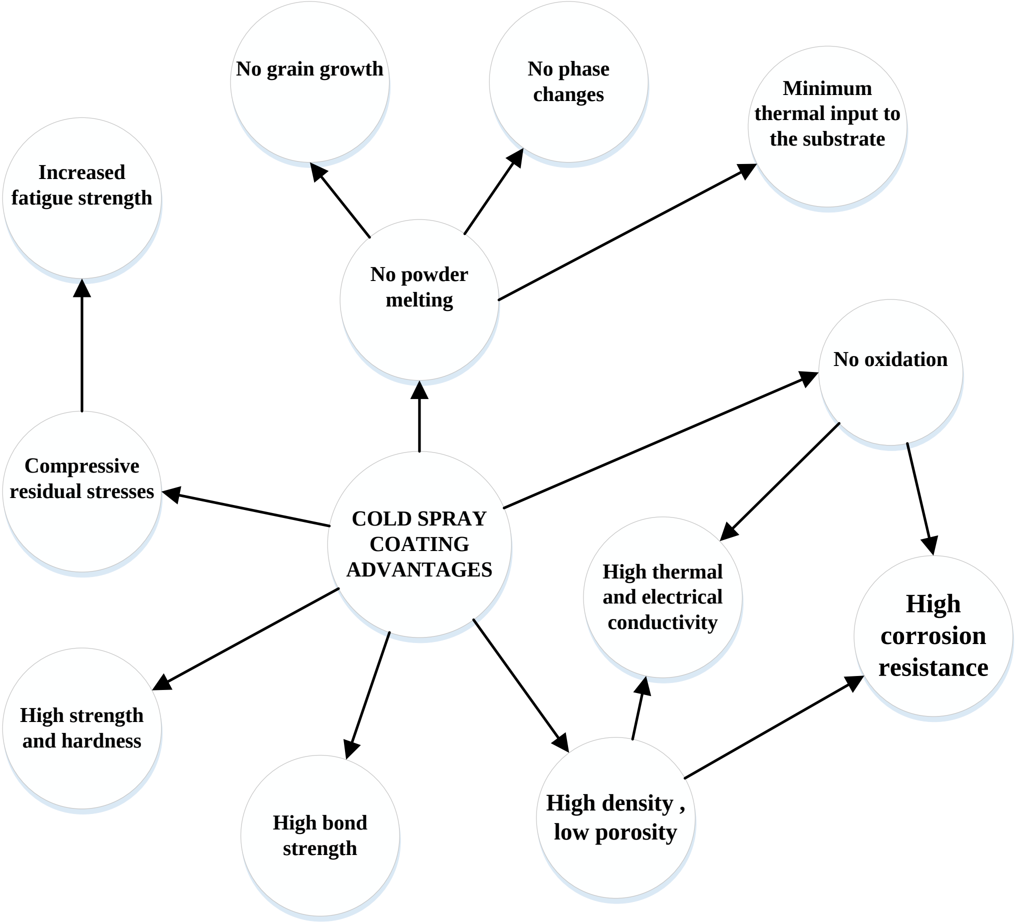
2.3.3 Benefits of cold spray

The benefits of cold spray are summarised in Figure 5 below. Villafuerte (2015) argues that most of these properties are interrelated; for example “no oxidation, high density and low porosity” properties of cold spray coatings maximise both its thermal and electrical conductivity, which may favour high corrosion resistant conditions. Karthikeyan (2007) argues that the main benefit of cold spray technology lies in its ability to provide solid state deposition that results in coatings of unique characteristics, e.g., oxide free.

There are generally two types of advantages of cold spray technology i.e., manufacturing advantages and the deposited material property advantages. The advantages depicted in Figure 5 are the deposited material property advantages. Manufacturing advantages come from the novel idea of cold spray presenting an environmentally friendlier alternative to producing new machinery or parts by reworking them. Even better, it cuts the waste footprint short because the technology is currently used as a remanufacturing tool (Villafuerte, 2015).

In essence, cold spray technology reduces or eliminates the adverse effects manufacturing practices have on the environment. However, like any other process, cold spray has potential environmental, health and safety risks such as noise pollution and powder handling (Villafuerte, 2015). A detailed review of the benefits and limitations of the technology are outlined in Villafuerte’s recent book titled Modern Cold Spray. Process and Applications.

Figure 5: Summary of cold spray coating property advantages



2.3.4 Limitations of cold spray

This section highlights some of the challenges or limitations of cold spray technology discovered to date. There are many challenges with regards to the technology whether in research or development; however, only a few alarming limitations will be noted. Addressing these challenges could potentially open avenues for the technology in many industries.

2.3.4.1 Material

The near zero ductility caused by plastic deformation of the spray particles is one of the greatest challenges with cold spray technology. The technology is said to be limited to a small range of metals or composites that have a sufficiently low-temperature ductility. Such metals are but are not limited to aluminium, copper, nickel, titanium, tantalum, silver and zinc, just to name a few (Champagne, 2007). Other coatable materials are blends of metals or non-ductile species such as Al-Al_2O_3 (Irrisou, Legoux, Ryabinin, Jodoin & Moreau, 2008), WC-12Co blended with nickel (Melendez & McDonald, 2013, cited in Villafuerte, 2015).

Cold spray has also been successful in coating composites such as stainless steel, nickel-based alloys' (Inconel, Hastalloys) bond-coats (MCrAlY), metal-metal coatings like copper-tungsten (Cu-W) or copper chromium, metal-carbides like aluminium-silicon carbide (Al-SiC), metal-oxides like aluminium-alumina (Smith, 1999). Most of these materials are commonly used in components and panels in the aerospace and automotive industry. Materials such as ceramics and other non-ductile materials are still limited for coating with the use of cold spray because of their low plasticity. Ongoing research to increase the range of materials eligible for cold spraying continues.

2.3.4.2 Process

The high velocities and flows necessary in the cold spray process are said to result in high nitrogen/helium gas use (Villafuerte, 2015). This is one of the reasons for the high operational costs and lack of implementation in industry. Helium and nitrogen, the commonly used gases, are expensive.

2.3.4.3 Operations

The limitation of the availability of standard specifications is one of the greatest concerns with the technology. Most companies have their internal specifications; however, it is rather alarming that they are not available in the public domain for reference or use. According to Villafuerte (2015), one of the standard specifications that have been made readily available for public use to date is MIL-STD-3021 by the U.S. Army Research Lab, ARL, which is covered extensively in Chapter 12 of Villafuerte's *Modern Cold Spray: Materials, Process and Applications*.

Other limitations are the necessary resilience of the substrate materials that is essential for successful coating, i.e., the substrate material has to be hard enough for coating, and it is a line-of-sight process, making it difficult to spray inside surfaces. The poor line of sight of the sprayed substrates, such as pipes, is also an important limitation to be improved (Marrocco, 2008; Villafuerte, 2015).

2.3.5 The fourth industrial revolution and cold spray technology

Cold spray technology is one of the few technologies at the heart of the fourth industrial revolution. It has presented itself as an enabling technology for the use of several materials in high-performance industries' critical components. These materials might have been noted previously to have desirable properties; however, because of other material properties' limitations, implementation has not been widely deployed. Through material substitution enabled by cold spray technology, the automotive industry is able to produce faster lightweight cars which are fuel efficient.

The technology's ability to build plastic parts on demand which would have been traditionally build out of metals and its alloys, enables the construction of lightweight vehicles much quicker than before. The 3D printing also features in this revolution as it speeds up development times through prototyping, shortens or diminishes supply chain and enables remote parts production in automotive plants (Giffi et.al, 2014; Pathak et.al., 2017). The fourth industrial revolution also seeks to create smart factories, in which machinery run diagnostics and maintenance plans, logistics and supply chains are automated and on-time delivery is high. By creating "Smart factories", the revolution will change the value chain, i.e. the interaction of the virtual and physical systems of manufacturing. This allows for product customisation, flexibility and shorter lead times (Schwab, 2016). Cold spray technology is one of the technologies at the heart of this revolution through all these aforementioned features. These abrupt changes associated with the fourth industrial revolution have introduced a great deal of volatility, ambiguity and uncertainty as the race to become the first and remain relevant becomes even more vicious. Moreover, because the consumer market changes faster than in the past industrial revolutions.

2.3.5.1 Coatings of oxygen sensitive materials

Thermal spraying of oxygen sensitive materials such as titanium, aluminium, copper and magnesium is increasingly difficult due to the high rate of oxidation from the use of elevated temperatures. This challenge limits the use of conventional thermal processes such as plasma spraying on such materials.

The use of elevated temperature coatings introduces a brittle phase and microstructural defects such as oxides, porosity and phase transformation. These degrade the electrical, mechanical, and thermal properties of the sprayed substrate (Hofsajer & Botef, 2013). For example, Smith (1999) argues that although copper possesses high electrical and thermal conductivity, a plasma-sprayed copper has 15 percent of the conductivity of oxygen-free-high-conductivity (OFHC) of copper. He further argued that a defect-free cold-sprayed copper has 85 percent of the conductivity of OFHC copper (Smith, 1999).

Tin-bronze coatings are another example of materials used in the automotive industry that are oxygen sensitive. Their high strength, elasticity, good abrasion, and corrosion resistance properties render them important in automotive applications. However, bronze has high porosity and thus poor electrical conductivity. Tin-bronze and tin-bronze/quasicrystal (AlCuFeB) may be cold sprayed to improve these properties (Hofsajer & Botef, 2013).

It is evident from numerous studies such as those conducted or cited by Hofsajer et.al(2013), Sova et al.(2013) ,Moridi et al. (2014) and numerous authors that cold spray technology may be used to coat oxygen- sensitive materials to avoid oxidation and phase transformation that occur at high temperatures. These studies show improved micro hardness, density, porosity and conductivity upon cold spray application.

2.3.5.2 Nanostructured coatings

Nanostructures' exceptional attributes such as mechanical strength, wear resistance, thermosphysical and electrical properties render them materials of great interest in recent times. Even so, their processing and handling on an industrial scale present great challenges. What remains challenging and limits the use of nanocrystalline metals is making sure that the consolidation process can retain the nanostructure properties (Moridi et al., 2014).

Conventional thermal spray processes and powder metallurgy lead to unacceptable grain growth upon coating. In contrast, cold spray technology does not introduce grain growth to the material due to minimum thermal input during processing. The input preserves the desired structure of the substrate. Accompanied with ball milling, Moridi et. al. (2014) argues that cold spray technology is able to produce a complete nanostructured coating of high quality. This was also validated in a study of the "Consolidation of AL_2O_3/Al nanocomposite powder by cold spray," which showed that good quality coatings with low porosity are obtained from a combination of cold spray with milled Aluminium (Poirier, Legoux, Drew, & Gauvin, 2011).

The preservation of the powder properties of nanostructures help retain their attractive attributes such as lower resistivity and thus higher conductivity (Hofsajer & Botef, 2013). Cold spray technology has enabled the use of nanostructures in different industries such as its application in the electrical and electronic industry, due to its good electrical conductivity.

2.3.6 Current practices and initiatives in industry

In the following section the current applications of cold spray technology are examined. First, applications of the technology across different industries using different substrates are discussed. Table 1 further shows the property benefits of all substrates that were cold sprayed in the different industries (Pathak & Saha, 2017). The sections later dissects some of the latest developments in industry with regards to cold spray technology i.e. investments and challenges.

Table 1: **Current cold spray coatings applications in all the industries**

Coating materials	Primary property benefits	Applications
Ceramic coatings (glass, cement, linings)	Improved corrosion resistance and wear resistance	Furnace component, heat-treating equipment, chemical-processing equipment, heat exchangers, rocket-motor nozzles, exhaust manifold, jet-engine parts, and nuclear power plant components
Zinc-aluminium alloys	Sacrificial galvanic protection for corrosion resistance, oxidation, and sulfidation resistance	Bridges, ships, and other large structures, power boilers and other high temperature uses
Cobalt-based alloys	Improved wear resistances and high impact strength	Gate valves used in offshore industry, automotive engines, chemical processing and hydro-steam turbine industries
Nickel-based alloys	Good corrosion resistance to wear, oxidation and high temperature corrosion	Mill rolls, pumps, piston extruders and glass-mould industry. Aerospace, automotive, medical devices, agriculture, wearing plates and pump bushing.

Iron-based alloys	Improved wear resistances	Aero gas turbine, hydro or steam turbines, steel, rolling mills, cement, chemical processing and textile industries
Hard chromium	Improved wear resistances, heat abrasion, and high corrosion resistance	Hydraulic pistons and cylinders, piston rings, aircraft engine parts, plastic moulds, etc.
Copper, silver, aluminium and titanium alloys	Excellent electrical conductivity or superior corrosion resistance	Applications that require excellent electrical conductivity or superior corrosion resistance are the two areas of greatest interest to motive and electronics, etc.
Organic coatings (paints and polymeric or elastomeric coatings and linings)	Improved corrosion resistance, wear resistance, aesthetic appearance and excellent impact resistance	Aerospace, infrastructure, machine repair, agriculture harvesting components, oil drilling parts, etc.

From Table 1, it can be deduced that cold spray technology has seen adoption in different industries to different degrees across the world. However, the technology has yet to see any industrial application within the South African automotive industry.

Cold spray technology has had challenges and setbacks in implementation across different industries and countries; however, it has attracted a great deal of attention, buy-in and investors across the globe. Initiatives in the form of annual international conferences such as the International Thermal Spray Conference (ITSC) and the amount of investment in research and development by either private companies, educational institutions or the government over the last two decades attest to this (S. Singh et al., 2012; ASM Thermal Spray Society, 2013). This awareness and interest are a great start if the technology is to conquer the difficulties it has experienced to date.

In light of the benefits and great potential of this technology, a consortium of companies including Ford, Siemens Westinghouse, K-Tech, Pratt &Whitney, and ASB Industries started funding Sandia National Lab to do research on cold spray technology about a decade ago. To date, because cold spray is still relatively new to the market and industry as compared to conventional thermal spray technologies and its challenges, most of its facilities are housed in research laboratories in educational institutions or research houses. Educational Institutions such as Penn State University (United States of America), University of the Witwatersrand (South Africa) and Cambridge University (United Kingdom), to name a few, are institutions that have cold spray facilities and take pride in its research and development (Karthikeyan, 2004).

Research on cold spraying technology within this decade include a focus on process optimisation, optimisation of nozzle design and specifications that are at the heart of the operation as well as experiments that explore the conditions under which a wider range of materials can be cold sprayed. Some research into increasing particle velocity using computational methods in fluid dynamics and thermomechanical modelling have also been necessary for automated systems (Gartner, Stoitenhoff, & Kreye, 2006).

There are also several companies in aerospace, automotive, component/parts manufacturers and electronics industries that have implemented cold spray technology to supplement and expand their existing coating systems. Such companies include ASB Industries, TST Engineered Coating Solutions, Praxair Surface Technologies and Guyson (ASM Thermal Spray Society, 2013), all of which use the technology as a tool for the fabrication of components, preparation of protective surfaces, and refurbishment of mis-machined and damaged parts (Sova et al., 2013).

Companies such as Yazaki, an automotive parts company, has implemented the cold spray system and is said to have already produced copper harnesses for automobile electrical applications (Karthikeyan, 2004). More recently, it has been used for sealing up leakages and restoration of old machinery, the shaping and restoration of parts at automotive service plants, and the repair and retrieval of aircraft parts and plate stocks (Shkodkin, Kashirin, Klyuev, & Buzdygar, 2010).

Gas turbines operate under aggressive conditions such as high temperatures. These high temperatures make the gas turbine components prone to degradation due to high temperature creep and oxidation, crack formation by thermal stress, etc. (Ogawa & Seo, 2011). In gas turbine technology, the higher the gas temperature the higher the efficiency. This puts materials that can withstand higher temperatures under great demand. The dilemma of operating at high temperatures to obtain higher efficiencies at the cost of the gas turbine components faces many industries. Cold spray technology has thermal barrier coatings (TBC) that allows applications to use high gas temperatures well above the melting point of the substrate. There are numerous researches and experiments in industry such as that by Ogawa and Seo (2011) that used the nickel-based super alloy Inconel 738LC (IN738LC) to establish the possibility of applying cold spray techniques to repair gas turbine blades and other components.

2.4 Conclusion

In this chapter, pertinent literature to the topic, cold spray technology, was introduced. First, special focus was placed on local and global trends and challenges within the automotive industry. Thermal spray processes and its market were introduced and the differences between thermal and cold spay processes noted. The discussion highlighted the cold spray process as well as its benefits and limitations. Finally, some of the industrial applications and material benefits of the technology were described. This chapter highlighted that cold spraying is believed to be a great tool for efficient operations relative to other technologies. It also highlighted the drawbacks of cold spraying that have hampered its widespread application in industry. In the chapter that follows, the structure used for this research in pursuit of establishing a framework for effective automotive operations it outlined. The validation methods are also explained.

3. METHODOLOGY AND VALIDATION

Research is defined as a scientific and systematic search for pertinent information on a specific topic (Hornby, 2010). For most traditional researches, it is expected that the researcher would collect data or make an analysis. The research methods usually differ according to the type of research, type of information or data to be collected, availability of resources, and the structure of the research.

This research is a qualitative research. Qualitative research is characterised by the need to gain better understanding or perspectives of a topic and/or the motivation and reasons behind certain actions and setups in a given environment. The intention is to generate ideas and/or hypothesis with the end goal of proposing a realistic and reasonable solution (MacDonald & Headlam, 2006). Qualitative methods are non-mathematical and non-statistical. The data collection methodology may take many forms that generally include words (structured/semi structured interviews, questionnaires, quizzes), pictures and/or objects.

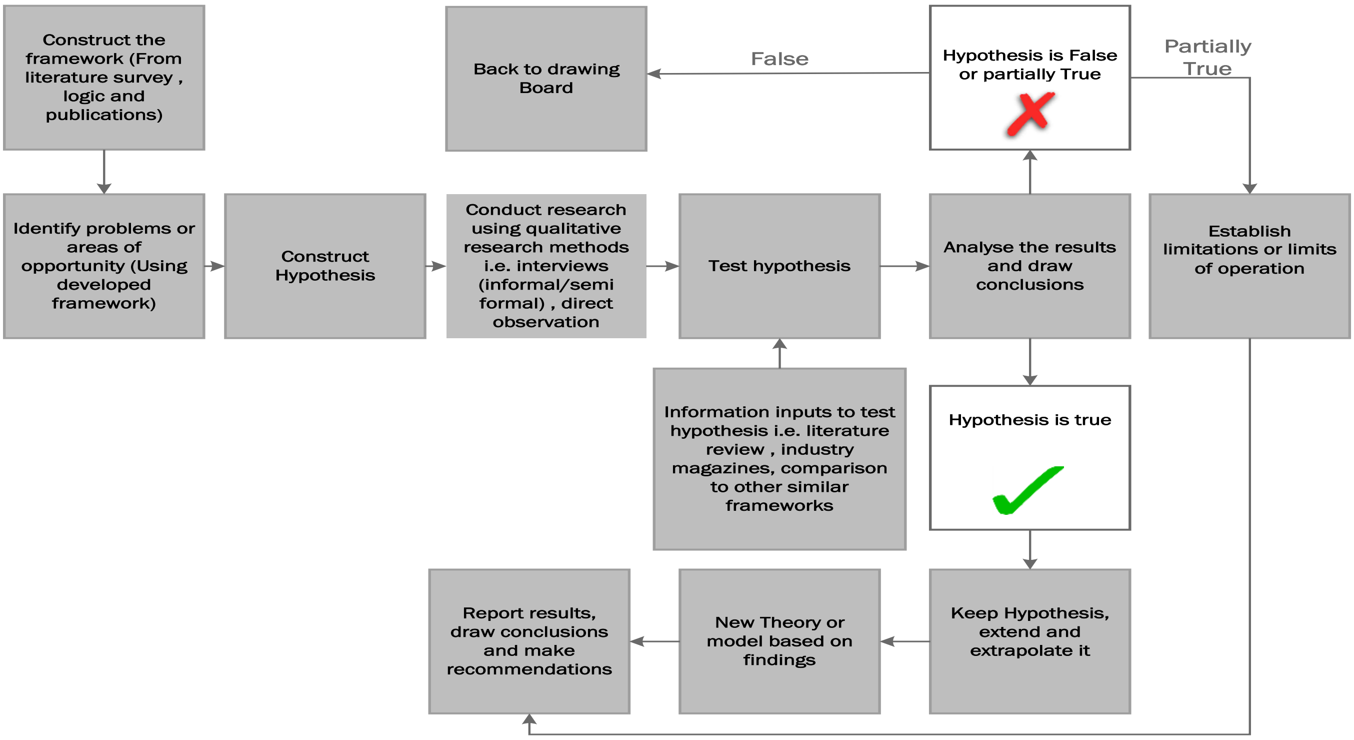
3.1 Research Method

The aim of the research was to create a framework to establish how the adoption of cold spray technology might assist in establishing effective operations within the automotive industry. The framework can also be used for the identification of problems and opportunities that could be resolved using cold gas spray technology. The qualitative research and its data collection methodology suit the research because the intention is to analyse and understand the operations of the automotive industry in pursuit of establishing a better understanding of how the industry operates, its current and future objectives, its options and the motivation behind the future goal of mobility and what it means for the vehicle design, production and most importantly end user. All of these are in line with the characteristics of what a qualitative research is.

The research consists of two sections. The first section is to develop a theoretical framework using the literature reviewed and logic. The second part will be to use the framework developed to identify opportunities and problems that the application of cold spray technology would hold for the automotive industry. The two sections are inseparable because the latter uses the arguments, experiments and applications in the former to identify opportunities, and argue for the validity of conclusions. Development and evaluation of the framework will be presented side by side, where arguments will be put forth and opportunities will be identified immediately afterwards.

In addressing the second step, the automobile (car) and its respective components will be the focus. The research will not use a specific model or OEM but rather a general 21st century vehicle, its components and their materials. This could include breaking complex issues into smaller manageable sub-problems and thus a number of hypotheses. Qualitative methods, such as informal written interviews and semi-structured interviews with experts in the industry who are specialists in their field will be used to identify and confirm problems or opportunities. The use of qualitative methods such as informal/semi structured interviews gives the researcher a certain degree of flexibility to pursue ideas and questions as they emerge during the interview to gain better understanding of the issues. This is in contrast to strictly structured interview (MacDonald & Headlam, 2006). The schematic diagram below summarises the methodology to be followed for the research.

Figure 6: Method of execution of the research



The framework will be developed using the literature reviewed and logic, and the framework will be used to identify challenges and opportunities. The literature review and logic thus forms the basis for the creation of the hypotheses. The hypotheses will be tested or validated using the literature and more specifically, comparison to frameworks of the similar kind. The constructed framework's ability to correctly identify problems in the field adds to its validity and applicability in the industry.

When a hypothesis is found to be true, the findings are the basis for more research where a theory can formulated and findings reported. This process will validate the framework's ability to identify cold spray applications and/or assist towards establishing efficient automotive industry operations. If the hypothesis is not supported then the issue is analysed to find the framework's limitations. The validation is not conducted with the intention of retaining the hypothesis, but to identify the framework's weaknesses in order to strengthen the framework and broaden its applicability. If the hypothesis is found to be partially true, it is imperative to establish the limits under which it is true and false. These partially true hypotheses might hold under very controlled or unfamiliar conditions; such conditions should not be overlooked or disregarded.

3.2 Sampling

The research will sample specialists knowledgeable on the automotive industry, fourth industrial revolution and its emerging technologies. Sampling will continue until "saturation of knowledge" has been reached, i.e., the researcher finds the same responses from different interviewees (Bertaux, 1981). The manner of determining how saturation of knowledge is reached or passed during sampling is uncertain and varies from one research to the other. Other factors that may influence the decision to stop sampling include the availability of desired and relevant specialists, the experience level of specialists, and the complexity of the content of research. The sample size is not rigid or defined; however, Guest, Bunce and Johnson. (2006) found that 12 interviews of a homogenous group is required to reach saturation. Conceptually, saturation may be the desired end point of data collection (Guest et al., 2006). With all these said, a minimum of 12 interviews will be conducted.

3.3 Validation Methods Used

Validation, by definition, is simply the process of establishing confidence in the usefulness of the framework with respect to whether it possesses a satisfactory level of accuracy for implementation in the real world or applicability in a similar setup and can thus identify and operate as intended without much difficulty (Martis, 2006).Validation of a framework is an important factor to ascertain the credibility of the framework. Martis (2006) argues that though validity is an essential part of a research, there is no single test that would assert the validity of a framework; rather, the level of confidence and thus validity in the framework increases as the framework passes more tests of practicality (applicability). The framework will be validated in the following ways (Martis, 2006):

- Correct identification of problems and opportunities in the field using the developed framework is one form of validating that a framework works. This form of validation asserts that the framework is applicable and is successful in finding problems and opportunities for cold spray technology.
- **Comparison to other frameworks** will be established by comparing the proposed framework with other 'valid' published frameworks of similar nature or within the automotive or transport industry such as Botef (2015) "Framework for Efficient Aerospace Operations" and "Cold Dynamic Spray Intergration Complexity".
- A combination validation scheme, as proposed by Khazanchi (1996), is implemented. The validation scheme proposed by Khazanchi includes points to validate concepts or frameworks. Applicable to this research are the following:
    - Is it plausible/reasonable? This criterion is useful to assess the apparent reasonableness of an idea and could be demonstrated by deduction from past research or theories.
    - Is it predictive? Would the concept or framework be able to predict, or at least demonstrate that given certain antecedent conditions, the corresponding phenomenon could be expected to occur.
    - Is it feasible? Does the proposed solution or framework have the potential to be implemented in the industry; in other words, is it possible or practical?
    - Is the framework effective? An effective framework should at least be able to serve the intended scientific purpose.

These are only a few points under the proposed validation method by Khazanchi (1996). These validation methods will be used to establish the credibility of the framework. The framework that shows how all the arguments put forth assist in establishing effective operations is another form of validation.

3.4 Conclusion

The intention of the research is to create a framework to establish how cold spray operations could assist in establishing effective operations in the automotive industry. The research is a qualitative research. The methodology consists of two steps, i.e., the development of the framework using a literature review and logic, and field work, which involves conducting semi-structured interviews with field experts or specialists

The created framework will be tested for validity through previous validated frameworks, and its ability to identify problems and opportunities in the field and show how effective operations are attained measured against the key performance indicators. Chapter 4 is also focused on evaluating the framework developed using Kazanchi’s (1996) model.

4. RESULTS AND ANALYSIS OF DATA

4.1 Introduction

Prior to the 1970s, plain carbon steel and cast iron were the materials of construction for motor vehicles. Over the years, this has slowly changed due to new and different industry requirements such as more stringent environmental regulations, reduction in vehicle weight and the need for improved engine efficiency. This has thus resulted in automotive OEMs' quest for improved designs that encompass material substitution, and that has led to the consideration and use of advanced materials such as high strength steel (HSS) and advanced high strength steel (AHSS) (Mallick, 2012; Musfirah & Jaharah, 2012). Advanced strength steel (AHSS) and High strength steel (HSS) are materials with a minimum tensile strength of 550 MPa and 290 MPa respectively. HSS have lower elongation values than AHSS, and the latter is commonly used in complex applications that require high formability. These materials are more prone to cracking during a collision or repair processes, particularly if heat is introduced to the process because the materials are brittle. As a result, most automotive manufacturers used to resort to plain carbon steel which however has lower corrosion resistance. Examples of HSS and AHSS materials currently being used and considered for automotive industry applications is titanium, aluminium, magnesium etc (Mallick, 2012).

Cold spray technology's ability to rework materials without introduction of heat higher than melting point of substrate and feedstock has enabled material substitution. The use of HSS and AHSS allows for gage downsizing, load carrying capacity and crashworthiness improvements of the structure of a vehicle(Mallick, 2012).. These aforementioned are key factors for consideration during weight reduction. The market for magnesium and aluminium as the largest structural metals of interest in the automotive industry has grown drastically over the past few years. A growth of nearly 15 percent per year and over 80 percent for each respectively has been documented (Musfirah & Jaharah, 2012).

In the modern automotive industry, it has become important but more difficult to profitably produce automobiles whilst ensuring product quality on the production line and in the field throughout the lifecycle of the vehicle. With the increase in demand of these alternative natural resources, they have consequently become costly. This challenge presents a new market opportunity for restoration and repair technologies to maintain the high product quality the industry desires. In addition, OEMs experience high production losses in the form of defective components and panels that are detrimental to the efficiency, profitability and thus the survival of the business. These repair technologies assist in the recovery of these units, thus ensuring that production volume, quality and profit targets are met.

The challenges and predicaments experienced in industry have already been discussed. The argument for cold spray technology as a technology of choice over conventional thermal spray technologies to support the automotive industry in the production and restoration of the body panels from defects, damages and material failures with specific materials that are deemed critical to the automotive industry has also been covered. The following section illustrates how the technology is suitable for use in industry currently and going forward.

4.2 Findings and Analysis

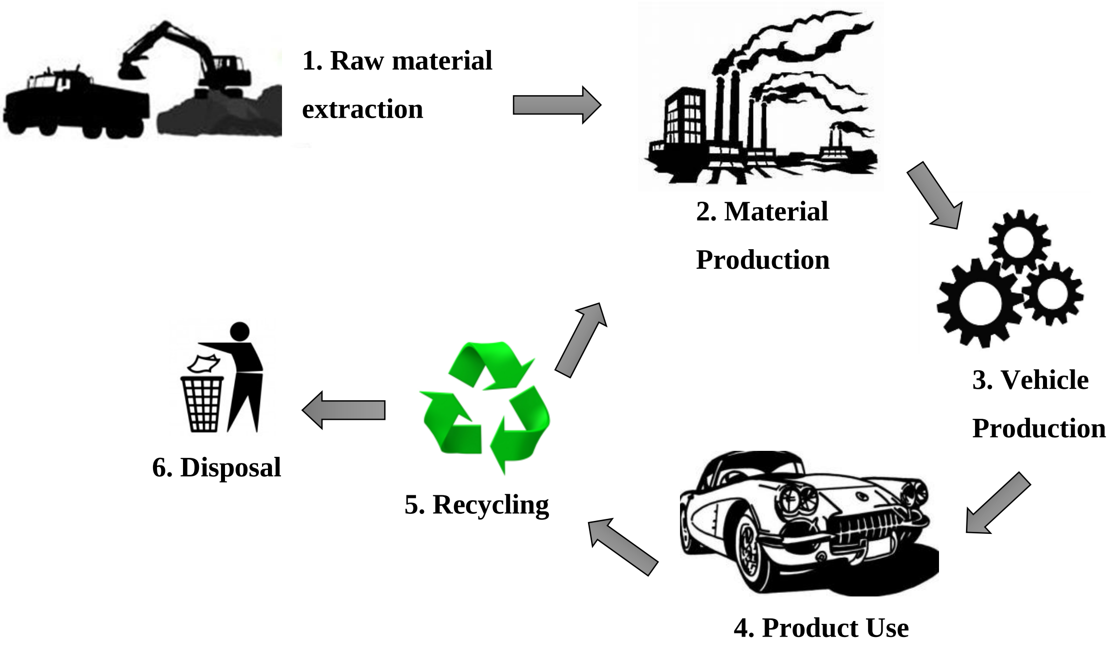
In the following sections, the vehicle and its current material of construction and possible alternative applications to consider in the near future will be dissected. Also explored, are the hypotheses constructed that are deemed essential to establish efficient automotive operations. In this section, all the constructed hypotheses will be tested using information from the literature survey; industry experts' publications, experiments and correspondence; and industry applications in pursuit of constructing a framework to establish efficient operations.

Before dissecting the vehicle, there are two important factors that drive the use and acceptance of new technologies within the market to ensure a proposed technology is environmentally friendly, sustainable and profitable. These factors are: cost implications and life cycle analysis.

4.2.1 Life cycle analysis summary

Recent years have witnessed the successful substitution of materials such as in the powertrain from steel to aluminium and magnesium. To date Mahindra, General Motors, Ford Fiesta and Figo are current vehicle models in mass production with an aluminium engine block and cylinder head (Bhargav, 2013). The use of these lighter materials such as aluminium and magnesium alloys is usually accompanied by adverse environmental effects as compared to conventional vehicle materials such as steel. This occurs particularly during the extraction and processing of the raw materials at press plants before they reach the automotive OEMs (Sullivan, Kelly & Elgowainy, 2018).

Figure 7: Life cycle diagram of a vehicle



According to Sullivan et al. (2018), most of these alternative materials' production stages have high energy consumption and thus emit more greenhouse gas emissions, which in turn, influences the life cycle of the vehicle negatively. Though this might be the case, from the vehicle production phase and functional unit point of view (product to use), there is an overall positive net influence in substituting steel with aluminium and magnesium (Sullivan et al., 2018). Based on this argument, the substitution of steel and cast iron with aluminium and magnesium alloys yields a lower impact throughout the entire life cycle of the vehicle and can be used or considered not only for the powertrain but the entire vehicle.

The recyclability of the materials in question is of paramount importance if the industry is to consider the replacement of conventional steel and cast-iron panels with aluminium and magnesium and their alloys. Due to recent increases in both consumption and application of these alloys, the amount of scrap generated from these processes is also expected to increase proportionally, i.e.; from extraction, processing, production line ,aftersales and product use (Ilic, Korac, & Kamberovic, 2002). Research of the recycling of aluminium and magnesium alloys shows that these alloys use approximately 5-10 percent less energy and emit 5 percent less greenhouse gases when compared to the primary production. Over one third of the aluminium produced globally originates from old, traded, and scrapped recycled aluminium components. The material can be continuously recycled without loss of any properties. Its economy is circular and is thus better termed "cradle-to-cradle" and not "cradle-to-grave" (GARC, 2009). Recyclability is an important aspect of the process as these metals increase in both demand and scarcity. This removes the adverse environmental effects and emissions associated with the primary extraction and metallurgical processing phases.

It is therefore apparent that magnesium and aluminium alloys support sustainability drives and initiatives across the globe. The lifecycle of the vehicle may have Red (as opposed to Green) sections, such as the material extraction and processing phase prior to reaching the OEMs, but it has an overall Green status from the production in the automotive manufacturing plant until the end of its lifecycle.

4.2.2 Cost benefit analysis summary

The maintenance of components forms an important part of the product life cycle. Without adequate and regular maintenance, components could easily fail before the expected period. The cost of maintenance of high-end critical components can be much lower than its complete replacement. Internal and external damages such as corrosion and wear and tear pose high risk not only in the automotive industry during production but also during product use in the field. This occurs particularly if components are exposed to aggressive environments such as high temperatures and pressure, slurries and debris.

Adequate repair technologies such as cold spray technology present great cost savings for customers and businesses for repairs, restoration of damaged and mis-machined components in the production line in job shops, panel beaters and aftersales facilities. Cold spray technology assists in avoiding complete replacements of expensive automotive parts eligible for coating, some of which are may be high-end, exclusive or discontinued models' components. The technology also assists in improving production output because returned or defective units are recovered (Pathak & Saha, 2017). This saves the costs of scrapping an entire unit or panel off the production line, which could cumulatively translate into millions.

As an additive manufacturing technology, it also offers OEMs the flexibility to produce parts on demand, thus supporting efficient manufacturing concepts such as just-in-time (JIT) and just-in-sequence (JIS) on production lines. Applying these concepts removes any waste associated with over production, costly inventory space and possible mismatch errors if the products have a variety of options produced on the same line. An example of this is metamaterials that are in essence rare ordered composites. Traditional metamaterials have a structured periodic lattice that interacts with an applied wave to produce unusual and useful properties such as negative refraction, artificial magnetism and near-field focusing. Today, most optical and electromagnetic metamaterials whose properties are determined only by their structures (cellular materials) are produced using microfabrication techniques in research settings (Pathak & Saha, 2017). Cold spray technology allows for on-demand production of these materials that are tailored for specific use. The technology thus saves businesses money in a variety of ways.

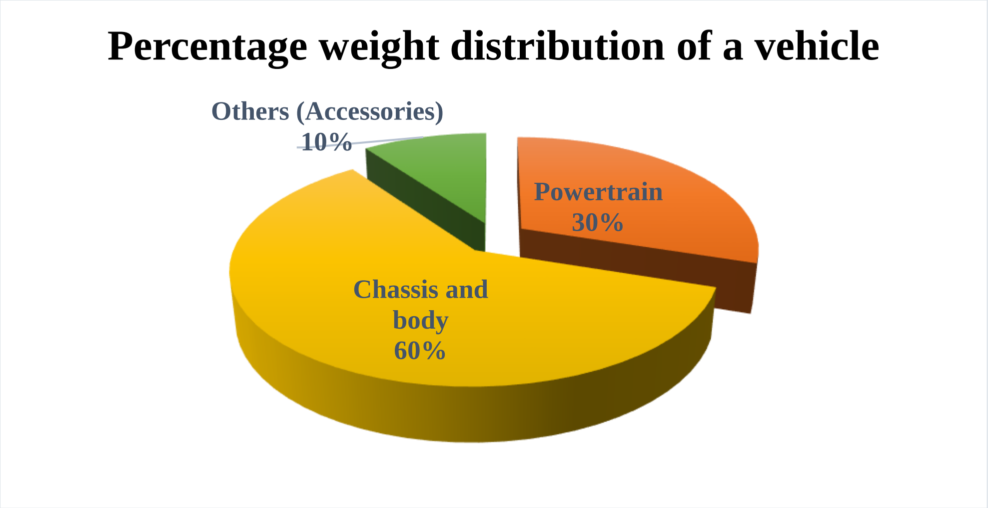
To quantify these savings, one would need to consider the process starting from extraction and processing of minerals (metallurgical processes), the processing (e.g., pressing processes), purchase by OEMs thereof, production of the vehicle (total CPU), transportation, delivery time, and the warehousing costs necessary for the complete replacement of panels (Pelsoci, 2015). This detailed cost benefit analysis is beyond the scope of this research. Pelsoci (2015) summarised the cold spray benefit analysis for aerospace panels using cold spray technology in his paper titled "Cost Benefit Analysis: ESTCP Funded Cold Spray Technology for DOD Applications." Another study documented by Karthikeyan (2000) in his paper titled "Cold Spray Technology: International Status and USA," showed that comparison between available technologies and cold spray leads to reduction in material input, reworks, finishing, and an overall deposition efficiency of 60-95 percent was obtained. This study was later used to develop different business cases to show the cost advantages of fabricating parts using the cold spray technology (Ghelichi & Guagliano, 2009). Even though the industries are different, for example, the automotive industry is more driven by volume as opposed to the aerospace industry whose average cargo fleet is 28 years old, the literature shows how the repair of critical components using similar materials of interest to the aerospace industry is not only cost effective for the automotive industry but also benefits businesses in general (Botef, 2015).

4.3 Dissecting the vehicle

In this section, different aspects of a vehicle are dissected with respect to their current and future materials of interest in the automotive industry. According to Mallick (2012), a vehicle can generally be divided into three divisions by weight, i.e., the powertrain, which includes both the engine and transmission components; the body and chassis components, such as hang-on parts; and other accessories such as the trim/interior of the vehicle, which includes but is not limited to seats, cockpit, wiring, décor strips and centre consoles.

Figure 8 shows that the chassis and body components, followed by the powertrain, have the most weight contribution towards the overall weight of the vehicle. Weight reduction in these areas of the vehicle presents great opportunities for automotive manufacturers to meet their short- and long- term goals of mobility.

Figure 8: Schematic representation of the weight breakdown of an average vehicle (Mallick, 2012)



4.3.1 Powertrain

The powertrain of the vehicle remains an important area of focus in both research and development; it is a group of components that generate and deliver power to the vehicle. This group of components are an integral part of the vehicle. The powertrain has high complexity and is of paramount importance to the performance of the vehicle. The engine forms part of the powertrain, and it commonly includes the piston, camshaft, timing chains, rocker arms, and other parts. The cylinder block, also known as the engine block, can be seen when the engine is fully stripped. It is one of the highest weight contributors of the powertrain with approximately 20-25 percent weight contribution (Nguyen, 2015).

In the past, powertrains were commonly made out of cast iron alloys due to their high availability, low costs and excellent mechanical properties such as high strength. Components such as transmission, engine blocks and cradles were initially made of cast iron for years before other alternatives were considered .As years passed, the powertrain developed and increased in complexity; the cast iron weight contribution to the powertrain has become limiting. The need to reduce the powertrain weight through material substitution to achieve fuel efficiency, better performance and lower greenhouse gas emissions became an urgent concern. The use of lighter, high strength alloys such as aluminium and magnesium were thus explored. However, the industry is still experiencing challenges with regards to high material cost and corrosion susceptibility in these materials of interest. Moreover, with these changes in materials, OEMs have had to further consider the necessary changes in production processes and technologies to support the substitution.

Engine blocks, engine cradles and transmission housings are a few examples of common components constructed of aluminium and magnesium in industry to date (Villafurte & Zheng, 2011). Most of the material substitution in industry has been widely deployed in low volume models such as sports cars because of necessary high material and insurance costs. As a result, most OEMs have had to resort to combining materials to achieve a balance between weight saving and costs, e.g., the use of general 1000 and 3000 series aluminium alloys. The Aston Martin Vanquish is a typical example of low volume models (~350 units per annum) that uses a combination of a wide range of materials. A mixture of carbon fibre, aluminium and steel are used for the following: sub-frame carrying the engine, transmission, front suspension, cylinder heads and blocks (Crolla, 2009). Other applications of aluminium in the powertrain and associated components include the brackets, brake components, suspensions (control arm and supports), steering components, air bag supports, steering shafts, knuckles, heat exchangers, radiators and instrument panels (Miller et al., 2000).

The use of cast iron in engine blocks and its associated components is still available on the market as it is still inexpensive relative to other materials of interest. It is also evident that more automotive manufacturers are substituting cast iron with lighter and stronger alloys for various reasons such as costs and material suitability. Ford is another example of an automotive manufacturer that uses a combination of iron and aluminium in the powertrain to achieve cost reduction, weight saving and longevity/strength. Models such as the Ford F-150 have a twin-turbocharged Nano V-6 engine constructed out of a “two-piece” block consisting of compacted graphite iron (CGI) sandwiched between aluminium heads and a thick die-cast aluminium frame. This application led to a weight saving of 317 kg of the total weight of 2983 kg, thus making it 10.6 percent lighter than its predecessors (Mallick, 2012; Giffi & Gangula, 2014). This gives the engine a great balance of strength, reduced costs and considerable weight saving. The general trend in industry is that most aluminium applications are in petrol/gasoline vehicles as opposed to diesel vehicles because of the latter’s different requirements, such as robustness and high combustion pressures (Nguyen, 2015).

Recent research and development efforts in magnesium alloys manufacturing processes have given rise to two magnesium alloys commonly used in the engine block namely AMC-SCI and Compacted Graphite cast iron (CGI) (Nguyen, 2015). These alloys have a competitive price, high temperature creep, lower weight, and double the fatigue limits (high strength) relative to aluminium and cast iron. These are a few of the properties that have made them popular for powertrain applications. Moreover, conventional pressing and sand-casting processes can be used, which reduces the necessary investment. These alloys are currently used in V6 and V8 cylinder blocks and heads in series productions around Europe, Asia and America in models built by Audi, Ford, Daimler, Scania, Chrysler and Hyundai groups (Dawson & Indra, 2012).

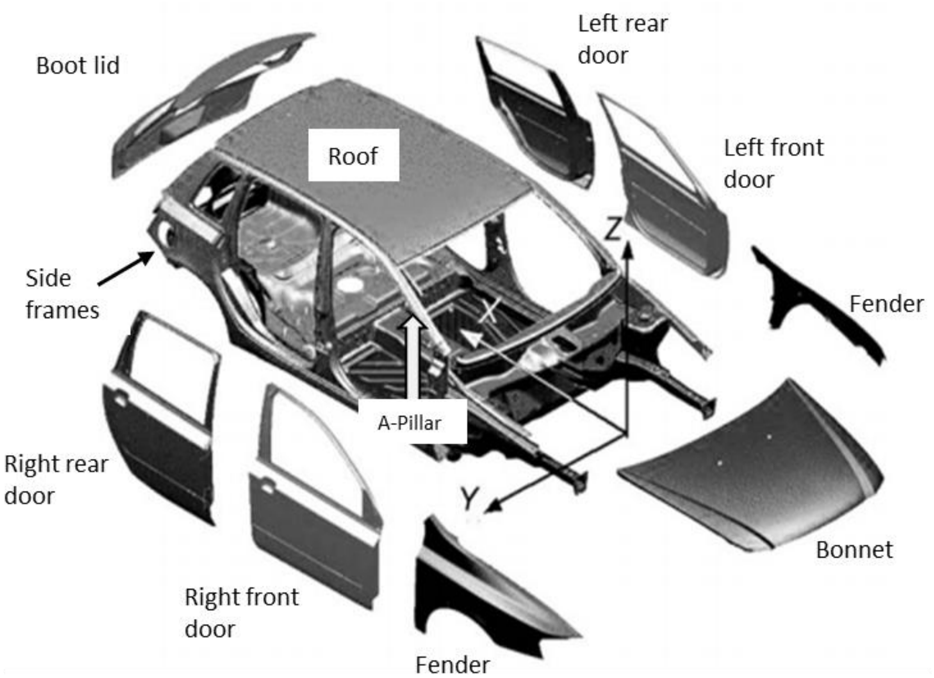
Magnesium alloys are commonly used for transmission cases and the structure of the oil pan, steering wheel, instrument panel, clutch brackets, cylinder blocks and head covers. They have also been recently used in the BMW composite engine (AJ62, a strontium containing alloy) and Mercedes Benz automatic transmission case (AS31, a silicon containing alloy) (Powell, Luo & Krajewski, 2012). These alloys are attractive for automotive manufacturers because they can be easily moulded into complex shapes (readily cast and machined), e.g., transmissions gearboxes (DeForce et al., 2009). Magnesium alloy’s susceptibility to severe corrosion has been a great challenge for application in industry, however this challenge has stalled the substitution of aluminium with magnesium in the powertrain applications that could have presented further weight savings because of magnesium’s lower density.

Material substitution is a complex process that requires production processes, technology, business strategies to be revised and be tailored to be products and component specific. Cold spray technology is envisaged as a suitable technology to enable the use of aluminium and magnesium alloys in various applications of the vehicle. More importantly, cold spray technology presents further reductions in vehicle weight by switching from aluminium to magnesium powertrains. In essence, cold spray technology enables unconventional materials eligible for coating to be considered for application in the powertrain. Through the superior coatings it offers for Thermal Barrier Coating (TBC), the corrosion protection necessary for such applications is provided.

4.3.2 Body and Chassis Components

Over the years, the structure and production of the body and chassis have evolved. In the 1900s, the chassis and the body were built as separate units widely known as composite bodies. The body was assembled on the chassis with mounting brackets. One of the latest common configurations includes monocoque bodies (Unibody), where several pieces of body panels are welded to the body frame that is attached to the floor group .The floor group, also known as the floor plan, is one of the largest pieces that is pressed out by stamping machines. Hang-on parts such as doors, bonnet (hood), boot lid (trunk lid/tailgate), side panels (fenders) and roof are also added using connecting bolts, nuts and hinges in either a best-fit automated line or manual operation using a labour force, as shown in the Figure 9 (Morello, Rossini & Tonoli, 2011). Other configurations commonly used in the automotive industry are outlined in Morello et al.'s book titled *The Automotive Body: Components Design*.

Figure 9: Body in white (BIW) with hang-on-part

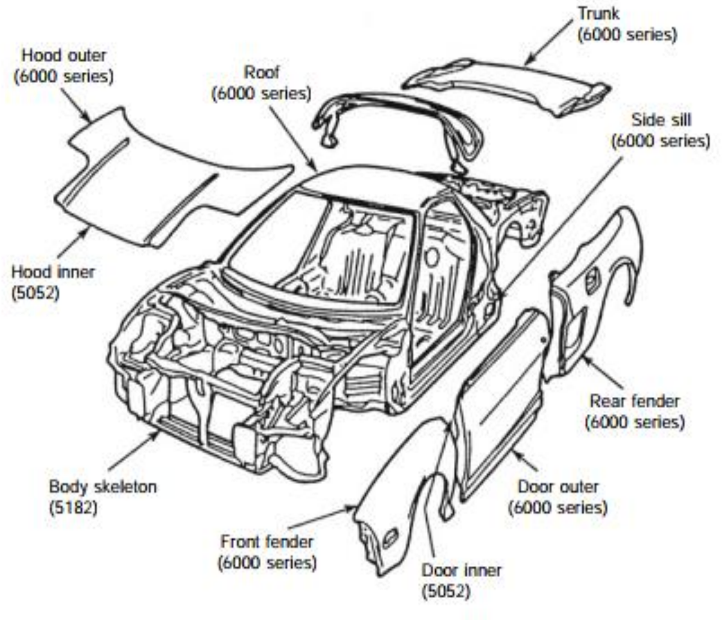


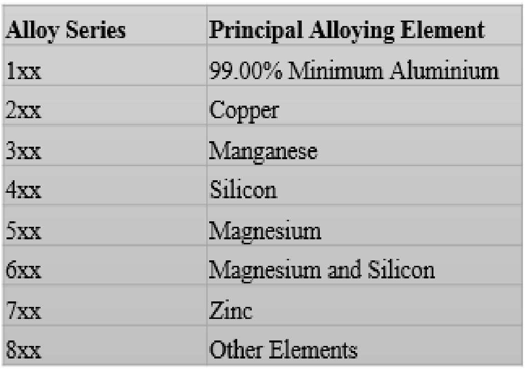
Note: Picture adapted from Morello et al. (2011).

The different configurations of the body and chassis play an important role as they affect the choice of material for construction, production dynamics (size and robustness of production), safety (e.g., general strength and crashworthiness of the vehicle), structural functions, space efficiency, weight distribution and partially affect aerodynamics. As the highest contributor towards the weight of the vehicle, reductions of the body and chassis present great weight savings.

Cast iron and steel have been common materials of construction for the body and its chassis components (Mallick, 2012). In recent years, more vehicles have deployed unconventional materials for construction of the Body-In-White (BIW) and its hang-on parts. The boot lid, bonnet, roof and front fenders of the various models such as Toyota (Crown), Subaru (Legacy and Forester), Mazda (Roadster), Mitsubishi (Lancer Evo.), Honda (Legend and S2000) and Nissan (skyline) models are examples of car models which have deployed aluminium alloys in more recent years. Models such as the Mercedes E-class and BMW 5 series use an all-aluminium alloy panel for the structure in front of the A-pillar and hang-on parts such as the front and rear doors (Sakurai, 2008). Most models including the BMW X3 still use a combination of steel and aluminium for the chassis and body for various reasons such as costs and safety. Figure 10 shows some of the vehicle parts and their respective alloys used in the Honda NSX sports car. Honda has led the industry in using aluminium for chassis-body applications (Crolla, 2009). It can be seen from the figure that the vehicle uses a combination of different aluminium alloys.

Figure 10: Aluminium alloys used in the Honda NSX vehicle





Alloy Series	Principal Alloying Element
1xx	99.00% Minimum Aluminium
2xx	Copper
3xx	Manganese
4xx	Silicon
5xx	Magnesium
6xx	Magnesium and Silicon
7xx	Zinc
8xx	Other Elements

Note: Picture adapted from Crolla, 2009

Audi has taken the lead in the mass production of high-end aluminium bodies made from two-thirds aluminium and one-third steel. It is reported that Audi in conjunction with Alcoa produced its Audi A8 and A2 from an aluminium space frame chassis (ASF). This model is said to be 40 percent lighter yet stiffer than contemporary steel monocoque (Miller et al., 2000; Crolla, 2009). The Ford AIV is built of stamped aluminium body structure with a total weight saving of 320 kg, translating to a 47 percent weight saving. Other manufacturers have also successfully built aluminium intensive vehicles that have been proven lighter than their steel counterparts such as the Renault, Lotus and Chrysler (Miller et al., 2000). The Honda NSX, unlike the Audi A8, used pressed aluminium sheets as opposed to extruding beams and an underlying frame, thus presenting a higher weight saving. This argument demonstrates the importance of the configuration of the chassis-body structure in the vehicle towards weight reduction and fuel efficiency. It also influences the choice of material of construction for the individual components. There are still certain critical areas such as the roof rail, inner longitudinal front and upper frame, B-post or pillar that are critical to the passenger safety during collisions that are still not deemed ready for material substitution in certain models. Through these examples, it has become clear that aluminium alloys are not confined to conventional casting applications such as in engine blocks and transmission housings.

In the late 1980s Al-Mg blended with Zinc, the 2000 series (Al-Cu) or 5000 series (Al-Mg-Si) alloys with Cu additions were commonly used for panels' construction. Aluminium alloys mostly used in modern day automotive industry include the 6000 series alloys (Al-Mg-Si) with a few exceptions of the 5000 series because of diversified industry requirements (Sakurai, 2008). This can also be seen from Figure 8. This attests to the notion that magnesium, aluminium and their alloys have become critical components in the automotive industry.

Magnesium alloys are generally used for seat frames, inner door frames, boot lid, inner door panels and wheels (Powell et al., 2012). Some magnesium alloys are also deployed in the front carrier structure and cross-car beam such as their application in the Range Rover Velar and Land Rover Discovery. The front seat frames of the Jaguar F-type are also made of die cast magnesium alloys, thus saving approximately 8 kg relative to its predecessor models. Mass production lines such as Ford, Chrysler and Volkswagen have also deployed the magnesium alloys for numerous generations and models for radiator support and gearbox and clutch housings. The greatest predicament with the use of magnesium is the severe corrosion to which the materials are susceptible, the low melting point and price instability. These are some of the reasons for the low use or deployment in industry.

The use of aluminium panels over steel for chassis and body structures introduces a corrosion challenge to the industry. This is because steel panels are zinc-coated to achieve acceptable paint durability. Cold spray technology is suitable for corrosion protection application on aluminium alloys and provides protection against general and high corrosion.

More recently, the industry has also used nanostructures in automobile components in low volume productions and in prototypes for hang-on parts such as doors in the BMW i8 (DesignWorks (BMW), 2018). Automotive manufacturers could consider the use of carbon nanotubes and nanocomposites in the future for mass production because of its density (thinner than human hair) and increased strength relative to steel. Carbon Bucky fibres comprise a tensile strength ~150 GPa about 50 times that of steel with 1/5th of the weight stronger than steel. Their use also assists in achieving lighter vehicles without compromising the stiffness and crashworthiness of the vehicle (Presting & Ulf, 2003). In light of the attractive features of this material, complexity of material handling and challenges associated with mass production of this material, cold spray technology is capable of supporting optimal material utilisation and ensuring zero waste through its rework application.

4.3.3 Assembly and other accessories

The assembly of the vehicle comprises interior and exterior furnishing and accessories such as the radiator grill, emblems, door handles, deep rail and side skirt that accentuate the features and appeal of the product for either aesthetics or protection of the car or consumer against environmental damage. The interior of the vehicle primarily comprises of the cockpit and all its associated wirings, centre console, seats, mats, trunk lid compartment and furnishings. The exterior comprises of the bumper, spoilers, front grilles and roof rails. Most of these are made of different fabrics (including leather), cardboard and plastic materials.

Nickel and chrome plated components have dominated in the past for decorative components (Additive Manufacturing for Automotive, 2015). Trim materials have variable specifications, but they need to be hard and heat and impact resistant depending on the components' individual functions. This is in order to ensure they are within crashworthiness and penetration resistance specifications of the automotive OEM, individual country's regulations and automotive industry regulations (Ghassemieh, 2011). In recent years, materials such as aluminized sheets have been used in high quality trim components for high end models. Pure decorative components, i.e., components without any mechanical function and plastic components have been aluminized to reduce costs and weight (Additive Manufacturing for Automotive, 2015). These have been used in low cost models for mass production. The Audi A8 air exit, Audi TT fuel cap, Audi S8 mirror housing, Jaguar and BMW door sills, Mini Cooper and other brands emblem and name plates are examples of current uses of aluminium in mass production trim lines (Additive Manufacturing for Automotive, 2015). Aluminium has also been used in trim components such as the deep rail, spoilers and sunroof guide rails. In mass production, it has been used on convertible hardtops for second and third generation Mercedes Benz, two-piece retractable hardtops of Ferrari California and Mercedes Benz Sl, and Range Rover Evoque with an aluminium roof and rails (European Aluminium Association, 2013).

Plastics have also been the common material of construction for trim components. Plastics are cheap, easy to produce and paint, and less dense as compared to metals; furthermore, they are readily available, highly recyclable and easy to mould into complex shapes. The ability to de-trim these components on defective parts for reuse and replacement when damaged has been an attractive feature for automotive manufacturers. The use of hollow structures can further reduce the weight of plastic trim components (Hamweendo, 2017). Metalizing these polymer components with the use of cold spray coatings would still give them the required metallic finish and protection against wear (Additive Manufacturing for Automotive, 2015).

Magnesium has not been successful with respect to trimmings as compared to body and chassis components. However, it has been used in low volume models such as the Porsche Carrera console and General motors production wheels (Powell et al., 2012). HVAC components, i.e., heating, ventilation and air conditioning components, are also a made from extruded magnesium alloys.

The use of other materials such as nanocomposites will also assist in vehicle weight reduction through trim components. Nanocomposites based on various metals or plastic matrix materials strengthened by metal or ceramic nanoparticles or nanoplatelets can improve the overall strength of components by a 100 percent. The use of polymer nanofiber nanocomposite is favourable because it is considerably thinner, lighter and stiffer than its metal counterparts. As such, it will yield much lighter trim components (Presting & Ulf, 2003). The challenge currently lies in the mass production of these materials to support high volume models for automotive OEMs. The cost implications of composite materials are usually higher (up to 10 times higher than carbon fibres) than conventional metals. Polymer composites low recyclability and slow production rates have also hindered their wide use in the automotive industry. The industry's lack of experience and comfort with these materials have also put a halt on its wide usage (Ghassemieh, 2011).

The use of unconventional materials such as glass fibre and carbon fibre reinforced plastics (CFRP) is currently limited to expensive models due to the high material costs and technology investments needed for production (Additive Manufacturing for Automotive, 2015). The window glasses and front and rear windscreens can also be substituted with a polycarbonate window. However, a clear, hard and scratch resistant coating of nanocomposites would have to be used such as nanolaminated clay-polymer stacks with aluminosilicates as clay minerals (Presting & Ulf, 2003).

Whilst most automotive OEMs have developed their products to be more technologically advanced, this has come at a hefty cost. The amount and complexity of the electronic wiring within the vehicle have grown exponentially, moving across the vehicle back and forth because most sedan vehicles have the battery section in the trunk lid and the engine at the front (bonnet) (Crolla, 2009). In this regard, there lies an opportunity in the use of additive manufacturing for the production of integrated electrically conductive wiring (Giffi & Gangula, 2014).

4.3.4 Conclusion

Based on the arguments above, it is evident that the industry is making considerable efforts in the implementation of magnesium and aluminium. However, a few components that still remain a challenge and are still under development. Aluminium, magnesium and carbon fibre alloys are a few examples of materials that are prominent in the industry in both research and development. These materials support the vision of the automotive industry of lightweight products to achieve fuel efficiency and improved performance.

Cold spray remediates substrates such as magnesium and aluminium with material properties limitations that have put a halt on their use in the automotive industry for years, such limitations include susceptibility to severe corrosion, high temperature creep and oxygen sensitivity. It is also clear from literature that when magnesium is compared to aluminium and steel alloys and their respective grades, magnesium alloys are limited and costly alloys for automotive mass applications. Their use in the vehicle such as the powertrain would be a great weight saving for the industry as a whole. Experts have successfully developed high strength alloys that are suitable for powertrain applications at a reasonable market price such as AMC-SCI and Compacted Graphite cast iron (CGI). The use of nanocomposites in the automotive industry has also grown. This is evident from the research and development efforts from different automotive OEMs across the globe and application in new exclusive models. In general, high insurance, investment and material costs are the primary reasons these materials of interest have only been applied in high-end models. Nonetheless, their use attests to the importance of coating, rework or remanufacturing technology and its market. Cold spray technology presents a cost and time effective solution to all these challenges.

4.4 Hypotheses

The following section presents all the hypothesis constructed using the literature review in pursuit of answering the research question presented in the introductory chapter*: Are there cold spray research and development opportunities which, after consideration, could lead to an enhanced cold spray technology application in the automotive industry and more efficient automotive operations?*

The previous subsections and literature review form a basis for the arguments in this section. It is envisaged that, by deductive reasoning, if the same material of construction with equal or stronger process specifications are used in an experiment or applied in a particular industry, e.g., aerospace, through the same conditions, the results could be used in another industry, e.g., automotive industry. From the review of the literature the following can be deduced:

4.4.1 Hypothesis 1

*H*1: Cold spray technology is envisaged as a suitable tool for remediation of otherwise unserviceable magnesium components critical to the automotive operations**.**

Magnesium is the lightest structural metal with a density of 1.74 g/cm^3. It is 35 percent lighter than aluminium and 78 percent lighter than steel, all of which are major structural metals used in the automotive industry. It is less dense relative to most glass fibre-reinforced automotive polymers and similar in density to carbon fibre composites (Powell et al., 2012). Although the use of magnesium dates back to the 1930s, where 22 kg was used in the Volkswagen Beetle, it is because of its low density that its application in the automotive industry has increased drastically in the past decade, covering a wide range of applications such as the powertrain, chassis and body structures (Friedrich & Schumann, 2001). The industry did not have adequate surface engineering technologies to support the switch to magnesium, particularly when it comes to protection against severe corrosion.

The industry's needs and requirements have evolved over the years and thus weight savings were prioritised. This has driven the industry's building more fuel-efficient lightweight vehicles. However, magnesium alloys are still without adequate surface engineering technologies against corrosion, and they are very costly relative to most common structural components such as aluminium alloys and steel, thus making all its components high value material (Musfirah & Jaharah, 2012).

For most structural applications, magnesium is alloyed with other metals to enhance its physical and chemical properties. This is often still not enough because the components operate under aggressive environments. Alloying is essential because magnesium has high temperature creep and is more susceptible to galvanic corrosion. It is therefore more likely to experience premature component failure from pitting and localised concentrated stress (Powell et al., 2012; Botef, 2015).

Current conventional magnesium corrosion protection methods include organic, conversion (e.g., heat treatment, electrochemical reactions and chemical immersion) and chromate coatings. These are acceptable for general corrosion protection; however, they have limitations such as chemical access restrictions and handling issues, stringent surface preparation (i.e., water rinsing, alkaline and acid treatment), oxidation reactions, high rates of localised failure and chipping, and environmental and health risks (Villafurte & Zheng, 2011). All these technologies only offer general corrosion protection, which is not sufficient. Cold spray technology offers a solid-state oxide-free, hard, dense coating capable of general and severe corrosion protection, thermal barrier coating and dimensional restoration for magnesium components. It also offers users less material handling issues as compared to conventional methods.

Cold spray technology has been successfully demonstrated to provide coatings of superior quality through studies and demonstrations conducted by cold spray technology experts such as the following:

- Champagne, Leyman and Helfritch (2009) successfully applied different aluminium feeds for corrosion resistant barrier coating using cold spray technology on ZE41A-T5 magnesium substrate commonly used in transmission gearboxes (cited in DeForce et al., 2009). The repaired component’s strength, porosity and density were well above the product specifications. Different aluminium alloys coatings such as CP-Al, 5356 Al and 4047 Al were found to be 50 times greater as compared to plasma spray. This shows the superior coatings of cold spray technology as compared to other thermal processes i.e. plasma spray.

- AZ91D alloy is one of the most common die cast magnesium alloys. Although it has great mechanical properties, it has poor creep resistance and can thus not be used for high temperature operations such as the transmission cases and engine components (Musfirah & Jaharah, 2012). Experts performed a study on AZ91D magnesium alloy using pure aluminium and aluminium blended with 50% and 75% volume of intermetallic $Mg_{17}Al_{12}$ compound feedstock. The results of the study showed that the coating's porosity level, corrosion resistance and hardness had increased significantly upon addition (Hengyong et al., 2012). A similar study using AM60 magnesium substrate using aluminium coating showed similar results (Villafuerte, 2016).
- According to literature, several studies were conducted on thermal barrier coatings (TBC) using cold spray technology. These were initially conducted for gas turbines because of the need for high temperature systems. More recently, they have been developed for other engine components. MCrAlY bond coating with an underlying yttria partially stabilised Zirconia (YZS) is used for TBC in the engine (Moridi, 2014; Pathak et. al, 2017).

From these studies, it is evident that cold spray technology can be used to coat cast or dry-machined magnesium alloys. It produces coatings that have higher corrosion resistance and are denser, harder and less porous, making them suitable for use in the automotive industry. Based on the demonstrated ability of the technology to coat magnesium substrates alongside cold spray technology's technical and economic advantages, other similar components can be considered for repairs, dimensional properties' restoration' and corrosion protection.

4.4.1.1 Future applications

Magnesium alloys used within the automotive industry to date include, in no particular order, cylinder block and heads, transmission cases, steering wheels, cross-bar beams, roof frames, trim, seat frames, brake brackets, clutch brackets, transfer cases and gearbox, valve covers and air bag housings (Powell et al., 2012). One of magnesium's greatest break throughs lies in its application in the powertrain such as the engine block because of the low density. The breakthrough will be in producing high strength panels that can substitute critical safety components such as the side frames and side frame middle /B-post reinforcements that are currently constructed out of steel or iron.

Based on the literature presented, it can be concluded that magnesium alloys can be used for many more applications in the automotive industry through cold spray coating to achieve efficient operations. The technology can be useful for the repairs and dimensional properties' restoration. It can further be used to improve material properties such as high corrosion susceptibility in magnesium and its alloys thus assisting in the substitution of conventional materials with magnesium.

4.4.2 Hypothesis 2

*H*2**:** Cold spray technology is envisaged as a suitable tool for remediation of otherwise unserviceable aluminium components critical to the automotive operations.

Aluminium is one of the advanced alternative materials that are currently in high demand within the automotive industry. Aluminium is 65 percent less dense as compared to steel, and it has been widely used in industry for its good corrosion resistance, high strength-stiffness-to-weight ratio, and good formability as compared to magnesium (Mallick, 2012). It is for these reasons aluminium alloys are likely to be used for two of the most critical housings, i.e., the block and the head in the engine because of the weight saving and better creep resistance (Musfirah & Jaharah, 2012). As such, aluminium alloy's physical and chemical properties have put it ahead for implementation in the industry relative to magnesium alloys. Even though this might be the case, aluminium alloys can still suffer from premature failure due to corrosion pits and localised stress concentration, amongst many other reasons (Botef, 2015). Cold spray technology is envisaged as a suitable tool for remediation of mis-machined components, corroded and worn out parts, and many more applications.

The following applications and studies demonstrate the possibility of coating aluminium substrates using different feedstock material with a cold spray process.

- The 5083 aluminium alloy substrate, largely used in automotive bodies and shipping industry for its formability, strength, corrosion resistance and weldability, was successfully cold sprayed using Al-Alloy coating. AA5083 is commonly used for wheels, chassis, and sub-frames in the vehicle (Van der Hoeven, Zhuang, Schepers, De Smet, & Baekelandt, 2002). The alloy has high strength, but it is highly susceptible to intergranular corrosion if exposed to high temperatures, hence welding the material results in loss of mechanical integrity and in heat-affected zones (HAZ).

The outcome could lead to additional cracking. The experimental results of the coated aluminium substrate showed higher coating density and improved adhesion, and there was no evidence of oxidation, (Sridharan, Maier, Hauch, & Devan, 2013).

- An experiment for the repair of a Fiat aluminium engine block made from A380 (Al-Si) aluminium die casting alloy was spray coated and TIG welded and the results compared. The cold sprayed coating had increased strength (hardness), was defect free and displayed better corrosion protection as compared to the TIG welded engine block (Astarita, Coticelli, & Prisco, 2016).
- Another study conducted by Leyman and Champagne also demonstrated successful cold spray coating using aluminium alloy 7075-T73. Pure aluminium as opposed to aluminium alloys showed superior corrosion resistance (cited in Leyman, 2008).
- Al-5Sn and Al-10Sn alloys were also successfully prepared using cold spray technology (Ning, Kim, Kim, & Lee, 2009). These alloys are commonly used in the automotive industry because of the suitable friction properties and shear surface they introduce to the aluminium matrix.

Various experts within the aerospace and automotive industry have demonstrated and reported on the successful application and thus acceptable results attained by the use of cold spray technology on aluminium components.

4.4.2.1 Future Applications

Aluminium is currently used for automobile parts such as cylinder heads, pistons, valve covers, transmission housing and shafts, radiators, car body and wheel rims (Musfirah & Jaharah, 2012). On-the-market car models such as the BMW X3 have aluminium applications. Potential future applications exist in the body shell for mass production (including body frames and A, B and C pillars/posts). A complete use of aluminium and its alloys in the powertrain also presents further savings; however, economies of scale need to be considered for mass production.

4.4.3 Hypothesis 3

***H*3**: Cold spray technology is an additive manufacturing technology that will assist the automotive industry achieve efficiency.

Significant strides in additive manufacturing (AM) have changed how products are designed, developed, produced and finally distributed (Giffi & Gangula, 2014). Additive manufacturing, also known as 3D printing, is the process of producing layer-by-layer coatings to create 3D objects from CAD files, as opposed to using subtractive methods such as traditional CNC machining (Pathak & Saha, 2017).The cold spray process has become attractive to automotive manufacturers as an enabling technology for additive manufacturing. For the automotive industry, it has opened avenues for newer designs and cleaner, lighter and safer products that are produced at shorter lead times and lower costs (Giffi & Gangula, 2014).

The cold spray process, as an additive manufacturing technology, presents an innovative way to produce parts and components faster than powder-bed or powder-fed processes due to lower lead and cycle times. The technology boosts of high deposition rates that are 1000 times faster than current state-of-the-art direct metal laser sintering technologies. Its ability to produce quality parts is because the crystalline structure of the components are not altered, which puts it ahead of other technologies of the same kind. This feature allows tailoring the repair microstructure as per the applications needs (Pathak & Saha, 2017). This will work best for production lines with multiple products and options on the same line.

Plastic 3D printing has had major success; as such, it has been widely deployed in the automotive industry mainly for prototyping. Over the years, however, metal printing has also improved. The latter will benefit the automotive industry immensely once it is fully developed. At the moment, 3D plastic printed lattice structures can be metal coated using the cold spray process to give them the necessary metallic properties such as the required strength and finish. Cold spray technology can therefore be used to produce both lattice structures and to coat the plastic components with a metallic overlay (Villafuerte, 2014).

Cold spray technology's ability to produce components using different plastic feeds, usually in lattice structures, without any compromise on strength promotes the use of lighter products, which in essence contributes towards weight saving targets of different automotive manufacturers (Giffi & Gangula, 2014; Hamweendo, 2017). Cold spray technology can practically and efficiently be used to produce porous structures suitable for use in different industries such as medicine and automobiles. These structures have less mass density compared to their solid counterparts, so they can be used to replace existing solid plastic components used for trimming the vehicle to achieve weight savings (Hamweendo, 2017). This could significantly reduce the trim weight contribution to the vehicle without compromising the quality and functions of the components. Another opportunity lies in the reduction of weight and complexity of wirings within a vehicle. Additive manufacturing can reduce vehicle weight and improve functionalities through integrated electrical wiring through hollow structures (Giffi & Gangula, 2014).

Currently, most automotive manufacturers and suppliers use 3D printing for rapid prototyping; however, 2-D technology is also capable of supporting mass production. The technology enables the production of complex geometrical components that would otherwise take time with traditional methods. Furthermore, additive manufacturing removes the need for new tooling for different products; therefore, 3D technology gives OEMs flexibility to respond promptly to market changes and needs at even lower prices. Process changes can thus be implemented immediately. This allows for the production of more variable products (flexibility) that are custom made to suit customer needs such as variable strength and electrical conductivity. The automotive industry market is currently thriving under the customisation of products to meet customer needs. Cold spray technology is a great enabler of this aspect of business at very low costs. With this in mind, cold spray can also be instrumental in producing prototype models during the design stage of new products or improving existing ones (Giffi & Gangula, 2014).

Additive manufacturing is currently used for the production of aluminium alloy pumps and valves for fluid transportation in the powertrain. Aluminium alloys are used for cooling vents in the exhaust; bumpers and wind breakers are made of polymers. Methods used for the fabrication of these components includes selective laser sintering, fused deposition modelling and electron beam melting (Giffi & Gangula, 2014). In the future, cold spray technology can be used for production, restoration of dimensions and coatings for the majority of the trim components such as the dashboard, bumpers and hang-on parts’ interior trimming. Other components on the vehicle that could adopt the use of this technology include the wheel rims, large BIW panels, and hang-on parts such as doors, frames, and bonnet and trunk lids. The majority of these applications depends largely on the industry’s ability to stabilise metal-based additive manufacturing processes for the production of large components. Alternatively, the trim components could adopt the use of metallic coating over a porous/lattice structure.

Cold spray technology as an additive manufacturing technology has brought changes in the supply chain and management processes. It removes the need for transportation of parts through its real-time, on-demand printing, possible errors in the supply chain and longer lead times. In the future, it could have real-time production of components in-house for both the production line and even aftersales, which removes the need for inventory (Giffi & Gangula, 2014). In-house mass production removes the need for transportation of components that often affect production through unavailability of parts when demanded. For example, natural disasters have previously left automotive OEMs short on parts and resulted in unplanned and costly shutdowns. Toyota, Honda, Nissan and BMW are a few of the OEMs that have found themselves in this situation after an earthquake hit Japan in 2011 and more recently in 2017, leaving their Japanese suppliers unable to deliver parts across the globe (Autoblog, 2017; Autonews, 2017).

Parts availability and service delivery are also important aspects of the aftersales market for the automotive industry. At the same time, automotive manufacturers are faced with challenges of balancing inventory levels, service delivery time and costs. As a result, only high runners are kept in warehouses to balance space and costs. Additive manufacturing allows for on-demand and onsite repairs as well as parts fabrication that match customers demand (Giffi & Gangula, 2014). This is particularly important for low volume models, exclusive models and models that have been discontinued in the market such as vintage vehicles.

It has already been established that cold spray technology can also be used as a rework technology; therefore, in the future, businesses could think of mobile additive manufacturing systems to allow for reworks offsite if they have multiple facilities, multiple panel beaters and job shops, or mini factories in the vicinity. All these facilities can offer services that can be done remotely and closer to the customer or point of use. Alternatively, customers could purchase car or parts designs that they could 3D print at a central offsite and public facility.

The main question at hand should be the ability of additive manufacturing to take over mass production systems in the automotive industry at the given line speeds. The Urbee was the first additive manufactured vehicle with over fifty additive manufactured parts. It comprises geometrically complex components that could not have been produced through traditional methods in the short period over which it was produced (Giffi & Gangula, 2014). This vehicle shows the possibilities of additive manufacturing in taking over large operations with shorter lead times.

The racing environment, such as Formula 1, has different requirements for personal vehicles because the environment is characterised by high speed, reliability and efficiency. More than ever, the weight of the vehicle is of paramount importance. The specifications for individual parts often changes from circuit to circuit, so short production and restoration times are a necessity. Whilst the production of additive manufactured parts is efficient and has many advantages over hand-forged or metal machined components, they are presumed to not be as strong or heat-resistant. The strength of the parts is important in a racing environment because this aspect of the automotive industry has different specifications; the driving conditions of this section of the automotive industry are extreme. The metallic components produced through cold spray technology are durable enough to support this industry. Furthermore, cold spray technology overlay coatings can be used for hardness coatings by applying thin metallic coating layers over plastic components, e.g., spray coating copper over plastic (Additive Manufacturing for Automotive, 2015).

Cold spray technology presents a sound solution to challenges in transportation, high lead times, reproduction, geometrically complex components and controlling inventory levels. That cold spray's deposition rate is higher than other thermal spray technology also attests to its ability to be adaptable to various production systems' cycle times (Pelsoci, 2015). Moreover, its ability to give the production line flexibility without many tooling changes makes it attractive in modern-day volatile markets. With all these in mind, the use of cold spray process as an additive manufacturing technology would assist in ensuring efficient operations in the automotive industry.

Whilst the technology is still under development, the most important aspect to consider is the compatibility of cold spray with existing additive manufacturing processes such as SMS and direct metal deposition (DMD). The use of multiple additive manufacturing technologies can be used to fabricate complex multifunctional components and to assist where cold spray technology falls short currently. For example, a study conducted by Sova et al, (2013) showed the feasibility of combining two additive manufacturing techniques to achieve the intended goal. A cross section of a wall of injection mould was produced using a combination of additive manufacturing techniques. The nickel shell was produced using electroplating. In a quest to improve the heat transfer from the nickel mould, the Cu-SiC and pure copper layers were deposited using cold spray. This layer was also deposited to improve adhesion between pure copper and pure nickel. This argument illustrates how the combination of existing additive manufacturing technologies alongside cold spray technology can work together to achieve improved results and thus much more efficient operations.

4.4.4 Hypothesis 4

*H*4: Investment in education can help with the identification and implementation of cold spray technology and thus help towards achieving effective operations in the automotive industry.

Collaboration between the industry and educational institutions, particularly with respect to research, is instrumental in supporting the evolution of existing technologies and ensuring the successful introduction and integration of emerging technologies in the market. Collaboration will ensure that OEMs, component manufacturers (press shops) and panel beaters are able to forecast, adapt and embrace the continuously changing industry requirements and focus. The current focus is materials revision, product improvements and technological advancements such as steering control and autonomy features, fuel-efficiency improvements, safety standards and design implications, and environmentally friendlier products, e.g., regulations such as greenhouse gas emissions and EU standards. Collaboration is envisaged to be instrumental in fast-paced industries such as the automotive industry, where trends change instantly. However, the development and qualification of such technologies need to be timeous. This is particularly true because of the level of consideration and knowledge needed to implement the slightest design and operational changes in the automotive industry to improve either the functional and/or structural aspects of the vehicle. The lack of knowledge by OEMs about technologies in the market such as the cold spray process hinders and delays such advancements.

For cold spray technology as an emerging technology to succeed in the automotive industry, there must be a clearly defined mission, vision, objectives and strategy on how it can fit into already existing structures to give the desired quality and ensure efficient operations. Clear mandates by automotive OEMs, technology experts and developers ensure cold spray’s applications are tailored to suit different production setups, product requirements and businesses. For example, with regards to the fourth industrial revolution, a study conducted by Breunig et al. (2016) showed that only 30 percent of the technology suppliers and 16 percent of manufacturers have an overall strategy for transitioning into the fourth industrial revolution. It is evident that most companies can easily be left behind in the transition to this new era because of no clear understanding of what is required of them. A clear fourth industrial revolution strategy would show what the roles of all parties involved would be and thus ensure a smooth transition; the same analogy applies to cold spray technology.

One of new technology’s challenges is the need for new and different skills set necessary to see it through design and production stages. It takes time to train people to be competent in the running, maintenance and troubleshooting of new equipment (Sarasini et al., 2014). For this technology to become reliable, efficient and adopted across the automotive industry, it needs an army of well-trained associates across all levels of the business. At the moment, there is no structure for the training and qualification with the required skill sets; in other words, training still needs to be structured and standardised (Additive Manufacturing for Automotive, 2015).

Cold spray technology has made major strides in the aerospace industry as opposed to the automotive industry, and this could be partly because of the lack of information sharing and facilitation in the automotive industry. The lack of public knowledge about such technologies could be due to factors such as the lack of standards in the public domain and lack of investment in research and development in the automotive industry as compared to the aerospace. Other factors include isolation of research hubs and their concentration in certain geographical locations, thus inhibiting the globalisation of ideas, and high investment costs particularly for an emerging technology (Botef, 2013). However, would the construction of more research hubs across the globe assist in the implementation of emerging technology? It is envisaged that, once public discussion and demonstration platforms that facilitate information sharing and integration are established that include all relevant parties and key players, i.e., technology developers, different and relevant industry experts, and research and educational institutions’ representatives, emerging technologies will transform the industry and see greater success.

These demonstrations should include conferences, exhibitions and investments in cold spray technology laboratories across the globe in educational institutions and research hubs. Initiatives in the form of annual international conferences such as the International Thermal Spray Conference (ITSC) and the amount of investment in research and development (R&D) by private companies, educational institutions or the government over the last two decades are examples of the initiatives taken. Despite these initiatives, the industry is still not where it should be to support industry changes (S. Singh et al., 2012; ASM Thermal Spray Society, 2013). Investments in more research laboratories worldwide should also be within the scope. To date, only the Gauteng-based University of the Witwatersrand has the first ever cold spray process research laboratory in Africa.

Incorporation of industry transformations in academic curriculum on all levels of higher education at university and technical colleges could facilitate the required education of such technologies (Botef, 2013). With this in mind, the University of Wales is reported to be supporting numerous leading automotive OEMs to develop low carbon automotive technology for both passenger vehicles and motorsport (Hilton, 2017). Wales is famous for producing engines for most of the United Kingdom's OEMs and has been reported to have become more attractive recently for automotive investors because of new and expanded vehicle production. These types of collaborations with educational institutions will accelerate the needed integration.

Finally, information transfer and implementation of support structures for the industry by technology developers would bridge the identified gaps and limitations of the technology. The increase in investment on such fronts will help with conquering some of the frontiers the technology is facing, such as expanding materials suitable for cold spray technology for the industry and specifications issues. This is because, with expansion across the industry, different products and materials will be simultaneously under study. The increased support structure from cross-industry experts, technology developers, OEMs, investors and education institutions is envisaged to fast track this process. This proactive, informative and engaged approach will assist in current and long-term continuous improvement on all fronts. From the argument put forth thus far, there is a clear and urgent need for information integration between researchers, educational institutions and automotive manufacturers in order for emerging technologies such as cold spray technology to see greater success in the automotive industry.

4.4.5 Hypothesis 5

*H*5**:** Cold spray technology is a Green technology that stands to reduce emissions in the automotive industry currently and going into the future.

The automotive industry, which includes the entire transport industry i.e. cars, small and big trucks, has been reported to be amongst the highest contributors to greenhouse gas emissions in the world. Its contribution has been reported as approximately 14 percent relative to other sectors (Benz, 2007). In recent years, the world has taken drastic measures such as the drafting, ratification and enforcement of stronger environmental regulations such as the Kyoto Protocol and EU standards (UNFCCC, 2008). More countries are starting to hold industries such as the automotive OEMs liable for emissions to ensure compliance by monitoring emission rates in production plants and ensuring compliance of their products, namely, vehicles. The industry is thus under even more pressure to achieve the agreed upon reductions, which has pushed industries towards Greener technologies, processes, designs and products during the production phase and throughout the entire lifecycle of its products.

Cold spray technology's ability to rework mis-machined or corroded parts removes the need to produce a new vehicle in place of a scrapped unit. This indirectly reduces emissions by ensuring there is no reproduction and thus removes the associated production wastes and emissions incurred in the process. In essence, the technology presents an opportunity to remove the environmental damage associated with primary production. For example, with the use of cold spray technology for repair of magnesium components, OEMs avoid the following (Pelsoci, 2015):

- Emissions from primary production: For every ton of primary production from magnesium oxide (MgO) ores, 17.8 tons of carbon equivalents are generated.
- The primary extraction and processing of the alloys, i.e., mining, refining and recycling of rare elements that are added to magnesium for reinforcement also have significant emissions. The use of toxic acids or high temperatures in the refining process pose a huge environmental risk.
- The transportation of magnesium from the mine site to refinery, press shops then to customers (OEMs and buyer) and those associated emissions.

- Processing emissions: The emissions from the press shops for the casting of the panels and any other emissions by the OEM for production of the vehicle such as gases, paints (including sealer and wax), metal shavings, packaging waste, water, etc.

Pelsoci (2015) argues that the technology presents a great opportunity in terms of repairing surfaces that are not prepared with chromate. As standard practice, chromate has been coupled with magnesium to prevent galvanic corrosion using either Chromate Dow 17 or chromate conversion coating. The substrates are usually treated with chromate to ensure effective paint bonds, protection from corrosion creep by forming a protection layer. However, studies have shown that the use of hexavalent chromate presents both land and water pollution risks to the society. Harsher restrictions have been imposed to regulate the use of chromate due to health, safety and environmental issues because hexavalent chromate has carcinogenic effect and the associated dangers of waste disposal of the process discards. It has been demonstrated that components can be repaired for dimensional irregularities using cold spray without the standard use of chromate surface treatments; instead an anodized non-chromated tagnite. Currently, there is still a need to use a primer and topcoat after reworking, both of which are eco-friendly. Ongoing research into the process with non-chromated primers is still being conducted. The use of cold spray as an alternative renders it a green technology as it removes the use of chromate in the process flow.

Cold spray technology as an additive manufacturing technology removes the need for transporting parts. In future, it could have real-time production of components in-house for both the production line and aftersales, which removes the need for inventory, e.g., stock warehouses. In-house rapid mass production could easily remove the need to transport components across continents and the associated emissions (Giffi & Gangula, 2014). Cold spray is seen as a Green solution because it removes any transport emissions associated with deliveries and also with production emissions from the supplier because cold spray technology has lesser emissions.

It has already been demonstrated in hypothesis 2 that the use of cold spray technology will help in the remediation of mis-machined aluminium parts and components. In addition, the substitution of steel with aluminium leads to weight reduction (Moridi, Hassani-Gangaraj, Guagliano, & Dao, 2014). Weight reduction contributes towards a Greener system if the entire lifecycle of the vehicle is taken into consideration (study cited in Knight, 2011). The study showed that the initial stage of the production of advanced materials such as aluminium is deemed Red because of its associated emissions, however with cold spray technology, the overall life cycle of the vehicle is Green and thus the substitution is environmentally friendly and sustainable (Sullivan et al., 2018).

The substitution of a heavier metal such as mild steel or cast iron with a lighter metal such as aluminium or magnesium in a car or light truck is reported to potentially eliminate approximately 20 kg of carbon dioxide over the lifetime of the vehicle (Musfirah & Jaharah, 2012). According to research conducted at the University of Cambridge by Julian Allwood, global energy use can be reduced through the use of lighter vehicles (cited in Knight, 2011). Scientists from Steel World conducted an experiment that demonstrated that a weight saving of approximately 300-500 kg can be achieved, and by rule of thumb, this translates to 10 percent of the vehicle weight and means a 5.5 percent fuel economy improvement in the vehicle (Musfirah & Jaharah, 2012). Considerable weight reduction leads to an increase in fuel economy and improvements in emissions. Therefore cold spray technology is a weight saving enabler and deemed a Green technology.

4.4.6 Hypothesis 6

***H*6**: Proper implementation of cold spray technology would complement current conventional thermal spray systems and help towards ensuring efficient operations.

The lack of infrastructure and systems to assist and give a platform to emerging technologies can be catastrophic to industries with the evolving expectations and ever-changing needs of their end users. A convergent pressure from all points is to continuously improve existing systems at all levels. Questions are raised about how receptive South African markets and industries are to changes and what can be done to ensure acceptable and considerate transitions with revolutionary technologies that occur swiftly.

A major hurdle with emerging technologies in the 21st century includes the lack of collaboration between industries and research and educational institutions. There is a gap in industry about how technologies can be better introduced and managed to compliment current systems where the industry is shifting towards another revolution.

Comparison of the thermal spray technologies and cold spray technology showed what the benefits of the latter are in contrast to conventional thermal spray technologies. For example, the use of conventional thermal spray technologies limits coating and thus the application of certain materials such as nanostructures because they are heat sensitive. The cold spray process is a technology to consider for complementing and expanding current conventional thermal spray technologies, if not a replacement (S. Singh et al., 2012). This is due to some of the limitations of the technology that are yet to be addressed in both research and development. A complimentary use of cold spray with existing processes stands to benefit the industry through efficient operations and ensuring the intended process goals are achieved. For example, a study conducted showed the feasibility of combining two additive manufacturing techniques whereby a cross section of wall of injection mould can be produced using a combination of additive manufacturing techniques (Sova et al., 2013). Pairing DMD and SMD with cold spray technology could help address these issues and ensure more efficient products. This ensures product quality and costs savings from potentially scrapped units on the production line.

With all these factors in mind, it is imperative to explore how integration can take place. Exploration raises the question: “How does an industry/company ensure proper implementation of the cold spray technology into their already existing systems to ensure efficient operation?” Possible options for facilitating that process are the following:

1. Provide cold spray technology training, information sharing and facilitation, i.e., materials, production, equipment, specifications, technical and quality standards, inspections and maintenance, testing process for quality assurance, etc.
2. Identify parts suitable for coating across all relevant departments that handle the metal sheet and thus the BIW, such as collaboration with planning departments about materials and product changes and press and body shops about the logistics.
3. Involve all departments that will be affected by the introduction of the technology, e.g., suppliers, aftersales, production, quality, product integration and planning.
4. Encourage continuous improvement (CIP) from all ranks within the business, including associates, operators, foremen and process leaders to management. This means that the information integration, training and development needs to be done across all ranks too, ultimately starting with the people who will be critical users of the technology, for example

the foreman’s loading and building the units, shop floor management, etc., eventually including passive users like auditors, inspectors, logistics and press runners.

5. Involve research experts, cold spray consultants or university academics throughout the implementation process, i.e., the planning, commissioning, buy-off and process-optimization process.
6. Encourage cross-technology or plant support to share lessons learned and experiences with regards to the use of new and advanced technologies, as well as information and documentation. This ensures remote access to the information that is currently limited.
7. Support robust production lines such as automated best-fit lines because they have shorter cycle times. Automation offers quality assurance through reproducibility of results. This is appropriate for process fault finding and data collection as opposed to manual setups. The option to install the system remotely or operate it manually assures the product can be re-worked/produced at remote places in the plant without hindering production on the main line.
8. Consider material eligibility and other processes that will be affected by changes in material across the production cycle, e.g., aluminium and steel joining introduced a change from normal spot welding to self-piercing riveting and flow drilling, clinching, adhesive bonding and weld-bonding.

These are only a few considerations to ensure successful implementation of cold spray technology within existing production lines. Last, one of the most essential parts of ensuring proper implementation is by reliability and repeatability of process results. These can be attained only if the process is stable and capable (Thermal Spray Society, 2017). Reliability and repeatability of process results could be achieved through implementation of regular process checks and analysis, optimisation mechanisms and suitable control systems, e.g., diagnostic tools, trouble shooting, sensor monitoring, and inspections (systems or manual). The adoption and acceptance of this technology in industry asks for a paradigm shift.

4.5 Schematic Representation and Discussion of Proposed Frameworks

It has been argued thus far that cold spray is a Green technology that offers quality and superior coatings for critical components and materials within the automotive industry. It was noted that integration of this technology into businesses can assist with ensuring efficient operations that minimises inventory, helps towards attainment of zero waste, offers on-demand supply and improved cycle and lead times, can provide variable products with minimal tool changes, and diminishes the adverse effects associated with primary production. It was also noted that the technology has not made much headway in South Africa, one of the countries with the biggest economies in the Sub Saharan Africa. It is envisaged that the technology will be of great benefit to the automotive industry in achieving efficient operations based on benefits listed. Based on the literature reviewed and arguments put forth so far, the following section summarises the findings and presents the framework to be tested.

4.5.1 Issues to address for immediate expansion of cold spray technology

Cold spray manufacturing and repair process should not be viewed in isolation but as a component of a much broader framework to achieve the intended goal (Botef, 2013). Different aspects of business should be considered; these include but are not limited to the strategies, markets, investments, people development and product customisation.

The framework is summarised in the subsequent sections. The framework incorporates findings from the semi-structured interviews conducted using specialists knowledgeable about additive manufacturing, the automotive industry, and/or the fourth industrial revolution. The verbatim interview scripts are included in Appendix E. The framework takes an integrated approach in order to explore how OEMs and their business partners can achieve efficient operations in light of the findings presented in previous chapters.

Figure 11: Framework of immediate issues for cold spray technology expansion.

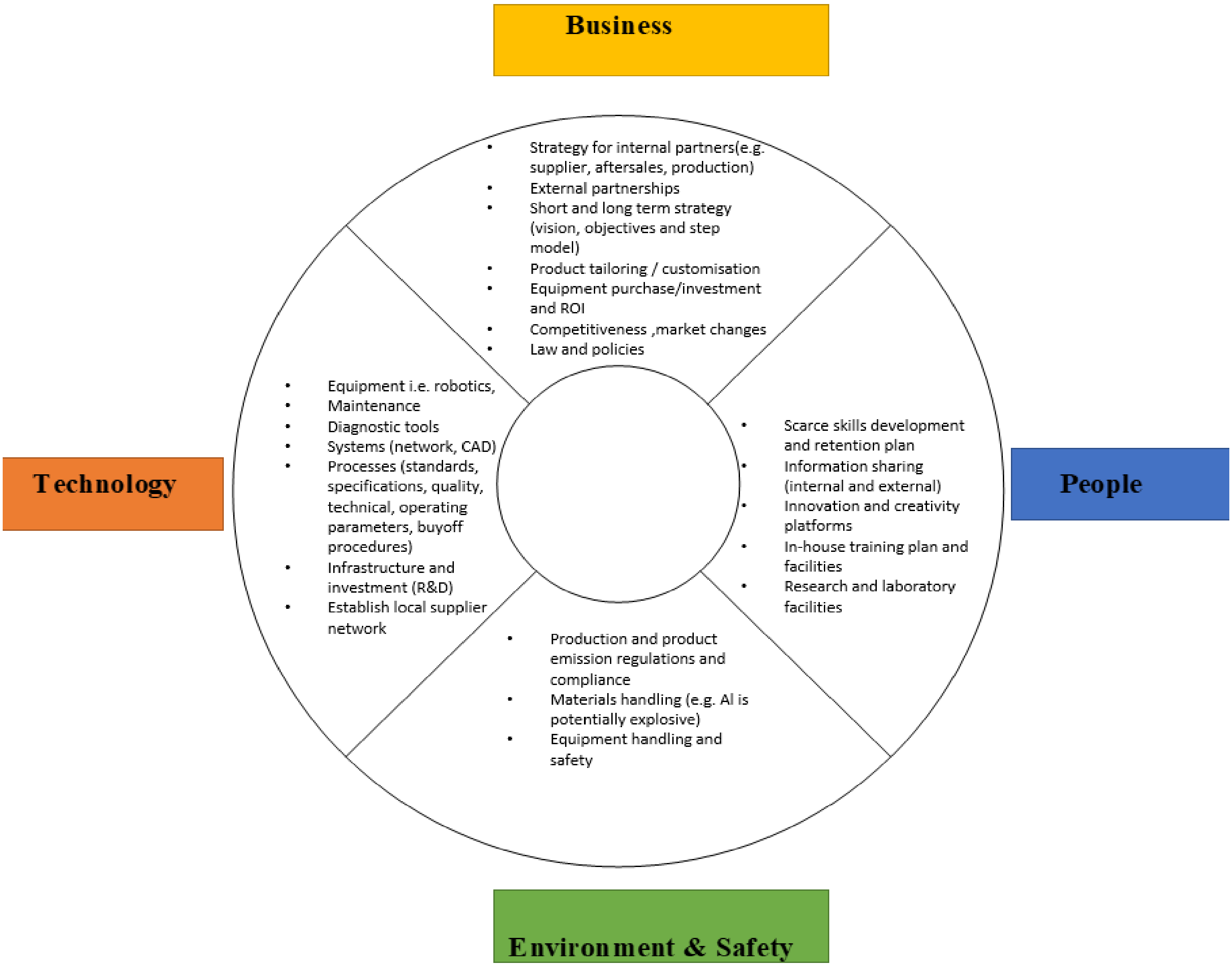


Figure 11 presents principal issues that the industry needs to address for immediate expansion of cold spray within the automotive industry. This is particularly true in regions such as South Africa Where the technology is non-existent on an industrial scale. This model is more focused on the OEM as opposed to the entire automotive industry. The framework considers four key subdivisions, namely, business (includes strategy and market), technology, environment and safety, and people.

4.5.1.1 Business (incl. market and strategy)

In 2017, the global market for thermal spray technologies had grown to an estimated USD 8.097 billion, which translates to approximately ZAR 121 billion with the exchange rate of ZAR 15 at the time of writing. Cold spray commercialization presents an opportunity for a wide range of industries to explore new profit avenues. The aerospace industry and gas turbine industry has been the largest end-users of cold spray; however, the automotive industry has been the fastest growing end-user sector with an estimated 8 percent growth rate by 2023. The North American markets still dominate the global thermal technology markets to date (Mordor Intelligence, 2016).

The customer-demand shift in the automotive market from purchasing new vehicles to preowned and large fleets for businesses, such as Uber and car-sharing opens a completely new opportunity for rework technologies for fleet owners. Similarly, exclusive and low volume models such as sports and vintage cars also have an unexplored market within the cold spray coatings and applications' market. The local industry's aim to increase production volume to 1.2 million vehicles by 2020 through initiatives such as APDP is an opportunity for such technologies to facilitate high vehicle production at shorter lead and cycle times. Cold spray also boasts of high deposition rates faster than conventional technologies and can thus facilitate industry growth (Pelsoci, 2015; Pathak & Saha, 2017).

The South African automotive industry remains one of the key sectors for the Sub-Saharan Africa and SADC region with numerous international automotive OEM plants. As one of the largest manufacturing sectors, it contributed an average of 6.9 percent to South African GDP in 2017-2018, thus creating over 110 000 jobs countrywide. These statistics attest to the importance of the survival, growth and success of the industry to the country and continent. Most of the vehicles assembled locally are for export markets such as Japan, United States of America and Europe (ASCCI, 2017).

In order for a country to compete on a global scale and attract lucrative investors for its trade in today's markets, it needs to be technologically advanced and efficient; however there are other factors that drive these decisions, such as costs, commercialisation, payback period, benefit, employment, etc. When asked about what businesses should do to increase the adoption of emerging technologies in the automotive industry, the interviewees advised that "Businesses should conduct frequent technology audits that will indicate redundancy of current technology and the need for new or improved versions, invest in technology forecasting tools, adopt high-risk propensity management, and align businesses strategies with new technology adoption and implementation." From the interviews it was also clear that the inability of the automotive industry to be agile in the consideration and adoption of emerging technologies, as well as investing in in-house research facilities, delays its progress significantly relative to other industries such as the aerospace, where emphasis is put on high precision and enabling technologies. This drastically reduces the competitive advantage of a country and industry; there are missed opportunities for improving current processes and products and exploring new markets/customer demands. South Africa has seen significant decrease in its global competitiveness index on the global scale from 45th place to 61 in the past decade (Schwab, 2016). Innovation and technological readiness are a few of the factors taken into consideration for the index ratings.

It is important to recognise that new technologies come with instability and disruption. However, they also have potential to introduce improved and reliable systems that could further facilitate jobs and increase economic growth and global competitiveness exponentially. Most emerging technologies are initially expensive as they battle with the economics of scale. As the world becomes more inclusive through trade, there is a need to invite investors on board to ensure businesses remain competitive, profitable and provide secure employment whilst balancing the cost factor. It is important to ensure industries are not left behind in technological advances and industrial revolutions.

A few aspects that automotive OEMs who implement the technology should initially consider are the following:

- Set immediate, medium- and long-term strategies clearly outlining the objectives, vision, and steps in applying the technology and its influence on business.
- Roll out an integration plan/strategy for all departments. All business partners, such as suppliers, aftersales services and production need to be involved and understand the effects of the technology on their operations. For example, the introduction of cold spray for aluminium panels affects joining technology in production. It shifts their operations from spot welding to self-piercing riveting. Logistics will also be affected in terms of parts handling, supply chain and packaging. An integrated approach reduces the probability of failure.
- Institute product/service customisation and return of investment (ROI) for all OEMs, particularly for OEMs with wide product portfolios.

- Partner with businesses with similar interests to accelerate the success rate and improve competitive advantage, e.g., BMW has partnered with INTEL, MobiEye and Delphi to develop systems for autonomous driving systems (BMW Group, 2016). Another example is the University of Wales that is supporting numerous leading automotive OEMs to develop low carbon automotive technology for both passenger vehicles and motorsport (Hilton, 2017). This concurrent engineering could facilitate a reduction in resources and costs as well as encourage skills sharing. It essentially reduces product development time, improves productivity and shortens product market time (Botef, 2013).
- Interviewees suggested that, “Businesses can start with a pilot phase of small parts manufacturing or certain aspects of the business before rolling out the technology on a broader scale.”
- Create a series of products (new) within the brand that will be purely manufactured using additive manufacturing; these assist with ensuring brand identity and marketing the product to customers. It further creates awareness of the products and technologies used for production, e.g., electric vehicles for BMW. "OEMs should not necessarily incorporate emerging technology for old car brands but should use emerging technology to produce completely new cars within the brand," said an interviewee.

4.5.1.2 People

One of the industry’s biggest challenges, particularly with emerging technologies, is the rare-skills set and competencies that have not been developed in large numbers in the labour force over the years across the globe (Sarasini et al., 2014). Comparison between the previous industrial revolutions and upcoming fourth industrial revolution is the new technology landscape that requires more specialists as opposed to general workers. Another pressing matter for OEMs will be the timeframe to facilitate skill development and the necessary succession plan in line with the next revolution.

OEMs who implement the technology should therefore consider:

- Developing a structured training and development plan.
- Opening avenues for information sharing internally such as within the group (multiple production plants) and externally with enabling partners such as technology developers, other OEMs, industries with similar interests, etc.

- Collaborating between automotive OEMs and research hubs, industry and government will bridge the skills gap.
- Creating a platform for creative solutions and innovative thinking, e.g., pilot plant or innovation centre with prototypes. This gives workers a platform to give input on the changes they would like to see to make technology user-friendly for them in their work environment based on experience, e.g., continuous improvement.
- Using the "***Hones potential***" approach will assist to accelerate skills transfer, i.e., exposure to different job options in the industry, and improve innovative ideas was highlighted by interviewees.
- Investing in exposure or creating platforms that encourage global thinking, e.g., travel programmes, cross-manufacturing facilities, virtual focus teams with common goals was highlighted by interviewees.
- Adopting change management to reduce the impact of organisational culture shock and disruptions that come with the adoption of new technologies as well as political challenges.

4.5.1.3 Technology

Technology remains central to establishing efficient operations within the automotive industry. There are key issues to be addressed such as equipment performance and reliability, investment costs, maintenance and processes. Cold spray technology has been shown to be competent in providing a wide range of coatings and applications for different substrates, most of which have not been viable with other conventional thermal spray technologies. This novel technology presents an opportunity for material revision in automobiles whilst ensuring cycle and lead time reductions, weight saving, reduction in environmental impact and completely new supply chains through in-plant 3-D components printing.

With all these in mind, it is necessary for OEMs to consider the following for improved operations:

- "Alignment of necessary technology advancements with global trends, customer demands and business strategy" was the suggestion of an interviewee.
- Establishment of clearly outlined and documented process standards, operating parameters and specifications is required. One of the technology's limitations is publicly available process specifications. Collaboration between researchers, technology developers/experts,

automotive OEMs and suppliers will assist with establishing process specifications for specific operations and products.

- Establishment of buyoff procedures for all the reworks, reproduction and 3D printed panels.
- Consideration of the limitations of the technology and how the limitations impact OEMs' product ranges should be considered, e.g., the necessary breakthrough in high impact velocities by high power facilities and new nozzles that will finally extend the range of materials eligible for coating (Botef, 2013). Interviewees noted that it is important for the businesses to understand that, "The technology cannot be used everywhere and for everything."
- Research about automotive industry priorities and the necessary resources (including investment).
- Encouragement of combined research efforts between universities, automotive groups, research hubs, etc. in order to accelerate implementation, commercialisation and counteract challenges.
- Implementation of process checks/diagnostic tools such as inspectors (competency and capacity), alarms, sensors, monitoring systems, and feedback loops and optimisations thereof.
- Factoring in of maintenance and repairs over the lifetime of the equipment. It is important to invest in trained personnel and spares for that purpose.
- Provision for any necessary design changes in systems such as CAD files.

One of the cold spray's greatest limitations is the costly investment necessary for implementation. However, the return on investment from recovered units, reductions in inventory, lead times and other application justifies the costly equipment investment (Pelsoci, 2015). The interviewees also identified the unavailability of local suppliers as a great limitation.

4.5.1.3 Environment and safety

In recent times, it has been important for viable technologies to have minimal impact to the environment, particularly with the stringent laws passed for manufacturing industries. The safety of operating the equipment should be of paramount importance also.

Cold spray technology gives opportunities for new product developments by enabling the use of unconventional materials within the automotive industry through its superior coatings. For example, it has also been demonstrated that the overall lifecycle of aluminium and magnesium, as the materials of great interest within the industry, have minimal impact on the environment. Moreover these materials are recyclable, thus ensuring a cradle-to-cradle approach that further diminishes any adverse effects associated with primary production (GARC, 2009; Pelsoci, 2015; (Sullivan et al., 2018).

In addition, the automotive industry contributes an average of 14 percent towards the global greenhouse gas emissions. The industry's ambition to improve fuel efficiency and cut emissions by reducing the vehicle weight is enabled by the use of cold spray technology through material substitution. A Steel World experiment demonstrated that an approximately 300-500 kg weight saving can be achieved. This translates to a 10 percent vehicle weight saving and a 5.5 percent fuel economy improvement in the vehicle (Musfirah & Jaharah, 2012). Fuel-efficient vehicles emit less greenhouse gases, thus ensuring less environmental impact. Cold spray technology therefore supports the stringent laws and the policies imposed on manufacturing industries to move towards Greener productions and products globally. Cold spray is a Green technology.

Automotive manufacturers should consider the following for effective operations:

- Individual countries' emission standards for OEMs' products and production facilities' emissions.
- Risk assessments and safety loops/layers for the operation of machines.
- Establish the changes material substitution introduces when using non-conventional materials in the automotive industry, particularly in the process of material handling, e.g., aluminium is potentially explosive when in contact with water and grinding.
- Competency to operate the, diagnose, and fix faults.
- Government and relevant departments need to make room for consideration of new technologies onto the market; the OEM can align with respective regulators to ensure the adoption is covered in legislation from conceptualization to commercialisation.

4.5.2 Conclusion

The framework briefly presented a non-exhaustive list of current key issues to consider for efficient application of cold spray technology within the automotive industry. This will assist the automotive industry in being agile, given the pace at which global markets and the automotive industry are transforming. Automotive OEMs would need to establish collaborative efforts both vertically and horizontally within organisations, the automotive industry, research hubs and educational institutions. Moreover, a need exists for the realisation of a multidisciplinary skilled workforce.

There were a few factors noted that have put a halt on the adoption of cold spray into the automotive market. The interviewees noted the following factors:

- The automotive industry does not have a platform for knowledge exchange of available emerging technologies
- Lack of investment in high-cost equipment and return on investment (ROI)
- Complexities of the process and need for a unique skill set
- Application in mass production
- Availability of the raw materials for mass production, particularly for the new materials that the technology enables the use of, such as nanocomposites
- Unavailability of support structures such as research facilities and local suppliers
- Social challenges accompanied by adoption of new technologies such as culture, politics and change management.
- Innovation capacity of an industry and society

With this said, automotive OEMs need to invest in structured training, information sharing programmes or platforms, prioritise research topics that will widen materials eligibility, and optimise operations and equipment. The key to all these is high-risk propensity within senior management. According to the interviewees, to successfully implement the technology into the industry the effect on labour, customer demand, long-term benefits in the industry, global trends, cost of implementation, environmental effects and sustainability will need to be considered.

The issues may vary in priority and order; however, it is important for automotive OEMs to initially establish how the technology fits into the business and thus its product portfolio.

Moreover, the need to establish a long-term strategy and what the adoption of cold spray means in terms of transitioning into the next industrial revolution is apparent i.e how business in general will get affected. For effective operations to be established, the entire system needs to be carefully considered.

4.6 Validation of Framework

The validation of a framework is important to ascertain its credibility. No single test exists that would assert the validity of the framework. Rather, the level of confidence and thus validity of a framework increases as the framework passes more tests of practicality and applicability within a chosen environment (Martis, 2006).

The intention is this section is to show how the framework developed and presented and the arguments to support and dismiss the hypotheses will assist OEMs in establishing efficient automobile operations with cold spray technology. More importantly, it shows how all the hypotheses are interconnected and thus lead to the attainment of some of the key performance indicators for automotive manufacturers.

The framework’s limitation is that its focus is on automotive OEMs and not the entire industry. There are also limitations because one automotive OEM will differ from the next because of models (sedans, SUV, hatchback, small trucks), market, operations and brands thereof. The limitation for future considerations and development models is the fact that the market and automotive environment is volatile, ambiguous and uncertain. Therefore, future projections are based on prevailing atmosphere, however these may change.

Cold spray development and its incorporation in the automotive industry will not be an easy process, particularly because of the lack of infrastructure. However, the automotive industry can draw inspiration, knowledge and resources from other industries, such as the aerospace industry, which have already established a great deal with regards to the technology. The automotive industry will have to invest in deviation management, maintain continuous improvement, and strive for improved operations in line with its products. This framework validates how the research findings support key performance indicators for automotive OEMs and ultimately assist in establishing efficient operations. It also validates how the use of cold spray technology and its growth within the automotive OEMs can be facilitated. As discussed in the methodology, the validation of a framework will be as follows:

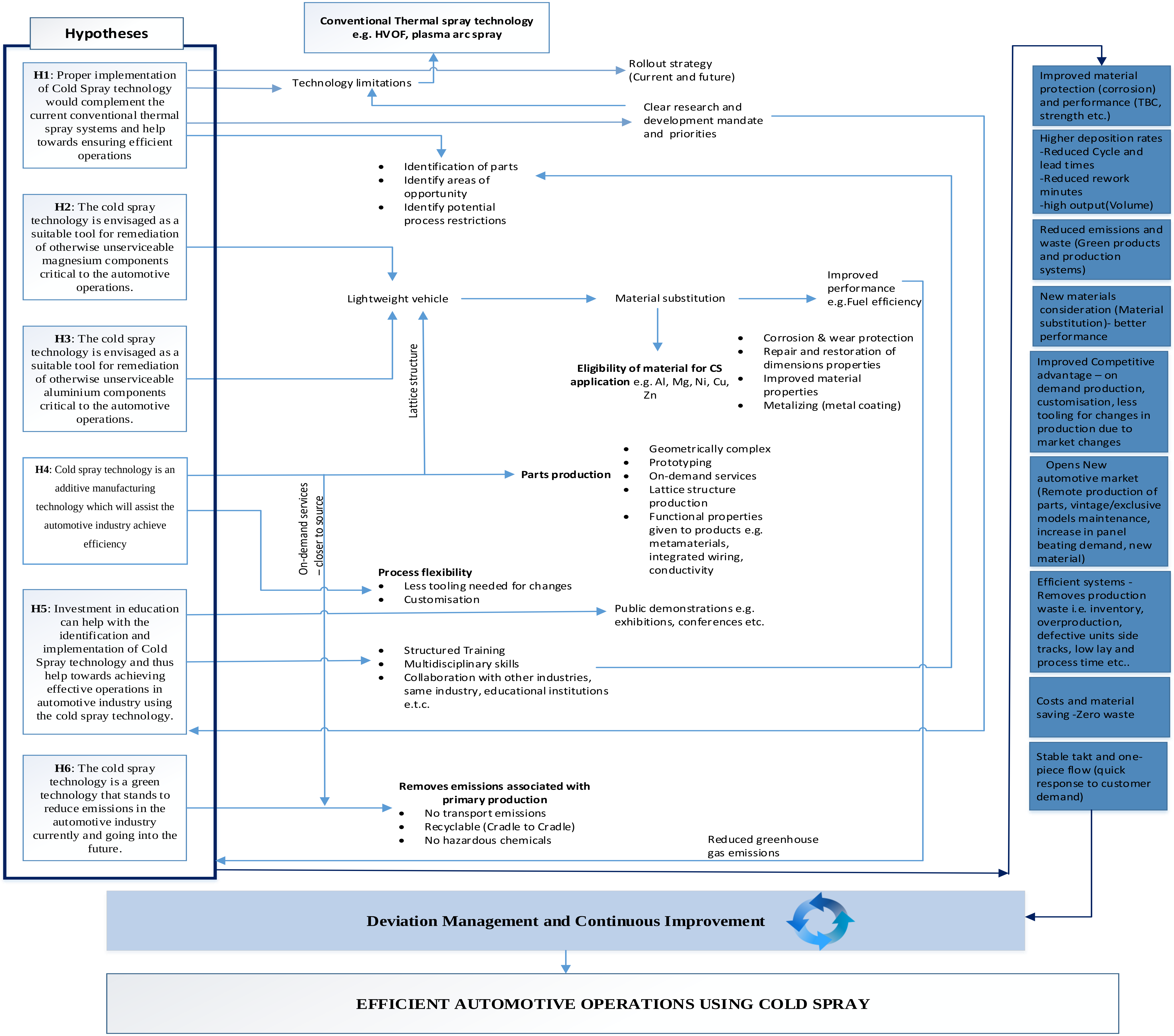


Figure12: Validation of hypotheses and how effective operations is achieved through each hypothesis.

4.6.1 Hypothesis and framework validation

The following section seeks to present an overview of the validation of the framework presented, the hypotheses and the arguments made. The following subsequent questions/key arguments are used as guidelines to establish the validity of the framework presented.

Correct identification of problems and opportunities in the field using the developed framework is one form of validating that it works. A valid framework is a framework that is applicable and is successful in identifying problems and opportunities for cold spray technology. The arguments have been helpful in establishing problems and opportunities within the industry and the limitations of the technology. The interviews with industry experts assisted in this regard. The arguments clarified the shortcomings of the automotive industry, technology and some of the reason applications will not be immediate in certain aspects, such as the B-post for safety reasons. The arguments have shown some advantages and opportunities for application as well as expansion of the technology, for example, through material substitution such as aluminium, nanocomposites, and magnesium.

4.6.1.1 Comparison to other frameworks:

Validity can be established by comparing the proposed framework with other ‘valid’ published frameworks of a similar nature or within the same industry. Comparison between the framework developed in this research and the framework developed by Botef (2015) presented in “Framework for Efficient Aerospace Operations” and “Cold Dynamic Spray Intergration Complexity” shows similarities in the key issues that industries need to consider for enrolment and expansion of the technology, such as market, technology and strategy. The two frameworks are focused on different industries, however. This does not discredit the premises for comparison because the subject matter to establish efficient operations remains the same even if the industries might be different; for example, the aerospace market is not volume driven. This makes maintenance within the aerospace industry the main focus as opposed to the automobile industry. Despite these differences, cold spray technology has a wide variety of applications that will fit the automotive industry, including maintenance of old vehicles such as vintage models.

4.6.1.2 Combination of a validation scheme as proposed by Khazanchi (1996)

The validation scheme proposed by Khazanchi (1996) includes a couple of points to validate the concepts or frameworks. Applicable to the research at hand are the following:

- Is it plausible/ reasonable? This criterion is useful to assess the apparent reasonableness of an idea and could be demonstrated by deduction from past research or theories.

  The framework developed is plausible/reasonable. The basis of the research arguments and framework is based on information from reputable and published journals and papers, books, literature, experiments, and current and predictive economic models. Some of the experiments have been tried and tested in the aerospace industry and applied in a few instances in the automotive industry in low volume models currently and in the past. Therefore, the framework arguments can be demonstrated from past research.

- Is it predictive? Would the concept or framework be able to predict, at the least, demonstrate that given certain antecedent conditions, the corresponding phenomenon was somehow expected to occur.

  The framework developed is not fully predictive; it is general. It used different business cases in both industry and research as a basis. It also does not cover the full range of challenges automotive OEMs may face upon adoption of the technology. It does cover the advantages of adoption of the technology. Therefore, the framework will be able to predict challenges and successes within the covered scope. It may, however, not be able to predict behaviours outside of the scope of the research or form a basis to draw a pattern or conclusions.

Is it feasible? Does the proposed solution or framework have potential to be implemented in the industry? Is it possible or practical?

The answer is yes, the framework is fairly practical.

- Is the framework effective? An effective framework should at least be able to serve the intended scientific purpose.

The framework does serve the intended purpose in assisting the automotive industry establish efficient operations. It showed the business and production performance indicators on which the adoption of the technology would have an overall effect.

4.7 Conclusion

This section has shown how effective automotive operations can be established using cold spray technology. It presented a framework based on argument and semi-interviews and tested all the hypotheses. The validity of the arguments was shown through Figure 9 with the emphasis on the deliverables or key performance indicators achievable through the adoption of the technology, such as zero waste, shorter lead and cycle times.

It was further validated that the framework is partially predictive, as well as reasonable and plausible. Figure 9 shows how each individual hypothesis contributes towards current and future automotive industry goals of mobility and world-class manufacturing facilities and production. The framework is not able to predict any behaviour or pattern outside the scope covered in the dissertation.

From the semi-formal interviews conducted, literature reviewed, arguments made, and the framework presented, it can be concluded that cold spray and additive manufacturing can benefit the automotive industry and assist in establishing effective operations in the following ways:

- Reduced development costs and time, e.g., through prototyping.
- Reduced production lead and cycle times.
- Flexibility in design changes (minimised complexity and design freedom).
- Reduced manufacturing costs through on-demand and customised products.
- Simplified one-step production of geometrically complex parts.
- Product customisation with minimal tool changes (increased flexibility).
- Zero waste by maximising material use through recovery of defective parts/units.
- Better line side and warehouse inventory control.
- Eligibility of new materials that present prospects of better product performance.
- Better precision and less defects from 3D printing than subtractive methods.

These are only a few benefits that indicate ways in which the adoption and commercialisation of cold spray technology in the automotive industry will assist in establishing efficient operations. In conclusion, the framework and arguments in Chapter 4 serve the intended purpose of assisting the automotive industry establish effective operations using cold spray technology. It is important to note, however, that for efficient operations to be established, OEMs need to look at the entire system including the business, people, technology, and environment.

5. CONCLUSIONS AND IMPLICATIONS

5.1 Introduction

This dissertation has been organised into five main chapters which were structured and focused on solving the following research question: Are there cold spray research and development opportunities which, by their consideration, could lead to an enhanced cold spray technology application in the automotive industry and more efficient automotive operations?

In the first chapter, the research topic, research background, research problem, angle and scope of coverage for the research was introduced. The necessity for the research was highlighted and the six formulated hypotheses to be addressed in the subsequent sections delineated.

Chapter 2 was a literature review of both the technology and the automotive industry locally and globally. The chapter incorporated the current status and future aspirations for the automotive industry, briefly highlighting the advancements necessary in both the cold spray technology and the automotive industry for the realisation of the current and future goals of mobility. It also described the materials of interest in the industry as well as cold spray technology's advantages and limitations. A description of the research methodology followed in Chapter 3, and the validation process of the framework was conducted in Chapter 4**.** The vehicle was dissected with a special focus on its current and future materials for construction. The hypotheses were also critically reviewed and discussed in Chapter 4.

Finally, in Chapter 5, the analyses and findings from the four chapters and their implications as well as the research's limitations are presented. Recommendations for any future work are also outlined.

5.2 Brief overview of the previous chapters

The first chapter of the report outlined the material limitations and production defects experienced in the automotive industry and the effects of these material limitations and defects on the production line and on the business in general. Special mention was made of the current state and how cold spray technology is envisaged to be a suitable tool for the removal of constraints. In the chapter, the background to the research, delimitations of scope and the terminology used was also introduce. The importance of the research to the automotive industry and cold spray technology particularly was summarized because the efforts are centralised around future of mobility and ensuring industries develop towards world-class manufacturing production plants in line with the fourth industrial revolution.

In the literature review, the focus of the second chapter, the current state of the automotive industry locally and globally with respect to the fourth industrial revolution, technological advancements, material substitution and cold spray technology and the important role it plays as an enabler was presented. How cold spray technology enables the attainment of the future goals of mobility, such as enabling lightweight vehicles construction, production of parts (3D printing) and reproduction (reworks) was covered. Cold spray's current uses in different industries, limitations and future were also addressed. Briefly highlighted were some of the future materials of interest that the automotive industry is considering with which cold spray technology is compatible or is currently viewed as eligible.

Based on the literature review, it can be deduced that only a few automotive OEMs are aware of strategies and technological advances needed for the transition into the next revolution and what this means for their businesses. Seemingly, the fourth industrial revolution has pushed some automakers to form strategic alliances to achieve common goals such as the reported collaboration between Renault and Nissan to develop zero emission transportation or the collaboration between BMW, Intel and MobiEye to enable completely autonomous driving. It is also apparent that the transition is largely dependent on the ability of the industry and automotive OEMs to identify and adopt enabling technologies such as cold spray technology.

The third chapter outlines the methodology used in the dissertation. It showed the suitability of the chosen methods in relation to the research type. The research consists of two sections, the development of a framework from literature review and semi-formal interviews of field experts. The sample size of the latter is also discussed. This section also explored the validation methods for the developed frameworks.

The fourth chapter of the dissertation was aimed at addressing the six respective hypotheses using literature inputs from reputable books, published papers, experiments and logic. The hypotheses were discussed more extensively in this chapter. The car was dissected into the powertrain, body and chassis components, and trim with a special focus on their weight contribution to the vehicle. Current and future materials such as aluminium, magnesium and nanostructures in industry research and development were discussed. A special focus on some of the future mobility goals such as vehicle weight reduction through the use of hollow structures, which could potentially be metalized for a high quality finish was also described.

Two aspects deemed important to modern day automotive industry were then explored, namely, life cycle analysis on the current materials of interest and a cost-benefit analysis of the adopting cold spray technology. It was deduced from literature that magnesium and aluminium have energy intensive primary production processes or metallurgical processes that deem their life cycle Red. These materials as used in automotive production plants and their product life in the field were found to be Green. Alongside their high recyclability, better termed "cradle-to-cradle," they have an overall Green life cycle analysis.

It was also deduced from the cost-benefit analysis conducted by experts in industry that the use of aluminium and magnesium is costly. In response to the unstable and ever rising prices of aluminium and magnesium, the industry has resorted to the use of variable alloys as a cost-effective solution. Adequate repair technologies such as cold spray technology present great cost savings for customers and businesses for repairs and restoration of damaged and mis-machined components on the production line and in job shops, panel beaters and aftersales facilities. Cold spray technology assists in avoiding complete replacement of expensive automotive parts, some of which are may be high end, exclusive or discontinued model components. As the largest manufacturing sector in South Africa and Sub-Saharan Africa, cold spray technology's ability to support the industry's aspiration to achieve higher volume and improved quality products for import and export markets is crucial for economic growth.

The framework for the current or immediate expansion of the technology within the automotive industry was then presented. The framework highlighted four important pillars, namely, market (including strategy), people, technology, and environment and safety. The framework showed the importance of collaborative efforts between industry, educational institutions and research hubs towards achieving effective operations. It was further argued that people skills development and equipment efficiency remain central to the success of the technology in industry, particularly with respect to the necessary rare skills that need to be developed in a short timeframe. Technology developers and suppliers should also ensure that the technology is inherently safe in design and has minimal environmental impact due to stringent laws passed in different countries that affect manufacturing industries. The framework's limitations lie in its focus on the automotive OEM and not the entire industry.

Last, validation of the framework and hypotheses presented in the initial subsections of Chapter 4 was addressed. The framework highlighted the key performance indicators attainable from cold spray technology applications and services, such as low cycle and lead times, reduction in waste, one-piece flow systems, and material properties that lead to improved performance and protection. It was argued based on the framework that research and development in industry is important to ensure continuous improvement and deviation management. It may be beneficial if OEMs invest in in-house research support infrastructure because such infrastructure will give instant support for varied product portfolios and production lines.

The importance of integrating cold spray as an emerging technology into current thermal spray processes and production systems and how this can be achieved was demonstrated. Each section was critically reviewed and discussed with a conclusion of the findings at the end.

Chapter 5 introduces the framework for future consideration of developments and issues pertaining to efficient automotive operations using cold spray technology with a focus on recommendations and future considerations. This framework was built on the same four pillars used for the framework for current or immediate expansion of cold spray technology. Using the framework, future challenges and considerations for OEMs and the automotive industry, such as the ambiguity and volatility of the markets that has made it difficult for more accurate projections to be made for future planning, are discussed. The ability of automotive OEMs to respond quickly to ever-changing industry trends and customer needs will be important for the automotive industries' success and survival. This concern is inseparable from the industry's ability to continuously invest in upskilling its labour force as per the industry's growth and developments. The ability of cold spray technology to support the future of mobility goals through its applications deems it an attractive investment for the industry in the future.

The aim of this final chapter is to summarise the findings and arguments. Whether the research question and hypothesis were adequately answered is also addressed and concluded. Implications of the research and practises are drawn based on the arguments presented.

5.3 Conclusion about the Research Question and Hypotheses

The research outlined in this dissertation was aimed at addressing the following research question: Are there cold spray research and development opportunities which, by their consideration, could lead to an enhanced cold spray technology application in the automotive industry and more efficient automotive operations?

Six hypotheses were constructed in pursuit of answering the research question. The research used literature publications such as reputable and published papers, books, journals, documented conference proceedings, consulting companies and expert reviews to confirm or dismiss the following research hypotheses:

*H*1: Cold spray technology is envisaged as a suitable tool for remediation of otherwise unserviceable magnesium components critical to the automotive operations.

*H*2**:** Cold spray technology is envisaged as a suitable tool for remediation of otherwise unserviceable aluminium components critical to the automotive operations.

*H*3: Cold spray technology is an additive manufacturing technology that will assist the automotive industry achieve efficiency.

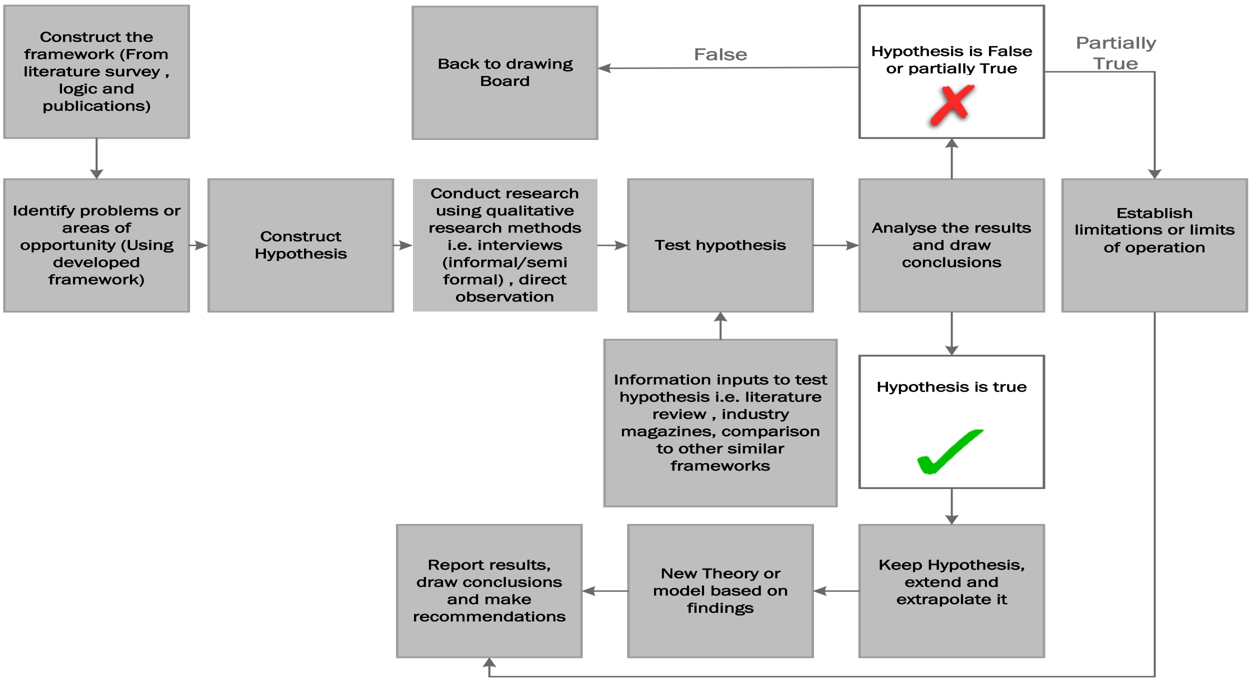
*H*4: Investment in education can help with the identification and implementation of cold spray technology and thus help towards achieving effective operations in the automotive industry.

*H*5**:** Cold spray technology is a Green technology that stands to reduce emissions in the automotive industry currently and going into the future.

*H*6: Proper implementation of cold spray technology would complement current conventional thermal spray systems and help towards ensuring efficient operations.

To answer the hypotheses, the loop demonstrated in Figure 13 was used.

Figure 13: Loop used to test hypotheses.



To test Hypothesis 1, which states, “Cold spray technology is envisaged as a suitable tool for remediation of otherwise unserviceable magnesium components critical to the automotive operations,” the magnesium material properties that are attractive and suitable for automotive applications were outlined. One of the most outstanding properties is its low density of 1.74 g/cm^3. This means magnesium is 35 percent lighter than aluminium (another material of great interest) and 78 percent lighter than steel (traditional material of construction of vehicles) (Powell et al., 2012). It was argued that magnesium’s limitations, such as its high temperature creep and susceptibility to severe corrosion has put a halt on its application across different industries (Leyman, 2008; DeForce, et al., 2009; Mallick, 2012). The unavailability of adequate surface engineering technologies to support and counter these limitations in industry has also played its role. Current corrosion methods such as organic, chromate and conversion methods only offer general protection. These methods use hazardous chemicals that have handling issues, oxidation reactions, and multiple process steps (Villafurte & Zheng, 2011). In contrast, cold spray technology offers oxide free, hard, dense, thermal barrier coatings, and severe corrosion protection coatings with minimal process steps (Botef, 2015; 0Villafuerte, 2015).

Recent research and development efforts in magnesium alloys manufacturing processes has given rise to two magnesium alloys commonly used in the engine block, namely, AMC-SCI and compacted graphite cast iron (CGI) (Nguyen, 2015). These alloys have a competitive price, high temperature creep, lower weight, and double the fatigue limits (high strength) relative to aluminium and cast iron. However, these alloys are usually used in low volume luxury models and cannot replace all magnesium alloys used in high-volume vehicles because of high insurance and cost implications. In light of this, automotive OEMs have resorted to the use of a combination of different alloys to balance out the cost per unit.

Magnesium applications in vehicles enable the necessary weight saving the industry seeks to build fuel-efficient vehicles (Knight, 2011; Musfirah & Jaharah, 2012). A few successful experiments and industry applications of cold spray using magnesium substrates such as the AZ91D alloy application to improve temperature creep of transmission cases and engine components were presented (Musfirah & Jaharah, 2012). Analysis of these coatings showed that the hardness, porosity, corrosion resistance improved significantly. Based on these arguments, it was concluded that cold spray technology is a suitable tool for remediation of otherwise unserviceable magnesium components critical to the automotive operations.

The second hypothesis is, “Cold spray technology is envisaged as a suitable tool for remediation of otherwise unserviceable aluminium components critical to the automotive operations.” The high demand for aluminium in the automotive industry is attributed to its material properties. It has good formability, a better corrosion resistance and a higher strength-stiffness-to-weight ratio in comparison to magnesium (Mallick, 2012). A review of the literature showed this is the motivation behind its application in two critical components, namely, the engine block and head (Musfirah & Jaharah, 2012). However, aluminium can still suffer from premature failure due to corrosion pits and localised stress (Botef, 2015).

Numerous applications and experimental studies conducted showed the ability of aluminium alloys to be cold sprayed. One such application is the 5083 aluminium alloy substrates largely used in automotive bodies and the shipping industry for its formability, strength, corrosion resistance and weldability. It was successfully cold sprayed using Al-Alloy coating. AA5083 is commonly used for wheels, chassis, and sub-frames in the vehicle (Van der Hoeven et al., 2002). The alloy has high strength; however, it is highly susceptible to intergranular corrosion if exposed to high temperatures. Welding the material results in loss of mechanical integrity in heat-affected zones (HAZ) that could possibly lead to additional cracking. The experimental results of the coated aluminium substrate showed higher coating density, improved adhesion and no evidence of oxidation, (Sridharan et al., 2013). From these arguments, it was concluded that cold spray technology is a suitable tool for remediation of otherwise unserviceable aluminium components critical to the automotive operations.

The third hypothesis is “Cold spray technology is an additive manufacturing technology that will assist the automotive industry achieve efficiency.” The cold spray process, as an additive manufacturing process has become attractive to automotive manufacturers as an enabling technology. It was argued that cold spray has changed how products are designed, developed, produced and distributed. It has opened avenues for newer designs and cleaner, lighter and safer products that are produced with shorter lead times and lower costs (Giffi & Gangula, 2014). Cold spray, as an additive manufacturing technology, presents an innovative way of producing quality parts faster than powder-fed processes (i.e., lower lead and cycle times) (Pathak & Saha, 2017) and can produce geometrically complex parts such those used in the Urbee (Giffi & Gangula, 2014).

Additive manufacturing has been used for prototyping; however, it has the ability to support production lines (Additive Manufacturing for Automotive, 2015). It can be used to produce lattice structures that could be coated for better furnish and protection (Villafuerte, 2014; Additive Manufacturing for Automotive, 2015). This supports the automotive industry’s vision of producing lightweight vehicles (Giffi & Gangula, 2014; Hamweendo, 2017). A good opportunity lies in the trim or assembly components of purely decorative parts. Metal printing using additive manufacturing is still limited; however, at the moment, metalizing these lattice structures presents a good solution whilst this application is still being developed. Further advantages of this application lie in its ability to support different process changes with less turnaround time because it requires less tool changes compared to its counterparts. Changes in supply chain such as real-time, on-demand printing of parts removes the challenges associated with transportation, inventory and warehousing space (Giffi & Gangula, 2014). Cold spray further allows for on-demand and onsite repairs, which enables customers to keep the aesthetic features of old and exclusive car models.

Cold spray technology presents a good solution to the challenges of heavy parts, transportation, high lead and cycle times, reproduction, geometrically complex components and controlling inventory levels. Based on these arguments, it is clear that cold spray as an additive manufacturing technology can assist the automotive industry establish efficient operations. It changes the way the processes, supply chains and aftersales markets have traditionally been designed and been working over the years. Based on the arguments, it is concluded that cold spray technology is an additive manufacturing technology that will assist the automotive industry achieve efficient operations.

The fourth hypothesis states that investment in education can help with the identification and implementation of cold spray technology and facilitate achieving effective operations in the automotive industry. It was argued that collaboration between industry and educational institutions will assist in supporting the evolution of existing technologies and ensure successful introduction and integration of emerging ones into the market. In-house research hubs may assist with instant responses to challenges and tailor applications for automotive manufacturers’ varied product portfolios post supplier commissioning and customer buyoff. Collaboration in industry might facilitate learning and information sharing, strengthen businesses’ abilities to forecast, and adapt and embrace continuously changing industry requirements. This is particularly instrumental in fast-paced industries such as the automotive industry where trends change instantly. However, the development of and qualification for such technologies also need to be timeous. This can only be achieved if suppliers, automotive manufacturers and research institutions invest in upskilling their people to support the necessary developments. This is important because of the level of consideration and knowledge needed to implement the slightest design, operational or decorative changes in a vehicle to improve either the functional, aesthetic, or structural aspects of the vehicle. The lack of knowledge by OEMs about technologies in the market such as the cold spray process hinders and delays such advancements. Creating platforms for these emerging technologies is important.

An argument made was that for cold spray technology as an emerging technology to succeed in the automotive industry, there must be a clearly defined mission, vision, objectives and thus strategy on how emerging technologies fit into already existing and future structures. A study conducted by experts revealed that only 30 percent of the technology suppliers and 16 percent of manufacturers have an overall strategy of what the transition into the fourth industrial revolution requires of them. It is evident that most companies can easily be left behind because there is no clear understanding of what is required of them.

Investment in education, teaching and learning means the following:

- Globalisation of ideas such as adopting tried and tested manufacturing good practises and information sharing. This will be easy to establish within automotive groups with multiple plants across globe.
- Information sharing across industries. The aerospace industry is a good base because it has developed much further than the automotive industry.
- Improving the availability of studies, information content, patents, specifications and literature to the public.
- Inclusion of industry technological developments in relevant curriculum such as higher education and technical colleges.
- More investment in research and development, such as research hubs, laboratories etc., across the world rather than concentrating them in specific regions.
- Public demonstrations including conferences, dialogue sessions, exhibitions etc., to increase and improve public knowledge about what is on the market.

Finally, it was argued that information transfer and implementation of these support structures for the industry would also bridge the identified gaps and limitations of cold spray technology. Information transfer and implementation of these support structures will also help with conquering some of the frontiers the technology is facing, such as expanding materials eligible for application and equipment optimisation. The increased support structure from cross-industry experts, technology developers, OEMs, government, investors and education institutions are envisaged as good methods to fast track the integration of emerging technologies such as cold spray and establish efficient operations. This proactive, informative and engaged approach will assist in the current and long-term continuous improvement on all fronts. Based on these arguments, it can be concluded that investment in education can help with the identification and implementation of cold spray technology and help towards achieving effective operations using the cold spray technology in automotive industry.

The fifth hypothesis states that cold spray technology is a Green technology that stands to reduce emissions in the automotive industry currently and going into the future. In the modern automotive and manufacturing industry, it is vital for technologies and products to be Green, i.e., demonstrate minimal to zero emissions. To explore this hypothesis, the arguments made were the following:

- Cold spray is a rework tool that removes the need for reproduction of an entire unit. This removes all associated production waste, emissions and any adverse effects from primary production. For example, for every ton of primary production (from MgO ores), 17.8 tons of carbon equivalent are generated (Pelsoci, 2015).
- The technology does not use any hazardous chemicals that risk the health and safety of the operators. Coatings are conducted with minimal process steps and surface preparation relative to thermal spray technology counterparts (Pelsoci, 2015).
- In the supply chain, the technology removes all emissions associated with transportation through its real-time, on-demand, and onsite production of parts (Giffi & Gangula, 2014).
- The life cycle analysis review presented in Chapter 4 suggested that the substitution of traditional mild steel or cast iron with lighter metals such magnesium and aluminium has an overall Green lifecycle benefit. Studies further showed that this substitution can potentially eliminate approximately 20 kg of carbon dioxide over the lifetime of the vehicle (Knight, 2011; Musfirah & Jaharah, 2012)). This substitution has not been possible previously due to unavailability of adequate thermal spray support technologies. Cold spray technology is therefore a Green technology.

These arguments attest to the notion that cold spray technology is a Green technology. It has been shown both directly and indirectly how the adoption of the technology reduces the production and product environmental impact.

The sixth hypothesis states that proper implementation of cold spray technology would complement current conventional thermal spray systems and help towards ensuring efficient operations. There is a gap in industry in terms of the introduction of new and emerging technologies. These emerging technologies should be better introduced and managed to compliment current systems. This gap needs to be closed urgently, particularly in an era where the industry is shifting towards another revolution with multidimensional changes.

- The use of cold spray technology to compliment current thermal spray technologies will assist in the transition of the technology in the industry; however, it is critical that cold spray technology be implemented properly. The question put forth to address this hypothesis and direct the arguments is “How does an industry/company ensure proper implementation of cold spray technology into their already existing systems to ensure efficient operations?” Based on the arguments made, the following will be required:
    - A clear map of what the adoption of the technology influences in terms of product, operations, processes, workers and business including any necessary actions.
    - Collaboration of all affected departments within the business with clear roles and responsibilities outlined.
    - Training, information sharing and facilitation on the technology and its influences on the business. Identification of opportunities will arise from these.
    - Continuous improvement should come from all ranks of the business; this means that the information integration, training and development needs to be done across all ranks, ultimately starting with the people who will be critical users of the technology.
    - Involvement of either research experts, cold spray consultants or university academics throughout the implementation process, i.e., the planning, commissioning, buy-off and process optimization process.
    - Consideration of material eligibility and other processes that will be affected by changes in material across the production cycle, e.g., aluminium and steel joining introduced a change from normal spot welding to self-piercing riveting and flow drilling, clinching, adhesive bonding and weld-bonding.

This hypothesis is subject to a great deal of argument because the implementation strategy is relative to a specific brand, manufacturer, market, product and its brand culture. Therefore, the hypothesis only covers the general scope necessary for a proper implementation. This hypothesis was shown to be only partially true.

5.4 Conclusions about the Research Problem

The purpose of this research was to address the following research question: Are there cold spray research and development opportunities which, by their consideration, could lead to an enhanced cold spray technology application in the automotive industry and more efficient automotive operations?

Six hypotheses were constructed and explored. Data inputs, information and literature presented support the notion that certain considerations in the research and development of cold spray technology could lead to enhanced cold spray applications within the automotive industry and assist in achieving effective automotive operations. A compelling argument was presented to show how efficient automotive operations can be achieved through the use of cold spray technology. This was validated through Figure 9 . Some inspiration was drawn from aerospace industry studies and its applications of cold spray technology.

Based on the research, there are cold spray research and development opportunities, which through their consideration, would establish effective automotive operations. For example, the integration of conventional thermal spray technologies and cold spray technology could lead to more efficient operations because some of the limitations of cold spray technology can be addressed. Arguments that indicate that Cold spray technology is not ready for a complete replacement of thermal spray technology are also evident, but the indications are that it should be used as a change agent for transitioning into the fourth industrial revolution alongside existing structures. Moreover, developments in 3D and additive manufacturing will not only assist in rework and repair applications but also change traditional supply chain processes and manufacturing processes. This may further assist in establishing efficient operations.

5.5 Research Contributions and Implications

The research implications and contributions of this dissertation are listed below. The dissertation presented the following:

- A novel approach to analyse the effects of adopting cold spray technology's applications in the automotive industry in pursuit of establishing effective operations considering opportunities, and pursuing research and development.
- A unitary approach of the effects of the adoption of the technology on different facets of the business. The approach considers the interrelations between business, technology, people, environment, product, production, etc.
- Materials to consider for future applications in the three divisions of the vehicles, namely, powertrain, body and chassis, and trim. The effects on overall production, product and business were also highlighted.

5.6 Research Limitations

The following section outlines some of the limitations of the research conducted:

- The research does not cover coating or process parameters used for coating aluminium, magnesium, or any other material covered in the dissertation.
- The research frameworks presented take different approaches and have a different focus, i.e., either the automotive OEM or the industry with respect to immediate adoption of cold spray technology and for future expansion.
- The research focuses on the adoption of the technology within a developing country such as South Africa with a great deal of growth potential and market.
- The research arguments are made based on the assumption that the industry is determined and willing to transition into the fourth industrial revolution and is willing to consider adopting emerging technologies for this transition.
- Frameworks were not tested or tried in industry; instead, industry experts' publications, experiments, studies and opinions were used to test the framework.

The points noted above do not devalue the research conducted.

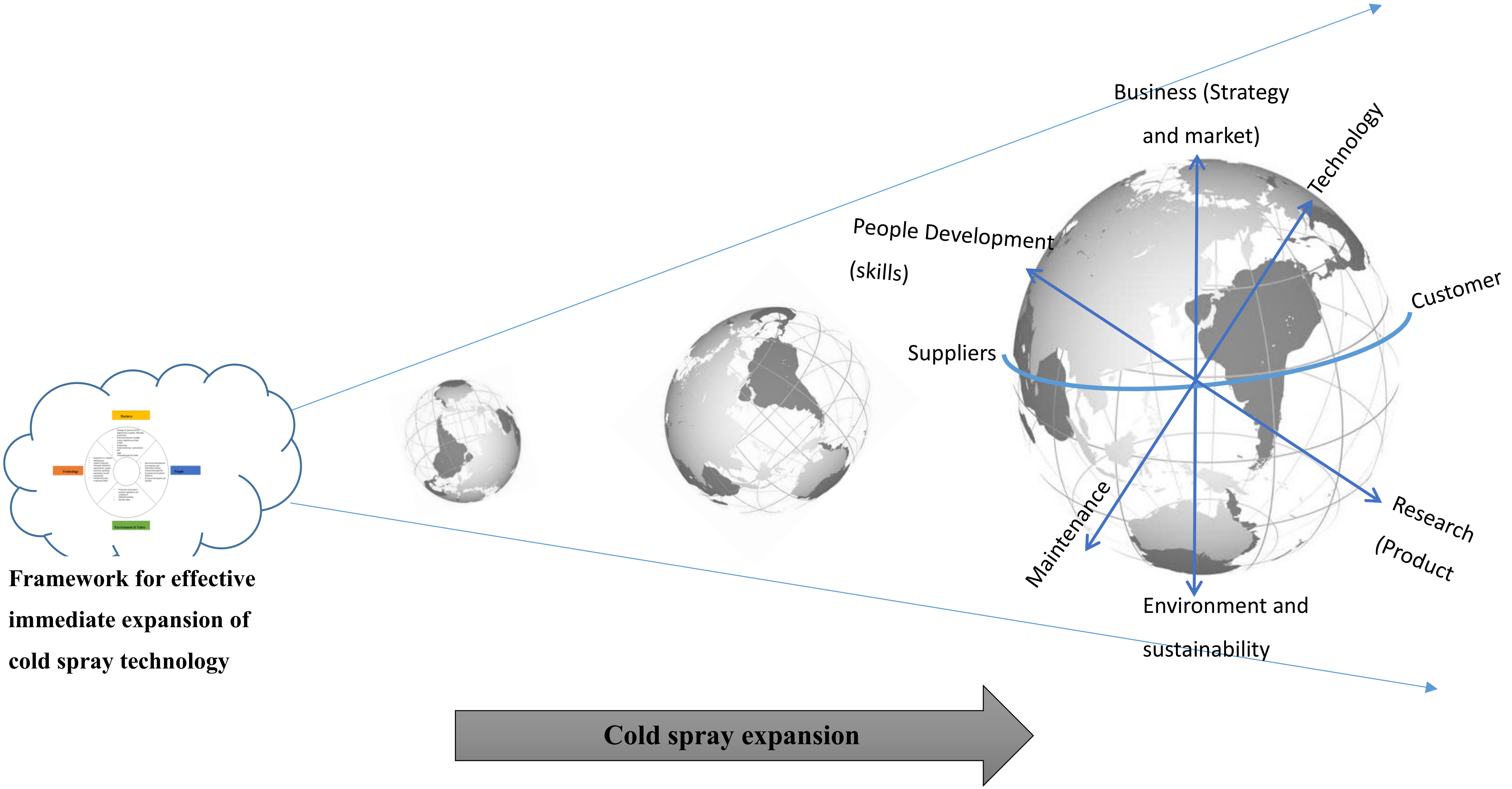
5.7 Further Research Recommendations and Suggestions

5.7.1. Framework for future considerations, developments and issues to address in cold spray for effective automotive operations

Today’s product development requirements include short turnaround time or realisation. This is due to volatile markets and ever-changing customer demands and expectations. The automotive industry is one of the few industries that invests in future products and operations timeously. This is evident from its prototype models such as the GINA, a flexible and water resistant translucent fabricated prototype model first designed in 2001 but unveiled to the public almost a decade later in 2008. To date, this model has not been not realised, but it has inspired certain applications such as the use of carbon fibres and “bird-wings” doors designs in models such as the BMW i8 (Design Works, 2018). To shorten this development period and realise quicker commercialization of concept vehicles, there is a need for more concurrent engineering and strong collaborations between all important stakeholders such as research hubs, educational institutions, and industries. This will assist in the design of more efficient operations and products with even shorter realisation periods.

The framework presented (see Figure 14) presents a view of the future expansion of cold spray technology. It starts with the framework proposed for current expansion of cold spray technology within the automotive industry. The product and service requirements and specifications have evolved over time and grown more complex. These requirements and specifications are expected to grow in complexity, functionality and structure. With this in mind, in the future, there will be a need for well-established technical and quality cold spray applications standards, which are made accessible for public reference or contained within a certain community of experts.

Figure 14: Framework for future considerations, developments and issues to address in cold spray in the automotive industry.



This model focuses on the industry as opposed to the OEM. It builds onto the four pillars used in the previous framework namely business (including market and strategy), technology, people and environment and safety. These issues are briefly discussed below.

5.7.1.1 Business (market and strategy)

Contemporary studies have shown how the transition into the fourth industrial revolution has exposed the industry to volatile and uncertain markets with phrases such as VUCA being used. This has made it challenging for OEMs to adequately plan ahead and strategize how businesses should adapt to this ever-changing environment through future planning and forecasting. If the markets are stable then the industry would be able prioritise topics of interest with OEMs, which would benefit the businesses by considering different business models and markets for their product portfolios. OEMs would therefore be able to explore other markets, look at trends within the automotive industry, adapt applications to suit these market trends, and explore those applications that will widen OEMs profit margins. Cold spray technology enables and supports these markets in various ways such as through material substitution and remote printing of complex production parts that have not been achieved before. Cold spray’s ability to support variable applications with minimal tool changes ensures that the market response turnaround time is minimal in terms of product implementation and realisation. It is also able to support product development efficiently through the use of its 3D printing of prototypes. More opportunities lie in partnering with other OEMs that are far ahead in development to ensure the development time is minimal.

5.7.1.2 Environment and sustainability

For viable product realisation, the environmental effects of production and products must form part of the design process. As stricter laws are passed, a need exists for suppliers and automotive OEMs to ensure the technology and all its product ranges contribute positively to current and future emission standards, such as particulate matter from the powder feed, in both the countries of production facility and customers.

The partnership with research institutions can also assist in exploring Green materials such as specialised fabrics and polymers that do not leave a high waste footprint. The compatibility of cold spray and Green primary production ensures an overall Green life cycle and contributes towards sustainability of the environment. Materials that need less energy for processing and have a high recyclability should be prioritized. With respect to cold spray technology, developers need to strive for improved systems by optimising the current systems to ensure it meets the stringent laws in individual countries and the industry in general.

5.7.1.3 Technology and maintenance

The automotive industry should also focus on rolling cold spray technology out to small scale operations that support automotive OEMs customer base's such as panel beaters and job shops. The focus should be on these support structures' education, resources and skills. More focus should also be put on improving the safety features of the equipment, automation, and the reliability and repeatability of results to ensure the process is capable for each application. The maintenance of the actual machinery as it ages and its upgrades are of paramount importance to ensure its optimal use and results.

The maintenance of vehicles as they age will also factor in; as such, the ability to 3D print parts centrally and in specified places through the purchase of parts designs from automakers will assist if it comes to realisation. Cold spray technology is definitely a north star as infrastructure will need to be set up and control of patented information for the vehicle designs established. The rollout and use of cold spray technology to job shops and panel beating services will ensure accessibility for customers who want repairs instead of complete replacement services.

Expansion of the use of the cold spray technology lies mainly on its ability to optimise the equipment, such as nozzle design and powder feed parameters. The optimisation of equipment will ensure that it is able to support critical operations within the vehicle and expand materials eligible for coating. Virtual manufacturing should be considered because it brings companies together to share skills, costs and jointly focus on one or multiple markets (Botef, 2015) .Virtual training is another step in digitalisation that the industry can consider to fast track upskilling its workforce. It is in line with the fourth industrial revolution and gives the workforce a feel of the actual operations at a central location, thus allowing workers to safely familiarise themselves with high technology before it being introduced to their work stations.

5.7.1.4 People development (skills set)

In the near future, it is expected that a considerable workforce would be trained and competent to support stakeholders with the use of cold spray technology. OEMs should invest in rolling out critical skills to the larger workforce and develop skill succession and retention plans using approaches such as “On-the-Job” and “Train-the-Trainer” training for the current and future needs of the industry.

It is also important to establish the workforce’s values and culture, which could affect how they interact with the machine, i.e., the man-machine interaction, which is also known as cognitive engineering. Exchange programmes and knowledge sharing across borders, industries and OEMs could assist in sharing knowledge, skills and good engineering practises in this regard. Group technologies will benefit from this approach because of similar products and brand values.

5.7.1.5 Research (product development)

Research forms an important aspect of new technology introduction to existing and evolving markets. It plays an important role of steering the technological advances and seeking alternatives to prevailing conditions including market changes and their influence on necessary technological changes, e.g., operating conditions, equipment design and efficiency, etc. It is the key to finding solutions to the limitations of the technology and offering OEMs hands-on support to ensure stable operations. It is critical that research institutions (private or governmental) focus on breaking barriers in industry and markets with the technology. The collaboration shortens development time and customises operations specifically for the industry and its product ranges. In-house research facilities will assist in fast tracking development plans as the primary focus will be placed on individual brands and brand vision and ensure quicker reaction to challenges.

5.7.1.6 Suppliers and customers

At the heart of this framework lies the supplier and customer. The ability of the supplier to respond to automotive OEMs needs and implement the necessary changes to customise the equipment and its functions for different product ranges is central to the success of the industry. The ability for the automotive OEMs to project changes in their customer needs is an important factor in order to remain competitive. However, its ability to respond well in time is just as important. For example, the British automotive industry’s inability to compete in the global market was the reason behind its downfall as the second largest manufacturer in the world to the twelfth largest manufacturer in five decades. Foreign markets were growing faster and built more economical, reliable and quality vehicles than their British counterparts. Automotive manufacturers were later forced to sell their national assets to their competitors namely Germany, France and Japan. Models such as Rolls Royce and Mini were sold to BMW, Tata bought Land Rover and Jaguar, and Volkswagen bought the iconic Bentley. This attests to the notion that there are catastrophic results when an industry is unable to adapt to its customer needs and market trends, adopt emerging and enabling technologies, and align its resources such as upskilling workers to be able to support the business and remain competitive. Cold spray technology, as an enabling technology for the future of achieving mobility goals, gives automotive manufacturers competitive advantage over its counterparts in the global market in various ways. These include quick tooling changes to support changes in production, the ability to support production to achieve high volume through its rework or remanufacturing ability, and making material revisions to ensure lightweight vehicles.

From literature and the arguments, alongside the research limitations, a need for research and development in the following areas exists:

- Optimisation of cold spray equipment that present opportunities in widening the scope of materials eligible for coating.
- In depth theoretical and practical research into the compatibility of different aluminium and magnesium alloys used by automotive manufacturers for coating eligibility.
- A cost-benefit analysis into cold spray technology specifically around the automotive industry (i.e., OEMs).
- Full review of the life cycle analysis of the materials of interest, looking at traditional coating processes vs cold spray technology, within the automotive industry.
- Opportunities presented by emerging technologies to enable swift transition into the fourth industrial revolution.

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7. APPENDICES

7.1 Appendix A: Glossary

Alloy: a mixture of metals or metal and another element.

Amorphous: also known as nanocrystal line solids, are solids characterised by their disordered atomic structure; examples include glass, gels, metallic glasses and polymers.

Composite: mixture of two or more materials, all of which have different properties, i.e., chemical and physical properties. The combined material has unique characteristics. It is usually constructed to achieve certain desirable properties that each individual material does not possess.

Conductivity: measure of a material to conduct heat or electric current based on its electron structure/arrangement.

Corrosion: the deterioration of a material due to a chemical or electrochemical reaction between the material and its surrounding environment.

Critical velocity: the velocity greater than the minimum velocity required for bonding to take place.

Ductility: ability for a solid material to be stretched into a wire when placed under tensile stress.

Erosion: removal of a material from a surface due to mechanical interaction between the surface and fluid or liquid and solid.

Fatigue stress: failure of a material due to the collective effect of stress applied to it repeatedly, which does not exceed the material’s tensile strength. The fatigue limits of the material are the stress at which failure occurs after a number of cycles.

Environmental foot-print, e.g., carbon/waste: the impact certain activities have on the environment and its ecological ability to assimilate the waste or damage done.

Grain growth: also known as recrystallization, occurs when there is a significant increase in grain size when material is exposed to elevated temperatures.

Nanophase materials: materials with a grain size between 1 and 100 nanometres. Generally known for their great strength relative to normal materials.

Patent: rights granted to inventors of products and processes that provide a solution to a known problem or an innovative way of conducting business.

Phase changes: change in the state of matter, e.g., from solid to liquid.

Plastic deformation: an irreversible change in a solid material without any fracture, usually caused by applied external forces.

Porosity: presence of pores or voids in a coating or material, usually expressed as a fraction or percentage by volume.

Residual stress: internal stress experienced by a material even after external forces that caused the initial stress have been removed.

Sub-assemblies: section of a production plant where a unit is constructed separately to be fitted into a larger unit within the same production section.

Wear: damage or destruction of a material or equipment from continuous use and/or friction.

7.2 Appendix B: Thermal Spray Processes

Thermal spray technologies have served different industries such as medicine, automotive and gas and turbine .The following sections briefly outlines different spray technologies in industry and their differences relative to cold spray technology. The main differences between these technologies is the amount of thermal and kinetic energy required for each process as shown in table below,

Table 2 Temperature variations of different thermal spray processes (Sulzer Metco, 2013)

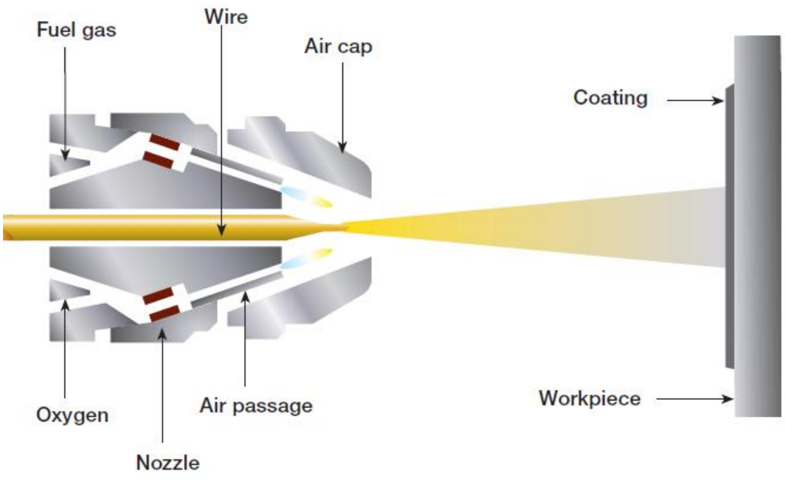
Characteristic	Powder Flame spray	HVOF	Electric Arc	Plasma spray
Gas temperature (º C)	3000	2600-3000	4000 (Arc)	12 000-16 000

7.2.1. Conventional Flame spray process

7.2.1.1. Wire Flame spray

Wire material is melted using a gaseous oxygen-fuel flame. Different fuel compressed gases may be used such as propane, hydrogen and acetylene. The melted and atomized wire is then directed to the substrate as shown in the diagram below.

Fig 15: Wire flame spray schematic diagram (Sulzer Metco, 2013)



7.2.1.2. **Powder Flame spray**

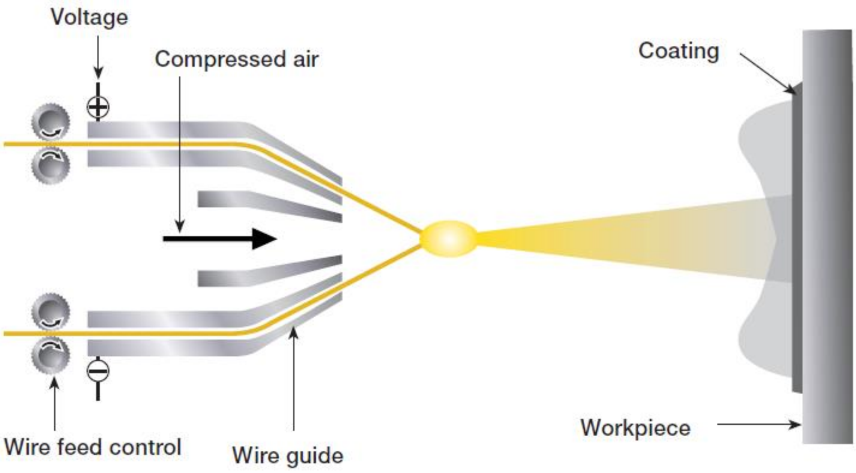
The powder flame spray process has the same principles as the wire flame spray however the coating material is powder instead of wire.

One of its advantage is that more material is available for coating. Powder management i.e. environmental pollution and exposure to workers is a challenge.

7.2.2. **Electric Arc wire spray**

An arc is produced by contact with opposite charged metallic wires. This leads to melting at the tip of the wire material. Air atomizes the melted spray material and accelerates onto the substrate. The spray rate can be adjusted by regulating the wire feed melting process.

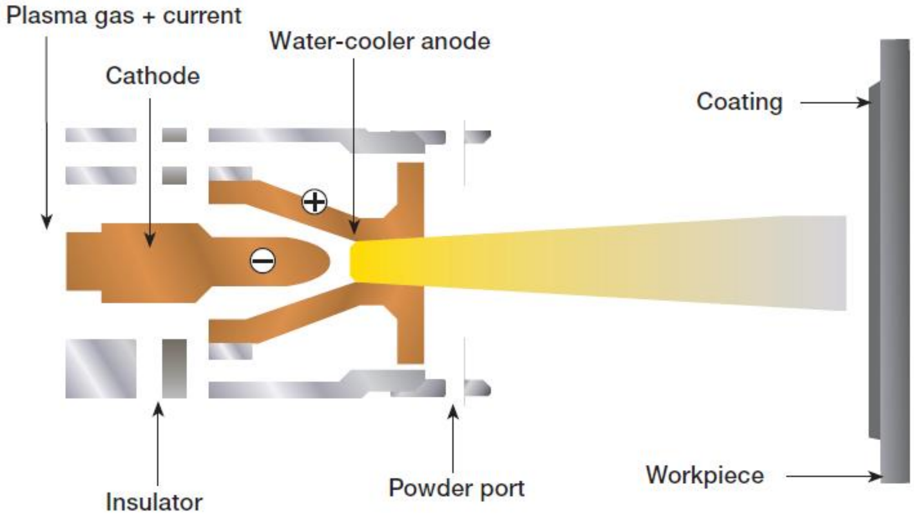
Fig 16: Schematic diagram showing electric wire arc spray process (Sulzer Metco, 2013)



7.2.3. **Plasma spray**

A high frequency arc is ignited between an anode (negatively charged rod) and a tungsten cathode (Positively charged rod). Helium, hydrogen, nitrogen or a mixture of gas flows through these electrodes. The temperatures of this process can rise up to 16000 degrees Celsius. The spray material is injected as powder outside

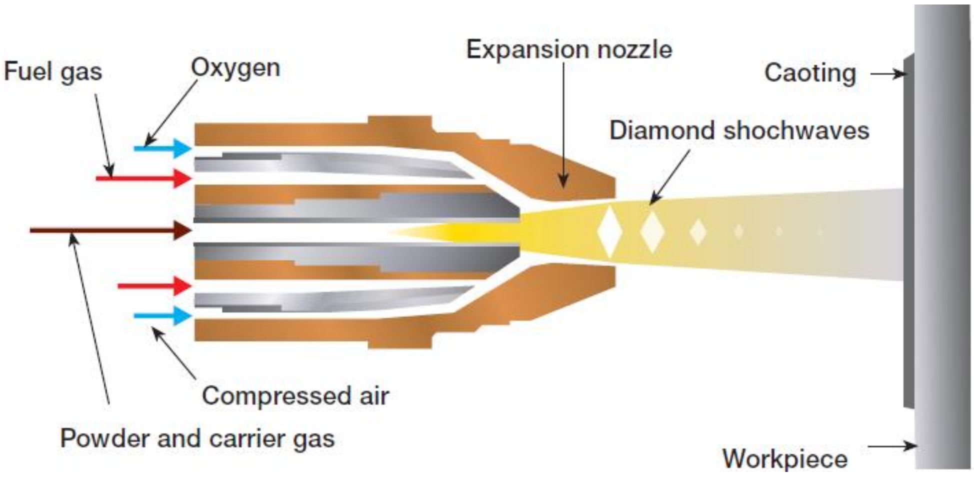
Fig 17: Schematic diagram showing Plasma spray (Sulzer Metco, 2013)



7.2.4. **High velocity Oxy-Fuel Spray (HVOF**)

This process uses a supersonic gas jet to propel a particle at high speed to achieve coating upon impact with the substrate. Natural gas, propane, hydrogen, propylene and acetylene as well as liquid fuels such as kerosene. This system uses a combination of kinetic energy and thermal energy.

Fig 18: Schematic diagram showing HVOF (Sulzer Metco, 2013)



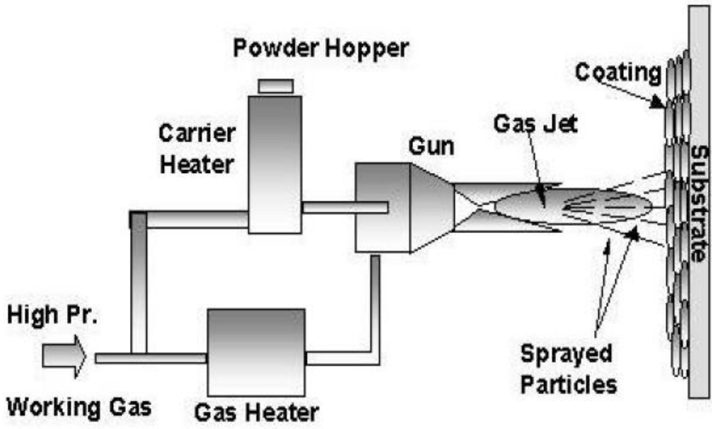
This process uses relatively low thermal energy in comparison to the conventional flame spray, plasma spray and electric wire spray processes.

7.2.5. **Cold spray technology**

The principle of cold spray is a high velocity supersonic gas jet (300 to 1200 m/s) is used to accelerate small powder particles towards a substrate where a coating is formed upon impact

(Papyrin, Kosarev, Klinkov, Alkhimo & Fomin, 2006). The term “cold spray” has been used to describe the process because both the temperature of the powder-laden gas jet and the temperature of the powder material are low enough to prevent phase change or stress in the deposit or substrate (Joining-Lab, 2012).The velocity of the particles needs to be above critical velocity before particles plastically deform and adhere to the substrate. Hydrogen or nitrogen may be used as feed gas.

Fig 19: Schematic diagram showing cold spray process (Karthikeyan, 2004)



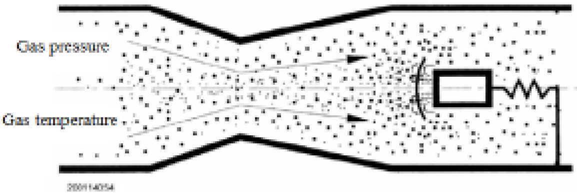
The process uses low heat input as shown in the table below, this ensures no melting takes place (no phase change occurs). The low heat input ensures deposition is free of oxides, reactions and other inclusions. Coatings have low porosity and strong bonds, improved thermal and electrical conductivity. Process boosts of high deposition rates equivalent or superior to other thermal processes Pathak et al (2017).

7.3 Appendix C: Cold Spray Technology

A brief history of cold spray technology

Cold spray technology was developed by Professor Anatoli Papyrin and his colleagues in the mid-1980s at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Science (ITAM SB RAS) in Novosibirsk (Champagne, 2007). Papyrin and his colleagues were busy studying models subjected to supersonic two-phase flow (gas-solid particles) in a wind tunnel (Alkhimov, Papyrin, Kosarev, & Nesterovich, 1994). The wind tunnel experiment was setup as depicted below and is explained in greater detail in Champagne's (2007) book titled "The cold spray material deposition process".

Fig 20. Wind tunnel test **(Hamweendo, 2017)**

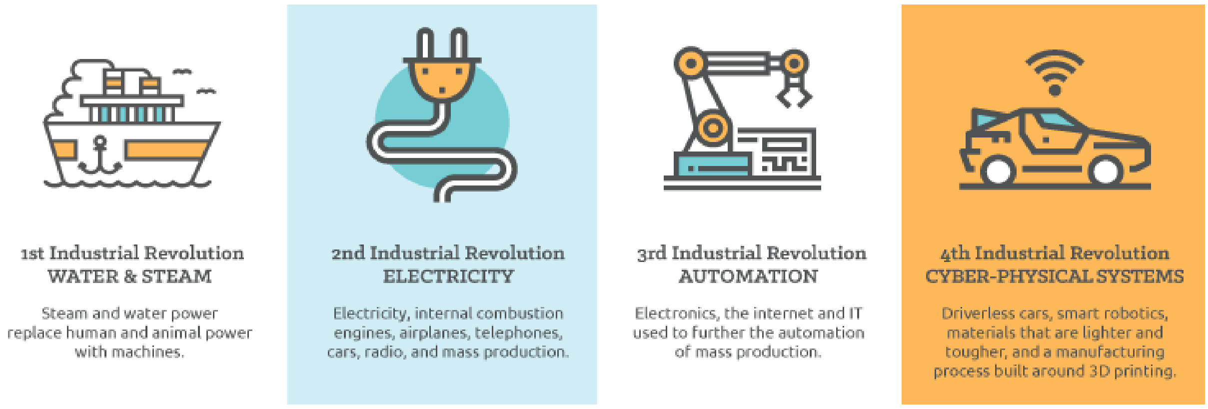


Champagne (2007) suggests that Papyrin and his colleagues managed to successfully deposit a wide range of pure metals, metal alloys and composites onto a variety of substrate materials and demonstrated the feasibility of the cold spray process for various applications. The research results were then used to develop the technology and its equipment. The US patent and European patent were issued in 1994 and 1995 respectively. Ever since then, numerous research houses and educational institutions have bought into the idea and are conducting research on various aspects of the topic. To date the technology has been adopted by numerous industries for a variety of applications. These include but are not limited to medicine, aerospace, gas and turbine etc.

7.4 Appendix D: Fourth Industrial Revolution and Cold spray technology

The word “**revolution**” means radical, abrupt change from the norm. History has documented a few revolutions to date which were triggered by the need for profound change in our social and economic systems thus bringing new and novel ways of manufacturing and thus technological advances (Schwab, 2016). These are shown in the figure below,

Figure 21: The fourth industrial revolutions (Barbora The Explorer ,2018)



A shift from foraging to a change in the way societies farmed using animals was the first step out of humanity’s primitive ways. The first industrial revolution, which took place around 1970 to 1840, encompassed the replacement of human and animal hard labour with steam and water powered machinery. The development of the steam engine was in this era. This drastically improved food production, which led to an increase in population growth and later development of towns.

The second revolution, which took place between the late 19th century and 20th century showed that mass production is possible. The second industrial revolution marked the transition from muscle to mechanical power. It was around this time that most towns started having powerlines and production facilities started the concept of an “**assembly line**”. The third revolution started around 1960, introducing the computer and its soft wares. It was called the “**digital age**”. The internet was introduced later in the 1990’s.

The fourth industrial revolution, which began around 2010 and builds on the advances brought fourth by the digital revolution. It is mainly characterised by the combination of digital, biological, mechanical systems such as machine learning (communicating robots), 3D printing and artificial intelligence. This revolution challenges manufacturers to build “Smart factories” where virtual and physical systems of manufacturing interact and make the best fit decision. It allows customisation of products without much changes to assembly lines (Schwab, 2016).

Fourth industrial revolution and cold spray

The automotive industry is one of the few industries largely affected by the fourth industrial revolution. In the context of the automotive industry it encompasses changes in design of vehicles to achieve fuel efficient vehicles. The latter can also be achieved through material substitution through weight reduction such as the consideration of plastics for building parts for parts traditionally build out of metals. 3D printing also features in this revolution as it speeds up development times through prototyping, shortens or diminishes supply chain and enables remote parts production in automotive plants (Giffi et.al, 2014; Pathak et.al., 2017). Cold spray technology is one of the technologies at the heart of this revolution through all these aforementioned features. These abrupt changes associated with the fourth industrial revolution have introduced a great deal of volatility, ambiguity and uncertainty as the race to become the first and remain relevant becomes even more vicious. Moreover, because the consumer market changes faster than in the past industrial revolutions.

7.5 Appendix E: Semi-Formal Interviews Information

7.5.1 APPENDIX E1: Interview Consent Form Template

Participant Letter of Consent

I (Name and Surname) …………………… agree to participate in the MSc research entitled "*Framework for the effective automobile operations using cold spray technology*" to be undertaken by Miss Ramaabele Yolanda Kupa under the supervision of Prof Botef, and certify that I have received a copy of this letter of consent.

I acknowledge that the research has been explained to me, and I understand what it entails, as follows:

1. I agree to partake in the study and assist the researcher for the purpose of this research.
2. There will be one interview that is expected to take no more than 1.5 hours.
3. The interviews will be NOT audio taped; notes will be taken by the researcher.
4. The processes of my division will be mapped out.
5. I will provide a brief tour of my manufacturing facilities at my discretion, and the researcher will record her own observations.
6. The researcher will be conducting the study alone.
7. I have the right to withdraw my assistance from this project at any time without penalty, even after signing the letter of consent.
8. I have the right to refuse to answer one or more of the questions without penalty and may continue to be a part of the study.
9. I may request a report summary based on the results of this study.
10. I am entirely free to discuss issues and will not be in any way coerced into providing information that is confidential or of a sensitive nature.
11. Pseudonyms will be used to conceal my identity and that of my company, my employees, my suppliers and my customers. The information disclosed in the interviews will be confidential.
12. Notes will be kept securely stored during the research and after the research has been completed.
13. This project was approved by the Faculty of Engineering and the Built Environment of the University of the Witwatersrand and the School of Mechanical, Industrial and Aeronautical Research Ethics Committee (non-medical) of the University of the Witwatersrand.
14. The research is sponsored by BMW South Africa plant Rosslyn.
15. If I have any questions or concerns about my rights or treatment as a participant, I may contact the Chair of the School of Mechanical, Industrial and Aeronautical Research Ethics Committee (non-medical) by email: Bruno.emwanu@wits.ac.za.

Signed: ______________________________

Date: _______________________________

Questions concerning the study can be directed to:

Ramaabele Yolanda Kupa
Tel: 082 609 9060 Email: 568600@students.wits.ac.za
Supervisor: Email: Ionel.Botef@wits.ac.za

7.5.2 Appendix E2: Interview Questionnaire Template

QUENSTIONNAIRE SAMPLE:

1. In what way would the automotive industry benefit from additive manufacturing and its associated applications?
   …………………………………………………………………………………………
   ………………………………………………………………………………
2. What are some of the key challenges that are hindering the implementation (adoption) and commercialisation of emerging technologies such as cold spray in the automotive industry?
   …………………………………………………………………………………………
   …………………………………………………………………………………………
   ……………………………………………………………………
3. What impact do these challenges have on OEMs and the overall automotive industry's growth and progress relative to other industries such as the aerospace?
   …………………………………………………………………………………………
   ……………………………………………………………………………….............................
   ....
4. What influence (negative or positive) do you think consideration of emerging technologies like cold spray would have on establishing efficient operations in line with world-class automotive manufacturing standards and facilities?
   …………………………………………………………………………………………
   ………………………………………………………………………………
   ……………………………………………………………………………………
5. What are some of the important aspects of business that should be considered for successful implementation of emerging technologies? Such as resources and strategies to ensure a swift introduction of these technologies into developing countries.
   …………………………………………………………………………………………
   ………………………………………………………………………………………
6. The world has grown more volatile and uncertain over the years, so businesses need to be agile. Researchers, industry experts and OEMs are working in silos to solve most problems in industry. What should OEMs or the automotive industry do

currently to bridge the gap between the industry experts, OEMs, researchers or technology developers in time for the next industrial revolution?

……………………………………………………………………………………

………………………………………………………………………………

7. What changes do you believe access to education (training and higher education), in-house laboratory facilities and research hubs could bring to the automotive industry, particularly in Third World countries (developing countries)?

……………………………………………………………………………………

……………………………………………………………………………………

8. How can businesses introduce these emerging technologies (additive manufacturing) without much disruption to business or their brand identities?

……………………………………………………………………………………

……………………………………………………………………

7.5.3 Appendix E3: Interview Questionnaire Responses

QUESTIONNAIRE RESPONDENT 1

1. In what way would the automotive industry benefit from additive manufacturing and its associated applications?
    - Additive manufacturing has the potential to approach zero waste manufacturing by maximizing material utilization.

Follow-up Question: In what way would it achieve this?

- Through its ability to rework vehicles or defective hang-on parts.
- Better inventory control reduces errors in mismatch, redundant parts (overstocking)

2. What are some of the key challenges that are hindering the implementation (adoption) and commercialisation of emerging technologies such as cold spray in the automotive industry?
    - Most automotive companies have a culture of some sort in terms of how their products are manufactured. Since these companies are multinational, the culture takes into consideration both the economic and social status of several nations. Therefore, the feasibility of cold spray technology would depend on the availability of resources and skills of the technology in both developed and developing countries.
3. What impact do these challenges have on OEMs and overall automotive industry's growth and progress relative to other industries such as the aerospace?
    - This reduces the rate at which the automotive industry grows as compared to aerospace where the emphasises are on higher precision, and this requires newer/emerging technology.
4. What influence (negative or positive) do you think consideration of emerging technologies like cold spray would have on establishing efficient operations in line with world-class automotive manufacturing standards and facilities?
    - New technologies carry a potential disruption to the current processes and organisation in general. Deciding to implement cold spraying technology in the automotive industry is a long-term commitment that management is hesitant to make due to lack of people with skills to operate and maintain/service cold spray equipment.

    Follow-up Question: What kind of disruptions are these and how can management bridge the identified skills gap?

    - Disruptions come in the form of change and culture shock, which would need change management to reduce impacts and man-machine interaction, and process changes can cause instability. The skills gap can be bridged by tailored training and education programmes to address identified skills needs.
5. What are some of the important aspects of business that should be considered for successful implementation of emerging technologies? Such as resources and strategies to ensure a swift introduction of these technologies into developing countries
    - Identifying any cultural or political challenges as well as their potential solutions.
    - Do you have local companies to supply and maintain/service cold-spray equipment?

- Do you have enough skilled people available locally to operate the cold-spray equipment? If no, what plans do you have to transfer the skills to the people?
- Do you have experts in the field of cold-spray to monitor and control the cold spray processes?

6. The world has grown more volatile and uncertain over the years; so, businesses need to be agile. Researchers, industry experts and OEMs are working in silos to solve most problems in industry. What should OEMs or the automotive industry do currently to bridge the gap between the industry experts, OEMs, researchers or technology developers in time for the next industrial revolution?

- The automotive industry is primarily production driven. However, to bridge the gap between the industry and researchers, an industry should establish a research unit. The unit should have expert researchers working together with universities and other research institutions such as the CSIR.

7. What changes do you believe access to education (training and higher education), in-house laboratory facilities and research hubs could bring to the automotive industry particularly in Third World countries (developing countries)?

- Access to the abovementioned would open doors for new markets within developing countries and increase the competitive advantages of local manufacturing.

8. How can businesses introduce these emerging technologies (additive manufacturing) without much disruption to business or their brand identities?

- Emerging technology should be marketed similar to product marketing. A good/proper marketing of the technology would ensure that everyone knows and understands the technology thoroughly before it is even introduced within the business. Align the market with an explicit implementation plan to eliminate all the grey areas regarding the feasibility of the technology within the business. Clearly state and emphasise the unique selling points of the technology.

QUESTIONNAIRE RESPONDENT 2

1. In what way would the automotive industry benefit from additive manufacturing and its associated applications?

- Lead time will be significantly improved
- Eligibility of new materials for use within the industry
- Significant costs reduced on prototyping

2. What are some of the key challenges that are hindering the implementation (adoption) and commercialisation of emerging technologies such as cold spray in the automotive industry?

The key challenges are the following:

- The complimentary resources such as:
    - Skills,
    - Tacit knowledge
    - Training
- The willingness from management to support emerging technology

3. What impact do these challenges have on OEMs and the overall automotive industry's growth and progress relative to other industries such as the aerospace?

   The challenges are the following:

   - Support and maintenance for implementers of the technology
   - Limited competitive advantage on a global scale

4. What influence (negative or positive) do you think consideration of emerging technologies like cold spray would have on establishing efficient operations in line with world-class automotive manufacturing standards and facilities?

   The influence of cold spray technology on efficient operations are the following:

   - Repair of defective parts (material splits, corrosion) and complete units
   - Quality improvements on process stability
   - On-time delivery of parts through the efficient additive manufacturing

5. What are some of the important aspects of business that should be considered for successful implementation of emerging technologies? Such as resources and strategies to ensure a swift introduction of these technologies into developing countries.

   The important aspects to be considered are the following:

   - Complimentary resources (training, skills, human resource)
   - Alignment of technology and business strategy
   - Education curriculum to be adapted for emerging technologies
   - Investment into emerging technologies, as well forecasting tools
   - Frequent technology audits
   - High risk propensity for senior management

6. The world has grown more volatile and uncertain over the years, so businesses need to be agile. Researchers, industry experts and OEMs are working in silos to solve most problems in industry. What should OEMs or the automotive industry do currently to bridge the gap between the industry experts, OEMs, researchers or technology developers in time for the next industrial revolution?

   The following should be done to integrate the stakeholders:

   - Virtual teams to be setup with common goals
   - Incorporation of partners into the business strategy
   - Horizontal integration of the internal departments
   - Vertical integration with the external organisations
   - More collaborations with university and industry will bridge the gap between theory and applied knowledge

7. What changes do you believe access to education (training and higher education), in-house laboratory facilities and research hubs could bring to the automotive industry particularly in Third World countries (developing countries)?

   The following changes could be envisaged:

   - Improved technology transfer opportunities
   - Increased diffusion of the technology
   - Reduction of information overflow for emerging technologies

8. How can businesses introduce these emerging technologies (additive manufacturing) without much disruption to business or their brand identities?

   The following could be done to increase the adoption of emerging technology:

   - Improve the skill and education level of the employees
   - There's a need for flexible and dynamic management
   - Empowerment of employees
   - Support structures on all levels

QUESTIONNAIRE RESPONDENT 3

1. In what way would the automotive industry benefit from additive manufacturing and its associated applications?
   - Reduction in development costs (prototyping), reduced prototype lead times, reduced manufacturing costs, flexibility in design changes, minimised complexity and design freedom, acessibility.
2. What are some of the key challenges that are hindering the implementation (adoption) and commercialisation of emerging technologies such as cold spray in the automotive industry?
   - Cost of the equipment, complexity of the process, i.e., preparation of surface conditions and different applications, application in mass production, availability of raw material for mass production, level of expertise available and required in the industry
3. What impact do these challenges have on OEMs and the overall automotive industry's growth and progress relative to other industries such as the aerospace?
   - Cost of services to the end user, Inability to embrace new technologies, missed opportunities meeting customer demands, cover wide spectrum of customer demands**.**
4. What influence (negative or positive) do you think consideration of emerging technologies like cold spray would have on establishing efficient operations in line with world-class automotive manufacturing standards and facilities?
   - Cold Spray is currently applied at OE level on certain applications. With further extensive research, exploring different applications within the industry, i.e., at OE level or service repair environment. It could be enhanced for the benefit of the end user, also ensuring the service providers are kept up to date with current and new technologies.
5. What are some of the important aspects of business that should be considered for successful implementation of emerging technologies? Such as resources and strategies to ensure a swift introduction of these technologies into developing countries.
   - Build up innovation capacities, address social challenges, implement programs to build up unique competences, understand demographics and key industry value chain
6. The world has grown more volatile and uncertain over the years, so businesses need to be agile. Researchers, industry experts and OEMs are working in silos to solve most problems in industry. What should OEMs or the automotive industry do currently to bridge the gap between the industry experts, OEMs, researchers or technology developers in time for the next industrial revolution?

- To bridge the gap the following must be considered: labour and industry, manufacturing, engineering & technology, economic development strategies, transportation system analysis.

7. What changes do you believe access to education (training and higher education), in-house laboratory facilities and research hubs could bring to the automotive industry particularly in third world countries (developing countries)?
    - Human capital – Build up a highly skilled workforce with specific expertise
    - Broadens perspective – Exposure to global understanding
    - Hones potential – Exposure to different job options in the industry
    - Eliminate inequality – Reduction of economic and social inequality
8. How can businesses introduce these emerging technologies (additive manufacturing) without much disruption to business or their brand identities?
    - Certain critical factors would have to be considered, i.e., effect on labour, customer demand, long-term benefits in the industry, global trends, cost of implementation, sustainability.

QUESTIONNAIRE RESPONDENT 4:

1. In what way would the automotive industry benefit from additive manufacturing and its associated applications?
    - Production of lightweight parts that would result in overall lightweight vehicles which are fuel-efficient.
    - Quicker parts production which will result in new vehicles being introduced to the market in short periods of time
    - Waste elimination of limited non-reusable resources since additive manufacturing eliminates waste more efficiently than subtractive manufacturing.
    - Elimination of parts failure due to skills limitation and human error since production methods such as 3D printing do not require the manufacturer to be skilled in the manufacturing method (All the manufacturer needs to know is the printer setup and the printer will do the rest.)
2. What are some of the key challenges that are hindering the implementation (adoption) and commercialisation of emerging technologies such as cold spray in the automotive industry?
    - Such technologies are still relatively new and are not cost efficient compared to old technologies.
    - Tough country legislations that are too strict to allow easy transition from conceptualization to commercialization.
    - Skills required in new technologies are very limited and that makes it difficult for effective implementation of such technologies.
    - Resources required for new technologies are limited (e.g., Autodesk products are relatively inefficient in 3D modelling and design due to complexity in parts geometry).
    - Companies are afraid of taking risks in implementing new technologies.

3. What impact do these challenges have on OEMs and the overall automotive industry's growth and progress relative to other industries such as the aerospace?
   - In my opinion, all these industries share similar impacts of the mentioned challenges.
4. What influence (negative or positive) do you think consideration of emerging technologies like cold spray would have on establishing efficient operations in line with world-class automotive manufacturing standards and facilities?
   - A positive influence in that shorter production times will be achieved without compromising on quality of finished automotive products. Introduction and implementation of emerging technologies will come at an economic cost (as in any change of technology) and modification of world-class facilities, but in the long run, a lot of economic cost will be saved via waste elimination of limited non-reusable materials, little investment in waste disposal processes, little investment in manual labour, faster production times, quicker introduction of products to the market and energy saving procedures introduced by emerging technologies.
5. What are some of the important aspects of business that should be considered for successful implementation of emerging technologies, such as resources and strategies to ensure a swift introduction of these technologies into developing countries?
   - Investment in skills development of people to run such technologies.
   - Thorough market analysis should be conducted so that human and material resources capacity in developing countries is sufficient to supply market demands.
   - Implementation should be initiated in areas with good infrastructure in developing countries.
   - Companies with traditional technologies must be encouraged to be involved in the implementation of emerging technologies because such companies tend to be a barrier of emerging technologies in developing countries.
6. The world has grown more volatile and uncertain over the years, so requires businesses to be agile. Researchers, industry experts and OEMs are working in silos to solve most problems in industry. What should OEMs or the automotive industry do to bridge the gap between the industry experts, OEMs, researchers or technology developers in time for the next industrial revolution?
   - Support systems that are focussed on involvement of both automotive industry, and researchers/technology developers must be established and venues should be created for close interaction starting from conceptualization down to commercialization.
7. What changes do you believe access to education (training and higher education), in-house laboratory facilities and research hubs could bring to the automotive industry particularly in Third World countries (developing countries)?
   - Innovation
   - Cheaper production methods
   - Manufacturing of vehicles suitable for conditions in developing countries
8. How can businesses introduce these emerging technologies (additive manufacturing) without much disruption to business or their brand identities?
   - Begin with pilot phase of small parts manufacturing.

- Create a series of vehicles within their brands that are manufactured by additive manufacturing (same concept as electric vehicle series for BMW, i.e., they should not necessarily incorporate emerging technology to old car brands but should use emerging technology to produce completely new cars within the brand).

QUESTIONNAIRE RESPONDENT 5

1. In what way would the automotive industry benefit from additive manufacturing and its associated applications?

- Increased adaptivity allows one to react quicker to changes. This could be a great advantage for vehicle model changes, equipment changes, etc.

2. What are some of the key challenges that are hindering the implementation (adoption) and commercialisation of emerging technologies such as cold spray in the automotive industry?
    - Traditional technologies/methods (such as pressing and moulding) are currently more robust and cheaper.
    - Emerging technologies first have to prove themselves.
    - Emerging technologies cannot yet be implemented everywhere and for everything.
    - Knowledge about the emerging technologies is not readily available.
    - Not enough specialists in this field are available.
    - Traditional mind set mind hinder new technologies.
3. What impact do these challenges have on OEMs and the overall automotive industry’s growth and progress relative to other industries such as the aerospace?
    - Slow implementation might hinder growth.
    - As these emerging technologies cannot be used in all areas at OEMs and automotive industry, the effect in these areas might be negligible.
    - In general, it will be difficult to compare the impact, as the production volume is very different. I feel that the emerging technologies are currently more valuable for production with lower volumes, such as the aerospace industry. For higher production volumes, the emerging technologies are currently not yet able to challenge the traditional technologies.
4. What influence (negative or positive) do you think consideration of emerging technologies like cold spray would have on establishing efficient operations in line with world-class automotive manufacturing standards and facilities?
    - I am not completely sure what you mean with this question. However, I think the emerging technologies will have an influence on establishing more efficient operations, especially in the development of vehicles that are built up from composites, such as the BMW i vehicles. This can already be seen at these plants, i.e., the plant in Leipzig.
5. What are some of the important aspects of business that should be considered for successful implementation of emerging technologies, such as resources and strategies to ensure a swift introduction of these technologies into developing countries?

- Costs (funding)
- Availability of equipment
- Availability of local support and knowledge
- Traditional way of thinking

6. The world has grown more volatile and uncertain over the years, so businesses need to be agile. Researchers, industry experts and OEMs are working in silos to solve most problems in industry. What should OEMs or the automotive industry do currently to bridge the gap between the industry experts, OEMs, researchers or technology developers in time for the next industrial revolution?
   - Work more effectively together with research facilities, such as universities and other industries. There should be more transparency and collaboration**.**
7. What changes do you believe access to education (training and higher education), in-house laboratory facilities and research hubs could bring to the automotive industry particularly in Third World countries (developing countries)?
   - I feel a balance between both is required.
8. How can businesses introduce these emerging technologies (additive manufacturing) without much disruption to business or their brand identities?
   - The implementation will be different in the different technologies in the automotive industry. At BMW SA, it is also evident that the emerging technologies will most probably only be implemented at suppliers, as Plant Rosslyn is not producing their own parts, i.e., all body and assembly parts are produced and delivered by external suppliers. In my opinion, one will have to convince or encourage suppliers to consider the emerging technologies and make them aware of them.

QUESTIONNAIRE RESPONDENT 6

1. In what way would the automotive industry benefit from additive manufacturing and its associated applications?
   - Reduced lead times for prototyping
   - Effect changes in design much quicker (better visualisation and understanding)
   - Saves material when compared to conventional subtractive methods of manufacturing
   - Less tooling required.

1. What are some of the key challenges that are hindering the implementation (adoption) and commercialisation of emerging technologies such as cold spray in the automotive industry?
   - Ability to support mass production in specific materials in use; currently, it is largely used for plastic and selected metals materials.
   - The rapid application needed such as parts production.
2. What impact do these challenges have on OEMs and the overall automotive industry’s growth and progress relative to other industries such as the aerospace?
   - In hinders growth within the industry.
   - Very slow development and no competitive edge.

3. What influence (negative or positive) do you think consideration of emerging technologies like cold spray would have on establishing efficient operations in line with world-class automotive manufacturing standards and facilities?
   - Removes unnecessary variables, e.g., reduces supplier independence through printing of small parts.
   - Future testing and production of parts such as engineering changes can be done.
4. What are some of the important aspects of business that should be considered for successful implementation of emerging technologies? Such as resources and strategies to ensure a swift introduction of these technologies into developing countries.
   - Skills set necessary for successful implementation; training across the board.
   - Right choice of technology/equipment for specific products.
   - Understanding of the product and equipment compatibility, e.g., materials' handling and behaviour.
5. The world has grown more volatile and uncertain over the years so businesses need businesses to be agile. Researchers, industry experts and OEMs are working in silos to solve most problems in industry. What should OEMs or the automotive industry do currently to bridge the gap between the industry experts, OEMs, researchers or technology developers in time for the next industrial revolution?
   - R&D would help; however, it doesn't make sense to have an R&D section at every plant within the group.

   Follow-up question: Please elaborate.
   - It creates more silos because the plants and their respective R&D's would be working in silos. There needs to be collaborative efforts between the plants and the R&Ds. Educational institutions can assist with skilled students in rare-skill sets positions.
   - Dynamic feedback loop between all four parties to ensure relevance of topics and technological developments.
6. What changes do you believe access to education (training and higher education), in-house laboratory facilities and research hubs could bring to the automotive industry particularly in Third World countries (developing countries)?
   - Informed workers make better decisions and will do troubleshooting much better.
   - It ensures there is no roles ambiguity and gaps within the business
7. How can businesses introduce these emerging technologies (additive manufacturing) without much disruption to business or their brand identities?

   Generally, businesses which invest in new innovative technologies are bound to benefit than those who do not.
   - This means more consumer market.
   - Wider range of products and variety to the product portfolio.

   Follow-up question: There is bound to be disruption, whether the change is good or bad with the introduction of machinery. How best should businesses lessen these changes and disruptions?
   - They can lessen the disruptions in the work environment through education.

- In the market they can start market research and projections well in time, sample the market through trials.
- Sequence of implementation is supplier outwards into the market; therefore, businesses need to ensure the suppliers are able to support the changes.

QUESTIONNARE RESPONDENT 7

1. In what way would the automotive industry benefit from additive manufacturing and its associated applications?

- Quicker lead-times
- Cost cutting on a larger scale

Better repeatability with fewer defects

2. What are some of the key challenges that are hindering the implementation (adoption) and commercialisation of emerging technologies such as cold spray in the automotive industry?
    - Not tried and tested on a commercial scale
    - Fear of change
    - Mastering of technology
3. What impact do these challenges have on OEMs and the overall automotive industry's growth and progress relative to other industries such as the aerospace?

   Because of unit volumes per annum there is room for slower growth and progress mainly on additive manufacturing on the automotive industry while aerospace more maintenance based needs the progression much quicker than automotive. Investing in such changes can be slowly featured in for automotive industry which is good for automotive.
4. What influence (negative or positive) do you think consideration of emerging technologies like cold spray would have on establishing efficient operations in line with world-class automotive manufacturing standards and facilities?
    - Positive, more efficient lines, better repeatability and control.
5. What are some of the important aspects of business that should be considered for successful implementation of emerging technologies? Such as resources and strategies to ensure a swift introduction of these technologies into developing countries.
    - Capital budgeting, skills management, timing to introduce these changes with the tough financial times, sustainability of and most importantly the environment.
6. The world has grown more volatile and uncertain over the years, so businesses need to be agile. Researchers, industry experts and OEMs are working in silos to solve most problems in industry. What should OEMs or the automotive industry do currently to bridge the gap between the industry experts, OEMs, researchers or technology developers in time for the next industrial revolution?
    - I personally am for continuous working in Silos, this would bring unpredictable results which could revolutionaries the way we see OEMs and the automotive industry. If it wasn't for the World War technology and science wouldn't have advanced the way it did in the late 1800s and early 1900s and that required countries (their scientists) to work in silos; people perished bus science was the biggest winner. The setup should continue as is.

7. What changes do you believe access to education (training and higher education), in-house laboratory facilities and research hubs could bring to the automotive industry, particularly in Third World countries (developing countries)?
    - This would change thinking from theoretical to a more practical based thinking. With that kind of thinking major steps can be made in growing and progressing automotive industry.
8. How can businesses introduce these emerging technologies (additive manufacturing) without much disruption to business or their brand identities?
    - Start small scale as an add to the business, slowly integrate it into the system by moving away from old methods and using more recent ones.

QUESTIONNARE RESPONDENT 8:

1. In what way would the automotive industry benefit from additive manufacturing and its associated applications?
    - Additive manufacturing offers great range of shapes that can be produced, quickly and efficiently. Rapid prototyping is swift.
2. What are some of the key challenges that are hindering the implementation (adoption) and commercialisation of emerging technologies such as cold spray in the automotive industry?
    - Some very specific issues which arise in the motoring industry e.g. cold spray needs near-200 ductility of which metals is ductile. There is also the high cost of helium, which might cut into Return of Investment.
3. What impact do these challenges have on OEMs and the overall automotive industry's growth and progress relative to other industries such as the aerospace?
    - Slow adoption of cutting edge technology and practises which results in a flow down in the development of essential tech that can improve automobiles.
4. What influence (negative or positive) do you think consideration of emerging technologies like cold spray would have on establishing efficient operations in line with world-class automotive manufacturing standards and facilities?
    - One of the biggest advantages of cold spray technology is high productivity which ultimately boosts throughput. And there is also zero toxic waste which is good for the environment.
5. What are some of the important aspects of business that should be considered for successful implementation of emerging technologies? Such as resources and strategies to ensure a swift introduction of these technologies into developing countries.
    - Tailoring these emergent technologies to the automotive industries as opposed to the blanket adoption. Impact on throughput and the environment.
6. The world has grown more volatile and uncertain over the years, so businesses need to be agile. Researchers, industry experts and OEMs are working in silos to solve most problems in industry. What should OEMs or the automotive industry do currently to bridge the gap between the industry experts, OEMs, researchers or technology developers in time for the next industrial revolution?

    - Knowledge sharing and collaboration.

7. What changes do you believe access to education (training and higher education), in-house laboratory facilities and research hubs could bring to the automotive industry, particularly in Third World countries (developing countries)?
    - These will narrow the gap in terms of quality of the product between 1st world, and 3rd world factories or plants. Also this will illuminate the need for the hiring of the 1st world specialists in the 3rd world countries.
8. How can businesses introduce these emerging technologies (additive manufacturing) without much disruption to business or their brand identities?
    - Phased and controlled agile process or lean launching in such a way that damages are observed and responded to rapidly.

QUESTIONNARE RESPONDENT 9:

1. In what way would the automotive industry benefit from additive manufacturing and its associated applications?

    - There would be significant reduction in waste, time to market would be reduced, there would be quicker changeovers, automotives would be more customisable resulting in increased customer focus, product lifecycle would be reduced, and there would knowledge explosion and great learning. Most importantly, there will be sustainable triple bottom line (planet, people, profit).

2. What are some of the key challenges that are hindering the implementation (adoption) and commercialisation of emerging technologies such as cold spray in the automotive industry?

    - Lack of infrastructure, capital, policy, regulation, conflicts of interests, lack of adequate supply chain development, lack of leadership alignment and improvement needs prioritisation, and fear of conventional job losses.

3. What impact do these challenges have on OEMs and the overall automotive industry's growth and progress relative to other industries such as the aerospace?

    - These challenges are forcing OEM's and the overall automotive industry to stick to conventional technologies which impacts on their innovativeness, competitiveness and profitability.

4. What influence (negative or positive) do you think consideration of emerging technologies like cold spray would have on establishing efficient operations in line with world-class automotive manufacturing standards and facilities?

    - Emerging technologies would result in operations being more efficient, enabling the industry to have quicker turnaround times and expand the services they can offer. Emerging technologies would also displace and make many conventional jobs redundant. However, it is anticipated that these jobs would be replaced with even more jobs.

5. What are some of the important aspects of business that should be considered for successful implementation of emerging technologies? Such as resources and strategies to ensure a swift introduction of these technologies into developing countries.

    - Bottom up market analysis, considering innovation strategy, agile planning and management of the implementation, upskilling and empowerment of all the workforce in order to break the resistance to change, change management, effective risk management and product lifecycle assessment processes.

6. The world has grown more volatile and uncertain over the years, so businesses need to be agile. Researchers, industry experts and OEMs are working in silos to solve most problems in industry. What should OEMs or the automotive industry do currently to bridge the gap between the industry experts, OEMs, researchers or technology developers in time for the next industrial revolution?
    - The industry should develop an iterative, research & development like framework to guide decisions about when and how to collect needed information from all groups involved in innovation and solving the industry problems.
7. What changes do you believe access to education (training and higher education), in-house laboratory facilities and research hubs could bring to the automotive industry, particularly in Third World countries (developing countries)?
    - Access to the above mentioned would drive economic growth in third world countries because knowledge is considered a key driver of economic growth. This knowledge would lead to innovations or inventions which can be sold and/or commercialised and made available to the end user.
8. How can businesses introduce these emerging technologies (additive manufacturing) without much disruption to business or their brand identities?
    - Business should introduce these emerging technologies incrementally and iteratively whilst acquiring validated learning along the path and upskilling the workforce. Middle managers should play a big role in this process.

QUESTIONNARE RESPONDENT 10:

1. In what way would the automotive industry benefit from additive manufacturing and its associated applications?
    - Improved cycle and lead times in production, improved customer turn around time, reduced waste through some of its rework features.
2. What are some of the key challenges that are hindering the implementation (adoption) and commercialisation of emerging technologies such as cold spray in the automotive industry?

    - Lack of development, capital, skills gap and knowledge on emerging technologies

3. What impact do these challenges have on OEMs and the overall automotive industry's growth and progress relative to other industries such as the aerospace?
    - They delay overall growth and inhibit competitiveness

4. What influence (negative or positive) do you think consideration of emerging technologies like cold spray would have on establishing efficient operations in line with world-class automotive manufacturing standards and facilities?
    - Emerging technologies can introduce disruptions to organisations however they can also improve product quality, efficiency of production, cut costs and general organisation such as the working environment.

5. What are some of the important aspects of business that should be considered for successful implementation of emerging technologies? Such as resources and strategies to ensure a swift introduction of these technologies into developing countries.
    - Market demands and changes , skills sets needed, organisational changes and investment

6. The world has grown more volatile and uncertain over the years, so businesses need to be agile. Researchers, industry experts and OEMs are working in silos to solve most problems in industry. What should OEMs or the automotive industry do currently to bridge the gap between the industry experts, OEMs, researchers or technology developers in time for the next industrial revolution?
    - The industry can work on a database or research unit based on analysisng market trends and making this data available for the OEM's to make informed decision
7. What changes do you believe access to education (training and higher education), in-house laboratory facilities and research hubs could bring to the automotive industry, particularly in Third World countries (developing countries)?
    - Access to the above mentioned would bring economic growth particularly to poor countries, it would bring upto speed and standard with other plants. It will give platform and chance of competitiveness fr local OEM;s who have no international plants
8. How can businesses introduce these emerging technologies (additive manufacturing) without much disruption to business or their brand identities?
    - Pilot these technologies which have been identified long before they roll them out. Continuous training of work force to be within required skill level

QUESTIONNAIRE RESPONDENT 11

1 In what way would the automotive industry benefit from additive manufacturing and its associated applications?

- Improved response time to changes because prototypes can be made quicker, planning times are reduced, integration of changes will be swifter

2. What are some of the key challenges that are hindering the implementation (adoption) and commercialisation of emerging technologies such as cold spray in the automotive industry?

- The technologies need to prove reliable. OEM's cannot afford to have blanket adoption.
- Mindset shift is needed and OEM's ought to challenge the known and attainable
- Specialists for each of these technologies is necessary.

3. What impact do these challenges have on OEMs and the overall automotive industry's growth and progress relative to other industries such as the aerospace?

- OEM's get left behind with innovation
- Lost opportunity into improved systems

4. What influence (negative or positive) do you think consideration of emerging technologies like cold spray would have on establishing efficient operations in line with world-class automotive manufacturing standards and facilities?
5. They can improve systems or completely deteriorate existing systems if not properly implemented or compatible.
6. What are some of the important aspects of business that should be considered for successful implementation of emerging technologies, such as resources and strategies to ensure a swift introduction of these technologies into developing countries?

- funding
- Equipment, spares and support availability

7. The world has grown more volatile and uncertain over the years, so businesses need to be agile. Researchers, industry experts and OEMs are working in silos to solve most problems in industry. What should OEMs or the automotive industry do currently to bridge the gap between the industry experts, OEMs, researchers or technology developers in time for the next industrial revolution?

- Work more effectively together with research facilities, such as universities and other industries. There should be more transparency and collaboration**.**

8. What changes do you believe access to education (training and higher education), in-house laboratory facilities and research hubs could bring to the automotive industry particularly in Third World countries (developing countries)?

- Do we really need multiple laboratory or research facitilites? I believe a research hub may be decentralised but still beneficial for other countries, there needs to be improved information sharing platforms .Education will assist with support in underdeveloped countries

9. How can businesses introduce these emerging technologies (additive manufacturing) without much disruption to business or their brand identities?

- Businesses can start with small manageable sections and take lessons lerned forward into larger areas.
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QUESTIONNARE RESPONDENT 12

1. In what way would the automotive industry benefit from additive manufacturing and its associated applications?

    - Shorter lead-times
    - Improved turnaround times for customers

2. What are some of the key challenges that are hindering the implementation (adoption) and commercialisation of emerging technologies such as cold spray in the automotive industry?

    - Fear of change
    - No knowledge of technology

3. What impact do these challenges have on OEMs and the overall automotive industry's growth and progress relative to other industries such as the aerospace?

    - Automotive might be different to aerospace, however aerospace tis moe knowledgeable on emerging technologies and also has a higher risk taking likelihood

4. What influence (negative or positive) do you think consideration of emerging technologies like cold spray would have on establishing efficient operations in line with world-class automotive manufacturing standards and facilities?

    - Positive-More efficient production lines, better control because of improved equipment,
    - Negative – more low skilled labour might lose jobs

5. What are some of the important aspects of business that should be considered for successful implementation of emerging technologies? Such as resources and strategies to ensure a swift introduction of these technologies into developing countries.

    Skills management, clear timing plans and financial break down of each.

6. The world has grown more volatile and uncertain over the years, so businesses need to be agile. Researchers, industry experts and OEMs are working in silos to solve most problems in industry. What should OEMs or the automotive industry do currently to bridge the gap between the industry experts, OEMs, researchers or technology developers in time for the next industrial revolution?

    - Collaborative approach needs to be established at all levels, this reduces costs of investment for individual brands or OEM's.

7. What changes do you believe access to education (training and higher education), in-house laboratory facilities and research hubs could bring to the automotive industry, particularly in Third World countries (developing countries)?

    - Training enables informed decision making, skills sets across the board will also help towards successful implementation.

How can businesses introduce these emerging technologies (additive manufacturing) without much disruption to business or their brand identities?

- Start with a pilot or start small scale