

UNIVERSITY OF THE WITWATERSRAND

SCHOOL OF MECHANICAL, INDUSTRIAL AND
AERONAUTICAL ENGINEERING

**IMPROVING THE MACHINABILITY OF Ti-6Al-4V USING
INNOVATIVE LASER SHOCK PEENED CEMENTED
CARBIDE INSERTS**

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A thesis submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy.

October, 2019

DECLARATION

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I, the undersigned, declare that this thesis is my own unaided work, being submitted to the University of Witwatersrand, Johannesburg for a Degree of Doctor of Philosophy.

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ABSTRACT

The effect of cutting tool composition manipulation and cutting edge laser modification for rapid heat dissipation during Ti-6Al-4V machining were investigated. Innovative cutting tool inserts produced by liquid phase sintering (LPS) and spark plasma sintering (SPS) were used for this research, and their effect during face milling of Ti-6Al-4V was investigated under the following process parameters: cutting speed ranged from 60 to 300 m/min, depth of cut from 0.5 to 1.5 mm at a constant feed/tooth of 0.1mm. Cutting insert performance was assessed in terms of flank wear, response to cutting force, temperature, and surface roughness.

Composition manipulation with Mo₂C (wt%) additions inhibited grain growth resulting in cutting tools with better combined mechanical properties. The inserts produced by LPS had higher fracture toughnesses (K_{IC}) than their SPS counterparts. This was due to their larger and more uniformly distributed binder pools resulting from the formation of the liquid phase during LPS. On the other hand, the SPS inserts had smaller WC grains giving higher hardnesses. Laser peening (LP) of the cutting tool inserts slightly improved their mechanical properties. Notwithstanding, the LP inserts experienced rapid wear during face milling trials at higher depth of cut (1mm and 1.5mm) and speeds (100m/minute – 300m/minute). The introduction of ridges on the rake face of the cutting tool inserts improved upon their cutting performance and wear resistance. A clear relationship between the cutting tool hardness and workpiece surface roughness was established, with the Ti-6Al-4V workpieces surface roughness decreasing with increased cutting tool hardness. Furthermore, the inserts with higher hardness had better abrasive wear resistance.

DEDICATION

I dedicate this project to God Almighty, my source of wisdom, knowledge and understanding. He has been the source of my strength throughout this program. I also dedicate this work to my beloved wife; Marlisa da Filomena Ofem whose encouragement has made sure that I give it all it takes to finish that which I have started. To my son; Tyrese, who have been affected in every way possible by this quest. Thank you. My love for you can never be quantified. God bless you.

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1 Introduction

Titanium and its alloys are the most attractive materials in the aerospace industry because of their good mechanical (i.e. stiffness, toughness, etc.) and chemical properties (i.e. corrosion resistance, biocompatibility, etc.) [1997Ezu]. The grade V alloy of titanium (Ti-6Al-4V) is the most used titanium alloy, accounting for more than 50% of the global production, with 80% of this being used in aerospace and medical industries [2007Lut]. Nonetheless, the utilization, application and commercialization of Ti-6Al-4V remains limited, mainly because of its high machining cost which results from rapid tool wear and poor surface integrity [1997Ezu]. The inherent properties of Ti-6Al-4V are also drawbacks to its machinability [1997Ezu]. The low heat dissipation by Ti-6Al-4V during machining results in the cutting edge of the tool absorbing over 30% of heat generated [2008Abe]. This results in high thermal stresses and frictional forces, which enhances different cutting tool degradation processes. The Council for Scientific and Industrial Research, South Africa (CSIR) has stated that “Ti-6Al-4V has the potential to serve as a strategic economic drive for South Africa, should low-cost titanium manufacturing become available” [Url2013].

Although continuous effort is being made towards developing new tool materials which would extend tool life during titanium machining, tungsten carbide based cemented carbide tools remain the most used tools for Ti-6Al-4V machining due to their better combined properties [1997Ezu, 2014Gen]. These tools which are usually metal matrix composite materials comprising of a cobalt (Co) matrix embedded with tungsten carbide (WC) particles are mainly consolidated by liquid phase sintering (LPS) [2008Dav]. However, with limitations in LPS such as long sintering times and WC grain growth, new sintering techniques such as Spark Plasma Sintering technique are of interest [2014Gen]. The fracture toughness (K_{IC}) of cemented carbide tools has been identified as a vital mechanical property

for Ti-6Al-4V machining [2016Ofe, 2014Gen], as cutting tools with poor K_{IC} experience rapid wear and even catastrophic failure during Ti-6Al-4V machining [2016Ofe]. As such, various researches have been conducted to improve the K_{IC} and other mechanical properties of cemented carbides through manipulation of tool composition [2014Gen, 2016Lek]. Laser Peening (LP) has also been identified as a surface technique which can be used to enhance mechanical properties such as; fracture toughness, fatigue life, yield strength and hardness of some metallic materials [2001Cla, 1996Pey]. These improvements are mainly connected to laser peened induced plastic deformations causing compressive residual stresses closer to the processed surface of metallic components [1996Cla]. It is therefore envisaged that composition manipulation, binder substitution and successful application of laser peening to cemented carbide tools could improve upon their mechanical properties and overcome several drawbacks associated with Ti-6Al-4V machining.

Researchers have also shown that the segmentation of chips and the attachment of workpiece material to the flank face of cutting tools during machining protects the tools from rapid wear [2005Wan, 2105Lot]. Thus, it is also envisaged that the introduction of ridges to the rake face of these innovative cutting tool inserts for bulk attachment of workpiece debris and the introduction of chip breakers could lower tool-chip temperatures and improve chips disposal, thereby resulting in lower tool wear and better surface finish. The work material used for this investigation is Ti-6Al-4V (ASM4911). The machining tests were carried out on 114 workpieces using a Bridgeport GX1000 milling machine. The cutting performance during the milling operation was evaluated using performance investigators such as resultant force, temperature, flank wear, surface roughness, and chips.

1.1 **Hypothesis**

Composition manipulation, binder substitution and laser peening would improve upon hardness and fracture toughness of innovative WC-cemented carbide inserts. Likewise, –laser peening, introduction of ridges and chip breakers on the rake face of these cutting tool inserts would further enhance their cutting and wear resistance during Ti-6Al-4V machining.

1.2 **Objectives**

The main objectives of this study are:

- To improve upon the mechanical properties of innovative WC cemented carbide tools through composition manipulation, binder substitution and sintering technique variation.
- To improve upon the mechanical properties, cutting resistance and wear resistance of innovative WC cemented carbide tools for Ti-6Al-4V machining through laser peening.
- To improve upon the cutting resistance and wear resistance of innovative WC cemented carbide tools through the introduction of ridges on the rake face of these inserts.
- To improve upon cutting resistance, wear resistance, and likewise chips disposal during Ti-6Al-4V machining through the introduction of chip breakers on the rake face of innovative WC cemented carbide tools.

1.3 **Problem statement**

Based on superior properties of Ti-6Al-4V, such as its exceptional thermal resistance, high chemical reactivity, good strength to weight ratio and excellent corrosion resistance [1997Ezu], Ti-6Al-4V is an important material in the aeronautical and automobile industries. Contradictory, these superior properties impairs its machinability [1997Ezu, 1984Mye]. The

thermal resistance of Ti-6Al-4V and its good strength opposes plastic deformation required for chip formation [1990Mac]. This results in excessive build-up of temperature on the tool face and consequently premature failure [1990Mac]. Furthermore, the high chemical reactivity and low modulus of elasticity of Ti-6Al-4V shortens tool life, resulting in increased machining cost [1997Ezu]. Tungsten carbide (WC) based cemented carbides are the most used tool materials accounting for over 70% of all cemented carbide tool production [1998Upa]. Notwithstanding, WC cemented carbide tools suffer rapid wear during Ti-6Al-4V machining [1997Ezu, 1990Mac]. This has been attributed to their poor mechanical properties such as; hardness and fracture toughness [2016Ofe, 2014Gen]. Furthermore, the high temperature and high stresses at and/or close to the cutting edge during machining reduces the strength on cutting edge resulting in accelerated wear, built-up-edge, and poor surface finish of machined component [1990Mac, 2016Ofe]. This research therefore seeks to improve upon the mechanical properties of cemented carbide tools for Ti-6Al-4V machining, as well as provide effective measures to minimise the weakening of the cutting tool edge which results in rapid wear during Ti-6Al-4V machining.

1.4 **Overview**

In this study, an attempt was made to improve the microstructure and mechanical properties of WC-Co cemented carbides through the addition of Cr_3C_2 and Mo_2C (wt%), Ni binder substitution and spark plasma sintering. Attempts were made to improve the mechanical properties of the sintered compositions through laser peening. To improve cooling and chip dissipation capabilities of the cemented carbide tools, ridges and chip breakers were introduced to the rake of the cemented carbide tools. The mechanical properties and flank wear rates of the resulting cutting tool inserts were studied. The surface roughness of the machined Ti-6Al-4V workpieces was also studied.

Chapter 2 gives a detailed literature review on Ti-6Al-4V, WC-cemented carbides, powder metallurgy used for their processing, different sintering techniques, effects of grain size, alternative binders, laser peening, laser ablation, face milling, resultant forces, temperature, flank wear, chip formation patterns and surface roughness.

Chapter 3 gives a detailed description of all the experimental procedures and equipment used.

Chapter 4 analyses microstructure and mechanical properties of the sintered samples.

Chapter 5 analyses resultant forces, temperature, flank wear, chip formation and surface roughness during the face milling of Ti-6Al-4V.

Chapter 6 contains a detailed overall discussion of the results.

Chapter 7 is the final conclusions, research contributions, and recommendations for future work.

2 Literature Review

2.1 Workpiece material

Titanium grade V alloy (Ti-6Al-4V) is the workhorse alloy of the titanium industry [2010Dav]. It exists in the alpha + beta phase, with aluminium as the alpha stabilizer and vanadium as the beta stabilizer [2010Dav]. Ti-6Al-4V is composed of 6% aluminium, 4% vanadium, 0.25% iron, 0.2% oxygen, and 89.55% titanium, making it significantly tougher than commercial titanium possessing the same stiffness and thermal properties [1993Hon]. The excellent properties of Ti-6Al-4V (Table 2.1 and Table 2.2) has made it an important engineering material for industrial applications [1996Jon, 1997Ezu].

Table 2.1. Mechanical properties of annealed Ti-6Al-4V [1996Joh].

Properties	Metric	Comment
Hardness, Brinell	334	Estimated from Rockwell C.
Hardness, Knopp	363	Estimated from Rockwell C.
Hardness, Rockwell C	36	Estimated from Rockwell C.
Hardness, Vickers	349 MPa	+13
Tensile Strength, Ultimate	950 MPa	-8
Tensile Strength, Yield	880 MPa	-
Elongation at Break	14 %	+4
Reduction of Area	36%	-10
Modulus of Elasticity	113.8GPa	-8
Compressive Yield Strength	970 MPa	+5
Notched Tensile Strength	1450 MPa	+1
Ultimate Bearing Strength	1860 MPa	e/D = 2
Bearing Yield Strength	1480 MPa	e/D = 2
Poisson's Ratio	0.342	-
Charpy Impact	17J	V-notch
Fatigue Strength	240 MPa	At 1E+7 cycles. Kt*= 3.3
Fatigue Strength	510 MPa	Unnotched 10,000,000 Cycles
Fracture Toughness	75 MPa-m ^{1/2}	-
Shear Strength	550 MPa	Ultimate shear strength

Table 2.2. Thermal properties of annealed Ti-6Al-4V [1996Joh].

Properties	Metric	Comment
CTE, linear 20 °C	8.6 $\mu\text{m/m-}^\circ\text{C}$	20 -100 °C
CTE, linear 250 °C	9.2 $\mu\text{m/m-}^\circ\text{C}$	Average over the range 20-315 °C
CTE, linear 500 °C	9.7 $\mu\text{m/m-}^\circ\text{C}$	Average over the range 20-650 °C
Specific Heat Capacity	0.5263 J/g- °C	-
Thermal Conductivity	6.7 W/m-K	-
Melting Point	1604 – 1660 °C	-
Solidus	1604 °C	-
Liquidus	1660 °C	-
Beta Transus	980 °C	-

Conversely, these excellent properties of Ti-6Al-4V impairs its machinability [1997Ezu, 1984Mye]. For example, when machining Ti-6Al-4V at high speed where temperatures exceeds 900 °C, its high strength opposes plastic deformation required for chip formation. This results in excessive build-up of temperature on the tool face and consequently premature tool failure [1990Mac]. Furthermore, the high chemical reactivity of Ti-6Al-4V makes it react with almost all tool materials at temperatures exceeding 500 °C. This reaction often leads to chipping, welding or premature tool failure [1970Zla].

2.2 Machinability of Ti-6Al-4V

The machinability of materials largely depends on their ability to plastically deform, fracture, as well as sustain stresses, strain, strain rate and temperature during machining [1995Bay]. Titanium alloys have generally been considered as “difficult-to-machine” because of their inherent properties [1997Ezu, 2001Sha]. The alloy of interest, Ti-6Al-4V has a very low thermal conductivity which results in the concentration of high cutting temperature (over 1000 °C) on the cutting tool tip during machining [2014Pra]. This high temperature on the tool rake during chip disposal results in higher machining forces, built-up-edge formation, segmented chip formation, reduced strength on cutting edge, and poor surface finish [1990Mac, 2016Ofe]. The relatively low modulus of elasticity of Ti-6Al-4V is another inherent property affecting its machinability [2006Nou], as it causes machining vibrations

which results in rapid tool wear poor surface finish [1997Ezu]. Based on intrinsic material hardness, many tools should be capable of machining Ti-6Al-4V. Nevertheless, many of the harder tools prematurely fail during Ti-6Al-4V machining because of the reasons mentioned above, in addition to chemical affinity that causes chemical wear [1997Ezu]. WC cemented carbide tools and Polycrystalline diamond (PCD) tools are some of the few tools extensively used tools for Ti-6Al-4V machining [1997Ezu].

2.3 **Cutting tools and cutting tool materials**

Cutting tools are designed to operate in extreme temperatures, as well as resist the severe friction that occurs between the tool and chip, and between the tool and newly machined surface [1989Boo]. The selection of cutting tool materials is therefore based on their ability to withstand high thermal stresses, as well as resist wear, brittle fracture and chemical affinity during chip formation [2016Ste]. The choice of tool material for a given operation depends on the volume of parts to be machined, the workpiece material, the required accuracy, and the capabilities of the available machine tools [2016Ste]. To prevent sudden catastrophic failure during machining, it is always advisable to use tool materials that will yield high fracture toughness, hardness, and thermal conductivity [2016Ste]. Sintered WC-cemented carbides (WC/Co) are the most frequently used tool materials in titanium machining [1997Ezu, 2014Gen], mainly because of their promising mechanical properties and relatively cheaper production cost [2008Dav, 1997Ezu]. These tools primarily consist of tungsten carbide bonded within a ductile cobalt matrix [1975Bro, 1998Upa], and their properties are derived from the constituents, i.e. hard, wear resistant and brittle carbides and tougher, more ductile metal binders (cobalt, nickel or iron) [1934Sch]. The development of WC/Co took place between 1923 and 1925, by Schroter for the Osram electrical lighting, to replace the costly diamond wire drawing dies for tungsten filaments [1925Sch]. Early cemented carbides typically consisted of 6 wt% Co binder in WC [1998Upa], but because of their good

hardness, several researches have been conducted to improve their mechanical properties [1998Upa, 2014Gen]. Studies have shown that additions of additives such as Cr_3C_2 and TiC can increase the stability of WC/Co at high temperatures [1986Cha, 1982Sar], as well as their corrosion and oxidation resistance [1987Pen]. Similarly, the partial or complete substitution of Co binder with Ni has also been known to improve the corrosion and oxidation resistance of cemented carbides [1996Hum].

2.4 **Production of cemented carbides tools**

Powders of hard refractory metals and metal binders are the foundation for cemented carbide tools [1998Upa]. The mostly used powders in cemented carbide production are WC , TiC , TaC and Cr_3C_2 [1975Bro]. These powders are transformed into tools through a process called consolidation [1998Upa]. Consolidation entails merging of small particles into single product of desired characteristics or shape. The processes involved in the consolidation of cemented carbide can be summarized as follows: comminution, pressing and dewaxing [1975Bro]. A schematic diagram showing detailed steps involved in the consolidation of cemented carbide is shown in Figure 2.1.

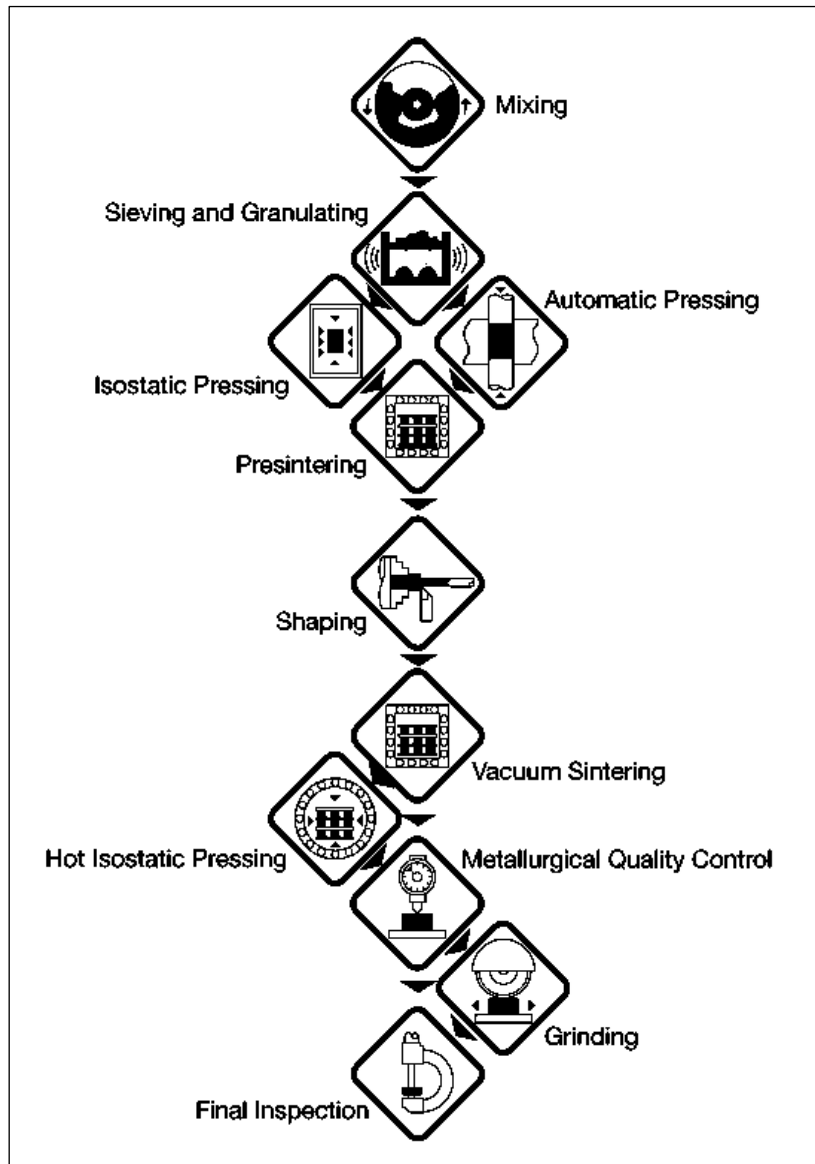


Figure 2.1. Processes involved in cemented carbide production [2017Url^a].

2.4.1 Consolidation of cemented carbides

2.4.1.1 *Comminution*

Comminution is the process of producing small particles by reducing the size of larger ones through mechanical force [2008Ran]. Milling, crushing and grinding are common comminution operations [2008Ran]. In WC/Co production, milling is usually carried to aid uniform distribution between WC and Co, as well as ensure that every WC particle is coated by Co and particle size reduction [2008Ran, 1998Bro]. Ball mills (Figure 2.2) and attrition

mills are some of the common mills used for the comminution of cemented carbides [1998Upa, 2014Gen]. Depending on the application, comminution can be carried out in dry (without liquid) or wet state (with liquid). In wet comminution, the liquid must be removed on completion by a decantation process followed by vacuum filtration, or using faster modern techniques such as rota-evaporators and spray drying [1998Upa].

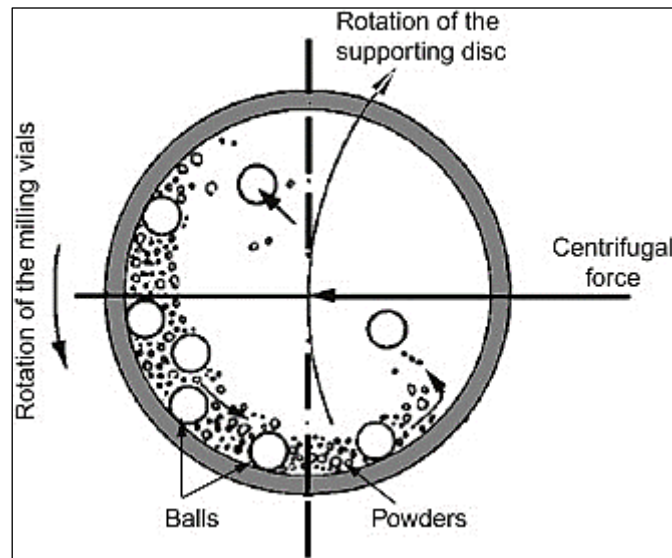


Figure 2.2. Schematic diagram of a tumbler ball mill [2015She].

2.4.1.2 *Pressing*

Pressing is done after comminution to consolidate the powders into desired shape and dimension, as well as seal any residual pores [1998Upa, 1985Ger]. Die compaction (by single or double action) and isostatic compaction (in all directions) are the two most common methods of pressing cemented carbides [1975Bro]. Compaction is attained after pressing, and 60% of theoretical densification can be determined [1975Bro]. To reduce the friction generated during pressing, wax, polyethylene glycol or paraffin are added to the composition before pressing [1998Upa].

2.4.1.3 *Dewaxing*

Dewaxing is the process of removing the wax which was added to reduce friction [1998Bro]. This process is usually carried out immediately after pressing, since the wax is no more useful, and if left behind can lead to porosity [1975Bro]. The dewaxing process usually involves heating the compacts in a vacuum or in hydrogen at temperatures near 400 °C [1998Upa]. After dewaxing, carbon loss protection (CLP) should be carried out to minimize carbon loss from reactions between WC and hydrogen and/or water vapour [1998Upa]. This can be achieved by packing the compacts in carbon, followed by presintering at temperatures ranging from 750 °C - 1000 °C to attain desired shapes [1998Upa].

2.4.2 *Sintering*

Sintering is the process of compacting and forming solid mass of material by heat or pressure at a temperature below melting point of the main constituent [1957Boc, 1959Kin]. The sintering of WC cemented carbides is carried out in a hydrogen or vacuum atmosphere [1998Bro], and is governed by the following parameters: temperature and time, geometrical structure of the powder particles, composition of the powder mix, density of the powder compact and composition of the protective atmosphere in the sintering furnace [1998Upa, 1957Boc].

2.4.2.1 *Temperature and time*

The composition of the WC cemented carbide, amount of binder and the sample thickness determines the sintering time [1998Upa]. Higher sintering temperatures usually results in shorter sintering time [1998Upa]. This is however not recommended in industry as it leads to WC grain coarsening, distortion of compacts, and increased furnace maintenance cost [1998Upa, 1957Boc]. Thicker compacts usually require longer sintering time [1957Boc].

Although this is also not advisable as it often leads to pore growth and cobalt vaporisation [1998Upa].

2.4.2.2 *Geometrical structure of the powder particles*

For a given sintering condition, the particle size of the powder play a vital role in its sinterability. Powders consisting of fine particles (particles of high internal porosity) sinter faster than powders consisting of coarse compact particles [1957Boc]. Nonetheless, fine particle powders are more difficult to compact than coarse particle powders [1957Boc]. Furthermore, compacts made from fine powder shrink more during sintering than compacts those made from coarse powder [1957Boc].

2.4.2.3 *Composition of the powder mix*

In order to achieve desired mechanical properties and control dimensional changes during sintering, the components of powder mixes must be carefully selected and proportioned [1957Boc]. When mixes of two or more different powders are sintered, alloying and bonding between the powders takes place simultaneously [1957Boc]. The amount of binder content present in a composition should also be carefully selected as it may affects factors such as density, hardness, transverse rupture, strength, tensile strength and thermal expansion of the sintered product [1975Bro].

2.4.2.4 *Density of the powder compact*

The density of the powder compact is directly proportional to the total contact area between powders [1957Boc]. Powder compacts with higher density have more efficient bonding and alloying during sintering due to the larger total contact area between powders [1957Boc].

2.4.2.5 *Composition of the protective atmosphere in the sintering furnace*

Tungsten carbide-cobalt hard-metals are sintered at high temperatures ranging between 1350 - 1650 °C, depending on the composition. At these high temperatures, chemical reactions between the powders and the surrounding atmosphere are possible. Additionally, the surface areas of the compacts are extremely high, especially when sintering fine powders (0.5 - 0.8µm), and this makes them susceptible to reaction with the sintering atmosphere [1998Upa].

2.4.3 **Liquid phase sintering**

Liquid phase sintering (LPS) is a dominant commercial sintering process used for forming high performance, multiple-phase components from powders (alloys and composites) that melt over a range of temperatures [2008Ran]. It involves sintering under conditions where solid grains coexist with a wetting liquid which makes the grains soluble [2008Ran]. Different microstructured evolution pathways are possible with liquid phase sintering [2008Ran]. Densification in liquid phase sintering occurs in three stages namely; rearrangement, solution-reprecipitation, and coarsening (Figure 2.3) [2004Pet].

2.4.3.1 *Rearrangement*

The formation of Liquid phase during melting wets the solid particles causing capillary forces to rearrange the particles into more dense pack [2008Ran, 1985Ger]. As a viscous solid, the powder compact responds to the capillary pressure increasing viscosity and decreasing porosity [1985Ger]. Rearrangement is slowed down by the friction between solid particles, but it is usually faster than other events and full density can be attained if the volume of liquid present is around 35% [1983Exn].

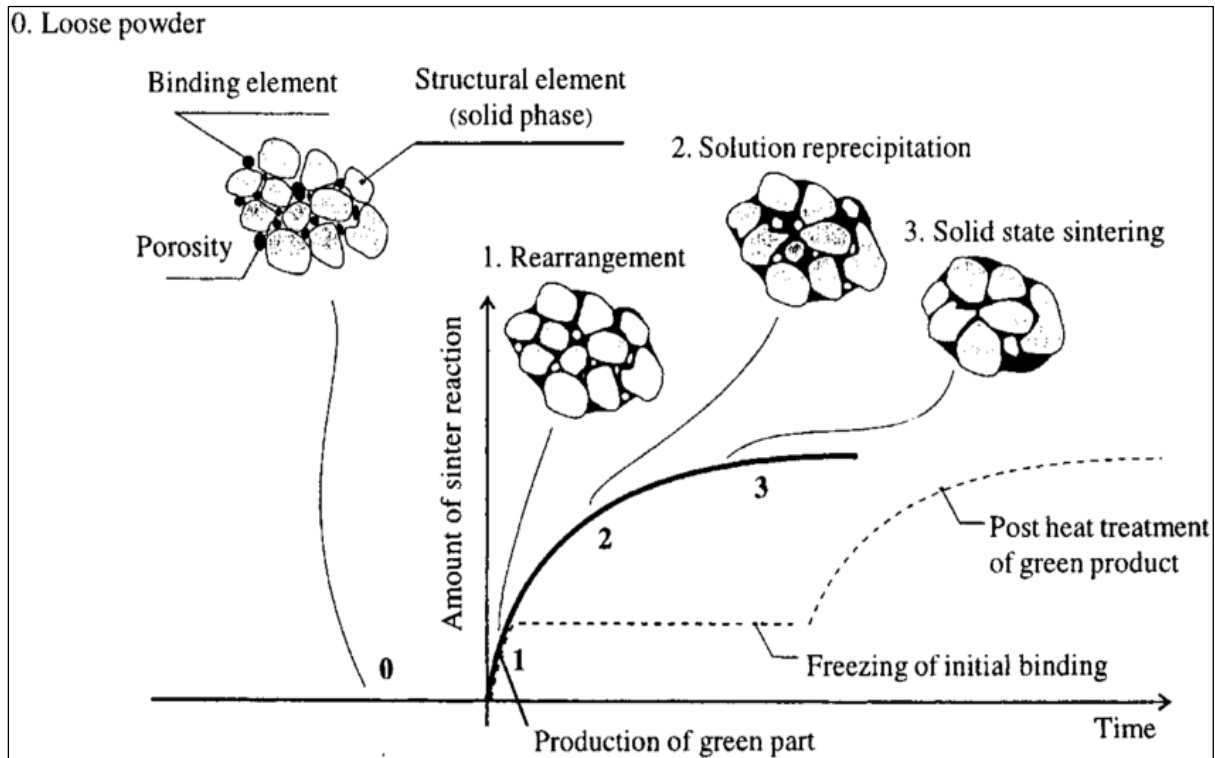


Figure 2.3. Microstructure changes during liquid phase sintering [2002Wan].

2.4.3.2 *Solution-reprecipitation*

Solution-reprecipitation is associated with microstructural coarsening [1985Ger, 1959Kin]. The effectiveness of solution-reprecipitation is dependent on the complete solubility of the solid in the liquid [1985Ger, 1998Upa]. Various mechanisms, such as Ostwald ripening, Ostwald ripening with shape accommodation, contact flattening, particle disintegration, coalescence and pore elimination by liquid flow are during solution-reprecipitation [1985Ger]. Solution-reprecipitation also contributes towards grain coarsening and densification [18985Ger].

2.4.4 **Solid phase sintering**

Sintering models are usually used to describe densification in solid phase sintering [1983Exn]. This is because the solid phase may sinter into a rigid skeleton [1983Exn].

2.4.5 Spark plasma sintering

Spark plasma sintering (SPS) also known as pressure-assisted pulse energizing process or pulsed electric current sintering (PECS) process, is an innovative sintering technique which uses uniaxial force and a pulsed direct electrical current (DC) to perform high speed consolidation of powders under low atmospheric pressure [2015Cha]. The high heating and cooling rates associated with SPS, results in higher densifications and lower grain growth [2013Tok]. The major advantages of SPS over conventional sintering are; ease of operation, accurate control of sintering energy, high sintering speed, high reproducibility as well as safety and reliability [1999Tok, 2012Sua]. Spark plasma sintering is performed in a low pressure or inert gas atmosphere, where the powders are loaded into graphite dies, and a mechanical system similar to uniaxial die pressing is used to apply a load of up to 1000MPa and a simultaneous high DC pulse current discharge on the powder (Figure 2.4) [2013Tok, 2002Mam]. Joule-heating heats up the sample and the sparking among the particles of sintered material leads to the faster heat and mass transfer [2013Tok].

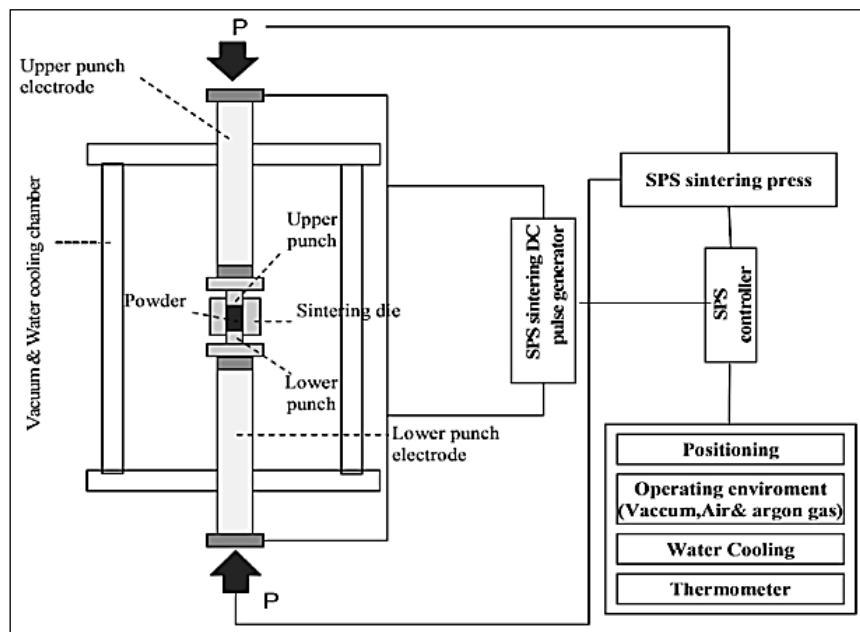


Figure 2.4. SPS system process configuration [2013Tok].

2.4.6 Microstructure and mechanical properties of sintered cemented carbides

2.4.6.1 *Microstructure*

The final microstructure of a sintered sample depicts its physical and mechanical properties which remains the major concern in cemented carbide production [1985Ger, 1983Has]. Properties such as grain size, solid-solid contact size, porosity, grain shape, and binder fraction can be analysed from microstructural observation [1985Ger]. Optical microscopy is mostly used for quality control and for microstructural evaluations in scientific studies for coarse grained hard metals [1970Woo].

2.4.6.1.1 Grain Size

Grains are typically single-phase single crystals, defined by their variance in crystal orientation from adjoining grains and the resultant grain boundaries formed between them to accommodate these variances [1998Upa] In production of cemented carbides, the control of WC grain size is the most carefully controlled variable besides carbon control [2014Gen]. This is because mechanical properties of cemented carbides are influenced by WC grain sizes [1998Upa]. Large grains act as starting point for discontinuous grain growth, while finer grains improves hardness and wear resistance [1978Exn and 2002Bro]. Typical WC grains range from submicron level to a few microns [1975Bro]. WC cemented carbide grains are affected by the processing methods, sintering techniques and parameters used for production [1975Bro, 1978Exn]. During sintering, solution-reprecipitation and coalescence results in WC grain growth [1959Kin]. Grain growth is also affected by the composition of the carbide [1970Woo]. For example, more rapid grain growth will occur with increased carbon content [1970Lar]. Additives such as TiC, Cr₃C₂ and ZrC which serve as good grain growth inhibitors should be added to the powder composition before sintering for reduced grain growth [1998Upa, 2002Wit]. Physical and mechanical properties of cemented carbides

2.4.7 Densification

Densification can be used as an indication of the effectiveness of the sintering process [1998Upa]. The density of a correctly sintered sample will be close to the theoretical density (the density that the sample would have if no voids were present) [1991Jen]. The density of WC cemented carbides varies from 10.5grams/cc to 14.8grams/cc [1985Ger].

2.4.8 Hardness

Hardness is the ability of a material to resist plastic deformation by indentation [1932Ast]. The hardness of WC-cemented carbides gives an indication of their ability to resist deformation under pressure of the chip [1941Eis]. WC-cemented carbides can be related to their hardness through microstructural parameters, such as WC grain size, binder content and degree of contact between carbide grains [1978Lee]. Poor densification lowers the hardness of the cemented carbides [1995Ban]. As shown in Figure 2.5, the hardness of WC cemented carbides decreases at temperatures above 600 °C [2000Chi]. Hot hardness is the ability of WC-cemented carbide to retain its hardness at elevated temperatures [1967Wes].

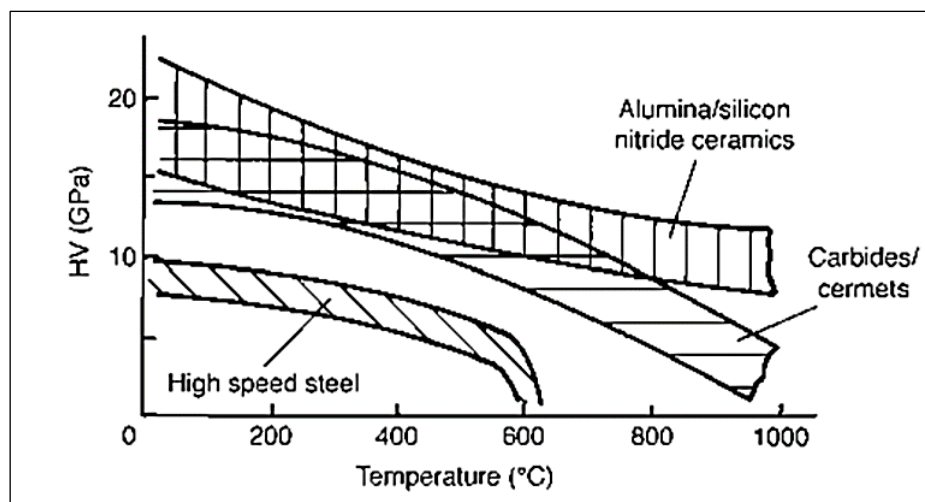


Figure 2.5. Relationship between temperature and hardness of cutting tool insets [2000 Chi].

The hot hardness of cemented carbide tools can be improved through additions of additives such as TiC, TaC and Ni [1982Suz]. These additives can improve resistance to plastic deformation and rate of strength loss with increased temperature [1982Suz]. The addition of Cr_3C_2 (wt%) inhibits grain growth for cemented carbides, resulting in improved hardness [1986Cha].

2.4.9 Fracture toughness

Fracture toughness (K_{1C}) is an indication of the resistance of a material to physical separation independent of specimen size geometry and finish [1976Sih, 1977BS]. The K_{1C} of cemented carbide varies with the amount of binder [1985Ger]. The higher the binder content, the tougher the carbide [1985Ger]. At elevated temperatures exceeding 600 °C, the K_{1C} of cemented carbide significantly increases because of the increased local plasticity/ductility, and crack healing and blunting [1984War].

2.4.10 Transverse rupture strength

Transverse rupture strength (TRS) also known as flexural strength is the maximum tensile stress at failure of a carbide loaded midway between supports [1998Upa]. It is an ultimate strength property for cemented carbides and encompasses the compressive, tensile and shear strength [1998Upa]. The TRS of a cemented carbide is usually affected by its carbon content due to varying composition of the binder phase [1970Exn]. For fine-grained alloys TRS increases with increased carbon content, and for coarse-grained alloys TRS decreases with increased carbon content [1954Gur, 1964Kub]. Schwarzkopf and Kieffer in an experiment [1960Sch], found out that hard metals bonded with cobalt had higher TRS compared to those bonded with iron or nickel.

2.5 **Cutting tool insert production**

The design of a cutting-tool insert has a significant influence on its machining performance [2016Ste]. Parts of consistent quality and predictable useful lives are usually produced if machining is done with properly designed tools [2016Ste]. On the other hand, improperly designed tools wear or chip rapidly, reducing productivity, increasing costs, and producing parts of deteriorating quality [2016Ste, 1982Sor]. Cutting tools may be designed as single point, multipoint or multifunctional tools depending on their intended application [1982Sor]. Single point tools are used for turning and boring operations, while multipoint tools are used for drilling and milling [2016Ste]. Multifunctional tools are used to machine multistep holes or features [2016Ste]. One vital criterion in aerospace tooling design is ensuring that the tool does not chip or break to avoid damaging an expensive workpiece [1982Tip, 2016Ste].

2.5.1 **Milling tools**

Milling is usually carried out using solid cutters with ground cutting edge, or pocketed cutter bodies fitted with inserts [1982Sor]. Different type of milling cutters exist, namely: face milling cutters, slot milling cutters and end milling cutters [1982Tip]. The choice of cutter is selected based on the intended milling operation. Face milling cutters are used for producing flat surfaces, while slot milling cutters are used for grooving and slotting [1982Sor]. Chamfering and plunging are carried out using end milling cutters [1982Tip].

2.5.1.1 ***Milling cutter design***

The following critical factors should be taken into consideration when designing any milling cutter: the cutting edge geometry, cutter density, cutter diameter, entry and exit angles, and the cutter construction [2002Des, 1998Ano, 2003Ano]. The standard cutting geometry for a milling tool is described by its radial and axial rake angles [2016Ste], because during milling, chip flow direction and thrust force is significantly affected by the axial angle, while cutting

power and tool life is affected by the radial angle [2016Ste]. Three possible combination of these two angles can be used in the design of standard milling cutters [2016Ste].

2.5.1.2 *Milling inserts design*

In the past milling was mostly carried out using solid single – point tools. But at present, indexable inserts are used for milling [2016Ste]. A typical geometry nomenclature of an indexable milling insert is shown in Figure 2.5. For a properly designed milling insert, the following critical factors must be taken into consideration [2016Ste]:

- Insert material and grade
- Insert shape
- Insert size
- Insert thickness
- Corner geometry (nose radius or flat)
- Groove (chip breaker) geometry
- Edge preparation
- Edge clamping/holding method
- Lead, rake, relief, and inclination angles

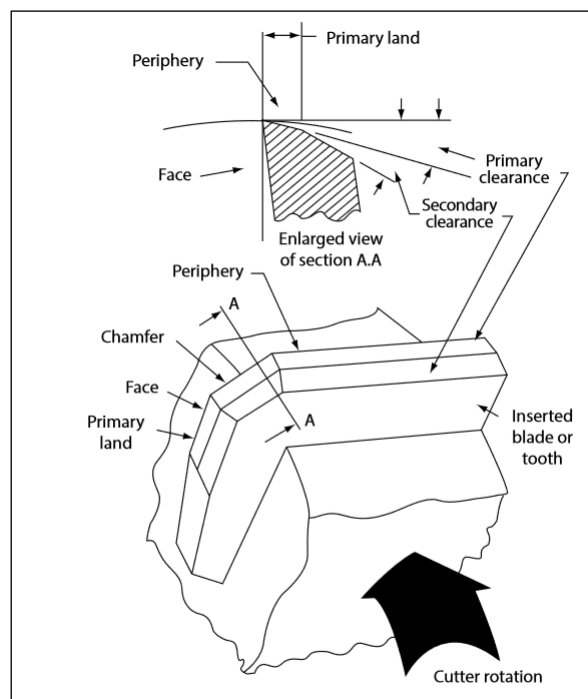


Figure 2.6. Standard terminology to describe the basic geometry of a single-point milling [2016Ste].

2.6 **Laser peening**

Laser peening (LP) or Laser Shock Peening is a material enhancement process for introducing compressive residual stresses in metallic components using lasers [2006Din]. Stresses generated beneath laser peened surfaces are beneficial for fatigue strength and fatigue life improvement [1990Ban; 1999Chu]. The generation of shock waves and plastic deformation in metallic materials using high energy laser pulse was first explored in 1963 [1963Whi]. The confined ablation mode for an improved LP process was established in 1968 [1970And], while the application of LP to metals was first investigated in 1968 [1996Cla]. After 1986, more systematic studies on LP applications have been carried out [1991Bal, 1998Fab]. Metal surface hardening has been achieved through laser peening, with the magnitude of surface hardening varying with respect to alloy type, microstructure and laser peening conditions [1976Cla, 1991Bal]. Furthermore, components with complex geometry (such as fastener holes in aircraft skins) and regions inaccessible by shot peening (such as small fillets and notches) have been treated using LP [1997Zha, 1996Man]. Compressive residual stresses in several materials, such as titanium alloys, aluminium alloys, steel grades, copper alloys, zinc, nickel based alloys, super alloys, brass and magnesium alloys have also been successfully increased by LP [2014Guj].

2.6.1 **Laser peening process**

Laser peening is performed by firing a laser pulse through flowing water over the surface (inertial tamping layer) to a workpiece that has been covered with a laser-absorbent sacrificial coating (ablative layer) (Figure 2.7) [1996Cla]. The absorbent coating becomes a plasma that is constrained by the adjacent coating and water layer, developing pressure pulses that propagate more than 1mm deep into the material as a shock waves [1996Cla]. The action of pressure pulse on the material results in plastic deformation and relative in-depth compressive residual stresses required for fatigue life and fatigue strength improvement [1996Cla]. To

fulfil the laser peening process, it is usually recommended to use a suitable laser system with average power level of several kilowatts, pulse energy of 100J and pulse energy of 30ns [2006Din, 1996Cla]. Furthermore, parameters such as the power density, laser wavelength, pressure, absorbent coating, and spot size (6-10mm) should be carefully selected for optimum result [2006Din]. For example in the laser peening of A356-T6 alloy specimen by Peryre et al and Fabbro et al, surface compressive residual stress increased by up to 145MPa when power density was increased from 1.5 to 2GW/cm². However, residual stress level decreased to 100MPa with further increase in power density to 3GW/cm² [1996Pey]. Similarly, compressively residual stress increased deeply below the surface with increase in pressure [1996Pey].

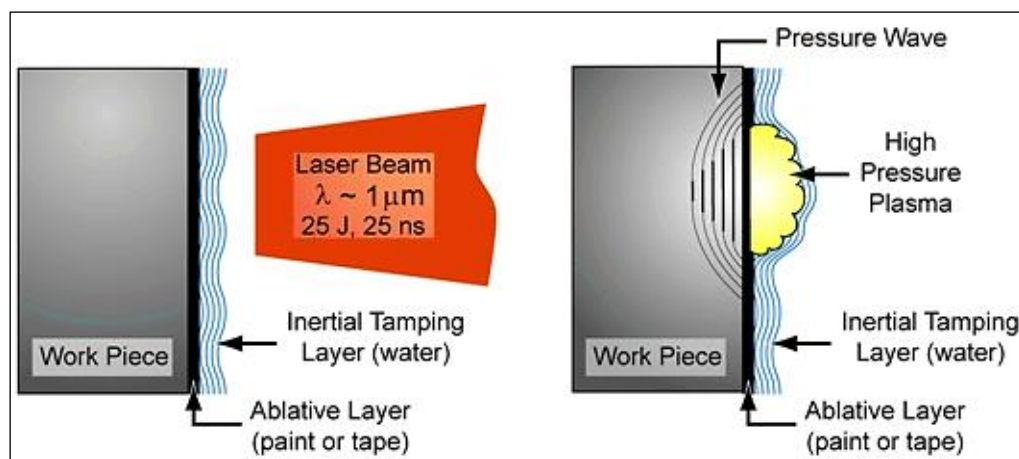


Figure 2.7. Laser peening process [2016Url].

2.6.1.1 *Power density and Laser wavelength*

The magnitude of surface residual stresses generated during laser peening depends on the magnitude of plasma pressure, which increases with increase in power density [1996Pey]. The laser power density has a certain threshold which when exceed, decreases residual stresses at the surface and increase residual stresses with depth [1996Pey]. The laser wave length is also a critical factors to consider when selecting a laser source for laser peening. A

wavelength of 1.064mm and a pulse duration of 10–100ns is generally recommended for use in a water-confined environment [2006Din]. The shock wave generation during laser peening can be enhanced by decreasing the wavelength of the laser whilst keeping the laser power density constant [1996Cla]. For metallic components a suitable laser system with power ranging from several hundreds watts to kilowatts and pulse energy of around 10 - 500J is required [2006Din].

2.6.1.2 *Transparent Overlay and Absorbent Coating*

Transparent overlay increases the plasma pressure during laser peening, by trapping the rapidly expanding plasma over the components surface [1996Pey]. This sudden high pressure against the component's surface causes a shock wave to propagate into the material. If the shock wave exceeds its dynamic yield strength, the material yields and deforms plastically [2006Din]. The absence of an overlay during LP results in the vaporisation of the opaque coating and expansion of the solid component [2006Din]. Materials such as water, or acrylic which are transparent to the laser beam can be used as an overlay [1996Pey]. However, the choice of the material depends on the substrate material density, and acoustics [1996Pey].

2.6.1.3 *Spot geometry and spot size*

The spot geometry of a laser can be changed to suit the intended application [1998Man]. For dense uniform packing of laser spots, a laser beam with a square profile is used instead of a round one [1997Man^a]. Laser spot sizes can also be varied depending on the laser power required and power density [2006Din]. Smaller spot sizes produce deeper surface compressive residual stresses on a material surface than larger spot sizes using the same laser power density (Figure 2.8) [2006Din]. The plastically affected depth from smaller spot sizes is also much lower compared to that of larger spot sizes [2006Din, 1994Zen]. Typically, the diameter of a laser spot size ranges from 6mm to 10 mm in practice [2014Guj].

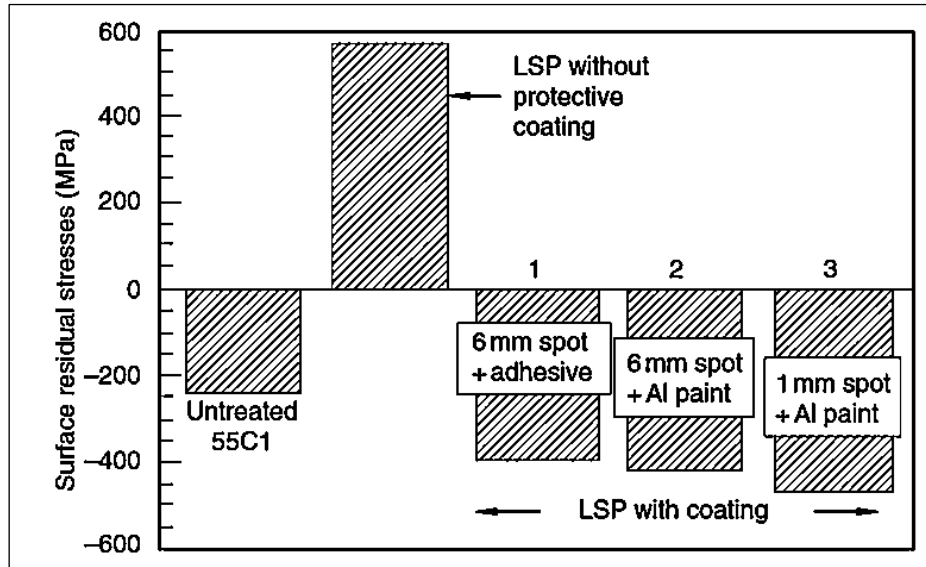


Figure 2.8. Surface residual stresses with different LSP conditions at 5 GW/cm² in a water-confining mode, (1) 6mm impact + aluminium adhesive, (2) 6mm impact + aluminium paint, and (3) 1mm impact + aluminium paint [1998Pey].

2.6.2 Application of laser peening

Laser peening has been successfully used to improve the residual stress profiles, microstructure, mechanical properties, fatigue life and fatigue strength of several materials including titanium alloys [1999Rus, 2000Bra, 2010Cao, and 2012Cao], aluminium alloys [1888Hon, 1979Fai, 2009Hat, 2011Mon, 1996Pey, and 2010Zha], different steel grades [2000Pey, 2011Ye, 2012Tra, and 1999Chu], etc. Hong and Chengye [1998Hon], in a laser peening experiment with aluminium alloys reported that; laser peening enhancement mechanical properties through grain refinement which resulted from plastic deformation [1998Hon]. In another laser peening experiment with welded AA5086-H32 and AA6061-T6 test specimen by Clauer *et al.* [1976Cla], it was found that laser peening significantly increased the dislocation density which was a prominent microstructural feature for hardness and strength. Peyre *et al.* has attributed the increase in dislocation density during LP to grain refinement [1996Pey]. A 22.2% improvement in fatigue life of Ti-6Al-4V has also been

reported by [2010Zha] after laser peening with an aluminium foil coating, a power duration of 10 ns and a power density of 5 GW/cm³ [2010Zha].

Although improvements in residual stress profiles, microstructure, mechanical properties, fatigue life and fatigue strength of several materials with laser peening has been reported in literature, a few contradicting results have also emerged. Ye *et al.* reported a decrease in fatigue life of Ti-6Al-4V after laser peening [2010Ye]. The decrease in fatigue life was attributed to destruction of the absorbent layer, stress concentration or increased surface roughness due to overlapped shocks [2010Ye]. Similarly, Rubio-González *et al.* reported only minor improvement in the hardness of duplex stainless steel after laser peening [2011Rub]. One can therefore emphasize that the effectiveness of any laser peening process will depend on the careful selection of LP conditions and parameters, as well as proper process monitoring.

Despite the numerous literature available on the application of laser peening to a variety of materials, the laser peening of cemented carbide tools for Ti-6Al-4V machining still remains a novelty. It is therefore envisaged that the laser peening of cemented carbide tools would improve their hardness and fracture toughness which is required for Ti-6Al-4V machining.

2.6.3 Analysis of laser peening

Depending on the laser peening conditions, parameters, and material, several changes could occur on the microstructure, surface roughness and residual stresses of the laser peened component [1996Cla]. These changes which could either be detrimental or beneficial can be evaluated using a wide variety of techniques. Features such as cracks, holes and solidified droplets can be observed using either transmission electron microscopy (TEM) or scanning electron microscopy (SEM) [1987Hof]. The surface roughness can be evaluated using a surface profilometer [2012Sad], while residual stresses in the laser peened material can be

observed using destructive techniques (sectioning, slitting, etc.), non-destructive techniques (X-ray, neutron diffraction, etc.), and semi destructive methods (hole drilling) [2011Ros].

2.7 Laser ablation

Laser ablation is the process of removing layers from solid material by irradiating it with a laser beam [2015Vei]. The precision of laser-induced stresses enables exact prediction and subsequent contouring of surfaces [2006Din]. The amount of material removed during laser ablation depends on the intensity, pulse length, and wavelength of the laser, as well as the material itself [2016Url]. Deformations in form of ripples, corrugations and craters can be introduced to materials with laser ablation techniques [2011Wol]. Recent advances in laser ablation technology have shown that conventional lasers, such as pulsed laser can be used for ablation of hard materials [2006Har]. But owing to issues of thermal effect and residue deposition [2005Ger], picosecond lasers are recommended because of their unique properties, such as ultrashort pulse duration and high peak power intensity [2018Wan]. This study envisages that laser ablation techniques can be used to introduce ridges on the rake face of the innovative cemented carbide tools for better heat dissipation.

2.8 Chip breaker

During milling operations, long stringy chips resulting from plastic deformation of the workpiece causes edge chipping, leading to premature tool failure [1989Boo]. This long hot, difficult to handle chips generated during machining can be effectively controlled using groove or obstructive chip breakers around the cutting tool edge [1989Boo, 2014Url]. Groove type chip breaker, are characterised by a small groove behind the leading cutting edge of the tool insert [2014Url]. This groove causes the chips to come out as continuous spiral, or as short chips which are broken against the uncut portion of the workpiece [2017Url^b]. The width and depth of the chip breaker groove significantly affects the chip shape, size, and

machining performance [2014Url]. The narrower the grooves the shorter the chips, and the deeper the groove the more tendency for chip jam and tip breakage [2017Url^b]. Meanwhile, obstruction type chip breakers may either be integral or attached to the cutting tool [2014Url]. This type of chip breaker can be adjusted to suit different cutting condition [2014Url].

In rough machining where large depth of cut and at high feed rates are used, chip control is a priority [2017Url^b], and chip breakers must be designed to have large breaker width and flat-negative land for effective chip control[2014Url, 2017Url^b]. Meanwhile, in finishing operations, where the feed is low and depth of cut is small, it is necessary to decrease the chip curl radius for easy chip breakage [2014Url]. The chip breakers should have a smaller breaker width, because the load on the cutting edge during finishing is low and sharpness is prioritized rather than cutting edge strength [2014Url].

This study proposes the introduction of groove type chip breakers on the rake of the cutting tool inserts for effective chip control.

2.9 **Milling**

Milling is a high speed material removal process in which rotary cutters are used to remove material from a workpiece by advancing in a direction at an angle with the axis of the tool [2000Tre]. This is accomplished by either spinning a cutter with many teeth at high speed towards the workpiece, or advancing the material towards the cutter, and/or using a combination of both approaches [2013Ush]. Milling operations can generally be divided into face milling and end milling (Figure 2.9a and Figure 2.9b) [2009Sch].

Face milling also known as “intermittent cutting action” is a milling technique used for surface level machining, and depending on the orientation of the axis of rotation of the 45° cutter relative to the cutting plane [2009Sch]. Face milling can be considered as either

horizontal or vertical [2009Sch]. End milling on the other hand refers to milling operations where flat bottomed cutters are used for machining at an axis vertical to the workpiece [2009Sch]. Face milling technique is usually recommended in manufacturing operations because of longer tool life and better surface quality [2014Kum]. This is because the smaller depth of cut used during face milling, as well as the full engagement of the cutter keeps the forces on either side of the centreline balanced [2014Kum]. Furthermore the chips during face milling are started out at a zero thickness [2014Kum]. The face milling of Ti-6Al-4V has been extensively covered in literature by Ezugwu, [1997Ezu], Genga [2014Gen], Ofem [2016Ofe], Balkrishna [2002Bal], Saini [2019Sai], and Li [2018]. Therefore face milling was selected for this experiment.

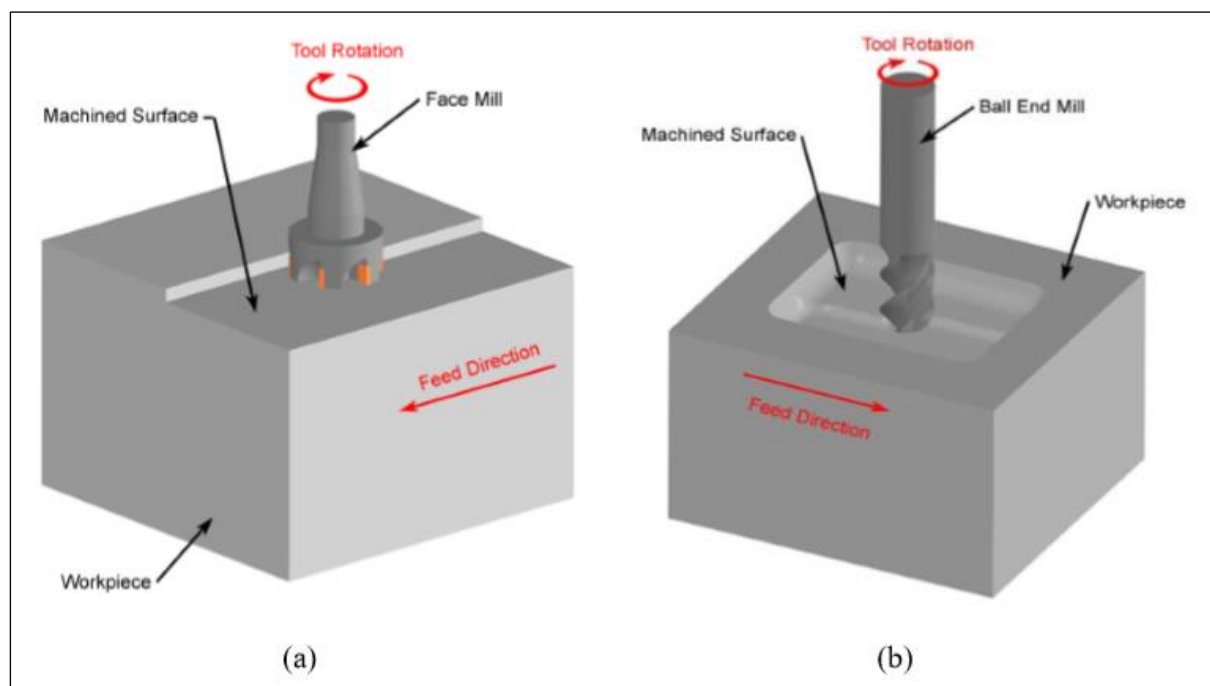


Figure 2.9. Schematic representation of milling operations: (a) Face milling, (b) End milling [2009Url].

2.9.1 Face milling parameters

The following cutting parameters are taken into consideration during face milling; cutting speed (vc), feed rate (vf), axial depth of cut (ap), radial depth of cut (ae), and material

removal rate (MRR). Appropriate understanding of these parameters is important for improving any milling process. Data on cutting parameter for titanium alloys been developed experimentally and will be discussed alongside milling parameters.

2.9.1.1 *Cutting Speed*

The cutting speed (v_c) is the cutting edge tangential peripheral velocity measured in m/minute [2005Yan]. It is the speed difference between the cutting tool and the surface of the workpiece it is operating on [2008Smi]. In any machining operation, the selection of appropriate cutting speed is important as this influences the resultant forces and temperature generated [2005Yan]. Cutting speed can generally be calculated using Equation 2.1.

$$v_c = \frac{\pi ND}{1000} \quad \text{Equation 2.1}$$

Where N is the spindle speed in rpm and, D is the tool diameter in mm [2005Yan].

Depending on the application and nature of the cutting tool insert, the cutting speed may be varied to suit different combinations [2013Ush]. Lower cutting speed, which permit for increased cutting depth, is used for roughing operations where high material removal rate is of primary interest [2013Ush], while a higher cutting speed is recommended for finishing operations where increased productivity and surface quality of the machined part is of interest [2013Ush]. This is because at higher cutting speeds, milling temperature is elevated and the strain hardening effect is eliminated owing to the thermal softening and ductility of the workpiece material [2008Smi]. Cutting speeds may also be adjusted based on chip shape and colour, rigidity of work holding, and machine horsepower meter readings [2004Dud]. The cutting speed has a considerable influence on tool life during titanium machining [1997Ezu]. In the past, the cutting speed for machining titanium alloys ranged from 18 to 30

m/min, until recently when cutting speeds exceeding 300m/min were attainable with enhanced cutting tool materials [1998Cha, 2008San].

2.9.1.2 **Feed Rate**

Feed rate (v_f) is the velocity at which the cutter is fed into the workpiece [2008Smi]. The selection of feed rate is dependent on the tool types, surface finish, power available at the spindle, tooling setup and rigidity of the machine, work-piece material strength and workpiece material machinability [1953Coo]. For milling machines where multi-tipped/multi-fluted cutting tools are utilized, the feed rate is usually dependent on the number of teeth on the cutter in addition to the desired amount of material per tooth to cut [2008Smi]. The greater the number of cutting edges, the higher the feed rate permissible for a cutting edge to work [1953Coo]. Increasing the feed rate during machining increases the machining forces [2012Mac]. The increase in machining forces is owing to the increased level of engagement between the cutter and workpiece [2016Ste]. Titanium alloys are very sensitive to changes in feed rate during machining, as this significantly affects tool life [1997Ezu]. However, Chandler [1978Cha], has recommended operating at a high speed for increase productivity. A general formula for calculating the feed rate during milling is given in Equation 2.2 below [1953Coo].

$$v_f = f_z Z N \quad \text{Equation 2.2}$$

Where:

v_f = feed rate (m/minute);

f_z = feed/tooth (mm/tooth);

Z = number of teeth and,

N = spindle speed (rpm or mm/minute) [1953Coo].

2.9.1.3 **Depth of Cut**

The depth of cut describes the thickness of the work piece material that is to be removed by the cutting edge during machining [2010Get]. The “depth of cut” during milling is represented by two parameters, the axial depth of cut (ap) and the radial depth of cut (ae) (Figure 2.10) [1993Saw]. Depending on the axis of orientation, both parameters indicate the level of engagement of the cutting tool into the workpiece [1993Saw]. Chandler [1978Cha], after conducting experiment on Ti-6Al-4V reported that; an increase in depth of cut from 0.75 – 3mm decreased tool life from 46 -14 min at a cutting speed of 60m/min. This is because the tool cuts through more material and therefore requires more cutting force to do so [1993Saw].

2.9.1.4 **Material Removal Rate**

Material removal rate refers to the volume of material removed or machined per time unit [1993Saw]. Material removal rate is usually high for roughing operations and low for finishing operations [1993Saw]. This is because of the variation in depth of cut for roughing and finishing operations [1993Saw]. The material removal rate is measured in mm³/min and is calculated using Equation 2.3 below [1993Saw].

$$MRR = \frac{ap . ae . vf}{1000} \quad \text{Equation 2.3}$$

Where ap = axial depth of cut, ae = radial depth of cut, and vf = feed rate.

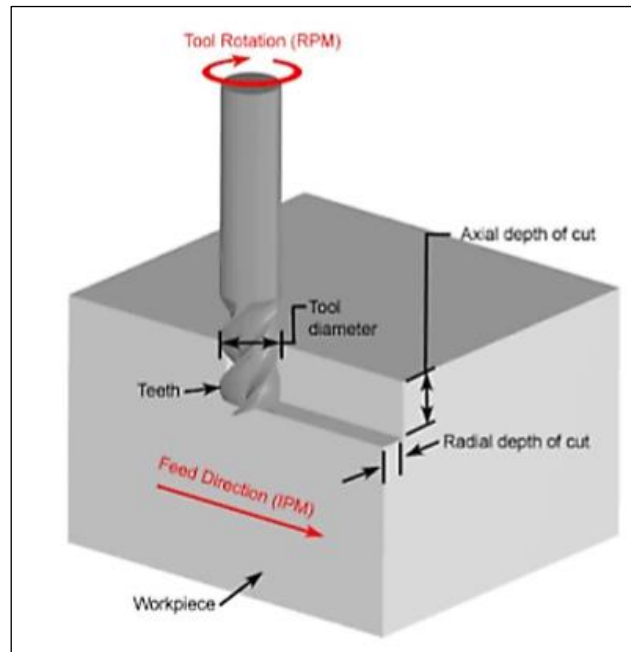


Figure 2.10. Schematic representation of axial and radial depths of cut [2009Url].

2.9.1.5 *Milling Time*

During face milling operations, the milling time can be calculated using Equation 2.4.

$$T_m = \frac{L + \left(\frac{D}{2}\right) + O}{v_f} \quad \text{Equation 2.4}$$

Where:

T_m = Machining Time (minutes)

L = Total length of the workpiece travel

D = Cutter diameter

O = Cutter Run Out Distance

v_f = Feed Rate

2.9.2 Cutting forces

Cutting force is a significant entity which characterises machining process. The cutting forces generated during machining influences both tool wear and surface roughness of machined components [2018Mas]. Konig [1978Kon] in an experiments with Ti-6Al-4V reported high mechanical stresses being concentrated on the cutting tool edge. Similar reports by Kholes [1985Kha] and Zlatin [1970Zla] attributed these stresses to Ti-alloy resistance to deformation at elevated temperatures. Many studies have also shown significant correlations between cutting force and machining parameters such as cutting speed, feed rate, depth of cut, etc. for different materials [2007Qia, 2010Tha, and 2006Zoe]. In orthogonal cutting operations, the component of the cutting force can be determined using either the cutter reference system or the table reference system [2016Ste, 1996Lal].

2.9.2.1 Cutter reference system

This system comprises of three force components (namely; tangential force, radial force and axial force) acting on the cutting edge as follows:

- The tangential force (F_t) acts tangentially to the effective radius of the cutter and represents the resistance to the cutter rotation.
- The radial force (F_r) acts perpendicular to the cutter axis along the radius of the cutter.
- The axial force (F_a) acts parallel to the spindle and contributes to the thrust force if the cutter has an approach lead angle [1996Lal].

The resultant force (F_R) of all the three force components can be determined using Equation 2.5 [1996Lal].

$$F_R = \sqrt{F_t^2 + F_r^2 + F_a^2} \quad \text{Equation 2.5}$$

2.9.2.2 *Table reference system*

In this reference system, a dynamometer is used to measure force components in the X, Y, Z directions as follows:

- Feed force (F_x): force component parallel to the machined surface and the feed direction
- Normal force (F_y): force component parallel to the machined surface and perpendicular to the feed direction
- Vertical force (F_z): force component parallel to the cutter axis and perpendicular to the feed direction [1996Lal].

The resultant force (F_R), for this reference system is determined using Equation 2.6 [1996Lal].

$$F_R = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad \text{Equation 2.6}$$

2.9.3 **Milling temperature**

In milling operations, all the cutting energy is assumed to be converted into heat energy which is distributed to the shear zone (75%), chip sliding on the tool face (20%), and tool sliding on the workpiece machined surface (5%) [2014Abd]. This is slightly different for Ti-6Al-4V milling, as over 80% of the heat generated is being absorbed by the cutting edge of the tool [2015Pra, 2008Pau, 1982Kom]. This is because of Ti-6Al-4V low heat dissipation (about 1/6 that of steel) [1982Kom, 2008Pau, 1997Ezu]. Temperatures exceeding 900°C are usually recorded when machining Ti-6Al-4V [2000Tre], with the bulk of this temperature being concentrated on the rake face of the cutting tool [2015Pra, 1989Boo]. These temperatures can further increase when milling parameters such as; speed and feed are increased [2005Sha, 2000Tre]. At elevated cutting temperatures, the tool and workpiece

material are thermally expanded resulting in reduced tool life, surface quality and cutting accuracy [2009Kik].

Since higher stresses and temperatures are usually concentrated on the rake face of cutting tool inserts during Ti-6Al-4V machining (Figure 2.11a and 2.11b) [2000Tre, 2005Wan]. This study envisages that the introduction of ridges on the rake face of the innovative cemented carbide tools would serve as confinements for Ti-6Al-4V debris, which will in turn act as a coating to protect the cutting tools against rapid wear [2005Wan].

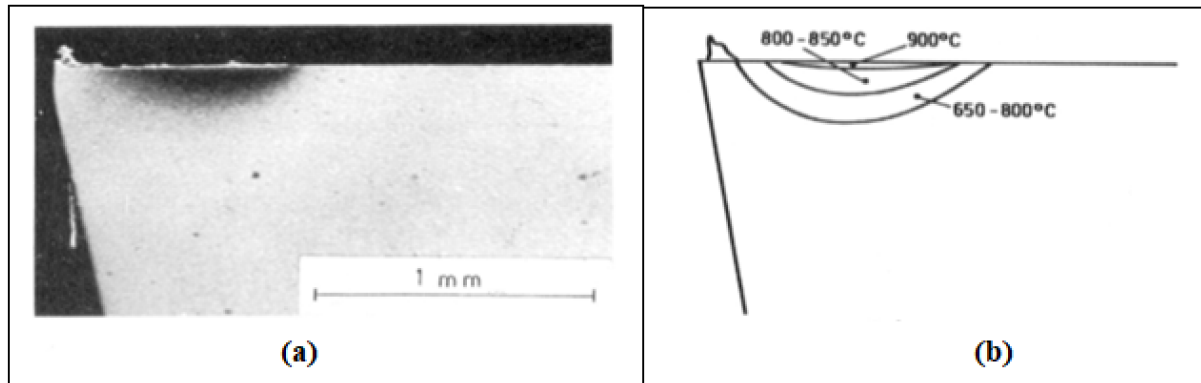


Figure 2.11 (a) Section through high speed steel tools used to cut commercially pure titanium, etched to show temperature distribution; (b) temperature contours derived from (a) [2000Tre].

2.10 Tool wear and tool life

Tool wear and tool life are critical consideration in metal cutting operations as they both raise production cost and degrade product quality [2009Che]. The performance of a cutting tool is usually assessed based on its life on the basis of certain wear criterion [2000Zoy]. Depending on the cutting condition, cutting material, and cutting tool composition, tools life and tool wear may vary [2005Sha]. For example, in the machining of Ti-6Al-4V with binderless cubic boron nitride (BCBN) tools, tool life increases with increased cutting speed [2005Wan]. The various types of cutting tool wear is shown in Figure 2.12 [2005Sha, 2009Che]. Catastrophic tool failure is also a failure mode which is undesirable and unpredictable, as it results in work

piece damage and downtime [1996Qui]. Some specific studies on tool wear during Ti-6Al-4V have been conducted by Wang [1988Wan], Subhas [1984Sub], and Ezugwu [1988Ezu].

During machining, the various types of tool wear can be monitored using the tangential force component, which tend to increases as tool wear increases [2008Cui]. This is because, the more blunt or damaged the cutting edge, the higher the cutting force produced [2011Yul]. Concurrently, the cutting temperature also increases as a result of the incremental cutting force resulting in rapid tool wear and reduced tool life [2011Yul].

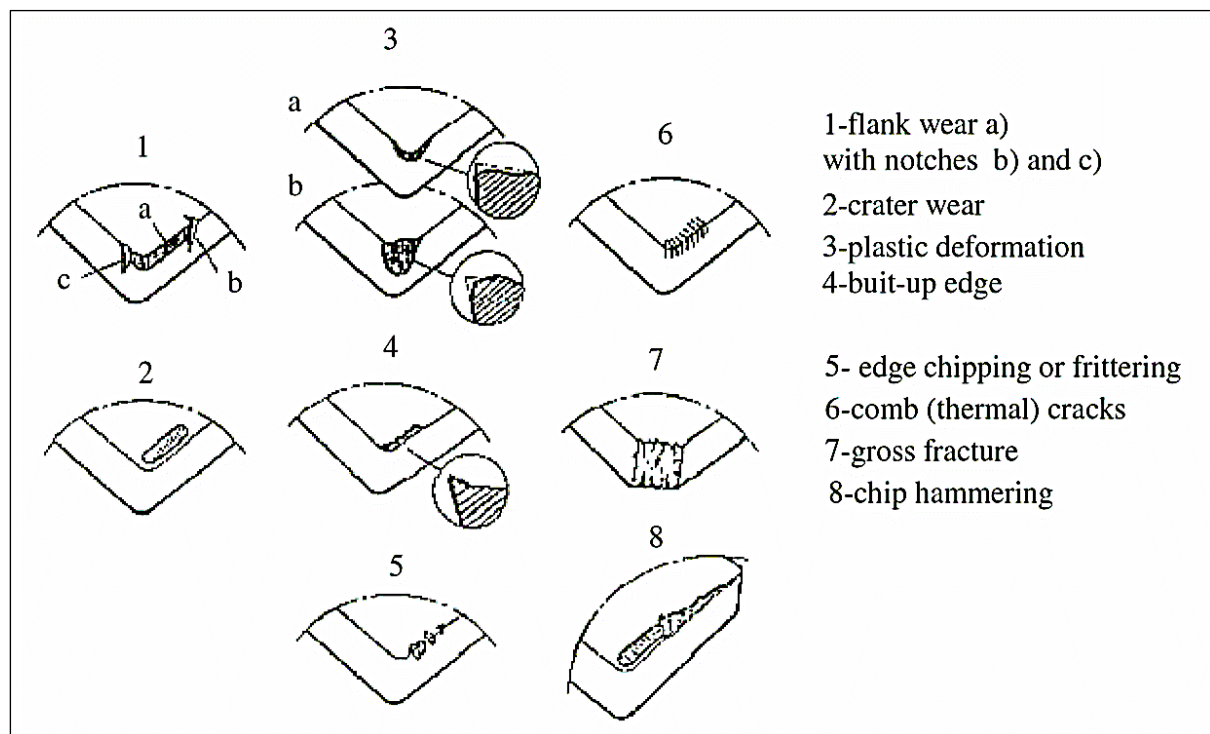


Figure 2.12. Basic types of failures and wear of cutting tools [2009Che].

2.10.1 Flank wear

Flank wear appears on the flank face of the cutting tool and results in the loss of relief angle on the clearance face, followed by increased contact length between the workpiece and clearance face [2005Sha, 2016Osk]. It is mainly caused by friction between the newly machined workpiece surface and the contact area of the tool flank [1989Boo]. Flank wear

increases the contact forces, tribological forces and temperature during machining [2016Osk]. Flank wear in titanium machining titanium with carbide tools is usually associated with fluctuations of cutting force caused by serrated chips [1987Mot]. Optical measurement of the width of the wear land (VB) can be used to determine the extent of flank wear [1989Boo].

2.10.2 Crater wear

Crater wear appears on the rake face of the cutting tool, characterised by the formation of crater. This type of wear is usually caused by the action of chips flowing along the tool face under severe pressure and temperature resulting in the removal of the rake face either by hard particle grinding or diffusion [1989Boo, 2000Chi]. In milling operations, crater wear increases drastically with an increase of cutting speed [2000Chi].

2.10.3 Chipping

Chipping is the breakage of a cutting tool edge, it occurs as a result of intermittent cutting or sudden subjection of mechanical, thermal and cyclic stresses on the cutting tool [2000Chi]. Chipping is the major failure mode when milling titanium alloys with WC cemented carbide tools [39]. Ezugwu and Machado [1998Ezu], reported that prior to chipping, an initial normal flank wear occurs and that this contributes to enhancing the first appear of chipping on the cutting tool [1998Ezu]. Cutting tools with low fracture toughness are generally likely to chip during machining [2000Chi].

2.10.4 Tool life criteria

A tool-life criterion is a predetermined threshold value of a tool wear measure [1989Boo]. The specification of the location and degree of wear is always necessary, since wear of flank and crater is not always uniform along the cutting edge [2000Chi]. The amount of cratering is determined by the measuring the deepest point of the crater [1989Boo], while the flank wear is usually greatest at the extremities (Figure 2.13) [1989Boo].

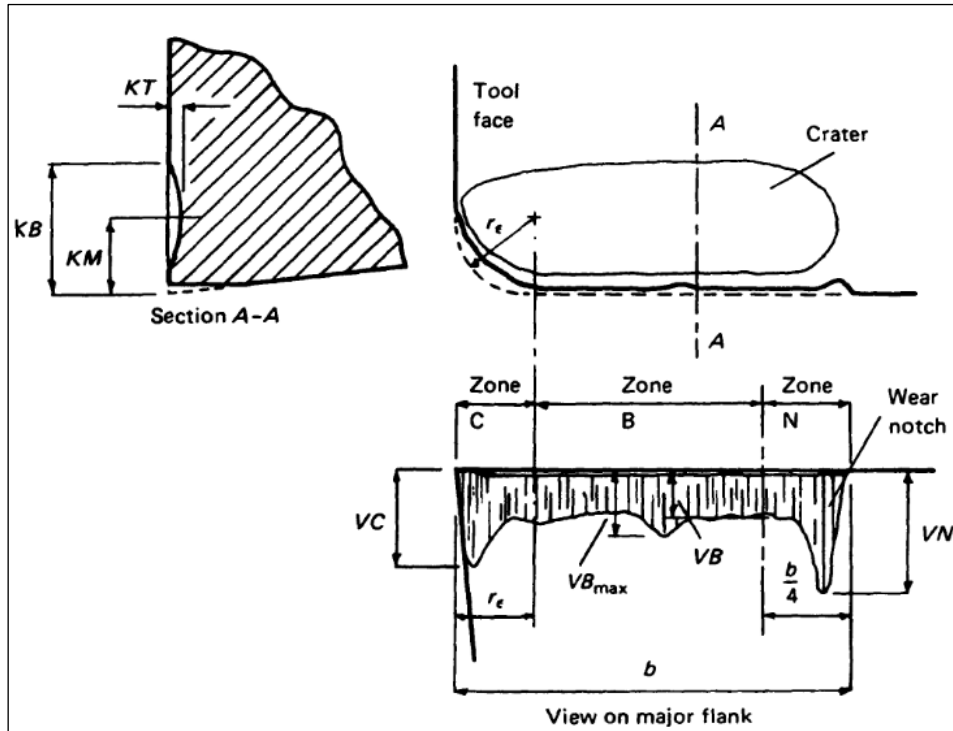


Figure 2.13. Some wear features in single point tools [1989Boo].

The following limit values are recommended by ISO3685:1993 for the tool wear of carbide tools: $VB = 0.3\text{mm}$ or $VB_{\max} = 0.6\text{mm}$ if the flank is irregularly worn, $KT = 0.06\text{mm} + 0.03f$, where f is the feed [1989Boo].

Taylor's tool life equation (equation 2.7) is also widely used to calculate tool life [2009Che].

$$V_c T^n = C \quad \text{Equation 2.7}$$

Where:

V_c = cutting velocity in m/min;

T = tool life in minutes, time taken to have a certain flank wear VB ;

n = a tool-material dependant constant;

C = a constant based on the tool and the workpiece.

2.10.5 **Wear Mechanism**

Wear in cutting tools can occur due to the following mechanisms; adhesion, abrasion, diffusion or chemical reaction (oxidation) [1989Boo, 2005Chi].

2.10.5.1 *Adhesive wear*

Adhesive wear is the repeated adhesion of workpiece or chip material to the tool, accompanied by tool failure [2000Chi]. It occurs at high temperature and pressure when the workpiece or chip materials weld to the surface of the cutting tool. The cutting action results in the fracture of the frictional junction formed between the tool and chip resulting in loss of tool surface particles [1989Boo]. This type of wear is common when machining with Ni-based super alloys [2000Chi]. In titanium machining, adhesive wear is likely to occur at temperatures above 740 °C [1995Sad].

2.10.5.2 *Abrasive wear*

Abrasive wear occurs when hard particles on the underside of the chip pass over the tool face and removes tool material by mechanical action [1989Boo]. The ability of a cutting tool to resist abrasive wear lies in its hardness relative to that of the workpiece material [2005Sha]. Abrasive wear is also influenced by the work hardening, crystallite orientation, elastic modulus of the contacting surfaces and distance cut [2005Sha, 2000Chi].

2.10.5.3 *Diffusive wear*

Diffusion wear is common during metal machining at high speeds and feeds where temperature is accelerated [2007Lui]. It is often accompanied by the decomposition of a component of one of the sliding surfaces [2005Sha]. Diffusive wear is dependent on the existing temperature and increases exponentially with increase in temperature [2000Tre, 2007Lui]. WC-Co cemented carbide tools are more resistant to diffusive wear and

deformation at high temperatures, and as such are more useful for Ti-6Al-4V machining [1975Fre].

2.10.5.4 *Chemical wear*

Chemical wear occurs when chemical compounds are formed by reaction of the tool with the work material, atmospheric gases or cutting fluid under high temperature [2000Chi]. Oxidation is a common factor to chemical wear affecting the rake and flank face of the tool [2000Chi]. In the machining of titanium with cemented carbide tools, a stable titanium carbide layer is usually formed between the tool and the chip [1991Ezuz]. This layer has high deformation resistance and adheres strongly to both the cutting tool and chip at high temperature [1998Ezu]. Contradictory, the titanium carbide layer formed on cemented carbide tool tip is not effective in suppressing wear [1998Ezu].

2.10.5.5 *Built-Up Edge*

Built-Up Edge (BUE) is a phenomena which occurs at lower cutting speeds when the friction between the chip and tool increases, causing a shear fracture in the vicinity of the tool face [2005Sha]. This is a common occurrence in titanium machining as cutting speeds are relatively low [1991EZU]. The formation of BUE increase the rake angle of the cutting tool inert, which in turn causes a decrease in the magnitude of the resultant force on the tool [2005Sha]. The gradual growth and rapid decay of the size of the BUE causes a saw-toothed finished surface [2005Sha]. Built-up edge can be eliminated by increasing the cutting speed, increasing the rake angle, and utilisation of cutting fluid [1957Nak].

2.11 Chip

The observation of chips during machining is crucial for information on material response (mechanical, thermal, thermo-viscoplastic, etc.) and process stability [2014Pau]. Unstable phenomenon such as BUE can also be detected from chip observation [2000Chi]. Chips can

be produced in various shapes and sizes [2000Chi], the ISO test standard identified eight basic classes and eighteen sub classes of chips as shown in Figure 2.14 [2016Ste].

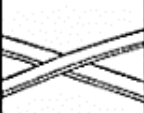
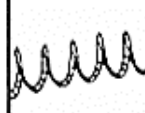
1. Ribbon chips	2. Tubular chips	3. Spiral chips	4. Washer-type helical chips	5. Conical helical chips	6. Arc chips	7. Elemental chips	8. Needle chips
							
1,1 Long	2,1 Long	3,1 Flat	4,1 Long	5,1 Long	6,1 Connected		
							
1,2 Short	2,2 Short	3,2 Conical	4,2 Short	5,2 Short	6,2 Loose		
							
1,3 Snarled	2,3 Snarled		4,3 Snarled	5,3 Snarled			

Figure 2.14. Chip classification according to ISO 3685 [2016Ste].

The cutting speed and feed rate significantly influences the type of chips produced during Ti-6Al-4V machining [2015Pra]. A general approach to chip classification identifies three chip types namely; continuous chip, continuous chip with built-up edge, and discontinuous chips [1989Boo].

2.11.1 Continuous chip

Continuous chips are common during machining of most ductile materials such as wrought iron, mild steel, copper and aluminium [1989Boo]. The formation of continuous chips takes place in the primary deformation zone and entails shearing of the workpiece material for chip formation and sliding the chip along the face of the cutting tool [1989Boo] (Figure 2.15). For continuous chips to occur during machining, the force transmitted to the chip across the interface between the chip and tool must be sufficient enough to deform the lower layer of the

chip as it slides along the tool face [1989Boo]. Continuous chips are undesirable as they lead to damage of cutting edge or cutting area [2014Pau].

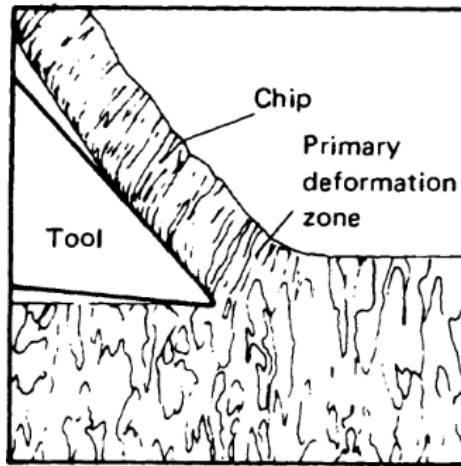


Figure 2.15. Continuous chip [1989Bro].

2.11.2 Continuous chips with built-up edge

Continuous chips with built-up edge (Figure 2.16) is usually common during machining at relatively low cutting speeds, where friction is so great that the chip materials weld to the tool face building up a layer upon layer of chip material[1989Bro]. This usually leads to the formation of BUE, which increases cutting tool wear and surface roughness of the machined component [1989B00].

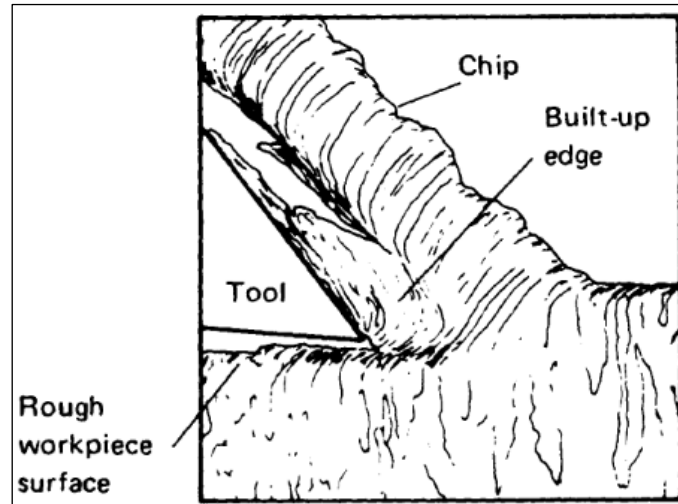


Figure 2.16. Continuous chip with built-up edge [1989Bro].

2.11.3 Discontinuous chips

Discontinuous or segmented chips (Figure 2.17) are mostly formed when machining ductile and brittle materials at very low speeds and high feed [1989Boo]. This is because when the ductile or brittle material undergoes severe strain, fracture will occur in the primary deformation zone when the chip is only partly formed [1989Boo]. During milling operations, discontinuous chips are desired as they reduce the cutting effort and tool – chip contact length [2014Pau].

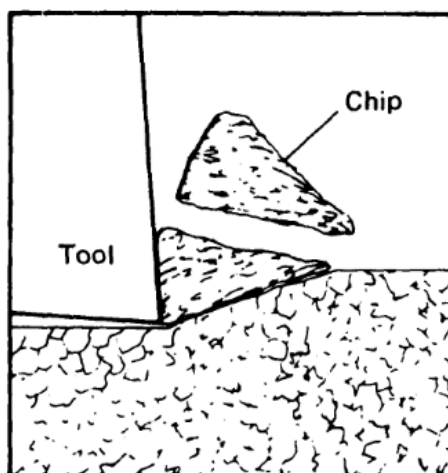


Figure 2.17. Discontinuous chips [1989Bro].

2.11.4 Chip formation mechanism

The formation of chip in metal cutting involves localised shear deformation of the work material by the cutting tool edge [1968Att]. In this process, the principal regions of interest are the primary deformation zone, the tool nose region, and the secondary deformation zone [2016Ste]. Deformations in the primary deformation zone have been of interest to many researchers with a number of theories been postulated. The Lee and Shaffer's theory among others will be considered in this section.

2.11.4.1 Lee and Shaffer theory

This theory assumes a uniform plastic zone in the chip, and applies the slip-line theory in obtaining the shear angle relationship for orthogonal cutting [2016Ste, 1968Att, 1996Lal]. It is based on the assumption that; for orthogonal cutting with continuous chip and no BUE, all deformation occurs on a plane inclined at an angle ϕ with respect to the plane of cut and the material stressed to yield point in the triangular region ABC (Figure 2.18) [2016Ste].

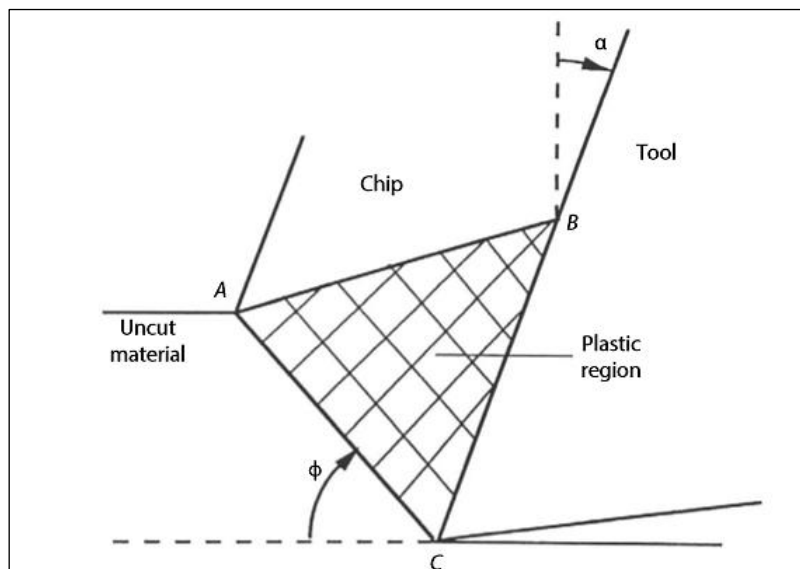


Figure 2.18 Lee and Shaffer's slip-line field solution for orthogonal cutting [2016Ste].

The derivation of the slip-line field solution is based on the following assumptions;

1. The workpiece behaves as an ideal plastic material.
2. The material is rigid up to its yield point and the effect of variation in strain rates and temperature can be neglected.
3. The inertia effect resulting from acceleration of material during deformation are negligible [2016Ste].

Succeeding the Lee and Shaffer's theory [1949Lee], are more realistic theories on the basis of various assumptions and for different cutting conditions. The Shaw theory [1953Sha], proposes that maximum shear stress is not at the shear plane, while the Oxley theory [1961Oxl] presents a strain hardening model of chip formation. Analysis of the Oxley and Palmer theory [1959Pal] implies that; tensile stress exist at the nose of the tool and the plastic zone extends beyond the nose of the tool.

2.12 **Surface roughness**

Surface roughness is one distinctive characteristics of surface topography which is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form [2008Gao]. If these deviations are large, the surface is rough, and if they are small, the surface is smooth [2008Gao]. A detailed overview of surface roughness can be seen in Figure 2.19. The roughness height determines the height of irregularities in the surface, while the roughness width defines the nominal distance between successive peaks which constitutes the predominant roughness pattern [2008Url]. The lay represents the predominant direction of surface pattern produced on the machined surface, and it also reflects the type of machine operation used [2008Url]. The roughness-width cut-off is the greatest spacing of the respective surface irregularities, and any irregularity outside this cut-off value is termed waviness [2009Bew].

The manufacturing process, tool type and cutting condition usually dictate the type of surface produced [1964Fei, 1970Fei]. For milling operations, surface roughness is strongly dependent on the cutting speed, with higher surface roughness at lower speeds and lower surface roughness at higher speeds [2005Sha]. The features of surface roughness and their potential causes are shown in Table 2.3. Different specialized techniques can be employed in analysing the surface topography of a material. The selection of a particular technique or combination of techniques is dependent on the surface area of interest [2012Sad]. Table 2.4 shows the common techniques which can be employed in observing/analysing surface integrity.

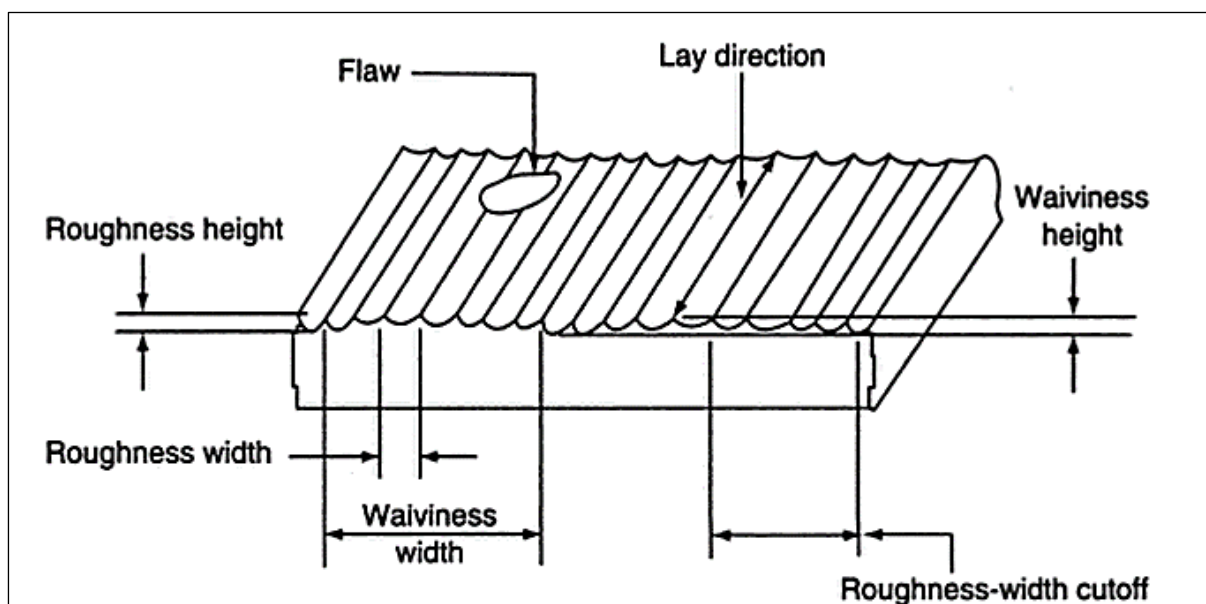


Figure 2.19. Surface roughness overview [2009Bew].

Table 2.3. Features of surface roughness and potential causes [2012Sad].

Surface feature	Cause
Form errors (flatness, roundness, straightness, cylindricity, etc.)	• Errors of machine tool slides, • Elastic deformations, • Erroneous fixation of tool or work piece, • Severe tool wear.

Cracks	• Tool-nose wear, • Built-up-edge formation, • Mode of chip formation, • Galvanic procedures.
Waviness	• Eccentric rotation of work piece or tool, • Vibrations in the Manufacturing system. • Tool wear, • Inhomogeneity of processed material.
Grooves	• Tool edge form, • process kinematics, • chip morphology

Table 2.4. Techniques for observing surface topography [2012Sad].

Area of Interest	Common Techniques	Identifiable defects
Surface Topography	• Profilometry, • Confocal microscopy, • Optical microscopy, • Interference microscopy, • Electron microscopy, • Metrology.	• Surface profile, • Surface roughness, • Waviness, • Lay, • Surface defects, • Distortion.
Surface Chemistry	• Laser probe mass spectrometry, • X-ray spectroscopy, • Auger spectroscopy, • X-ray microprobe analysis, Transmission electron microscopy.	• Surface composition.

A surface profilometer is the most common device used in measuring the roughness of a surface [2001Gri]. The profilometer measures the variations in surface feature as a function of position using a diamond stylus which runs perpendicular to the direction of the lay of the surface topography [2001Gri]. During roughness measurements the basic parameters of interest are; the average roughness (R_a), the root mean square (R_q), and the maximum height (R_z).

R_a is the average height of all the peaks with in a sample length on a surface (Figure 2.20), and it can be calculated using Equation 2.8 [2015Url].

$$R_a = \frac{1}{l} \int_0^l |Z(x)| dx \quad \text{Equation 2.8}$$

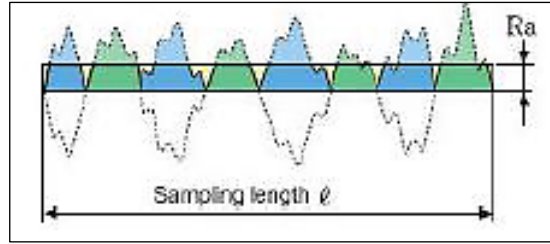


Figure 2.20. Average roughness, R_a [2015Url].

R_q is the root mean square that corresponds to R_a (Figure 2.21). It is calculated using Equation 2.9 [2015Url].

$$R_q = \sqrt{\frac{1}{l} \int_0^l |Z^2(x)| dx} \quad \text{Equation 2.9}$$

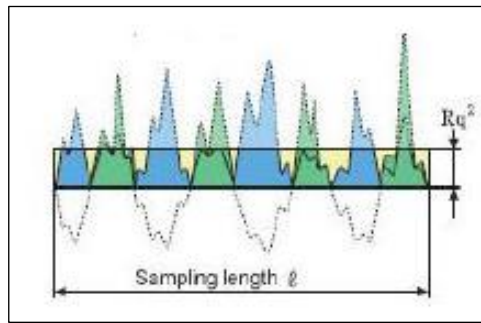


Figure 2.21. RMS Roughness, R_q [2015Url]

R_z is the result obtained by adding the maximum height to the maximum depth for a given sample length. These values are obtained from the datum which is set at the point R_a . R_z (Figure 2.22). R_z is calculated using Equation 2.10 [2015Url].

$$R_z = R_p + R_v \quad \text{Equation 2.10}$$

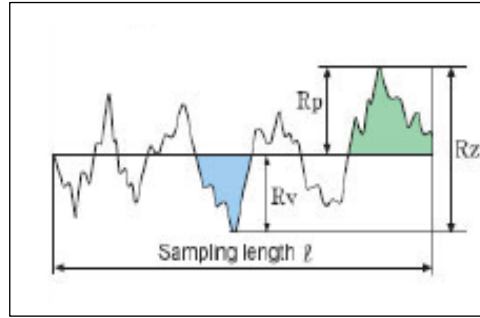


Figure 2.22. Average maximum height of the profile, R_z [2015Url].

2.13 Approach of study

Using the information from the literature survey, the first part of this study was to investigate the effect of Mo_2C (wt%) additions on grain size, microstructure and mechanical properties. Furthermore, through use of spark plasma sintering as a grain growth inhibitor, better mechanical properties were targeted.

The second part of the study was to investigate the combined effect of Mo_2C (wt%) addition and Co (wt%) binder substitution with Ni (wt%) on grain size, microstructure and mechanical properties of sintered samples. This was done with the aim of achieving lower grain sizes and better mechanical properties than WC-Co cemented carbides.

The third part of the study was to investigate the effect of laser peening on mechanical properties and performance of the sintered samples. This was done with the aim of achieving better mechanical and improved performance for all the sintered samples.

The fourth and final part of the study was to investigate the effect of cutting tool edge modification (Ridges and chip breaker) on performance characteristics of the blank inserts. The cutting temperature, resultant force, flank wear rate and surface roughness were selected as performance indicators.

3 Experimental Procedure

This chapter describes the experimental procedures, apparatus and facilities used for this research. A general illustration of the experimental processes is shown in Figure 3.1.

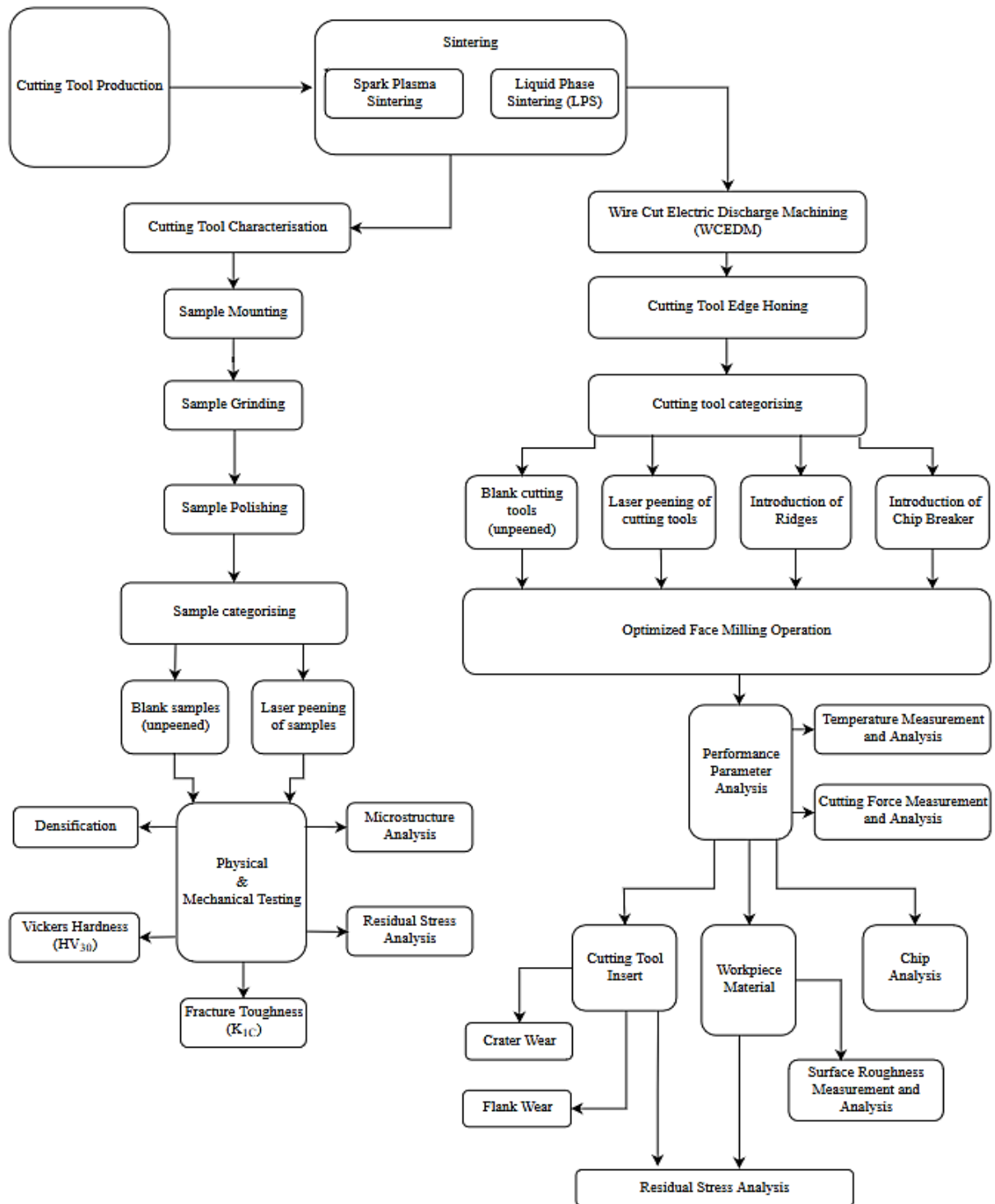


Figure 3.1 Overview of experimental processes

3.1 Consolidation of powders

To obtain the desired mechanical properties, the WC-Co used was doped with chromium and different types of carbides were added in a set proportion as shown in Table 3.1. The

individual powders were weighed using a Mettler Toledo PB303-S weighing balance (School of Chemical and Metallurgical Engineering, Wits University) before mixing each composition. For the powders compositions that were to be produced by liquid phase sintering (LPS), 2 wt% of polyethylene glycol (PEG) and 0.2 wt% of dispersant were added to the powder - ethanol -milling ball mixture before milling.

Table 3.1. Powder compositions.

Composition (wt%)	Abbreviation	Starting powder size (μm)
WC-0.5Cr ₃ C ₂ -10Co	W3	0.5
WC-0.5Cr ₃ C ₂ -3.5Mo ₂ C-10Ni	W4	0.5
WC-0.5CrC ₂ -3.5Mo ₂ C-10Co	M2	0.5

3.1.1 Powder Milling

To facilitate mixing of the powders and break powder agglomerates, a 70 mm diameter x 80mm stainless steel milling pot (Figure 3.2) was used to carry out wet milling of the investigated compositions. The milling was done using a portable 1kg capacity ball mill, 99% pure ethanol milling liquid, as well as WC-10Co (wt%) and steel milling balls. A ball-to-powder ratio of 5:1 was used. The powder compositions were milled at a speed of 66 rpm for 23 hours.

3.1.2 Drying and sieving of the powders

The powders were dried after milling in order to avoid formation of oxides in the composition during sintering. A Heidolph Laborator 4010 Digital rotaevaporator (School of Chemical and Metallurgical Engineering, Wits University) was used to carry out the powder drying process at 60 °C and 80 rpm for 1 hour. The low temperature of 60 °C used, was to avoid oxidation of powders since pure ethanol has a boiling point of about 78.3 °C [1968Gal]. To break down the powder cake that formed during drying and to eliminate any large

impurities ($>100\text{ }\mu\text{m}$) that might have been picked up during milling and drying, the powders were sieved using a $90\text{ }\mu\text{m}$ sieve.



Figure 3.2. Stainless steel milling pot.

3.2 Sintering

3.2.1 Spark plasma sintering

Consolidation of the milled composite was done using a HP D5 FCT system spark plasma sintering furnace (School of Chemical and Metallurgical Engineering, Wits University). The milled composite powder was poured into cylindrical graphite dies with inner and outer diameters of 20.9 mm and 40 mm respectively, and 48 mm height. Horizontal and vertical graphite papers were used to separate the powders from the die and punch set-up. Hexagonal boron nitride was placed on the graphite paper to prevent carbon diffusion from the graphite paper to the powders during sintering. The graphite die was wrapped in a carbon cloth to minimise the heat loss from the die surface. The composite powder assemblies were then loaded in graphite dies and heated in a vacuum (2 hPa). For the $\text{WC-0.5Cr}_3\text{C}_2\text{-10Co}$ (wt%) powder, a heating rate of $200\text{ }^\circ\text{C/minute}$ was initially used to heat up the composition to $1050\text{ }^\circ\text{C}$, after which a slower heating rate of $100\text{ }^\circ\text{C/minute}$ was used to heat the sample to a

temperature of 1240 °C. The temperature was then held at 1240 °C for 5 minutes, before cooling was applied at a rate of 200 °C/minute. In an interval of 30 seconds, the pressure applied was quickly varied from 16 MPa to 30 MPa at 1050 °C and from 30 MPa to 50 MPa at 1240 °C. The applied pressure was then maintained at 50MPa throughout the sintering cycle. An optical pyrometer was used to measure the temperatures during sintering. The pyrometer was positioned 1mm above the graphite die containing the powders and focused towards the upper central borehole of the graphite punch. The piston movement which indicated the degree of shrinkage during sintering was used to monitor the compaction of the composite powders in the axial direction.

The sintering profile for the WC-0.5Cr₃C₂-Mo₂C, 10Co (wt%) and WC-0.5Cr₃C₂-Mo₂C, 10Ni (wt%) powder compositions were varied to achieve good densification. The pressures ranged between 50 -70 MPa, while the temperature ranged between 1280-1300 °C respectively as shown in Table 3.2.

3.2.2 Liquid phase sintering

The milled powders were pressed into green compacts of 22 mm diameter by 5.2 mm thick shapes before sintering. The compacts were sintered using an ULTAR-TEMP Sinter-HIP furnace (Pilot Tools (Pty) Ltd.). The compacts were placed in the furnace heating chamber and heated in vacuum (0.04MPa) at an initial heating rate of 2.4 °C/minute to 270 °C. The temperature was held constant for 65 minutes, as the vacuum pump was turned off allowing the flow of hydrogen into the heating chamber for dewaxing. To ensure all the PEG was eliminated, dewaxing was carried out in four steps, using a series of heating rates and dwell times from 270 °C to 450 °C. To remove the hydrogen after dewaxing, the temperature was held at 450 °C for an additional 20 minutes, during which the vacuum pump was switched on. A heating rate of 4.2 °C/minute was then administered from 450 °C to 1000 °C, at which the

temperature was held for 5 minutes, with the vacuum pump turned off to allow flow of methane and hydrogen for carbon correction. To ensure replacement of the carbon lost to dewaxing, carbon correction was done [1975Bro]. Carbon control was done for 90 minutes, after which the vacuum pump was switched on to remove the methane and hydrogen. A heating rate of 3.3 °C/minute was used from 1000 °C to 1200 °C. At 1200 °C. Cobalt loss protection (CLP) was carried out by the addition of argon gas at a pressure of 0.37 MPa. The CLP was done using a heating rate of 3.5 °C/minute up to 1430 °C. The temperature was held constant for 75 minutes, and for the last 20 minutes, hot isostatic pressing (HIP) was done at 4.4 MPa to eliminate all the surface porosity [1975Bro]. Water cooling of the furnace was carried out at a rate of 3.5 °C/minute. The sintering conditions for other liquid phase sintered inserts are presented in Table 3.2.

Table 3.2. Sintering conditions

Composition (wt%)	Sintering technique	Abbreviation	Temperature (°C) and dwell time
WC-0.5Cr ₃ C ₂ -10Co	LPS	W3-L	1430 °C for 75 min
WC-0.5Cr ₃ C ₂ -10Co	SPS	W3-S	1240 °C for 5 min
WC-0.5Cr ₃ C ₂ -35Mo ₂ C-10Co	LPS	W4-L	1430 °C for 75 min
WC-0.5Cr ₃ C ₂ -3.5Mo ₂ C-10Co	SPS	W4-S	1280 °C for 5 min
WC-0.5Cr ₃ C ₂ -3.5Mo ₂ C-10Ni	LPS	M2-L	1430 °C for 75 min
WC-0.5Cr ₃ C ₂ -3.5Mo ₂ C-10Ni	SPS	M2-S	1300 °C for 5 min

3.3 Characterisation of sintered samples

3.3.1 Density measurement

The density of the sintered samples was determined by Archimedes' principle using a Sartorius ED224S density measuring machine. The samples were initially cleaned to remove the hexagonal boron nitride and graphite paper from the surface and then weighed in distilled water to attain the wet mass (W_2) and suspended mass (W_3) respectively. The wet samples were then dried in a Labotec INC-O-MAT oven (School of Chemical and Metallurgical

Engineering, Wits University) at a temperature of 80 °C for 24 hours. After which the samples were weighed in air to attain dry mass (W_1) [1955AST].

The true density was determined using Equations 3.1-3.3[1955AST].

$$\text{True volume of sample} = \frac{W_1 - W_3}{\rho_w} \quad (\text{Equation 3.1})$$

Where ρ_w is the density of distilled water at room temperature.

$$\text{True density of sample} = \frac{W_1 \rho_w}{W_1 - W_3} \quad (\text{Equation 3.2})$$

$$\text{Percentage densification} = \frac{\text{True sample density}}{\text{Theoretical density}} \times 100\% \quad (\text{Equation 3.3})$$

The theoretical density of the samples was obtained from the density and mass % of the individual constituents of the compositions (Equation 3.4), e.g. for WC-10Co (wt%), the density of WC is 15.7g/cm³ and Co is 8.9 g/cm³ [1992Scu].

$$\text{Theoretical density (g/cm}^3\text{)} = 100 \text{ wt}\% \times \left(\frac{90\text{wt}\%}{15.7\text{g/cm}^3} + \frac{10\text{wt}\%}{8.9\text{g/cm}^3} \right) \quad (\text{Equation 3.4})$$

3.3.2 Cutting of sintered samples

The cutting of the samples was done to attain a cross-section area from the outer surfaces to the centre, for representative characterisation. This enabled the testing of the sample from all edges to the centre, and also ensured that the properties were uniform throughout. A Struers Secotom-10 precision cutting machine (School of Chemical and Metallurgical Engineering, Wits University) was used for the cutting operation. The cutting was done using a 12 cm diameter Struers diamond coated wheel, a wheel cutting speed of 3500 rpm and feed rate of 0.02 mm/s was used to achieve a finished cut in 25 minutes. Water was used as a coolant throughout the cutting process.

3.3.3 Sample mounting

Mounting of the samples was done for easy handling of the samples during polishing of the exposed cross-section area after cutting, and to make them easier to hold. One half of the sample was mounted in Struers polyFast using a Struers Cito-Press 10 (School of Chemical and Metallurgical Engineering, Wits University) at 250 bar and 180 °C for 10 minutes. Water was used as a coolant during the process.

3.3.4 Sample grinding and polishing

Grinding and polishing were done to eliminate surface damage during cutting and to produce a smooth surface finish for microstructure analysis and mechanical testing. A Struers LaboPol-5 machine (Pilot Tools (Pty) Ltd.) was used for grinding and polishing of the samples. Piatto 220 and 1200 wheels were used for grinding, while AKASEL 9 µm, 3 µm and 1 µm cloths with Diamaxx diamond slurries were used for polishing. The parameters and lubricants used for grinding and polishing are shown in Table 3.3.

Table 3.3. Sample grinding and polishing procedure.

Process	Step	Wheel/Cloth	Lubricant	Speed (rpm)	Load (N)	Time (minutes)
Grinding	1	Piatto-120	Water	180	40	5
	2	Piatto-120	Water	180	40	10
	3	Piatto-120	Water	160	35	10
Polishing	1	Plaran-9µm	Diamaxx-9µm	300	35	10
	2	Daran-3µm	Diamaxx-3 µm	250	20	6
	3	Napal-1µm	Diamaxx-1 µm	250	20	3

3.3.5 Microstructure analysis

Microstructures of the cemented carbides were examined by scanning electron microscopy in the backscattered electron mode using a Zeiss high resolution SEM (School of Chemical and Metallurgical Engineering, Wits University). The SEMs were run at 15 kV acceleration voltage, at working distances between 10 -12mm. Both EDX point and area analyses were

carried out to identify phases. The SEM micrographs were used to analyse the homogeneity of the phase distribution, WC grain size and binder mean free path. Image analysis of the SEM micrographs was done using ImageJ software. For better understanding of variations within the microstructures as a result of specific additives, the grain interfaces at an atomic level were analysed using a high resolution transmission electron microscopy (HRTEM) and a JEOL ARM-200F (Centre for High Resolution Transmission Electron Microscopy, Nelson Mandela Metropolitan University). The samples for HRTEM were prepared using a Helios Nanolab which had a dual focused ion beam – scanning electron microscope (FIB-SEM) platform (Centre for High Resolution Transmission Electron Microscopy, Nelson Mandela Metropolitan University).

3.3.6 Mechanical properties

3.3.6.1 Hardness

A Mitutoyo AVK-Co (Pilot Tools (Pty) Ltd.) hardness indenter was used to measure the Vickers hardness of the polished samples. Loads of 30kg (HV_{30}) were applied with a square base pyramid-shaped diamond indenter (with interfacial angle of 136°) for 10 seconds. Five indentations were carried out at different regions on each sample. To avoid overlapping effects, a minimum distance of 0.75mm was kept between indentations. After removal of the load, the two diagonals the indentation left on the samples (Figure 3.3) were measured using a microscope and their average calculated. The Vickers hardness value of each sample was the quotient obtained by dividing the kgf load by the square mm area of indentation (Equations 3.5 - 3.7) [1922Smi]. The Vickers hardness value for each sample was derived from the average of 10 measurements.

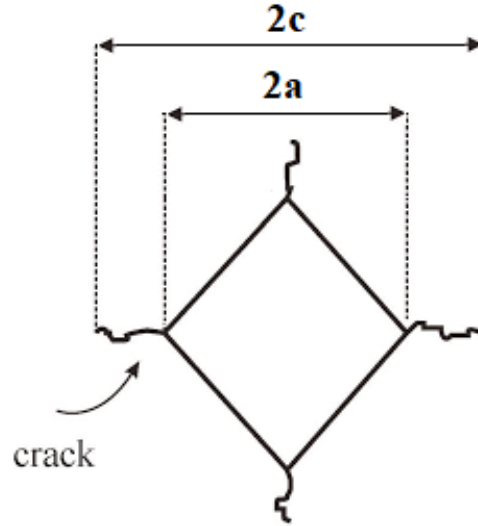


Figure 3.3. Vickers hardness test.

The Vickers hardness (HV_{30}) was calculated using the applied force and the length of diagonals ($D = 2a$ = Arithmetic mean of the two diagonals) (Equation 3.5 - 3.7).

Applied force (F) = Applied load (M) $\times$ gravitational gravity (g) (Equation 3.5)

$$F = M \times g$$

Where: M = 30kg for HV_{30} and, $g = 9.81\text{m/s}^2$

$$HV_{30} = \frac{F}{A} = 1.854 \frac{F}{D^2} \quad \text{(Equation 3.6)}$$

Where:

HV_{30} = Vickers hardness

M = mass (kg)

F = Force (N)

A = Area (mm^2)

D = Diameter (mm)

Therefore substituting for Equation 3.6;

$$HV_{30} = \frac{30 \times 9,81 \times 0.1891}{D^2}$$

The HV_{30} was then converted into hardness in GPa using Equation 3.7:

$$H \text{ (GPa)} = HV_{30} \times 0.009807 \quad \text{(Equation 3.7)}$$

3.3.6.2 *Fracture toughness*

The fracture toughness (K_{IC}) of the sintered samples was calculated from radial cracks produced at the edge of the indentations (Figure 3.3). The length of these cracks permit an accurate estimation of K_{IC} [1985She]. Shetty's equation (Equation 3.8) was used to accurately compute the fracture toughness (K_{IC}) of the samples, and all criteria for this equation were satisfied [1985She, 1990Spi]. The fracture toughness value for each sample were derived from the average of 10 measurements.

Criteria: $1.25 \leq c/a \leq 2.25$ and $0.25 \leq I/a \leq 2.5$.

Where:

c = crack length from the centre of indentation to the crack tip

a = half diagonal length of indentation, and

$I = c - a$.

$$K_{IC} = 0.0889H^{0.5} \times (F/4I)^{0.5} \quad \text{(Equation 3.8)}$$

Where;

H = hardness (GPa)

F = applied force (N) and,

I = average crack length (mm) given by Equation 3.9.

$$I = (2c-2a)/2$$

(Equation 3.9)

3.4 Cutting tool insert production

Cutting tool inserts with dimensions shown in Figure 3.4 were made from the 2 mm diameter by 5.2 mm thick bulk samples. The inserts were initially cut into 12.7 mm by 12.7 mm by 4.7 mm square shapes using a Fanuk Robocut α -O1A Electro-discharge machine (EDM) wire cutter. The squares were then lapped to the required thickness using a Peter-Walters 3R-1200 lapping machine, after which they were edge rounded face and end grounded to the final dimensions using an Ewag RS12 Edge profile grinder.

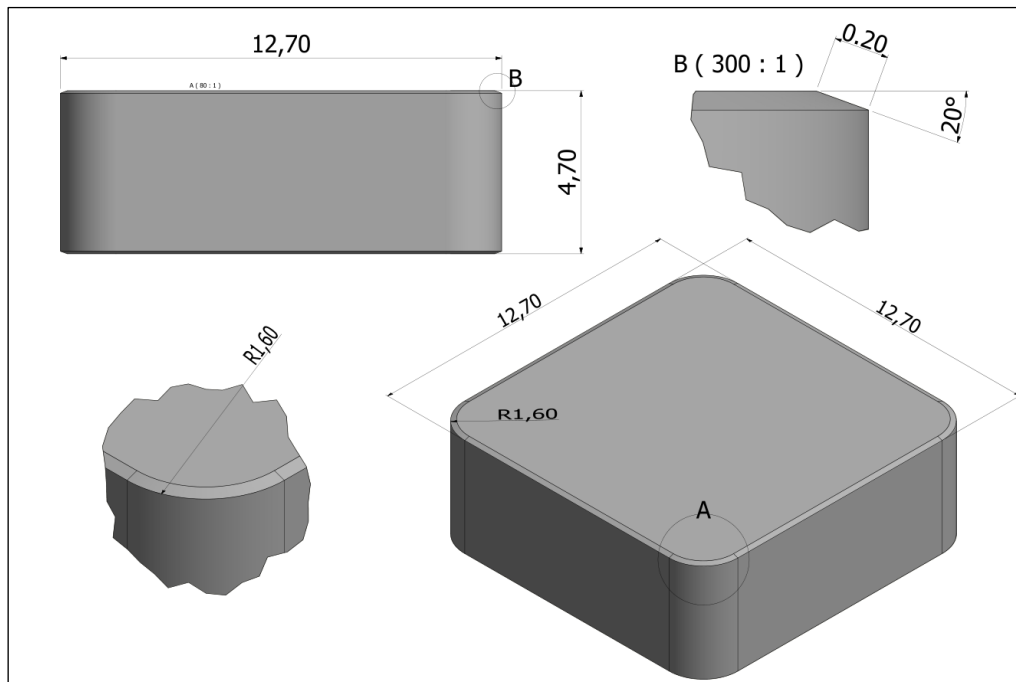


Figure 3.4 Cutting insert specification.

To eliminate sharp edges, improve geometrical tolerance and prevent premature failure due to high stress concentration at the cutting edge, the cutting tool inserts were edge honed between faces after grinding. The tool inserts were also edge chamfered to a radius of 200 μ m using an AUER SAN 1000 S1S machine (University of the Witwatersrand), after which they were

allocated for respective cutting edges processing (i.e. blank, laser peened, ridges, and chip breaker). A combined total of 24 cutting tool inserts were processed for this experiment.

3.4.1 Blank inserts

The blank cutting tool inserts category comprised of 6 cutting tool inserts which were selected per composition from each sintering technique. These tools were in their conventional ready-to-machine state with no additional processing carried out on their rake or flank.

3.4.2 Laser peened inserts

Laser peening was carried out on the characterisation samples and on 6 cutting tools inserts using a Spectra-Physics Quanta-Ray Pro 270 Nd: YAG Laser (National Laser Centre, CSIR) with a wave length of 1064nm, energy of 1750MJ/Pulses. It is important to mention that for each sintering technique only one cutting tool insert was selected per composition for laser peening. In addition laser peening was carried out on the cutting tool inserts after EDM wire cutting, grinding to required shape, and polishing operations were carried out. The cutting tools were stacked together and fastened together using an opaque tape which also served as an ablative layer. The stack was then mounted onto a mechanical system (2 degrees of freedom, vertical (Y) and lateral motion (X)) controlled by a specialized computer program and a CNC Mach 3 controller software. A beam was sent from the laser to mirror 1 where it was reflected to mirror 2 onto mirror 3 and through the lens, where it was concentrated onto the flanks of the cutting tools stack. The beam firstly moved through the transparent overlay (water layer which flows over the stack) before hitting the flanks of the cutting tools in the stack, where it vaporized, and as a result formed plasma. This plasma was confined between the stack and the water layer (transparent overlay) and thus creating a shockwave, which propagated through the material enhancing the material properties and increasing

compressive residual stresses within the material. The laser beam was localised to one spot (i.e. does not move), as the mounting plate holding the test stack moved with every pulse of the laser (laser in a pulsating mode). With every pulse the specimen was moved in the required sequence to obtain coverage over the test area (i.e. in the Y (stepping direction) and X (travel direction) direction), The laser peening parameters used for peening the characterisation samples and cutting tool inserts is given in Table 3.4.

Table 3.4 Laser peening parameters

Parameter	Value
Spot size	1.5 mm
Power intensity	12 GW
Focal lens	1.5 mm
Energy	1750 MJ/Pulse
Overlap	7 mm
Percentage (%)	33 %
Opacity	532 nm
Spatial and temporal beam profile	Gaussian
Repetition rate	10Hz
Wave length	1064nm
Pulse width	8 to 10ns
Working distance	8.28mm

3.4.3 Ridges inserts

Horizontal ridges profiles were machined to the rake face of 6 cutting tool inserts using a Medicon LD50C laser system (Czech Technical University, Prague). The ridges were machined 1mm from the cutting tool edges (Figure 3.5a and 3.5b). Selection of the cutting tool inserts was done to accommodate each composition in the respective sintering technique. The laser system used for machining had a wavelength of 1064nm, and a pulse repetition rate ranging from 1 to 60 KHz. Nanosecond pulses were used at an output power of 20W, while repetition rate was set at 5 KHz. A total of 5 passes of the laser parameters were used to form the ridges in each selected cutting tool. Proper intensity was set to create the desired profile.

3.4.4 Chip breaker inserts

The Medicon LD50C laser system (Czech Technical University, Prague) was also used to introduce L-shaped chip breakers on the rake face of 6 cutting tool inserts. The Selection of the cutting tool inserts was done to accommodate each composition in the respective sintering technique. The chip breakers were machined 1mm from the cutting tool edge as shown in Figure 3.6a and 3.6b. The operation was carried out using a laser output power of 20W and a repetition rate of 5KHz. The intensity was properly set to create the desired profile. A total of 300 passes of the laser was used to form the chip breaker.

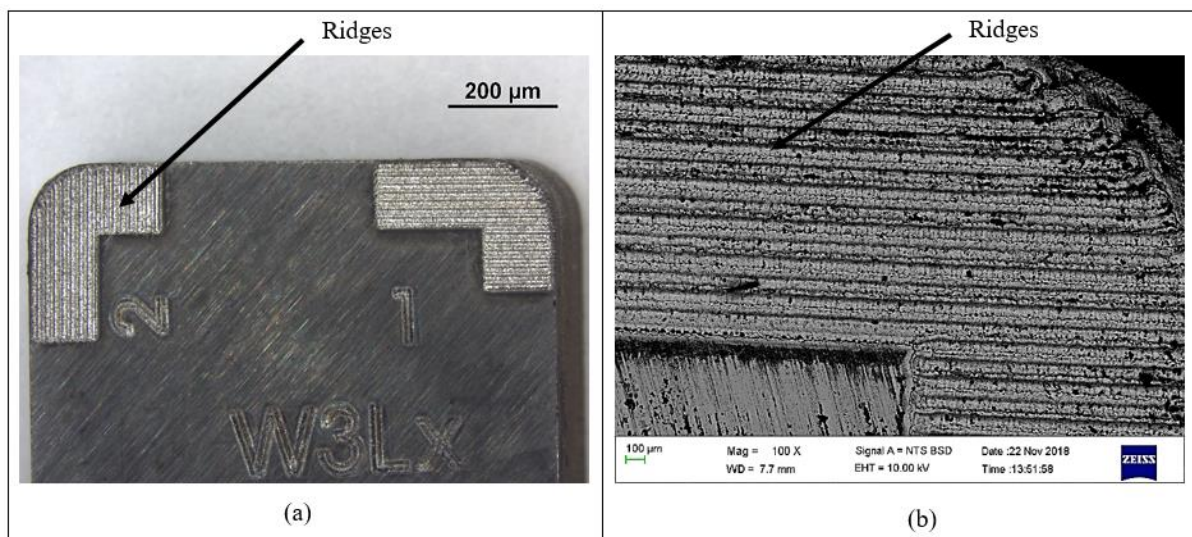


Figure 3.5 (a) Optical micrograph (b) SEM micrograph of ridges on the rake face of a cutting tool insert.

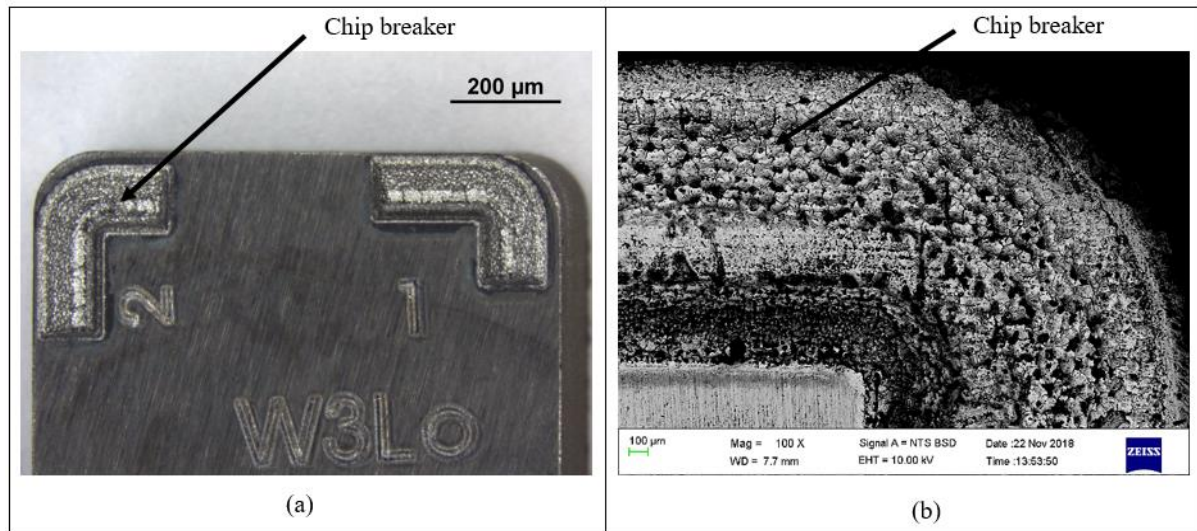


Figure 3.6 (a) Optical micrograph (b) SEM micrograph of chip breaker(s) on the rake face of a cutting tool insert.

3.5 Ti-6Al-4V machining trials

Milling trials were carried out on the 110 mm × 110 mm × 8 mm Ti-6Al-4V (AMS 4911) workpieces using a Bridgeport GX1000 CNC milling machine (School of Mechanical, Industrial and Aeronautical Engineering, Wits University). A total of 104 Ti-6Al-4V workpieces were used for this experiment. A vice was bolted to the CNC machine table to clamp the workpiece in place. For machinability study, only one effective cutting tool insert was used per milling trial. For each trial, the respective cutting tool insert was inserted into the BT40-22 45V cutting tool holder which had a radial depth of cut of 80mm (Figure 3.7). The nomenclature of all the cutting tool inserts used for this experiment is given in Table 3.5. The tool was fastened onto the tool holder with the desired cutting edge facing outwards. The tool holder was then locked onto the spindle of the CNC milling machine. The varied depth of cut (ap) and cutting speed (vc) were sequentially programmed into the CNC machine in accordance with the trials shown in Table 3.6 – Table 3.9. A constant feed (f) of 0.1 mm/tooth was maintained throughout.

F75 SN

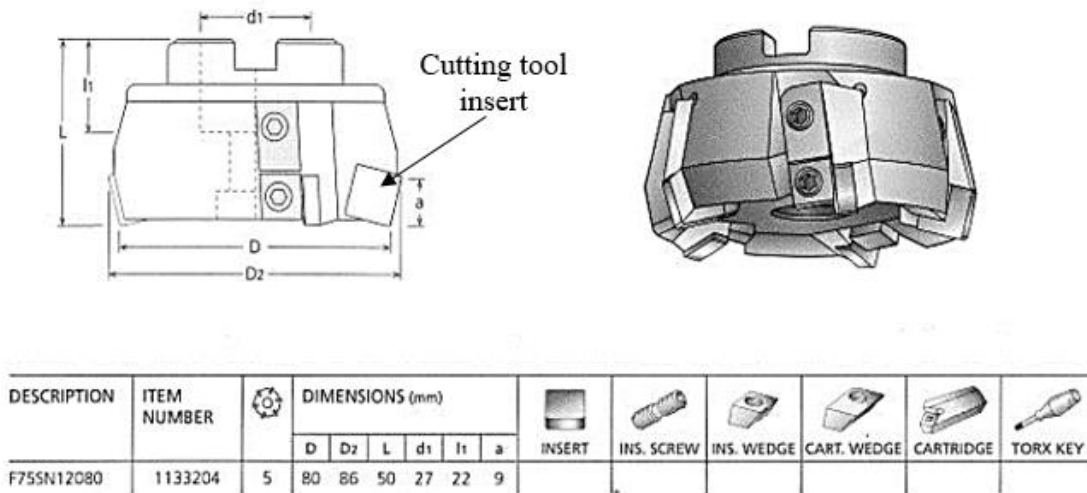


Figure 3.7 Tool holder geometry showing lone cutting tool insert used per milling trial

Table 3.5. Cutting tools nomenclature

Composition	Sintering	Category	Abbreviation
WC-Cr ₃ C ₂ -10Co (W3)	Liquid phase sintering (W3-L)	Blank	W3-L-B
		Laser peening (LP)	W3-L-LP
		Ridges (R)	W3-L-R
		Chip breaker (C)	W3-L-C
	Spark plasma sintering (W3-S)	Blank	W3-S-B
		Laser peening (LP)	W3-S-LP
		Ridges (R)	W3-S-R
		Chip breaker (C)	W3-S-C
WC-Cr ₃ C ₂ -Mo ₂ C-10Co (W4)	Liquid phase sintering (W3-L)	Blank	W4-L-B
		Laser peening (LP)	W4-L-LP
		Ridges (R)	W4-L-R
		Chip breaker (C)	W4-L-C
	Spark plasma sintering (W3-S)	Blank	W4-S-B
		Laser peening (LP)	W4-S-LP
		Ridges (R)	W4-S-R
		Chip breaker (C)	W4-S-C
WC-Cr ₃ C ₂ -Mo ₂ C-10Ni (M2)	Liquid phase sintering (W3-L)	Blank	M2-L-B
		Laser peening (LP)	M2-L-LP
		Ridges (R)	M2-L-R
		Chip breaker (C)	M2-L-C
	Spark plasma sintering (W3-S)	Blank	M2-S-B
		Laser peening (LP)	M2-S-LP
		Ridges (R)	M2-S-R
		Chip breaker (C)	M2-S-C

It is important to mention that the milling experiment was randomly designed to suit parameter for roughing, semi-finishing and finishing of Ti-6Al-4V. Also, during the roughing operations at ap of 1.5mm and 1mm, two effective milling passes were carried out per insert, per milling trial. However, for semi-finishing and finishing trials where ap was reduced to 0.5mm, only one effective milling pass was carried out per insert, per milling trial. Machinability study for the laser peened and chip breaker inserts were only conducted at the following cutting speeds and depth of cuts; 60m/minute and 1.5mm (roughing), 75m/minute and 0.5mm (semi-finishing), 100m/minute and 0.5mm (finishing). The only exceptions to this were the M2-S-C insert which was only utilised during milling at vc of 60m/minute and ap of 1.5mm, and the M2-L-C which was not utilised during milling at vc of 100m/minute and ap of 0.5mm.

A Flir T640 thermal imaging Camera (School of Mechanical, Industrial and Aeronautical Engineering, Wits University) was used to estimate the thermal variations at the cutting zone during the milling trials. To ensure accuracy in thermal readings, the Flir camera was mounted onto a tripod stand which was positioned 1m away from the cutting zone. The temperature range of the camera was between -40 to 2000°C, while the thermal sensitivity of the camera was 0.035 °C. The emissivity of the workpiece had to be determined for accurate thermal readings. This was done by heating one Ti-6Al-4V workpiece in a Labotec INC-O-MAT (School of Mechanical, Industrial and Aeronautical Engineering, Wits University) oven to 60 °C, then simultaneously measuring the temperature using a K-type thermocouple (School of Mechanical, Industrial and Aeronautical Engineering, Wits University) and the thermal camera. The temperature was determined using the thermocouple, while the thermal camera was used to calibrate the thermocouple reading. The emissivity value on the thermal camera that corresponded to the actual thermocouple temperature reading was the correct

emissivity of the workpiece. The emissivity of the Ti-6Al-4V workpiece was found to be 0.21.

The impact forces during the milling trials was measured using a Kistler 9255C dynamometer system with standard error of $\pm 15\text{N}$ (School of Mechanical, Industrial and Aeronautical Engineering, Wits University). The dynamometer force plate was attached to the workpiece clamping vice, while the data acquisition system was connected to a computer which had DynoWare software Version 2.5.3.8 software installed for data acquisition and computation. For each milling trial, the cutting force was measured for every one tenth of a second (1/10 sec) and resolved in the x, y, and z direction. The resultant force for every one tenth of a second for each milling trial was then computed using Equation 3.11, after which the average resultant forces were calculated.

$$\text{Resultant force } (F_R) = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad \text{Equation 3.11}$$

3.6 **Flank wear measurement**

A Leica DM600 metallurgical microscope was used alongside the Leica PC suite to capture micrographs of the cutting tool edges after the milling trials. The micrographs were analysed using the Leica PC suite to determine the flank wear on the cutting tools. To calculate the flank wear rate (FWR) for each cutting tool insert, the measured flank wear (VB) value after each milling trial was divided by the respective milling time in minutes as shown in Equation 3.12 [2014Gen].

$$\text{Flank wear rate (FWR)} = \frac{VB}{T} \quad \text{Equation 3.12}$$

Where;

VB = Flank wear in μm , and T = Milling time in minutes

3.7 Surface roughness measurement

The roughness of the machined Ti-6Al-4V surfaces after the machining trials were measured using a TR220 profilometer (School of Chemical and Metallurgical Engineering, Wits University). The profilometer had a diamond stylus with tip radius of 5 μ m. A total of 6 measurements were carried on each machined surface (at the cutter entry, midsection and cutter exit areas). The average roughness value for the 6 measurements was the true roughness value produced by the respective cutting tool insert.

Table 3.6 Milling conditions for the blank insert

Trail	Insert	Cutting speed (m/minute)	Depth of cut (mm)	Spindle speed (rpm)	Feed rate (mm/minute)	Milling Pass	Time (mins)
1	W3-L-B	60	1.5	240	24	2	15
2	W3-S-B	60	1.5	240	24	2	15
3	W4-L-B	60	1.5	240	24	2	15
4	W4-S-B	60	1.5	240	24	2	15
5	M2-L-B	60	1.5	240	24	2	15
6	M2-S-B	60	1.5	240	24	2	15
7	W3-L-B	60	1	240	24	2	15
8	W3-S-B	60	1	240	24	2	15
9	W4-L-B	60	1	240	24	2	15
10	W4-S-B	60	1	240	24	2	15
11	M2-L-B	60	1	240	24	2	15
12	M2-S-B	60	1	240	24	2	15
13	W3-L-B	75	1	300	30	2	12
14	W3-S-B	75	1	300	30	2	12
15	W4-L-B	75	1	300	30	2	12
16	W4-S-B	75	1	300	30	2	12
17	M2-L-B	75	1	300	30	2	12
18	M2-S-B	75	1	300	30	2	12
19	W3-L-B	75	0.5	300	30	1	6
20	W3-S-B	75	0.5	300	30	1	6
21	W4-L-B	75	0.5	300	30	1	6
22	W4-S-B	75	0.5	300	30	1	6
23	M2-L-B	75	0.5	300	30	1	6
24	M2-S-B	75	0.5	300	30	1	6
25	W3-L-B	100	0.5	400	40	1	4.5
26	W3-S-B	100	0.5	400	40	1	4.5
27	W4-L-B	100	0.5	400	40	1	4.5

Table 3.6 continued

Trail	Insert	Cutting speed (m/minute)	Depth of cut (mm)	Spindle speed (rpm)	Feed rate (mm/minute)	Milling Pass	Time (mins)
28	W4-S-B	100	0.5	400	40	1	4.5
29	M2-L-B	100	0.5	400	40	1	4.5
30	M2-S-B	100	0.5	400	40	1	4.5
31	W3-L-B	120	0.5	480	48	1	3.8
32	W3-S-B	120	0.5	480	48	1	3.8
33	W4-L-B	120	0.5	480	48	1	3.8
34	W4-S-B	120	0.5	480	48	1	3.8
35	M2-L-B	120	0.5	480	48	1	3.8
36	M2-S-B	120	0.5	480	48	1	3.8
37	W3-L-B	300	0.5	1120	112	1	1.5
38	W4-L-B	300	0.5	1120	112	1	1.5
39	M2-L-B	300	0.5	1120	112	1	1.5

Table 3.7 Milling conditions for the laser peened insert

Trail	Insert	Cutting speed (m/minute)	Depth of cut (mm)	Spindle speed (rpm)	Feed rate (mm/minute)	Milling Pass	Time (mins)
40	W3-L-B	60	1.5	240	24	2	15
41	W3-S-B	60	1.5	240	24	2	15
42	W4-L-B	60	1.5	240	24	2	15
43	W4-S-B	60	1.5	240	24	2	15
44	M2-L-B	60	1.5	240	24	2	15
45	M2-S-B	60	1.5	240	24	2	15
46	W3-L-B	75	0.5	300	30	1	6
47	W3-S-B	75	0.5	300	30	1	6
48	W4-L-B	75	0.5	300	30	1	6
49	W4-S-B	75	0.5	300	30	1	6
50	M2-L-B	75	0.5	300	30	1	6
51	M2-S-B	75	0.5	300	30	1	6
52	W3-L-B	100	0.5	400	40	1	4.5
53	W3-S-B	100	0.5	400	40	1	4.5
54	W4-L-B	100	0.5	400	40	1	4.5
55	W4-S-B	100	0.5	400	40	1	4.5
56	M2-L-B	100	0.5	400	40	1	4.5
57	M2-S-B	100	0.5	400	40	1	4.5

Table 3.8 Milling conditions for the ridges insert

Trail	Insert	Cutting speed (m/minute)	Depth of cut (mm)	Spindle speed (rpm)	Feed rate (mm/minute)	Milling Pass	Time (mins)
58	W3-L-R	60	1.5	240	24	2	15
59	W3-S-R	60	1.5	240	24	2	15
60	W4-L-R	60	1.5	240	24	2	15
61	W4-S-R	60	1.5	240	24	2	15
62	M2-L-R	60	1.5	240	24	2	15
63	M2-S-R	60	1.5	240	24	2	15
64	W3-L-R	60	1	240	24	2	15
65	W3-S-R	60	1	240	24	2	15
66	W4-L-R	60	1	240	24	2	15
67	W4-S-R	60	1	240	24	2	15
68	M2-L-R	60	1	240	24	2	15
69	M2-S-R	60	1	240	24	2	15
70	W3-L-R	75	1	300	30	2	12
71	W3-S-R	75	1	300	30	2	12
72	W4-L-R	75	1	300	30	2	12
73	W4-S-R	75	1	300	30	2	12
74	M2-L-R	75	1	300	30	2	12
75	M2-S-R	75	1	300	30	2	12
76	W3-L-R	75	0.5	300	30	1	6
77	W3-S-R	75	0.5	300	30	1	6
78	W4-L-R	75	0.5	300	30	1	6
79	W4-S-R	75	0.5	300	30	1	6
80	M2-L-R	75	0.5	300	30	1	6
81	M2-S-R	75	0.5	300	30	1	6
82	W3-L-R	100	0.5	400	40	1	4.5
83	W3-S-R	100	0.5	400	40	1	4.5
84	W4-L-R	100	0.5	400	40	1	4.5
85	W4-S-R	100	0.5	400	40	1	4.5
86	M2-L-R	100	0.5	400	40	1	4.5
87	M2-S-R	100	0.5	400	40	1	4.5
88	W3-L-R	120	0.5	480	48	1	3.8
89	W3-S-R	120	0.5	480	48	1	3.8
90	W4-L-R	120	0.5	480	48	1	3.8
91	W4-S-R	120	0.5	480	48	1	3.8
92	M2-L-R	120	0.5	480	48	1	3.8
93	M2-S-R	120	0.5	480	48	1	3.8

Table 3.9 Milling conditions for the laser peened insert

Trail	Insert	Cutting speed (m/minute)	Depth of cut (mm)	Spindle speed (rpm)	Feed rate (mm/minute)	Milling pass	Time (mins)
94	W3-L-C	60	1.5	240	24	2	15
95	W3-S-C	60	1.5	240	24	2	15
96	W4-L-C	60	1.5	240	24	2	15
97	W4-S-C	60	1.5	240	24	2	15
98	M2-L-C	60	1.5	240	24	2	15
99	M2-S-C	60	1.5	240	24	2	15
100	W3-L-C	75	0.5	300	30	1	6
101	W3-S-C	75	0.5	300	30	1	6
102	W4-L-C	75	0.5	300	30	1	6
103	W4-S-C	75	0.5	300	30	1	6
104	M2-L-C	75	0.5	300	30	1	6
105	W3-L-C	100	0.5	400	40	1	4.5
106	W3-S-C	100	0.5	400	40	1	4.5
107	W4-L-C	100	0.5	400	40	1	4.5
108	W4-S-C	100	0.5	400	40	1	4.5

4 Results for Microstructure, Physical and Mechanical Properties

In this chapter, the effect of composition manipulation, binder substitution, sintering technique and laser peening on microstructure, physical and mechanical properties of the sintered samples were deduced.

4.1 Microstructure of sintered samples

The scanning electron microscope – back scattered electron (SEM-BSE) micrographs of the WC-0.5Cr₃C₂-10Co (wt%) produced by LPS and SPS are shown in Figure 4.1. It can be clearly seen that the liquid phase sintered sample had larger WC grains and more homogenously distributed Co pools compared to their spark plasma sintered counterpart (Table 4.1, Figure 4.1a and 4.1b).

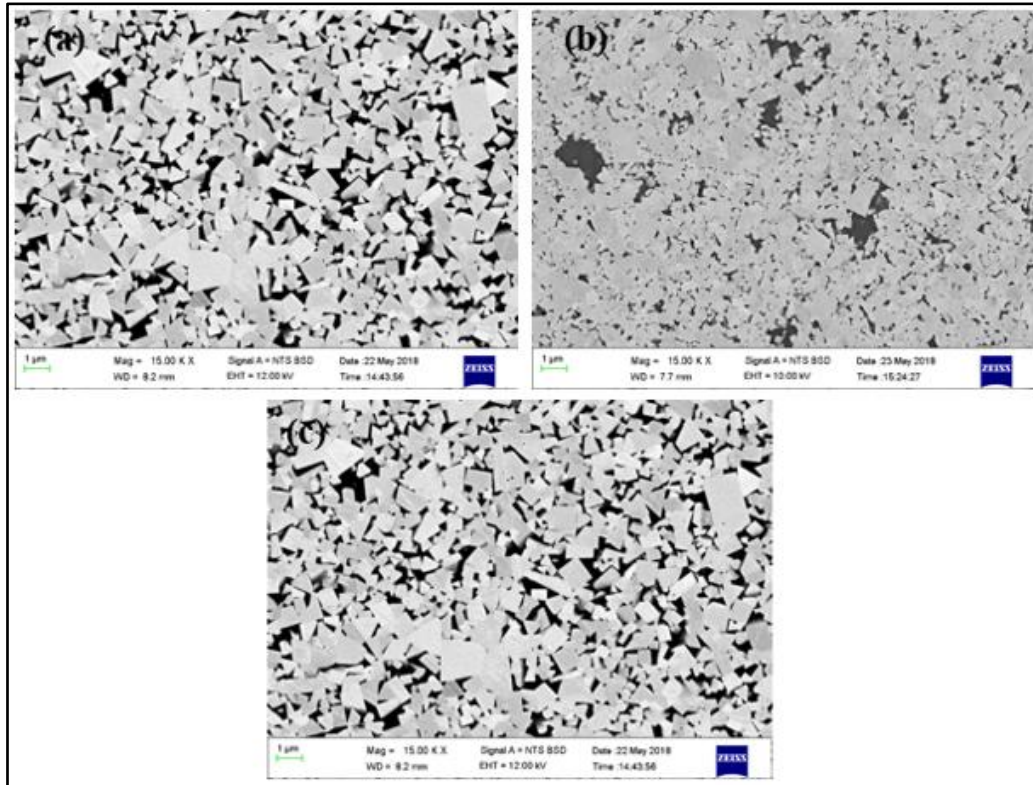


Figure 4.1. SEM-BSE images of WC-0.5Cr₃C₂-10Co (wt%): (a) Liquid phase sintered, (b) Spark plasma sintered, (c) Laser peened – liquid phase sintered.

Table 4.1. Sintered WC grain sizes

Composition (wt%)	Sample abbreviation	WC sintered grain size (µm)
WC-0.5Cr ₃ C ₂ -10Co	W3-L	0.66 ± 0.02
	W3-S	0.50 ± 0.01
WC-0.5Cr ₃ C ₂ -3.5Mo ₂ C-10Co	W4-L	0.53 ± 0.01
	W4-S	0.48 ± 0.02
WC-0.5Cr ₃ C ₂ -3.5Mo ₂ C-10Ni	M2-L	0.56 ± 0.01
	M2-S	0.45 ± 0.02

* L = liquid phase, S=spark plasma sintering

The WC grains were enclosed by cobalt as shown by the annular dark-field scanning transmission electron microscope (ADF-STEM) mapping in Figure 4.2. Laser peening had no significant effect on grain sizes of the sintered samples as shown in Figure 4.1c.

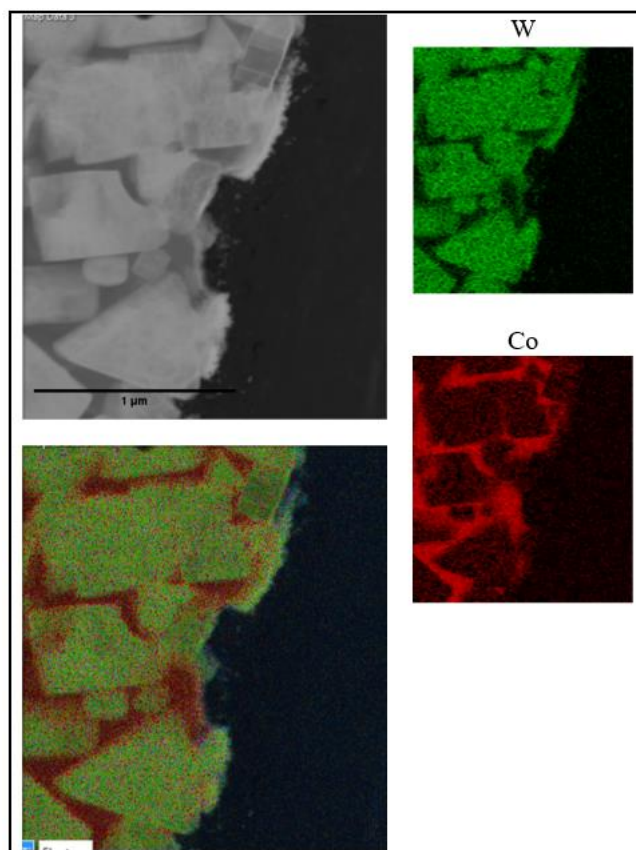


Figure 4.2. ADF-STEM mapping images of WC-0.5Cr₃C₂-10Co (wt%), showing W (green) and Co (red).

The addition of 3.5% Mo₂C (wt%) to the WC-0.5Cr₃C₂ -10Co (wt%) inhibited grain growth in both LPS and SPS techniques (Table 4.1 and Figure 4.3). The liquid phase sintered WC-0.5Cr₃C₂ -10Co (wt%) had a slightly lower mean grain size of $0.53 \pm 0.01 \mu\text{m}$, while its SPS counterpart had a much lower grain size of $.48 \pm 0.01 \mu\text{m}$ (Table 4.1). The Co pools for the spark plasma sintered WC-0.5Cr₃C₂ –Mo₂C-10Co (wt%) were larger and poorly distributed (Figure 4.3b). It was difficult distinguishing between molybdenum and cobalt in the SEM-BSE images, as they both had similar contrast (Figure 4.3). Nevertheless, the presence of molybdenum carbide in the microstructure was confirmed by ADF-STEM analysis (Figure 4.4). Cobalt was mainly present between the WC grains as seen from the ADF-STEM analysis (Figure 4.4).

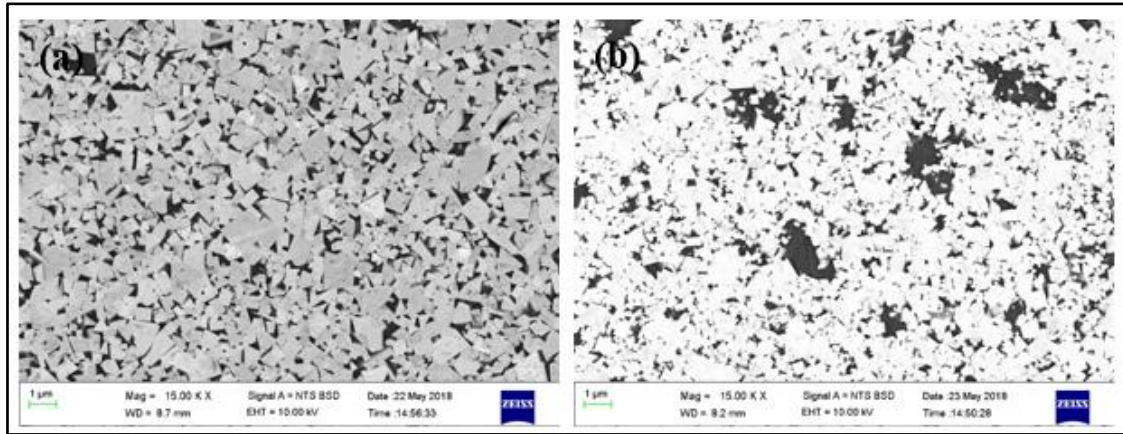


Figure 4.3. SEM-BSE images of WC-0.5Cr₃C₂-3.5Mo₂C-10Co (wt%): (a) Liquid phase sintered (b) Spark plasma sintered.

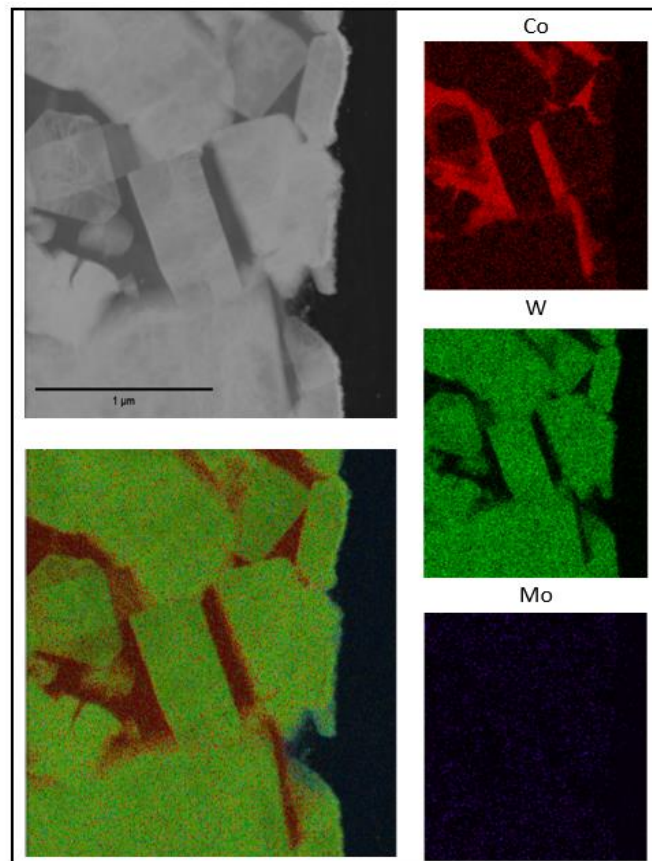


Figure 4.4. HAADF-STEM mapping images of WC-0.5Cr₃C₂-Mo₂C-10Co (wt%), showing Co (red), W (green) and Mo (blue).

The binder substitution of 10Co (wt%) with 10Ni (wt%) further inhibited grain growth for the spark plasma sintered WC-0.5Cr₃C₂-10Ni (wt%), resulting in the lowest grain size of $0.45 \pm 0.02 \mu\text{m}$ (Figure 4.5 and Table 4.1). The grain sizes for the LPS samples were slightly higher with binder substitution (Table 4.1). The binder pools for the WC-0.5Cr₃C₂-10Ni (wt%) samples were larger and more poorly distributed (Figure 4.5) compared to other sintered samples (Figure 4.1 and 4.3). It was difficult distinguishing between molybdenum carbide and nickel as they both had similar contrast in the SEM-BSE images (Figure 4.5). Nonetheless, the presence of molybdenum carbide in the microstructure was confirmed by ADF-STEM analysis (Figure 4.6). Nickel was mainly present between the WC grains as shown by ADF-STEM mapping (Figure 4.6).

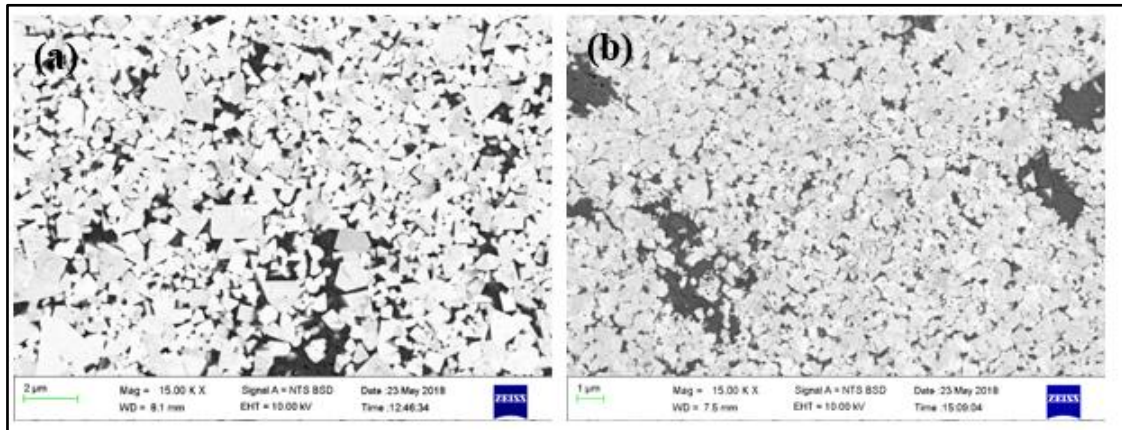


Figure 4.5. Figure 4.4. SEM-BSE images of WC-0.5Cr₃C₂-3.5Mo₂C-10Ni (wt%): (a) Liquid phase sintered (b) Spark plasma sintered.

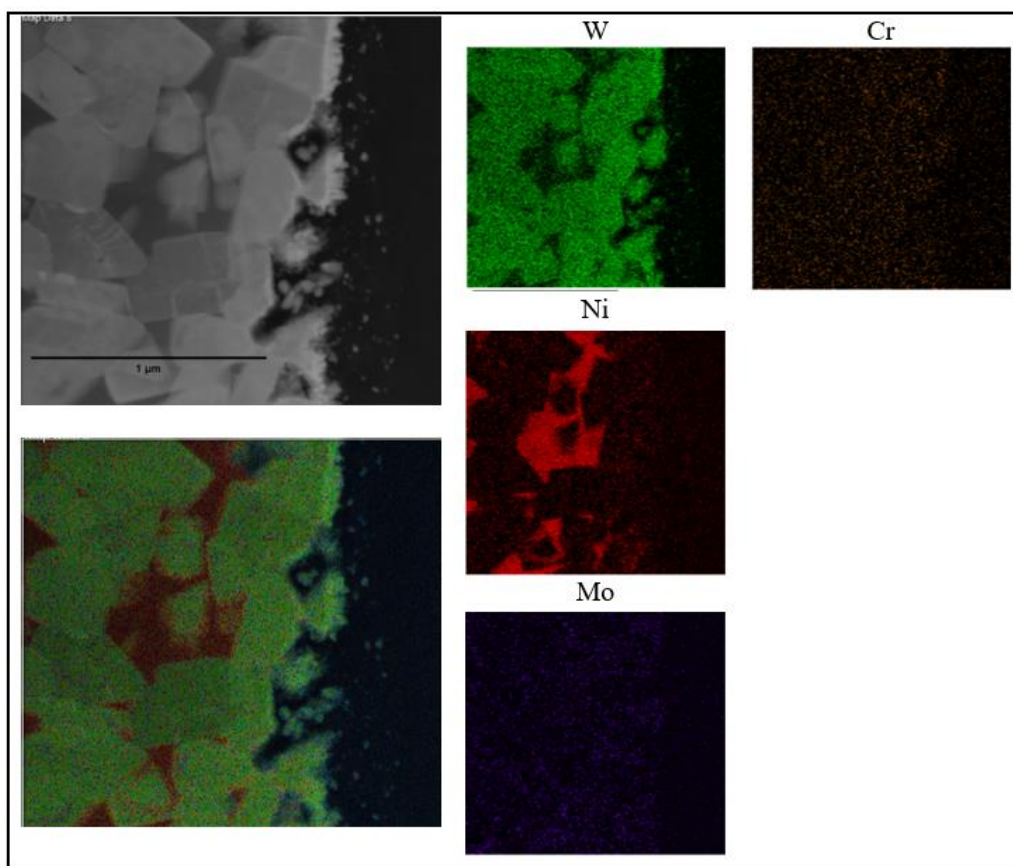


Figure 4.6. ADF-STEM mapping images of WC-0.5Cr₃C₂-Mo₂C-10Ni (wt%), showing Co (red), W (green), Mo (blue), and Cr (yellow).

4.2 Physical and mechanical properties of sintered samples

4.2.1 Densification

All the sintered samples achieved good densification of above 99% as shown in Table 4.2.

Table 4.2. Densification of sintered samples.

Composition (wt%)	Sample abbreviation	Densification (%)
WC-0.5Cr ₃ C ₂ -10Co	W3-L	99.21 ± 0.17
	W3-S	99.71 ± 0.09
WC-0.5Cr ₃ C ₂ -3.5 Mo ₂ C-10Co	W4-L	99.70 ± 0.18
	W4-S	99.75 ± 0.18
WC-0.5Cr ₃ C ₂ -3.5 Mo ₂ C-10Ni	M2-L	99.75 ± 0.34
	M2-S	99.98 ± 0.21

* L = liquid phase, S=spark plasma sintering

4.2.2 Hardness

4.2.2.1 *Hardness of blank samples*

The spark plasma sintering of the WC-0.5Cr₃C₂-10Co (wt%) resulted in 1.86 GPa higher Vickers hardness than the liquid phase sintered WC-0.5Cr₃C₂-10Co (wt%) (Table 4.3 and Table 4.7). Addition of 3.5 Mo₂C (wt%) slightly increased hardness for 0.5Cr₃C₂-Mo₂C-10Co (wt%) samples (Figure 4.7), The liquid phase sintered WC-0.5Cr₃C₂-Mo₂C-10Co (wt%) had > 0.63 GPa Vickers hardness, while its spark plasma sintered counterpart had > 0.42 GPa Vickers hardness (Figure 4.7 and Table 4.3). The binder substitution of 10Co (wt%) with 10Ni (wt%) resulted in a lower hardness of 13.58 ± 0.08 GPa for the liquid phase sintered WC-0.5Cr₃C₂-Mo₂C-10Ni (wt%). The substitution of binder had no significant effect on sample hardness during spark plasma sintering (Figure 4.7). The spark plasma sintered WC-0.5Cr₃C₂-Mo₂C-10Co (wt%) and WC-0.5Cr₃C₂-Mo₂C-10Ni (wt%) samples had very similar Vickers hardnesses of 16.96 ± 0.22 GPa and 16.98 ± 0.35 GPa (Table 4.3 AND Figure 4.7).

Table 4.3. Vickers hardness (HV₃₀) for sintered samples.

Composition (wt%)	Sample abbreviation	Vickers hardness, HV ₃₀ (GPa)	
		Blank	Laser peened
WC-0.5Cr ₃ C ₂ -10Co	W3-L	14.68 ± 0.13	15.16 ± 0.35
	W3-S	16.54 ± 0.28	16.61 ± 0.18
WC-0.5Cr ₃ C ₂ -Mo ₂ C-10Co	W4-L	15.31 ± 0.11	15.68 ± 0.26
	W4-S	16.96 ± 0.22	17.31 ± 0.28
WC-0.5Cr ₃ C ₂ -Mo ₂ C-10Ni	M2-L	13.58 ± 0.08	15.51 ± 0.21
	M2-S	16.98 ± 0.35	17.24 ± 0.21

* L = liquid phase sintering, S=spark plasma sintering

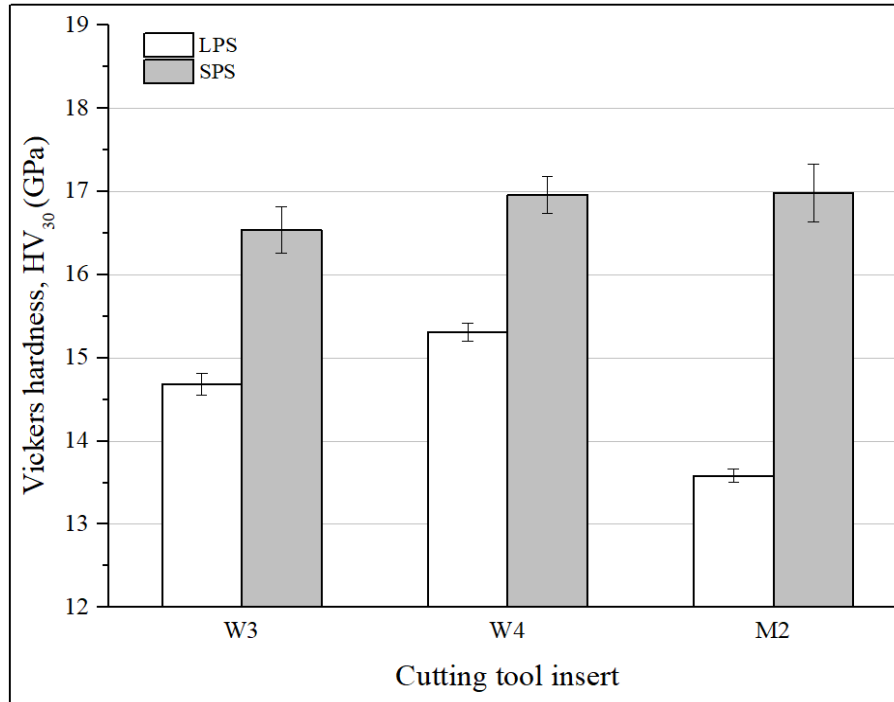


Figure 4.7. Comparison of Vickers hardness for sintered samples.

4.2.2.2 *Hardness of laser peened samples*

The liquid phase sintered WC-0.5Cr₃C₂-10Co (wt%) had a slightly higher Vickers hardness of 15.16 ± 0.35 GPa after laser peening (Table 4.3 and Figure 4.8). There was no significant change in the hardness of the spark plasma sintered WC-0.5Cr₃C₂-10Co (wt%) after laser peening (Figure 4.8). All the WC-0.5Cr₃C₂-Mo₂C-10Co (wt%) samples slightly higher hardnesses after laser peening (Figure 4.8). The liquid phase sintered WC-0.5Cr₃C₂-Mo₂C-10Co (wt%) had a slightly higher Vickers hardnesses of 15.68 ± 0.26 GPa, while its spark plasma sintered counterpart had the significantly higher Vickers hardness of 17.31 ± 0.28 GPa (Table 4.3 and Figure 4.8). Laser peening of the WC-0.5Cr₃C₂-Mo₂C-10Ni (wt%) resulted in higher Vickers hardnesses of 15.51 ± 0.21 GPa and 17.24 ± 0.21 GPa for the liquid phase sintered and spark plasma sintered WC-0.5Cr₃C₂-Mo₂C-10Ni (wt%) respectively (Table 4.3 and Figure 4.8).

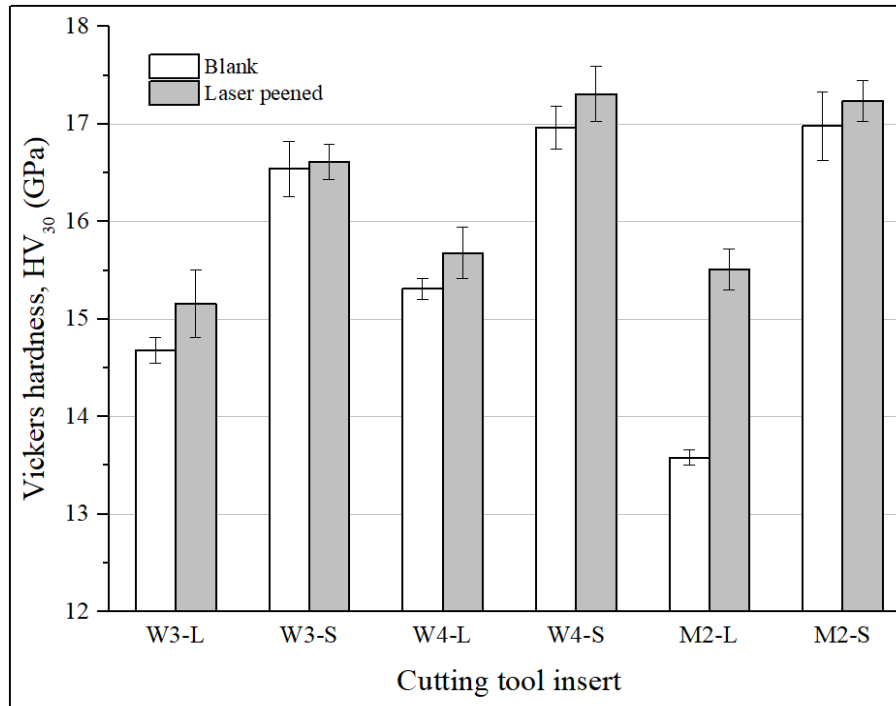


Figure 4.8. Comparison of Vickers hardness for laser peened and blank samples

4.2.3 Fracture Toughness of sintered samples

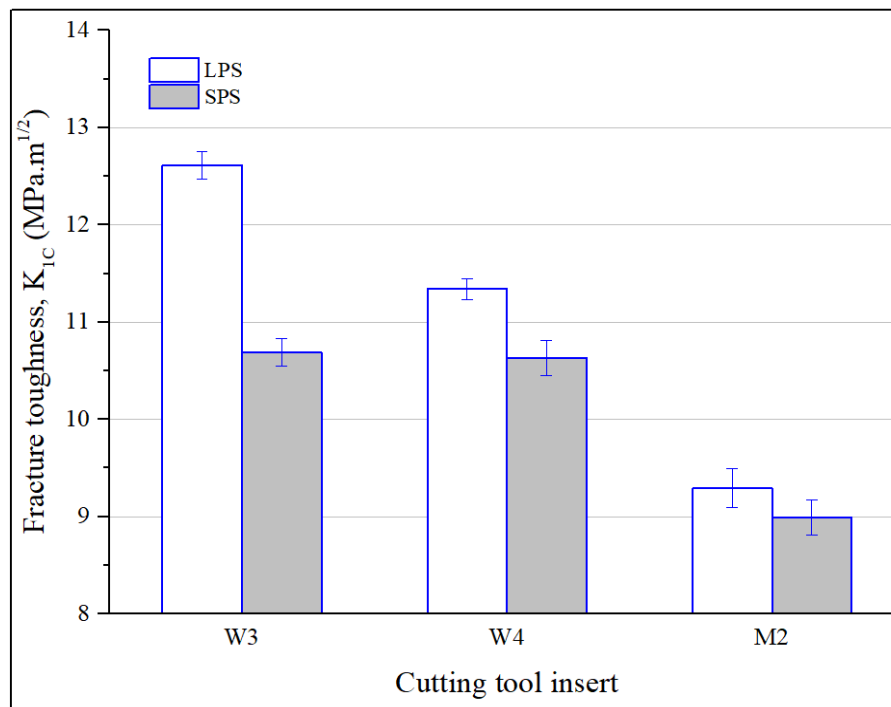
4.2.3.1 *Effect of composition manipulation and sintering on sample toughness*

The liquid phase sintered WC-0.5Cr₃C₂-10Co (wt%) had $> 1.92 \text{ MPa.m}^{1/2}$ fracture toughness than its spark plasma sintered counterpart (Table 4.4 and Figure 4.9). The addition of 3.5Mo₂C (wt%) significantly reduced fracture toughness for the liquid phase sintered WC-0.5Cr₃C₂-Mo₂C-10Co (wt%) (Figure 4.9). No significant change in fracture toughness was observed for the spark plasma sintered WC-0.5Cr₃C₂-Mo₂C-10Co (wt%) (Figure 4.9). The binder substitution of 10Co (wt%) with 10Ni (wt%) resulted in significantly lower fracture toughnesses for the sintered samples (Figure 4.4). The liquid phase sintered WC-0.5Cr₃C₂-Mo₂C-10Ni (wt%) had a very low fracture toughness of $9.29 \pm 0.20 \text{ MPa.m}^{1/2}$, while its spark plasma sintered counterpart had the lowest fracture toughness of $8.99 \pm 0.18 \text{ MPa.m}^{1/2}$ (Table 4.4).

Table 4.4. Fracture toughness (K_{1c}) for blank and laser peened samples

Sample abbreviation	Fracture toughness, K_{1c} (MPa.m ^{1/2})	
	Blanks (B)	Laser peened (LP)
W3-L	12.61 ± 0.14	12.90 ± 0.16
W3-S	10.69 ± 0.14	10.16 ± 0.33
W4-L	11.34 ± 0.11	12.13 ± 0.54
W4-S	10.63 ± 0.18	11.21 ± 0.16
M2-L	9.29 ± 0.20	10.66 ± 0.274
M2-S	8.99 ± 0.18	9.54 ± 0.51

* L = liquid phase, S=spark plasma sintering

**Figure 4.9. Comparison of fracture toughness for sintered samples.**

4.2.3.2 Effect of laser peening on fracture toughness of samples

The fracture toughnesses of the sintered samples slightly increased with laser peening (Table 4.4 and Figure 4.10). The liquid phase sintered and spark plasma sintered WC-0.5Cr₃C₂-10Co (wt%) had a slight increase in toughness of > 0.29 MPa.m^{1/2} and > 0.17 MPa.m^{1/2} respectively after laser peening (Table 4.4). Similar increased in fracture toughness was also observed for the WC-0.5Cr₃C₂-Mo₂C-10Co (wt%) (Figure 4.10), with the liquid phase sintered and spark plasma sintered WC-0.5Cr₃C₂-Mo₂C-10Co (wt%) having a higher K_{1c} of > 0.79 MPa.m^{1/2}

and $> 0.58 \text{ MPa.m}^{1/2}$ respectively after laser peening (Table 4.4 and Figure 4.10). The liquid phase sintered WC-0.5Cr₃C₂-Mo₂C-10Ni (wt%) had the highest increase in fracture toughness of $> 1.37 \text{ MPa.m}^{1/2}$ after laser peening, while its spark plasma sintered counterpart had $> 0.55 \text{ MPa.m}^{1/2}$ higher toughness (Table 4.4 and Figure 4.10).

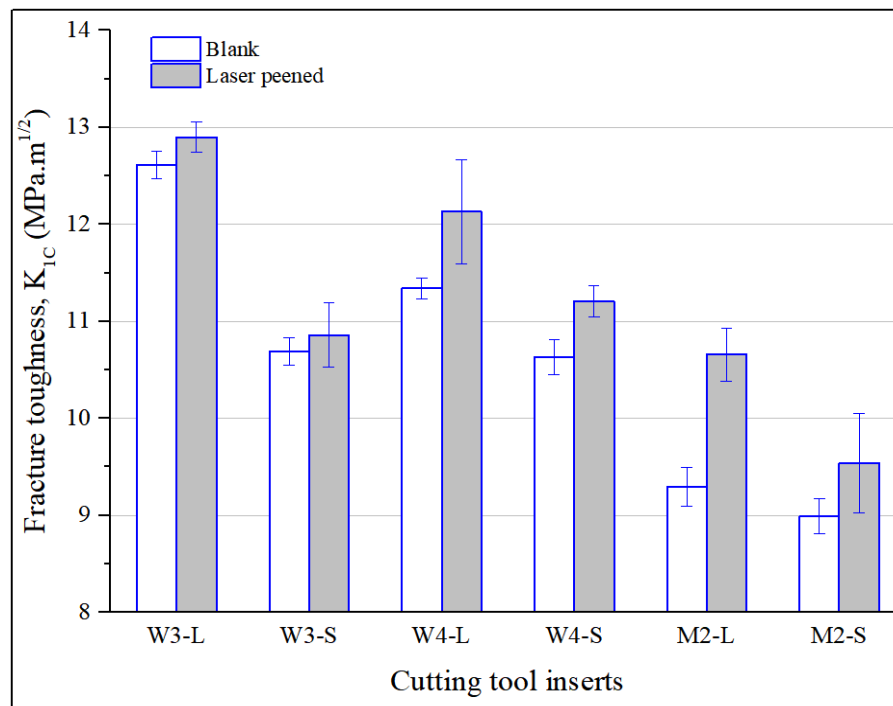


Figure 4.10. Comparison of Fracture toughness, K1C for blanks and laser shock peened samples.

5 Result for Face Milling Trials

During machining, performance characteristics such as resultant force, temperature, flank wear rate and surface roughness are usually influenced by the processing parameters. In this chapter an attempt is made to identify correlations and trends between process parameters and performance characteristics.

5.1 **Resultant forces**

The analysis of resultant cutting forces was highly vital for understanding the conditions under which the workpieces and cutting tools were performing. In this section comparisons are made between the resultant cutting forces experienced by the cutting tool inserts during the milling trials. The comparison is carried out with respect to tool composition, sintering technique and cutting tool edge. The resultant forces obtained from the analysed kistler dynamometer force data during each milling trial were used for this comparisons.

5.1.1 **Analysis of resultant forces at vc of 60m/minute**

The average resultant forces experienced by the cutting tool inserts during milling at cutting speed 60m/minute is presented in Table 5.1. At depth of cut of 1.5mm, the W4-L-B had a significantly lower resultant force compared to the W3-L-B and M2-L-B inserts (Table 5.1 and Figure 5.1). The inserts produced by spark plasma sintering experienced slightly higher resultant forces compared to their liquid phase sintered counterparts (Figure 5.2). Contrary to trends experienced by the blank inserts, the SPS inserts had slightly lower resultant forces than their LPS counterparts in the laser peened category (Figure 5.2), with the W4-S-LP and M2-S-LP insert having slightly lower resultant forces than their blank counterparts (Figure 5.2).

Table 5.1. Experimental results of resultant forces at vc of 60m/minute

Trial	Sample Abbreviation	vc [m/min]	ap [mm]	Average Resultant Force (N)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	60	1.5	1020.24	1174.38	693.56	725.62
2	W3-S	60	1.5	1031.75	1076.55	1082.88	1140.05
3	W4-L	60	1.5	750.84	1013.03	730.61	1098.12
4	W4-S	60	1.5	1092.06	974.75	1043.29	1453.04
5	M2-L	60	1.5	981.54	1098.26	1211.19	1036.21

6	M2-S	60	1.5	1093.54	1036.48	1530.56	1188.03
7	W3-L	60	1	604.60	-	493.73	-
8	W3-S	60	1	590.01	-	830.55	-
9	W4-L	60	1	632.15	-	636.67	-
10	W4-S	60	1	710.40	-	970.09	-
11	M2-L	60	1	702.98	-	689.24	-
12	M2-S	60	1	1328.18	-	848.62	-

* L = liquid phase sintering, S = spark plasma sintering, vc = Cutting speed (m/minute), ap = Depth of cut (mm), Kistler dynamometer error = $\pm 15N$.

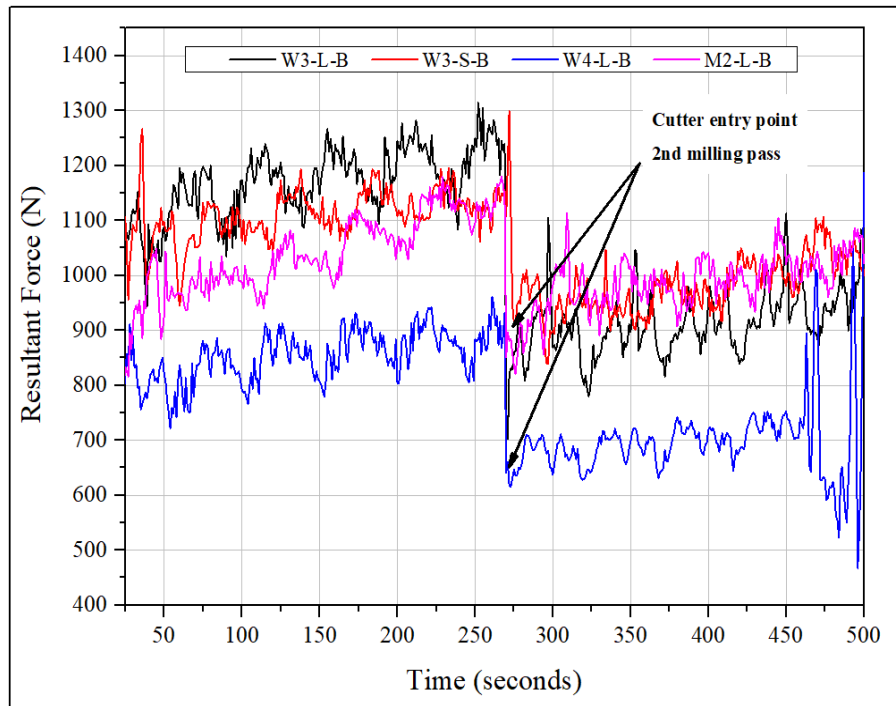


Figure 5.1. Variation in resultant forces with time for the W3-L-B, W3-S-B, W4-L-B and M2-L-B inserts during milling at a vc of 60m/minute and ap of 1.5mm.

The resultant forces for the spark plasma sintered inserts were fairly higher than that of their liquid phase sintered counterparts in the ridges category (Figure 5.2). The effect of ridges was clearly noticeable in the performance of the W4-L-R and W4-L-B inserts, as it resulted in significantly lower resultant forces (Figure 5.2). The W3-L-R insert had a significantly lower resultant forces of $693.56 \pm 15N$ (Table 5.1). In the chip breaker category, the spark plasma sintered inserts maintained high resultant forces (Table 5.1). The effect of chip breaker could

be clearly seen in the performance of the W3-L-C insert, as it resulted in a significantly lower resultant force of $725.62 \pm 15\text{N}$ (Table 5.1). A conclusion could clearly be drawn that at v_c of 60m/minute and a_p of 1mm, the W4-L-B insert had better resistance to cutting forces in blank and ridges conditions, while the W3-L-B had better resistance to cutting forces in ridges and chip breaker conditions (Figure 5.2).

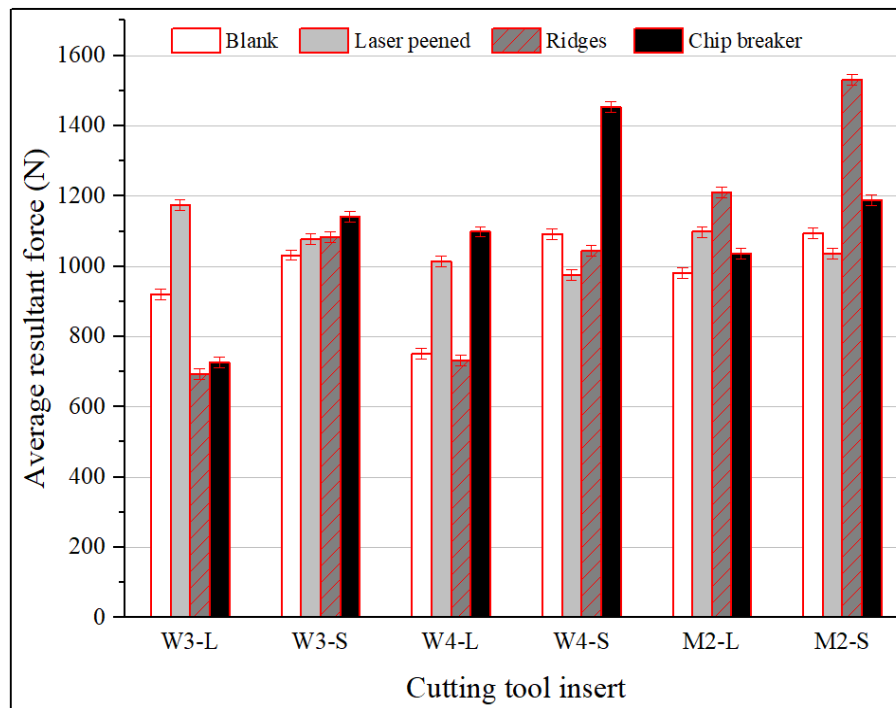


Figure 5.2. Comparison of resultant force for the cutting tool inserts during milling at a v_c of 60m/minute and a_p of 1.5mm.

A slightly lower resultant force was experienced by the blank and ridges cutting tool inserts with decreased depth of cut from 1.5mm to 1mm at cutting speed of 60m/minute (Table 5.1 and Figure 5.3). The W3-L-B and W3-S-B inserts experienced similar resultant forces of $604.60 \pm 15\text{N}$ and $590.01 \pm 15\text{N}$ respectively (Table 5.1), likewise the W4-S-B and M2-L-B inserts with resultant forces of $710.40 \pm 15\text{N}$ and $702.98 \pm 15\text{N}$ respectively (Table 5.1). Due to similarities in resultant forces, the effect of SPS on the performance of the blank W3 insert couldn't be deduced (Figure 5.4). However, in the ridges category, the SPS inserts had higher

resultant forces than their LPS counterparts (Figure 5.4). The effect of ridges on resultant forces was clearly seen for the W3-L-R insert, as it had significantly lower resultant force of $493.73 \pm 15\text{N}$ (Figure 5.4).

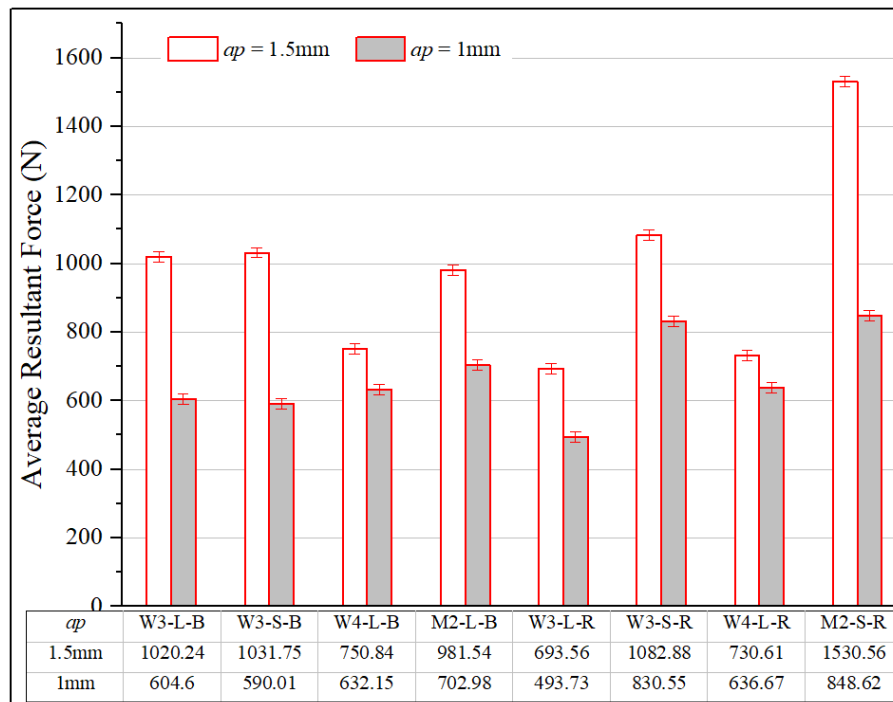


Figure 5.3. Variation in resultant forces for some cutting tool inserts with decrease in ap from 1.5mm to 1mm, during milling at vc of 60m/minute.

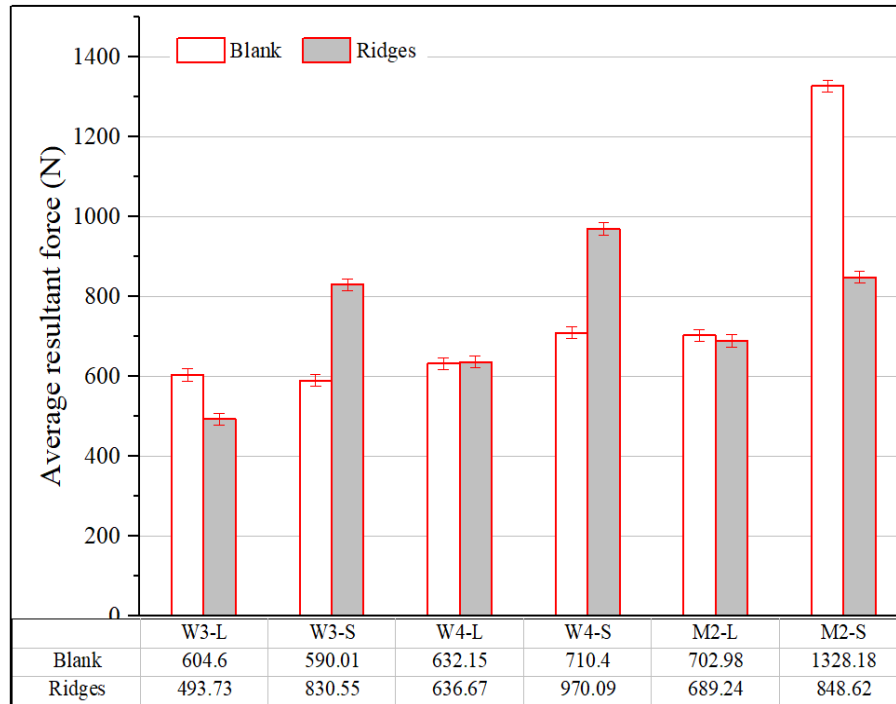


Figure 5.4. Comparison of resultant force for the blank and ridges inserts during milling at v_c of 60m/minute and a_p of 1mm.

5.1.2 Analysis of resultant forces at v_c of 75m/minute

Increased v_c from 60m/minute to 75m/minute while maintaining a_p of 1mm resulted in lower resultant forces (Table 5.2 and Figure 5.5). Similar resultant forces were experienced by the W3-L-B, W3-S-B and W4-S-B inserts (Figure 5.6), making it difficult to distinguish between the effect of Mo_2C (wt%) and sintering on resultant forces of these inserts. Nonetheless, the effect of sintering was clearly noticed in the performance of the M2-S-B insert, as it resulted in a significantly lower resultant force (Table 5.2 and Figure 5.6). The lowest resultant force of $447.8 \pm 15\text{N}$ during milling at v_c of 75m/minute and a_p of 1mm was experienced by the W3-L-R insert (Table 5.2).

Table 5.2. Experimental results of resultant forces at vc of 75m/minute

Trial	Sample Abbreviation	vc [m/min]	ap [mm]	Average Resultant Force (N)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	75	1	503.05	-	447.84	-
2	W3-S	75	1	513.37	-	580.20	-
3	W4-L	75	1	536.81	-	540.99	-
4	W4-S	75	1	510.92	-	520.42	-
5	M2-L	75	1	622.53	-	814.93	-
6	M2-S	75	1	480.86	-	680.99	-
7	W3-L	75	0.5	501.19	399.67	289.68	306.01
8	W3-S	75	0.5	366.86	296.53	288.69	108.12
9	W4-L	75	0.5	280.64	412.22	279.02	294.68
10	W4-S	75	0.5	342.57	312.90	423.52	329.46
11	M2-L	75	0.5	406.21	392.41	352.61	400.12
12	M2-S	75	0.5	348.93	300.54	230.15	-

* L = liquid phase sintering, S = spark plasma sintering, vc = Cutting speed (m/minute), ap = Depth of cut (mm), Kistler dynamometer error = $\pm 15\text{N}$.

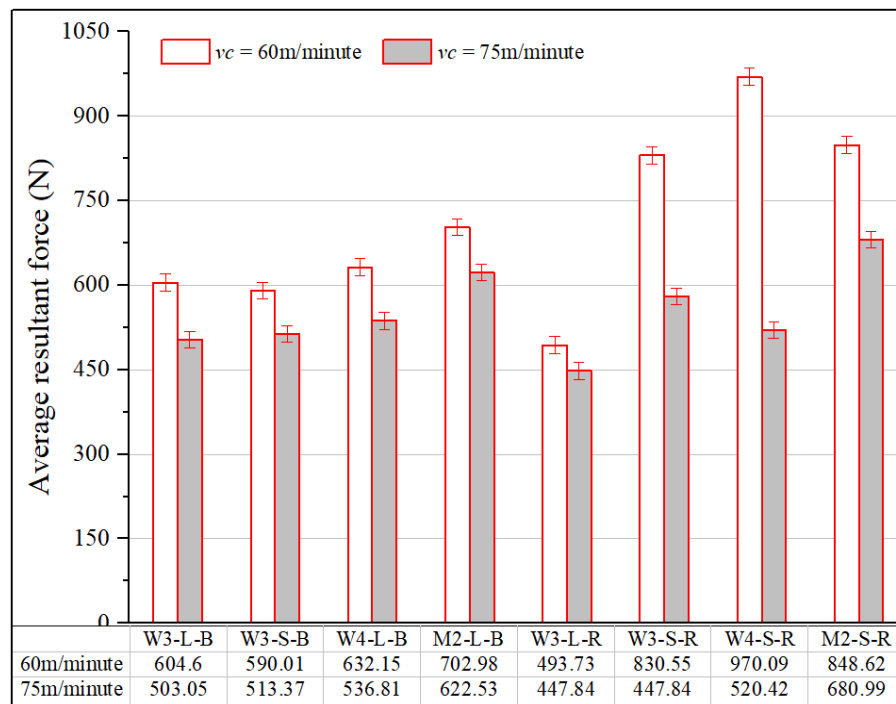


Figure 5.5. Variation in resultant forces for the blank and ridges inserts with increase in vc from 60m/minute to 75m/minute with ap at 1mm.

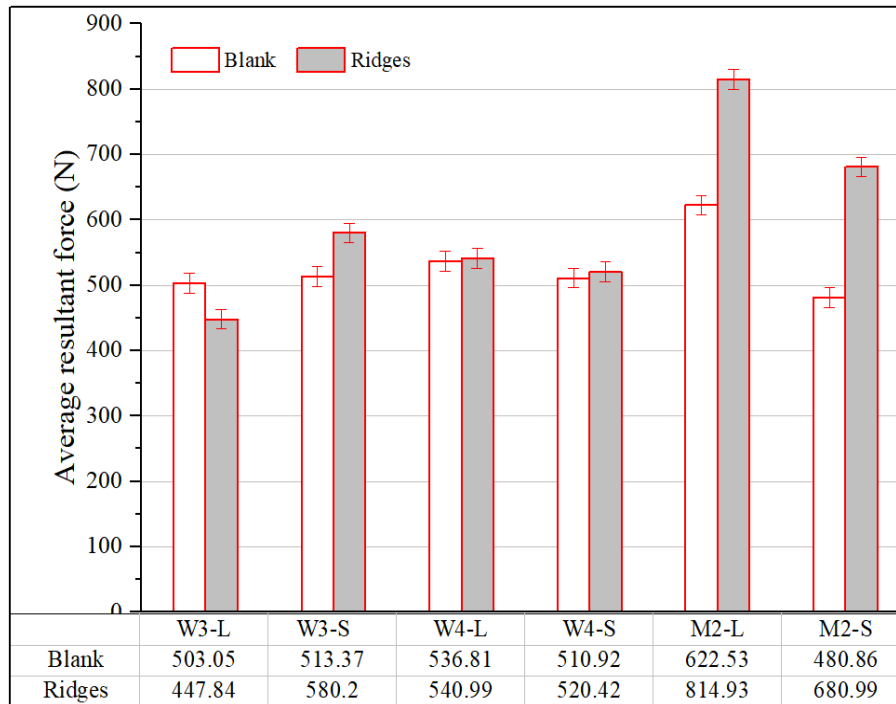


Figure 5.6. Comparison of resultant forces for the blank and ridges inserts during milling at v_c of 75m/minute and a_p of 1mm.

Reduced depth of cut from 1mm to 0.5mm, while maintain cutting speed of 75m/minute resulted in slightly lower resultant forces for the blank and ridges inserts (Table 5.2 and Figure 5.7). The only exception to this trend was the W3-L-B insert which maintained a slightly similar resultant force of 503.05 ± 15 N (Table 5.2 and Figure 5.7). The effect of composition on resultant force was clearly seen with the lower resultant forces of 280.6 ± 15 N experienced by the W4-L-B insert (Table 5.2). The SPS inserts experienced fairly lower resultant forces compared to their LPS counterparts in the blank category, with the W3-S-B insert having the lowest resultant force of 296.53 ± 15 N (Table 5.2 and Figure 5.8). Comparing the resultant forces for the laser peened inserts to that of their blank counterparts, it was clear that the laser peened insert generally had lower resultant forces (Figure 5.8).

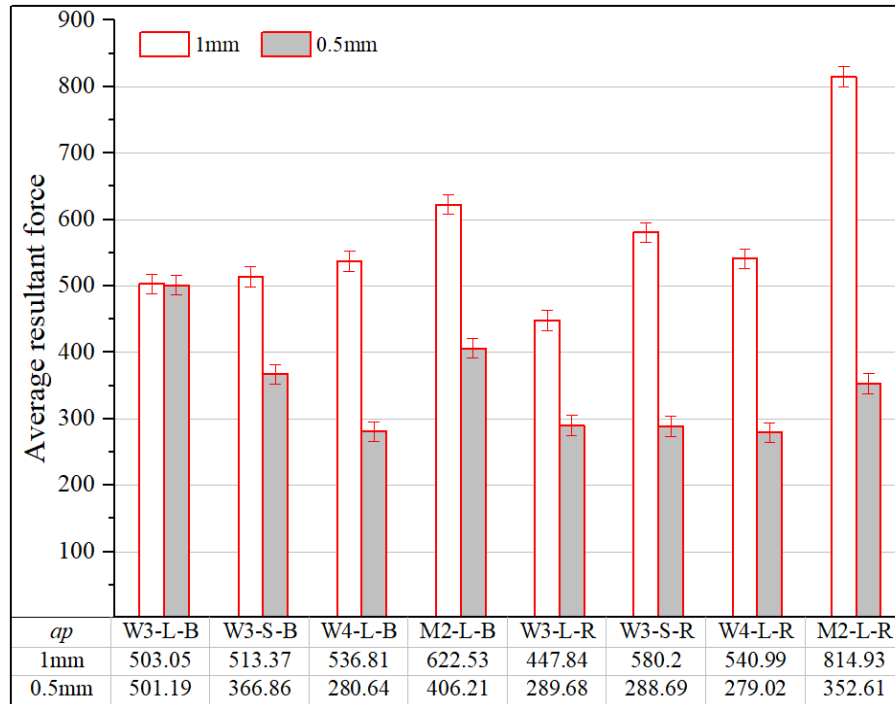


Figure 5.7. Variation in resultant forces for the blank and ridges inserts with decreased *ap* from 1mm to 0.5mm during milling at *vc* of 75m/minute.

The effect of ridges was clearly seen, as it resulted in lower resultant forces for all the cutting tool inserts except the W4-S (Table 5.2 and Figure 5.8). The M2-S-B insert had the lowest resultant force of $230.212 \pm 15\text{N}$ in the ridges category (Table 5.2). The introduction of chip breakers led to significant reduction in resultant forces for only the W3 inserts (Figure 5.8), with the W3-S-C insert having a record low resultant force of $108.12 \pm 15\text{N}$ during milling at *vc* of 75m/minute and *ap* of 0.5mm (Table 5.2 and Figure 5.8).

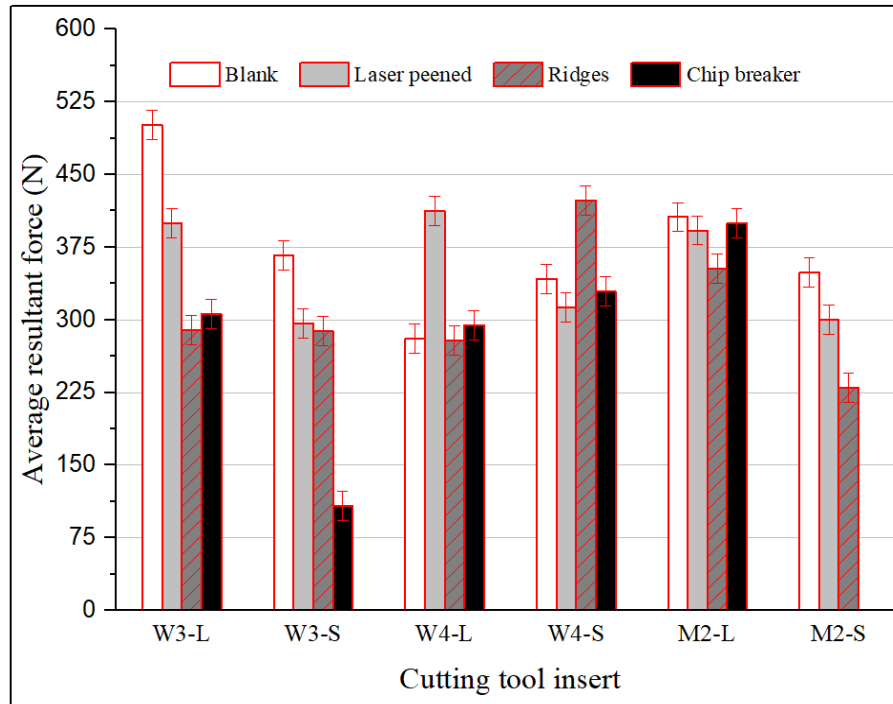


Figure 5.8. Comparison of resultant forces for the cutting tool inserts during milling at a vc of 75m/minute and ap of 0.5mm.

5.1.3 Analysis of resultant forces at vc of 100m/minute

Increased vc from 75m/minute to 100m/minute, while maintaining ap at 0.5mm resulted in significantly lower resultant forces for the W3-L-B and W3-L-LP inserts (Table 5.3 and Figure 5.9). All the other inserts experienced either similar or slightly higher resultant forces with this increase in speed (Table 5.3 and Figure 5.9). The resultant force for the W3-L-B insert was slightly lower than that of the W4-L-B and M2-L-B inserts (Figure 5.10). Similar resultant forces were experienced by the W3-L-B and W3-S-B inserts, and likewise the W4-L-B and W4-S-B inserts (Table 5.3 and Figure 5.10) making it difficult to distinguish the effect of sintering for these inserts in blank condition. The M2-S-B had the highest resultant force of $405.93 \pm 15\text{N}$ for the blank inserts (Table 5.3).

Table 5.3. Experimental results of resultant forces at vc of 100m/minute

Trial	Sample Abbreviation	vc [m/min]	ap [mm]	Average Resultant Force (N)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	100	0.5	342.93	338.34	371.21	417.91
2	W3-S	100	0.5	331.54	386.39	461.88	466.76
3	W4-L	100	0.5	362.10	953.72	333.90	434.45
4	W4-S	100	0.5	379.50	608.24	445.32	352.76
5	M2-L	100	0.5	373.03	356.14	385.34	-
6	M2-S	100	0.5	405.92	386.88	372.03	-

* L = liquid phase sintering, S = spark plasma sintering, vc = Cutting speed (m/minute), ap = Depth of cut (mm), Kistler dynamometer error = ± 15 N.

The laser peening of the cutting tools led to significantly higher resultant forces for the W4 inserts (Table 5.3 and Figure 5.10), with the W4-L-LP insert having the highest resultant force of 953.72 ± 15 N during milling at vc of 100m/minute and ap of 0.5mm (Table 5.3). The resultant force for the W3-L-LP and M2-L-LP were slightly lower than that of their SPS counterparts (Figure 5.10). In the ridges category, the W3-L-R and W4-L-R inserts had slightly lower resultant forces than their SPS counterparts (Figure 5.10). With the W4-L-R insert having the lowest resultant force of 333.90 ± 15 N in the ridges category (Table 5.3). All the ridges inserts, apart from the W4-L-R and M2-S-R inserts experienced higher resultant forces than their blank counterpart (Figure 5.10). The introduction of chip breakers generally resulted in higher resultant forces for all the cutting tool inserts (Table 5.3 and Figure 5.10).

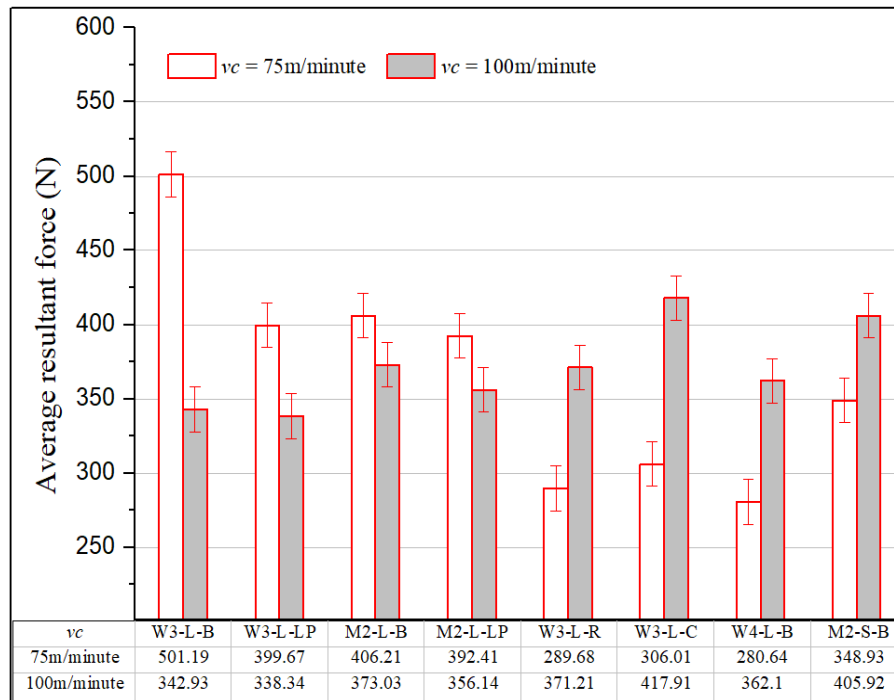


Figure 5.9. Variation in resultant forces for some cutting tool inserts with increase in vc from 75m/minute to 100m/minute at ap of 0.5mm.

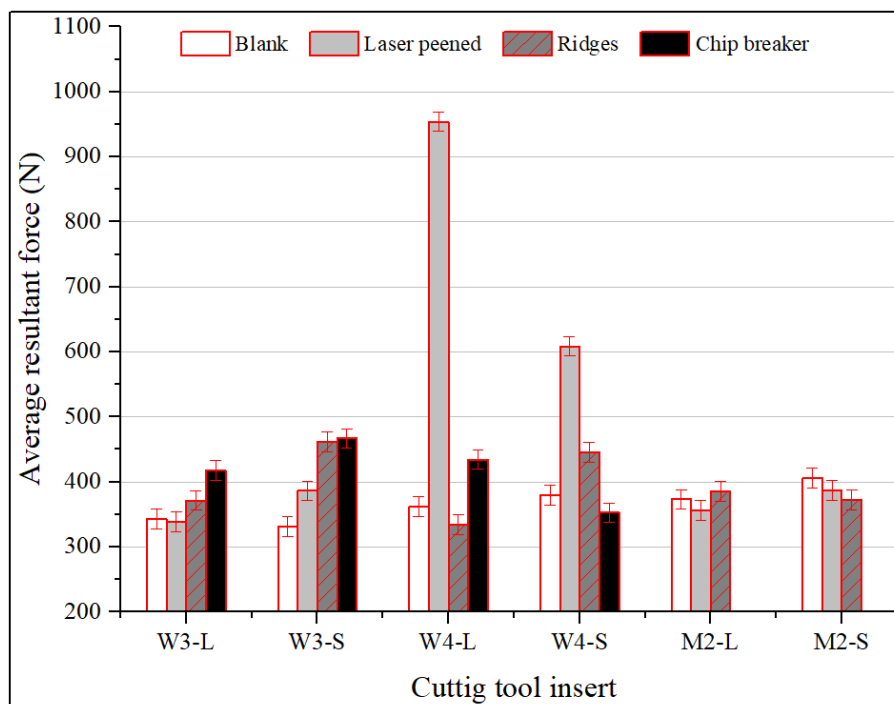


Figure 5.10. Comparison of resultant force for the cutting tool inserts during milling at a vc of 100m/minute and ap of 0.5mm.

5.1.4 Analysis of resultant forces at vc of 120m/minute

Increase in vc from 100m/minute to 120m/minute while maintain ap at 0.5mm resulted in lower resultant forces all the cutting tool inserts except the W3-L-B (Table 5.4 and Figure 5.11).

Table 5.4. Experimental results of resultant forces at vc of 120m/minute

Trial	Sample Abbreviation	vc [m/min]	ap [mm]	Average Resultant Force (N)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	120	0.5	629.68	-	396.31	-
2	W3-S	120	0.5	254.34	-	303.02	-
3	W4-L	120	0.5	291.10	-	347.23	-
4	W4-S	120	0.5	375.16	-	372.06	-
5	M2-L	120	0.5	256.45	-	222.18	-
6	M2-S	120	0.5	354.89	-	365.37	-

* L = liquid phase sintering, S = spark plasma sintering, vc = Cutting speed (m/minute), ap = Depth of cut (mm), Kistler dynamometer error = ± 15 N.

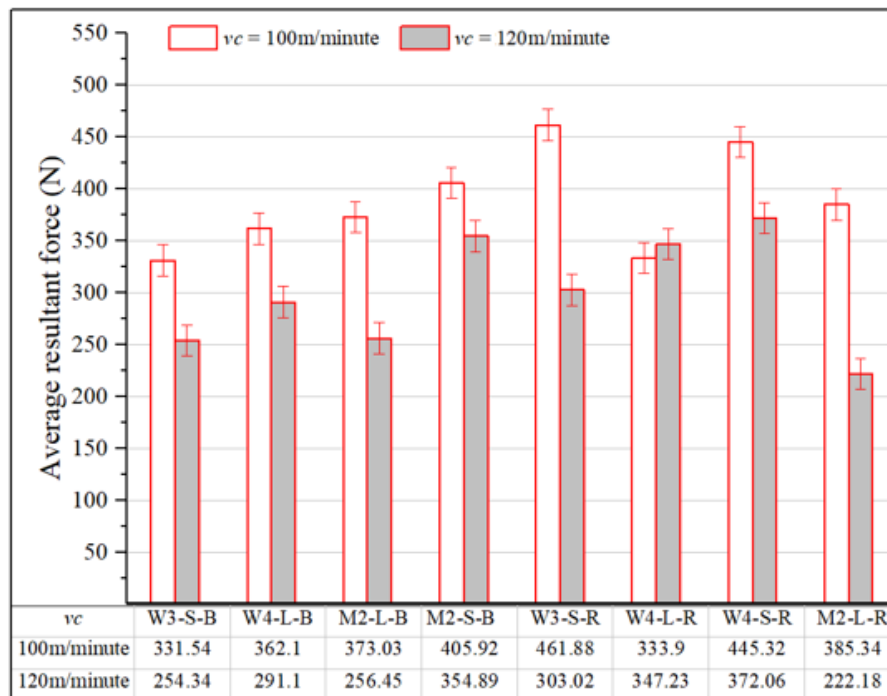


Figure 5.11 Variation in resultant forces for the blank and ridges inserts with increase in vc from 100m/minute to 120m/minute at ap of 0.5mm.

The W4-L-B and M2-L-B inserts had higher resultant forces than their SPS counterparts (Table 5.4). The predicted effect of chip breakers was only seen in the W3-L-R and M2-L-R inserts, as it resulted in lower resultant forces (Figure 5.12). The effect of sintering technique on the performance of the ridges insert could not be established.

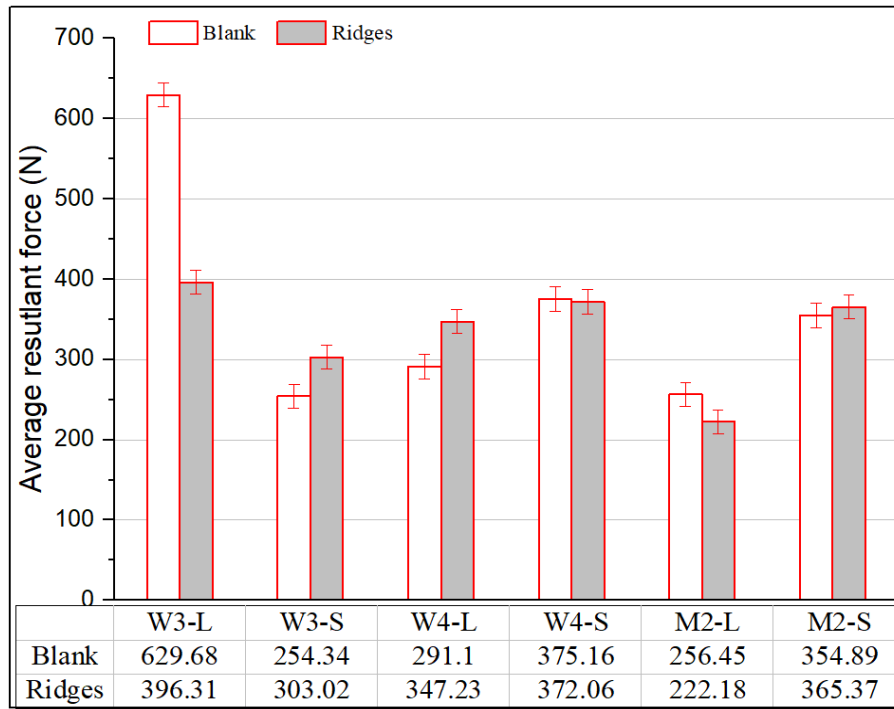


Figure 5.12. Comparison of resultant forces for the blank and ridges inserts during milling at vc of 120m/minute and ap of 0.5mm.

5.1.5 Analysis of resultant forces at vc of 300m/minute

Further increase in vc to 300m/minute with ap at 0.5mm resulted in higher resultant forces for the W4-L-B and M2-L-B inserts (Table 4.5 and Table 5.5). The W4-L-B insert experienced the lowest resultant force of $325.71 \pm 15N$, while the W4-L-B insert experienced the highest resultant force of $410.25 \pm 15N$ during milling at vc 300m/minute and ap of 0.5mm (Table 5.5 and Figure 5.13).

Table 5.5. Experimental results of resultant forces at vc of 300m/minute

Trial	Sample Abbreviation	vc [m/min]	ap [mm]	Average Resultant Force (N)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	300	0.5	410.25	-	-	-
2	W4-L	300	0.5	325.71	-	-	-
3	M2-L	300	0.5	380.26	-	-	-

* L = liquid phase sintering, S = spark plasma sintering, vc = Cutting speed (m/minute), ap = Depth of cut (mm), Kistler dynamometer error = $\pm 15\text{N}$.

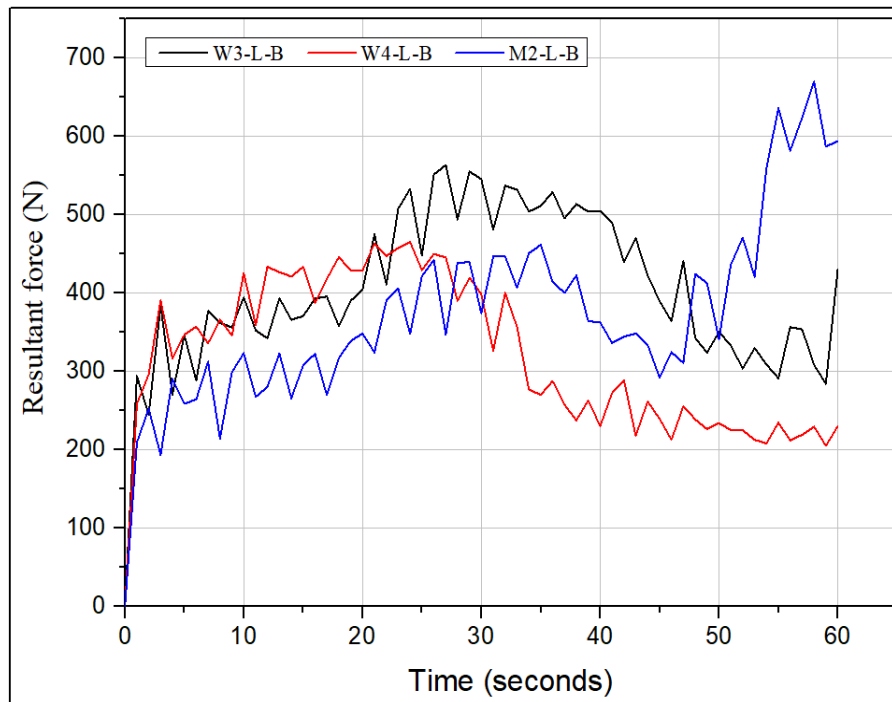


Figure 5.13. Comparison of resultant forces for the W3-L-B, W4-L-B, and M2-L-B inserts during milling at vc of 300m/minute and ap of 0.5mm.

5.2 Temperature

The high temperatures generated during machining are of critical importance as they lead to many economic and technical problems. These temperatures directly influence the tool face and tool flank leading to accelerated wear and thermal damage of the machining surface. In this section the indicative milling temperatures obtained from the Flir thermal camera are analysed in an attempt to find correlations and trends. Comparison are made between the

indicative milling temperatures and process parameters, with further analysis being carried out to understand the influence of composition, sintering and cutting edge type on temperature during Ti-6Al-4V machining.

5.2.1 Analysis of milling temperature at cutting speed of 60m/minute

At vc of 60m/minute and ap of 1.5mm, the W3-L-B insert experienced a lower milling temperature than the W4-L-B and M2-L-B inserts (Table 5.6). Similar temperatures were experienced by the W3-L-B and W3-S-B inserts, and likewise the W4-L-B and W4-S-B inserts making it difficult to determine the effect of sintering on temperature of the blank inserts (Table 5.6 Figure 5.14). Notwithstanding, the W4-S-B insert had the highest temperature of 770.57 ± 46.6 °C in the blank category (Figure 5.14). All the laser peened inserts, except for the M2-L-LP experienced higher temperature than their blank counterparts (Figure 5.14). The M2-L-LP insert had the lowest temperature of 697.81 ± 39.7 °C (Table 5.6), while the W3-L-LP and W4-L-LP had similar temperatures of 788.84 ± 48.1 °C and 790.60 ± 48.2 °C respectively (Table 5.6). The introduction of ridges to the cutting tool inserts resulted in higher temperatures for the W3-S-R, W4-S-R and M2-L-R inserts (Figure 5.14). The temperature for the liquid phase sintered - ridges inserts were slightly lower than that of their spark plasma sintered counterparts (Figure 5.14). The W3-L-R insert had the lowest temperature of 755.27 ± 45.8 °C in the ridges category, followed by the W4-L-R with a temperature of 789.00 ± 47.9 °C (Table 5.6 and Figure 5.14).

The introduction of chip breakers led to higher milling temperatures for all the cutting tool inserts (Figure 5.14). The W3-L-C insert had the lowest temperature of 705.90 ± 43.2 °C in the chip breaker category, followed by the M2-L-C with a temperature of 788.65 ± 18.1 °C (Table 5.6 and Figure 5.14).

Table 5.6. Experimental results of temperatures at v_c of 60m/minute

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Temperature ($^{\circ}\text{C}$)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	60	1.5	695.52 ± 39.7	788.84 ± 48.1	755.27 ± 45.8	705.90 ± 43.2
2	W3-S	60	1.5	667.06 ± 40.6	761.41 ± 46.2	832.26 ± 51.0	837.06 ± 51.4
3	W4-L	60	1.5	684.81 ± 40.9	790.60 ± 48.2	789.00 ± 47.9	792.25 ± 48.2
4	W4-S	60	1.5	770.57 ± 46.6	834.67 ± 51.2	890.99 ± 45.0	901.47 ± 55.8
5	M2-L	60	1.5	715.56 ± 43.0	697.81 ± 39.7	856.70 ± 52.6	788.65 ± 18.1
6	M2-S	60	1.5	721.67 ± 43.5	942.37 ± 58.5	876.01 ± 53.9	904.06 ± 59.3
7	W3-L	60	1	761.64 ± 46.2	-	714.49 ± 43.0	-
8	W3-S	60	1	701.27 ± 42.1	-	783.57 ± 48.6	-
9	W4-L	60	1	700.77 ± 42.0	-	790.88 ± 48.1	-
10	W4-S	60	1	750.79 ± 45.4	-	823.12 ± 49.8	-
11	M2-L	60	1	766.12 ± 46.4	-	730.91 ± 44.0	-
12	M2-S	60	1	775.99 ± 45.1	-	743.54 ± 45.0	-

* L = liquid phase sintering, S=spark plasma sintering, v_c = Cutting speed (m/minute),
 a_p = Depth of cut (mm).

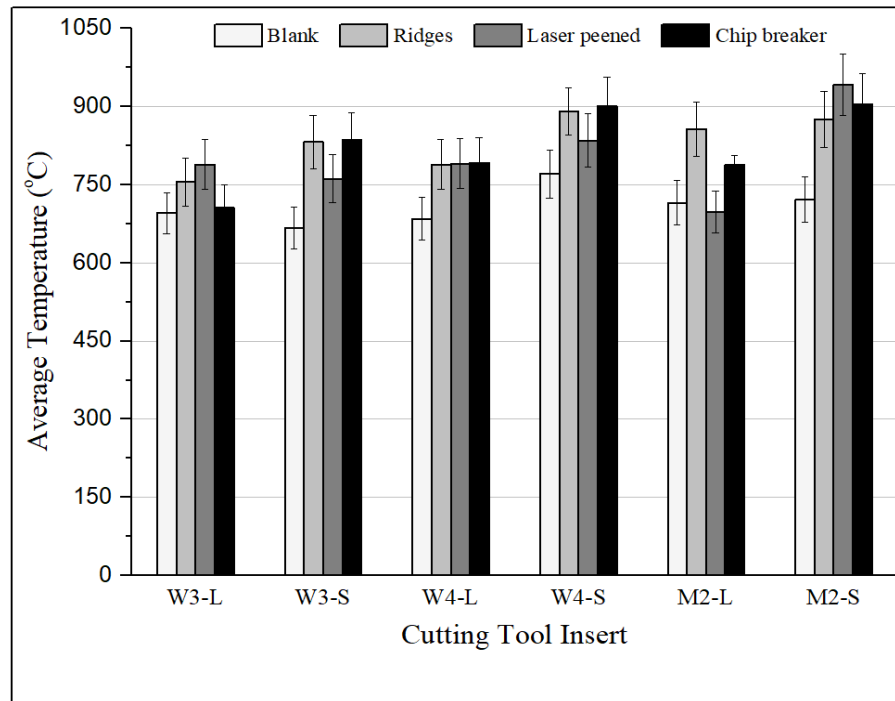


Figure 5.14. Comparison of average temperatures during milling at v_c of 60m/minute and a_p of 1.5mm.

A reduction in depth of cut from 1.5mm to 1mm resulted in slightly higher milling temperatures for the blank inserts (Figure 5.15). Contrarily, the ridges inserts experienced lower temperatures with this decrease in depth of cut (Figure 5.15). In the blank category, the W4-L-B insert had a lower temperature than the W3-L-B and M2-L-B inserts (Table 5.6 and Figure 5.15). The effect of SPS on temperature of the blank samples couldn't be determine as similar temperatures were experienced by almost all the SPS counterparts (Figure 5.15). The introduction of ridges increased milling temperatures for the W3-S-R, W4-L-R and W4-S-R inserts (Figure 5.15). All the other inserts had fairly similar temperature as their blank counterpart (Figure 5.15). The liquid phase sintered – ridges insert had slightly lower temperatures than their spark plasma sintered counterparts (Figure 5.15), with the W3-L-R insert having the lowest temperature of 714.49 ± 43.0 °C in the ridges category (Table 5.6).

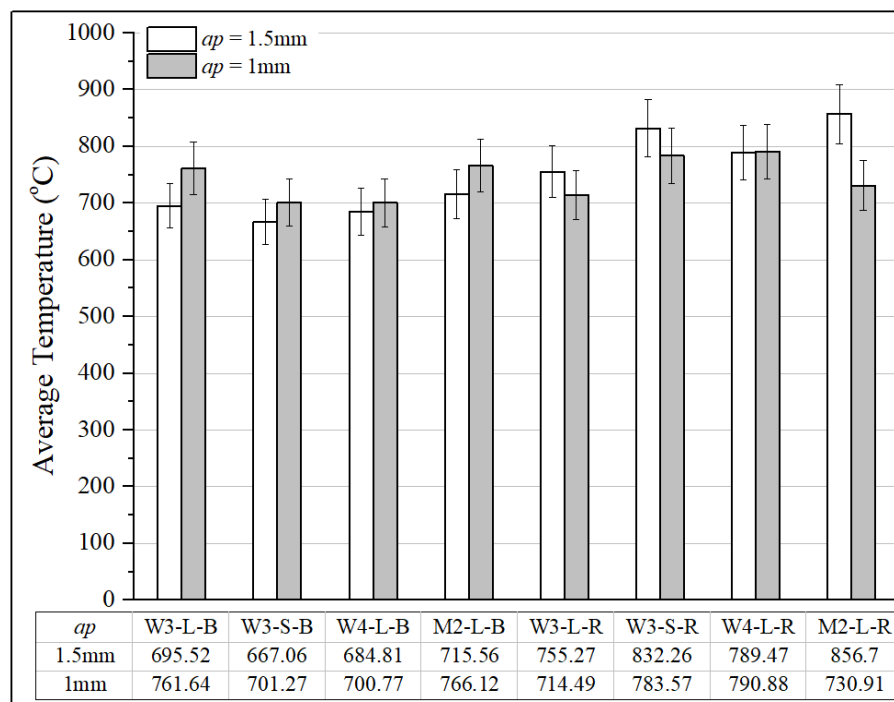


Figure 5.15. Variation of temperature for cutting tool inserts with decrease in *ap* from 1.5mm to 1mm, during milling at *vc* of 60m/minute.

5.2.2 Analysis of milling temperature at cutting speed of 75m/minute

There were generally no significant changes in the temperature of the cutting tool inserts with increased milling temperature from 60m/minute to 75m/minute at a_p of 1mm (Figure 5.16).

At v_c of 75m/minute and a_p of 1mm, the W3-L-B and W4-L-B inserts had similar temperatures of 645.01 ± 37.3 °C and 644.34 ± 38.3 °C respectively, while the M2-L-B insert had the highest temperature of 792.82 ± 48.2 °C in the blank category (Table 5.7 and Figure 5.17). The effect of sintering on temperature could only be determined for the W4 – blank inserts, as the W4-L-B experience a significantly lower temperature (Table 5.7). The introduction of ridges led to lower milling temperature for only the W3-L-R insert, as the other ridges inserts either experienced similar or slightly higher milling temperatures compared to their blank counterparts (Figure 5.17). The spark plasma sintered W3-S-R and W4-S-R inserts had higher temperature than their LPS counterparts (Figure 5.17), while the lowest temperature of 710.18 ± 42.5 °C in the ridges category was experienced by the W3-L-R insert (Table 5.7).

Table 5.7. Experimental results of temperatures at v_c of 75m/minute

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Temperature (°C)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	75	1	645.01 ± 37.3	-	710.18 ± 42.5	-
2	W3-S	75	1	650.97 ± 39.5	-	733.50 ± 44.2	-
3	W4-L	75	1	644.34 ± 38.3	-	776.71 ± 47.2	-
4	W4-S	75	1	747.46 ± 45.3	-	878.85 ± 54.1	-
5	M2-L	75	1	792.82 ± 48.2	-	862.31 ± 53.0	-
6	M2-S	75	1	732.51 ± 43.1	-	809.30 ± 49.4	-
7	W3-L	75	0.5	592.92 ± 35.1	555.73 ± 38.9	616.99 ± 36.6	530.73 ± 30.9
8	W3-S	75	0.5	540.00 ± 25.5	593.82 ± 41.6	510.47 ± 29.6	491.55 ± 29.6
9	W4-L	75	0.5	614.90 ± 36.3	545.41 ± 38.2	643.46 ± 38.3	574.33 ± 34.8
10	W4-S	75	0.5	532.86 ± 31.1	516.80 ± 36.2	724.30 ± 43.7	630.17 ± 37.3
11	M2-L	75	0.5	636.68 ± 37.8	522.13 ± 36.6	542.81 ± 31.6	567.43 ± 33.0
12	M2-S	75	0.5	563.27 ± 32.9	591.70 ± 41.4	543.09 ± 48.0	-

* L = liquid phase sintering, S=spark plasma sintering, v_c = Cutting speed (m/minute),

ap = Depth of cut (mm).

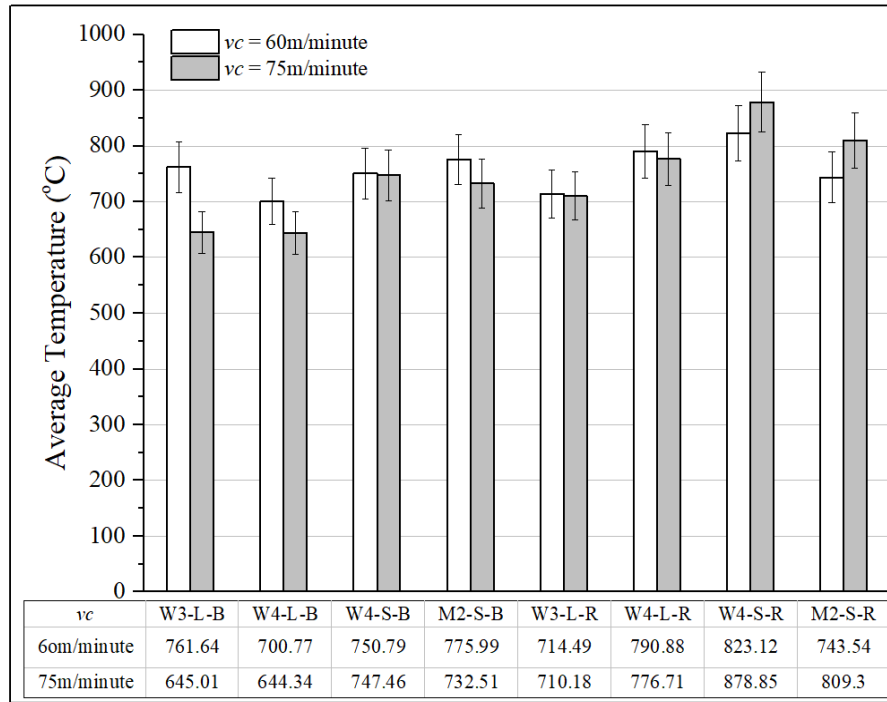


Figure 5.16. Comparison of temperature for cutting tool inserts with increase in vc from 60m/minute to 75m/minute, at ap at 1mm.

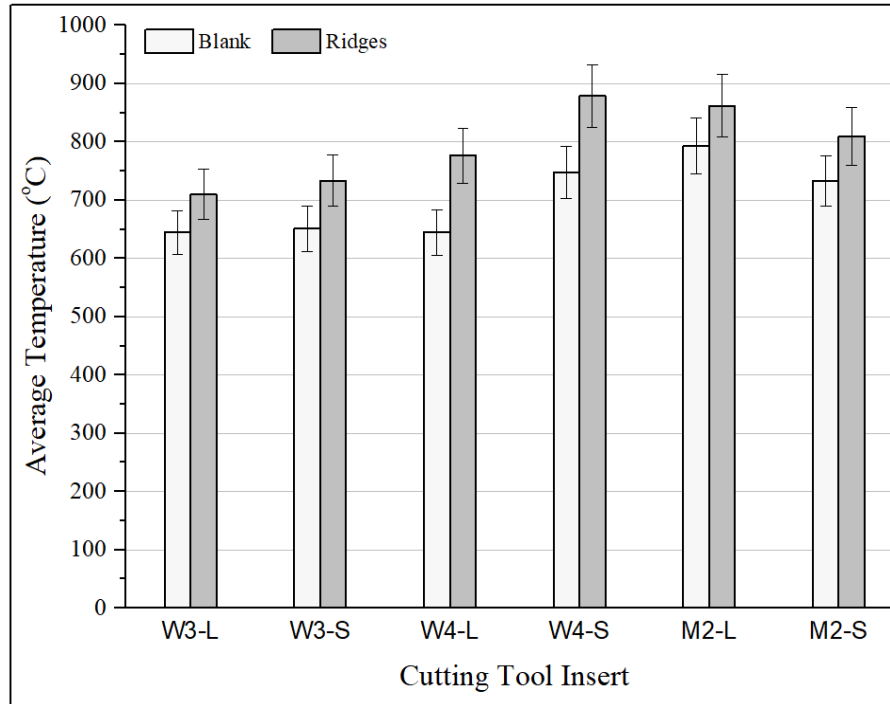


Figure 5.17. Comparison of average temperatures during milling at vc of 75m/minute and ap of 1mm.

A reduction in depth of cut from 1mm to 0.5mm at cutting speed of 75m/minute led to lower temperatures for both the blank and ridges inserts (Figure 5.18).

At vc of 75m/minute and ap of 0.5mm, the W3-L-B insert had a slightly lower temperature than the W4-L-B and M2-L-B inserts (Figure 5.19). The temperatures for the SPS were fairly lower than that of their LPS counterparts, with the W4-S-B insert having the lowest temperature of 532.86 ± 31.1 °C (Figure 5.19, Table 5.7). The effect of laser peening was noticeable in the liquid phase sintered inserts, with lower milling temperatures experienced after laser peening (Table 5.7 and Figure 5.19). Contrarily, the W3-S-LP and M2-S-LP inserts experienced slightly higher milling temperatures (Figure 5.19). The lowest temperature of 516.80 ± 36.2 °C in the laser peened category was experienced by the W4-S-LP insert (Table 5.7).

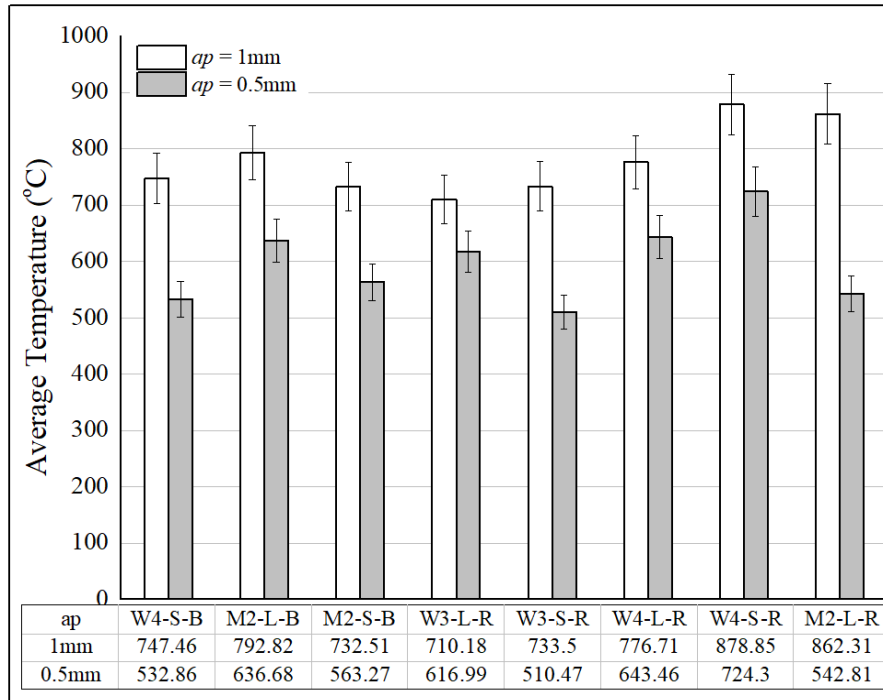


Figure 5.18. Variation of temperature for cutting tool inserts with decrease in ap from 1mm to 0.5mm at vc of 75m/minute.

The introduction of ridges led to a significant reduction in force for the M2-L-R insert (Figure 5.19). Nonetheless, other ridges inserts experienced fairly similar or higher temperatures than their blank counterparts (Figure 5.19). The temperature for the liquid phase sintered chip breaker inserts were significantly lower compared to that of their blank counterparts (Figure 5.19). The lowest temperature of 491.55 ± 29.6 °C during milling at vc of 75m/minute and ap of 0.5mm was experienced by the with the W3-S-C insert (Table 5.7 and Figure 5.19).

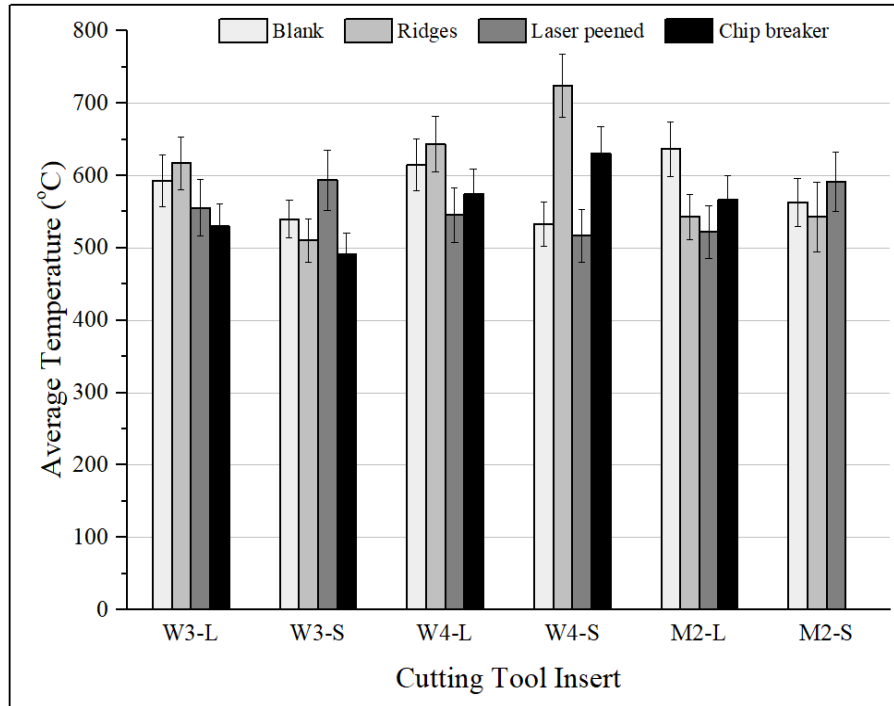


Figure 5.19. Comparison of average temperatures during milling at vc of 75m/minute and ap of 0.5mm.

5.2.3 Analysis of milling temperature at cutting speed of 100m/minute

The cutting tool inserts experienced significantly higher temperatures with increased cutting speed from 75m/minute to 100m/minute (Figure 5.20). In the blank category, the temperature for the W3-L-B insert was slightly lower than that of the W4-L-B and M2-L-B inserts (Table 5.8 and Figure 5.21). The spark plasma sintered W3-S-B and M2-S-B inserts had higher temperatures compared to their liquid phase sintered counterparts (Figure 5.21). The lowest temperature of 664.78 ± 39.50 °C in the blank category was experienced by the M2-S-B insert (Table 5.8).

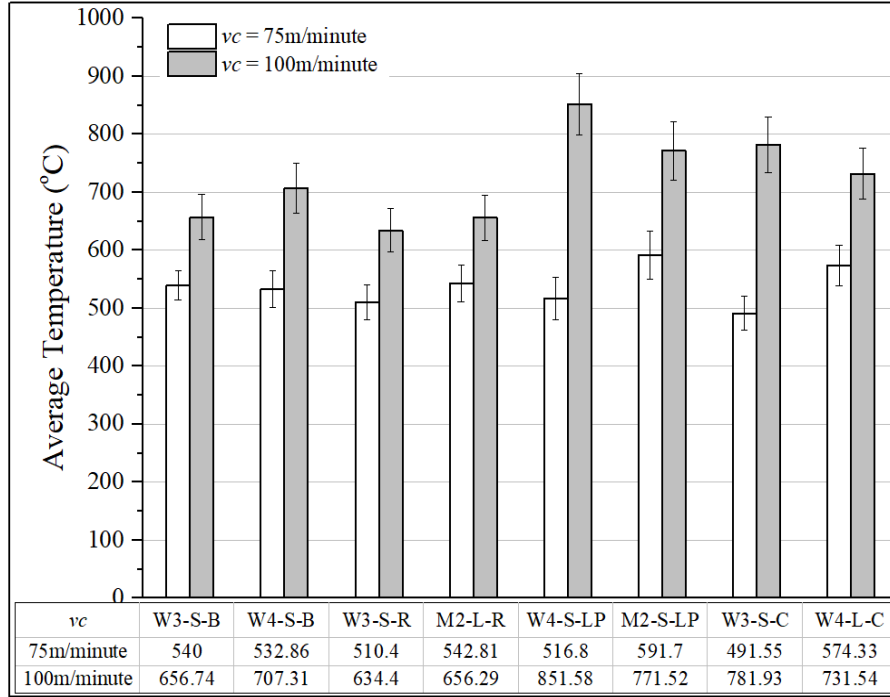


Figure 5.20. Comparison of temperature for cutting tool inserts with increase in vc from 75m/minute to 100m/minute, at ap at 0.5mm.

The effect of laser peening on the cutting tool insert was clearly seen, with reduced milling temperatures for all the laser peened inserts except the M2-S-LP (Figure 5.21). Similarly, the effect of the sintering effect was noticeable, with the LPS - laser peened inserts having lower temperature than their SPS counterparts (Figure 5.21). The lowest temperature of 518.93 ± 32.5 °C during milling at vc of 100m/minute and ap of 0.5mm was experienced by the W3-L-LP insert (Table 5.8). The introduction of ridges on the rake of the cutting tool inserts reduced the milling temperatures experienced by the cutting tool insert (Figure 5.21). The W4-L-R insert had the lowest temperature of 634.40 ± 37.6 °C in the ridges category (Table 5.8 and Figure 5.21). The introduction of chip breakers slightly reduced temperatures for the W3-L-C and W4-S-C inserts (Table 5.8 and Figure 5.21), while the W3-S-C and W4-L-C inserts maintained fairly similar temperatures as their blank counterparts (Table 5.8 and Figure 5.21).

Table 5.8. Experimental results of temperatures at vc of 100m/minute

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Temperature ($^{\circ}\text{C}$)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	100	0.5	690.88 ± 41.3	518.93 ± 32.5	666.50 ± 39.8	573.04 ± 33.6
2	W3-S	100	0.5	730.09 ± 43.9	577.05 ± 33.8	634.40 ± 37.6	781.93 ± 47.5
3	W4-L	100	0.5	739.79 ± 44.5	652.42 ± 38.8	725.96 ± 43.8	731.54 ± 44.1
4	W4-S	100	0.5	805.63 ± 47.7	851.58 ± 52.3	757.40 ± 47.9	753.11 ± 45.6
5	M2-L	100	0.5	768.81 ± 46.5	653.58 ± 38.9	656.29 ± 39.1	-
6	M2-S	100	0.5	664.78 ± 39.5	771.52 ± 50.4	663.60 ± 40.6	-

* L = liquid phase sintering, S=spark plasma sintering, vc = Cutting speed (m/minute), ap = Depth of cut (mm).

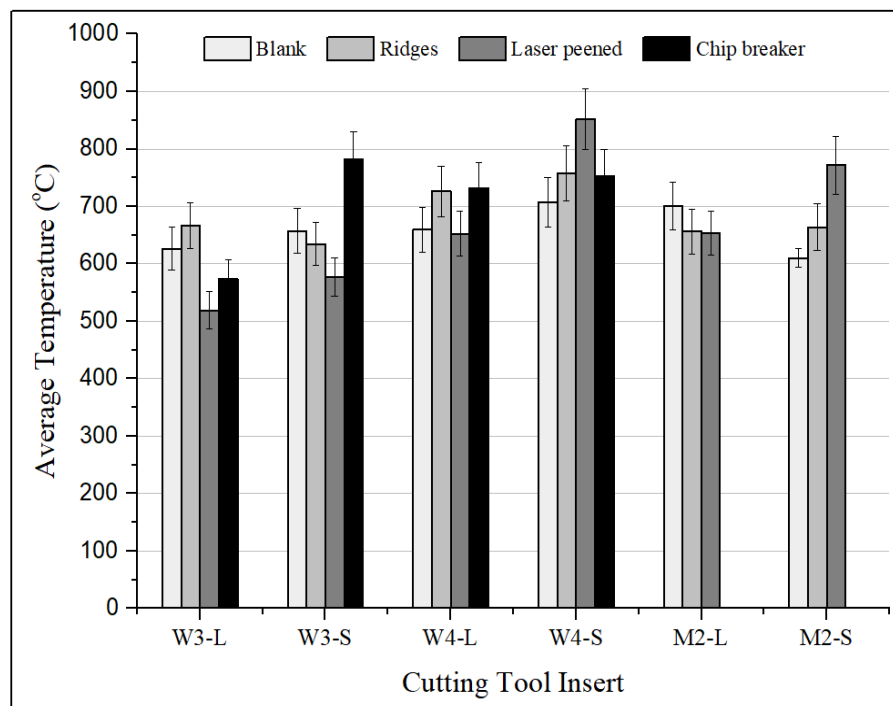


Figure 5.21. Comparison of average temperatures during milling at vc of 100m/minute and ap of 0.5mm.

5.2.4 Analysis of milling temperature at cutting speed of 120m/minute

Further increase in vc to 120m/minute, while maintaining ap at 0.5mm generally increased milling temperatures for the cutting tool inserts (Figure 5.22).

Table 5.9. Experimental results of temperatures at v_c of 120m/minute

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Temperature ($^{\circ}\text{C}$)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	120	0.5	805.38 ± 49.0	-	763.62 ± 46.3	-
2	W3-S	120	0.5	749.32 ± 45.2	-	606.02 ± 35.7	-
3	W4-L	120	0.5	767.67 ± 46.4	-	751.19 ± 45.0	-
4	W4-S	120	0.5	943.24 ± 58.4	-	660.60 ± 35.4	-
5	M2-L	120	0.5	846.27 ± 41.6	-	511.90 ± 28.6	-
6	M2-S	120	0.5	893.91 ± 52.4	-	867.39 ± 18.1	-

* L = liquid phase sintering, S=spark plasma sintering, v_c = Cutting speed (m/minute),
 a_p = Depth of cut (mm)

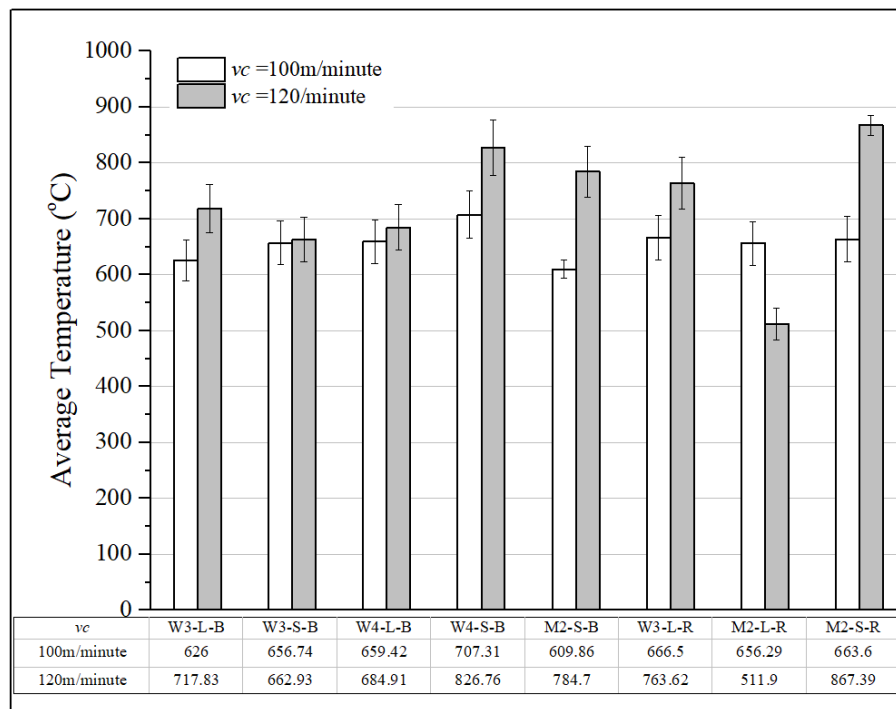


Figure 5.22. Comparison of temperature for cutting tool inserts with increase in v_c from 100m/minute to 120m/minute, at a_p at 0.5mm.

In the blank category, the W4-L-B insert had lower milling temperature than the W3-L-B and M2-L-B inserts (Table 5.9 and Figure 5.23). The W4-S-B insert had the highest temperature of 943.24 ± 58.4 $^{\circ}\text{C}$ during milling at v_c of 120m/minute and a_p of 05mm (Figure 5.23). The effect of ridges on temperature was clearly seen in the W3-S-R, W4-S-R and M2-L-R insert

as they all had significantly lower temperatures (Table 5.9 and Figure 5.23). The W3-S-R had the lowest temperature of 606.02 ± 35.7 °C during milling at v_c of 120m/minute and a_p of 0.5mm (Table 5.9).

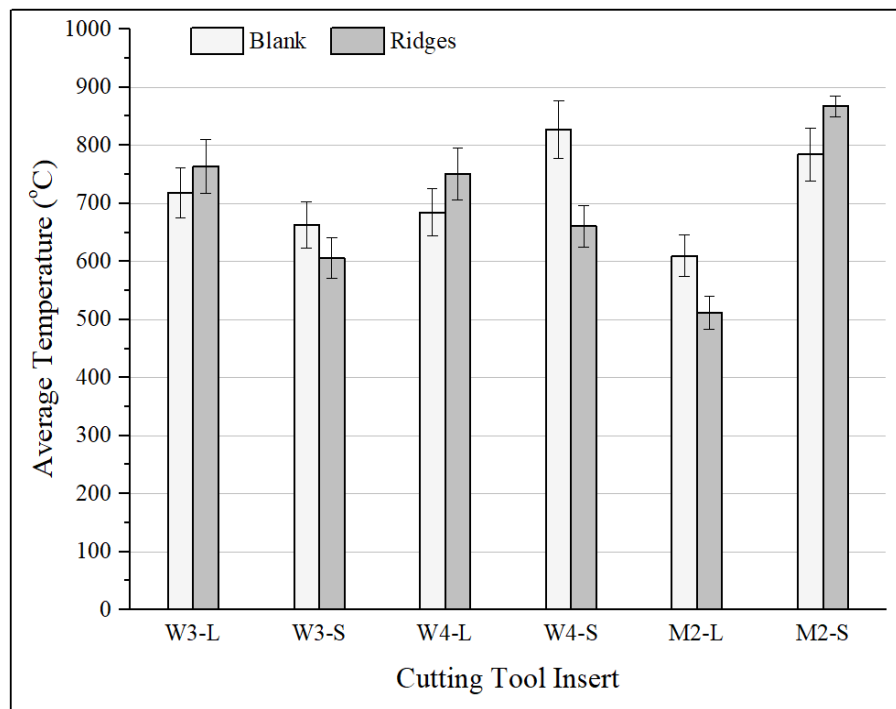


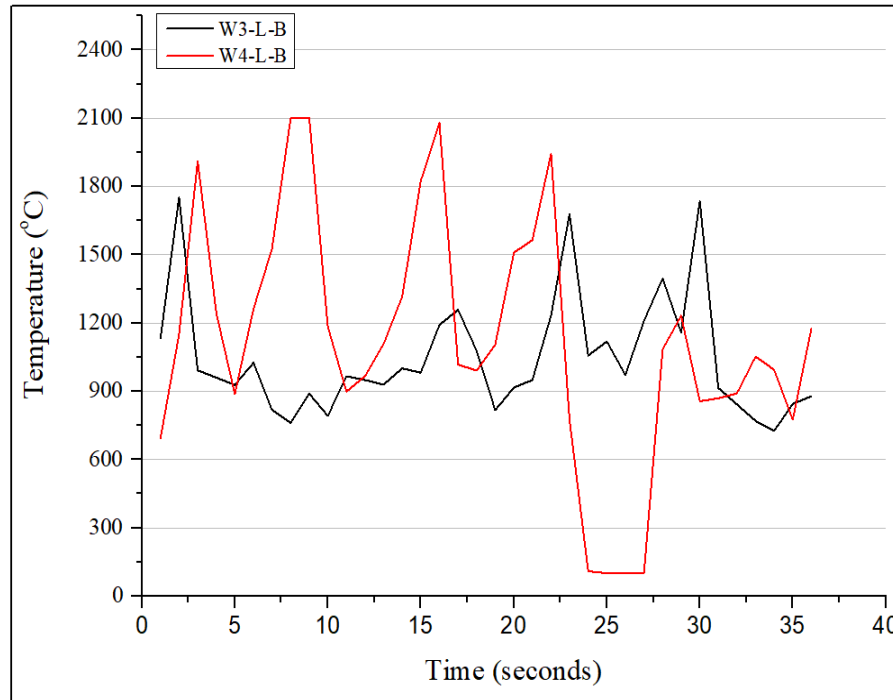
Figure 5.23. Comparison of average temperature for cutting tool inserts at v_c of 120m/minute and a_p of 0.5mm.

5.2.5 Analysis of milling temperature at cutting speed of 300m/minute

Significantly higher temperatures were experienced by the W3-L-B, W4-L-B and M2-LB cutting tool inserts with increase in speed from 120m/minute to 300m/minute at a_p of 0.5mm (Table 5.9 and Table 5.10). The W3-L-B insert had the lowest temperature of 1303.02 ± 76 °C, while the W4-L-B insert had the highest temperatures of 1191.02 ± 67.3 °C during milling at v_c of 300m/minute and a_p of 0.5mm (Table 5.10 and Figure 5.24).

Table 5.10. Experimental results of temperatures at vc of 300m/minute

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Temperature (°C)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	300	0.5	1043.49 ± 65.3	-	-	-
2	W4-L	300	0.5	1303.02 ± 76.0	-	-	-
3	M2-L	300	0.5	1191.02 ± 67.3	-	-	-

**Figure 5.24. Variation in milling temperature per second for the W3-L-B and W4-L-B inserts during milling at v_c of 300m/minute and a_p of 0.5mm**

5.3 Wear

The Flank Wear Rate (FWR) of the various cutting tool inserts after the milling trials are presented in this section. The effect of tool composition and sintering technique on wear of the cutting tool inserts during the milling trial is analysed, and likewise the effect of the tool edges on wear.

5.3.1 Analysis of tool wear at cutting of 60m/minute

The micrographs of the LPS and SPS cutting tool inserts after milling at v_c of 60m/minute and ap of 1.5mm is shown in Figure 5.25 and Figure 5.26 respectively, while result for flank wear rates at cutting speed of 60m/minute is presented in Table 5.11. The W3-L-B and W4-L-B inserts had negligible flank wear rates after milling at v_c of 60m/minute and ap of 1mm (Table 5.11 and Figure 5.25), while the M2-S-B insert had the highest flank wear rate of 44.52 $\mu\text{m}/\text{minute}$ in the blank category (Table 5.11 and Figure 5.26). The effect of sintering was clearly seen on the W3-S-B and W4-S-B inserts as SPS resulted in higher flank wear rates (Figure 5.26 and Table 5.11). The laser peening of the cutting tool inserts resulted in higher flank wear rates for all the LPS inserts (Figure 5.27). In the laser peened category, the W3-L-LP insert had a slightly lower FWR than the W4-L-LP and M2-L-LP inserts (Figure 5.27). The liquid phase sintered inserts had slightly lower FWRs than their spark plasma sintered counterparts in the ridges category (Figure 5.27). The W4-L-R maintained a negligible FWR as its blank counterpart, while the W3-L-R had a slightly lower FWR of 27.93 $\mu\text{m}/\text{minute}$ (Figure 5.27m Table 5.11). The M2-S-R insert failed prematurely (Figure 5.27). Compared to their blank counterparts, the FWRs for spark plasma sintered - ridges inserts were slightly higher (Figure 5.27). In the chip breaker category, The W3-L-C had a negligible FWR as its blank counterpart (Table 5.11), while the W4-L-C and W4-S-C inserts had significantly higher FWRs of 67.82 $\mu\text{m}/\text{minute}$ and 91.69 $\mu\text{m}/\text{minute}$ respectively (Figure 5.27).

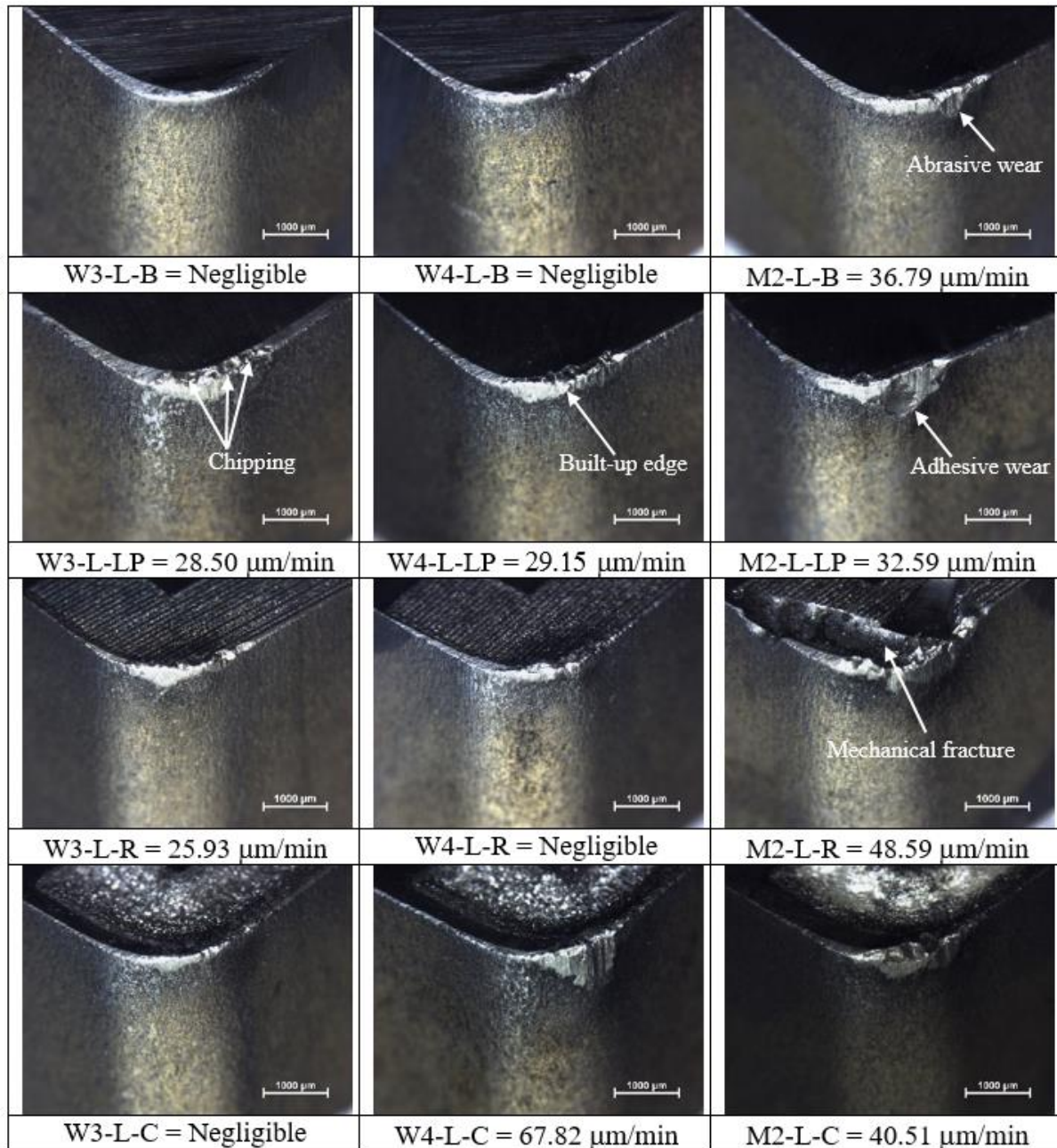


Figure 5.25 Micrographs of the LPS cutting tool inserts after milling at v_c of 60m/minute and a_p of 1.5mm (Flank wear in $\mu\text{m}/\text{minute}$).

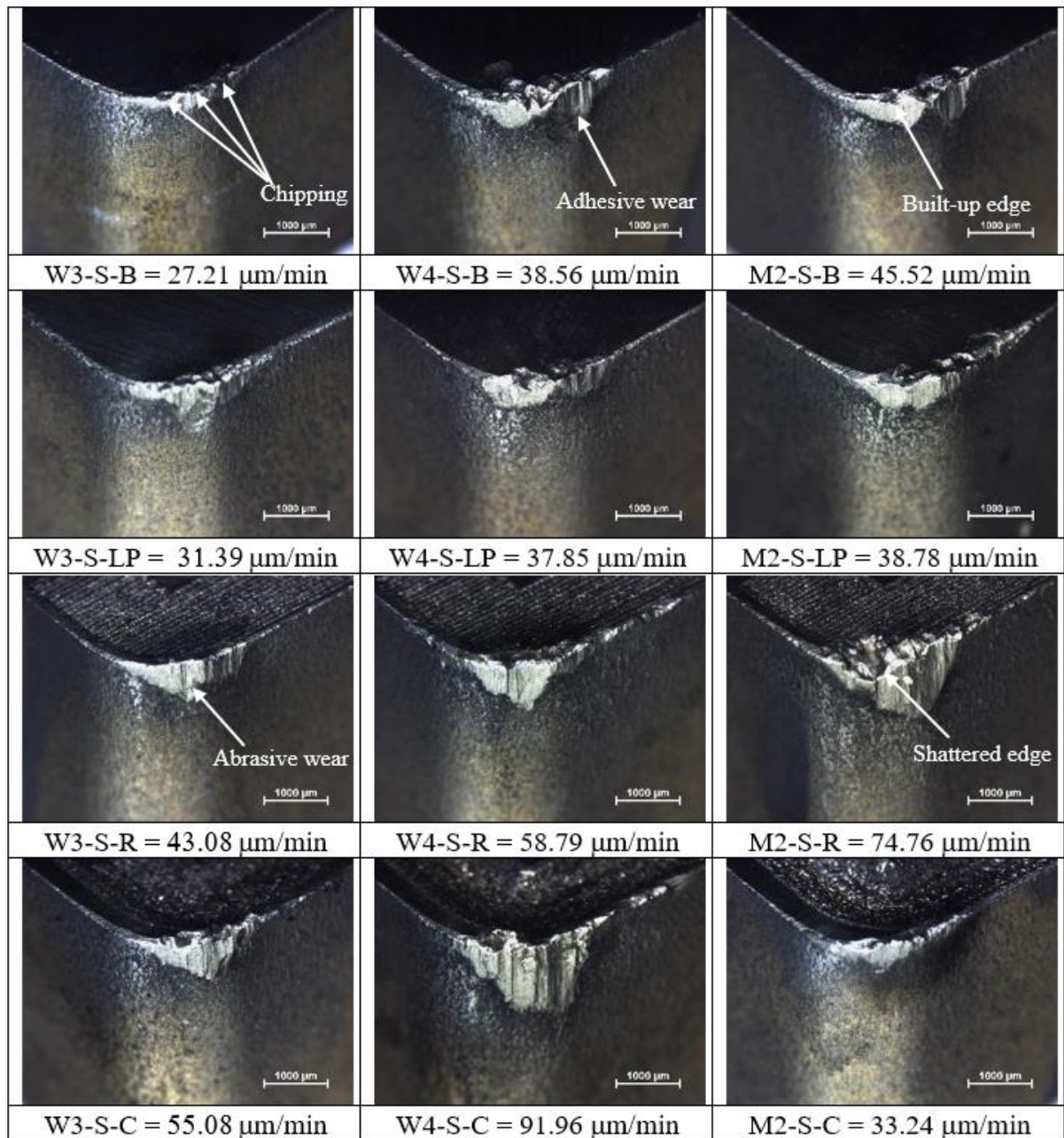


Figure 5.26 Micrographs of the SPS cutting tool inserts after milling at v_c of 60m/minute and a_p of 1.5mm (Flank wear in $\mu\text{m}/\text{minute}$).

Table 5.11. Experimental results of flank wear rates during milling at v_c of 60m/minute

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Flank wear rate ($\mu\text{m}/\text{min}$)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	60	1.5	Negligible	28.50	27.93	Negligible
2	W3-S	60	1.5	27.21	31.39	43.08	55.80
3	W4-L	60	1.5	Negligible	29.15	Negligible	67.82
4	W4-S	60	1.5	38.56	37.85	58.79	91.69
5	M2-L	60	1.5	36.79	55.59	48.49	40.51
6	M2-S	60	1.5	44.52	38.78	Shattered	33.24
7	W3-L	60	1	Negligible	-	Negligible	-
8	W3-S	60	1	21.18	-	45.11	-
9	W4-L	60	1	20.25	-	16.88	-
10	W4-S	60	1	23.94	-	54.93	-
11	M2-L	60	1	35.29	-	26.09	-
12	M2-S	60	1	59.54	-	41.43	-

* L = liquid phase sintering, S=spark plasma sintering, v_c = Cutting speed (m/minute),
 a_p = Depth of cut (mm).

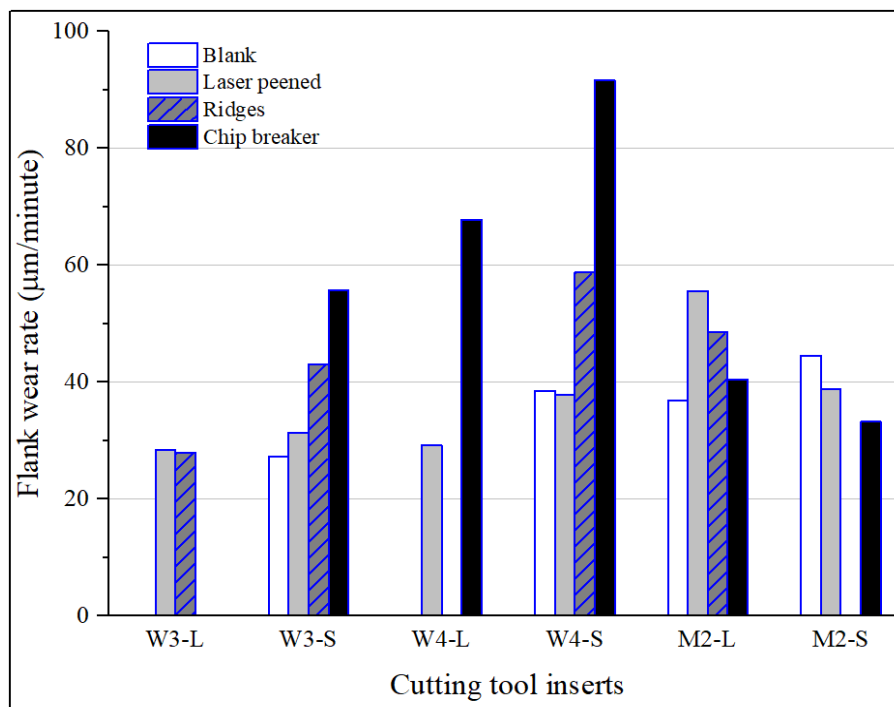


Figure 5.27. Comparison of flank wear rates for cutting tool inserts during milling at v_c of 60m/minute and a_p of 1.5mm.

A reduction in ap from 0.5mm to 1mm at vc of 60m/minute generally resulted in lower FWR for the cutting tool inserts (Figure 5.28). The only exceptions to this trend was the W4-L-B and W4-L-R inserts which had slightly higher flank wear rates of 20.25 $\mu\text{m}/\text{minute}$ and 16.88 $\mu\text{m}/\text{minute}$ respectively (Figure 5.28 and Table 5.11).

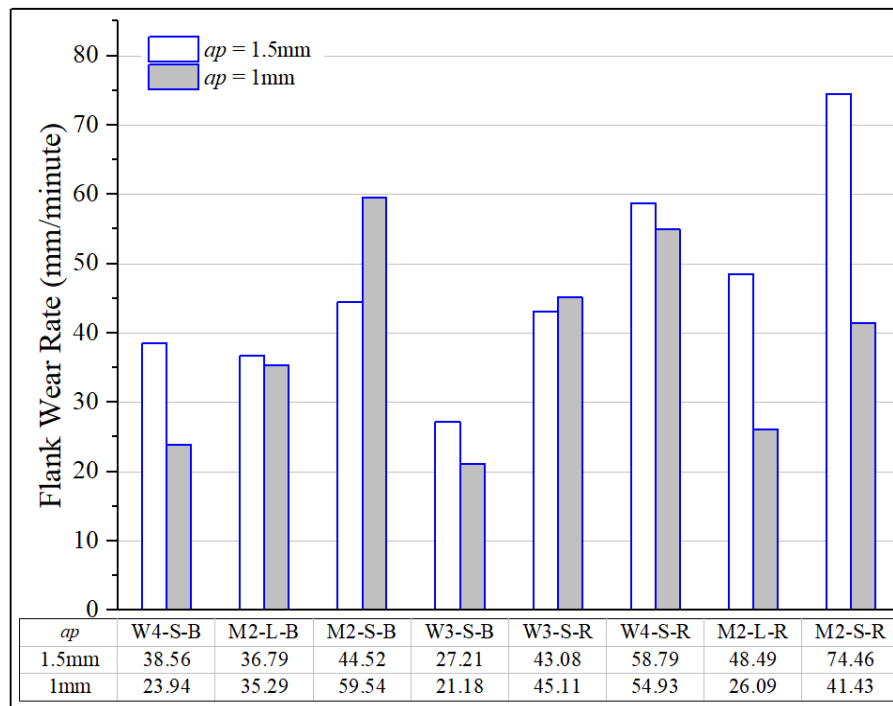


Figure 5.28. Variation in flank wear rate for cutting tool inserts with decrease in ap from 1.5mm to 1mm at vc of 60m/minute.

The effect of sintering could be seen in the blank category, with the liquid phase sintered inserts having lower flank wear rates than their spark plasma sintered counterparts (Figure 5.29). The W3-L-B insert had a negligible FWR (Table 5.11), while the W4-L-B and M2-L-B inserts had fairly lower FWRs of 20.25 $\mu\text{m}/\text{minute}$ and 35.29 20.25 $\mu\text{m}/\text{minute}$ respectively (Figure 5.29). The liquid phase sintered inserts had slightly lower flank wear rates than their spark plasma sintered counterparts in the ridges category (Figure 5.29). Compared to their blank counterparts, the flank wear rate for the liquid phase sintered - ridges inserts were

generally lower (Figure 5.29). The W3-L-R maintained a negligible as its blank counterpart (Table 5.11).

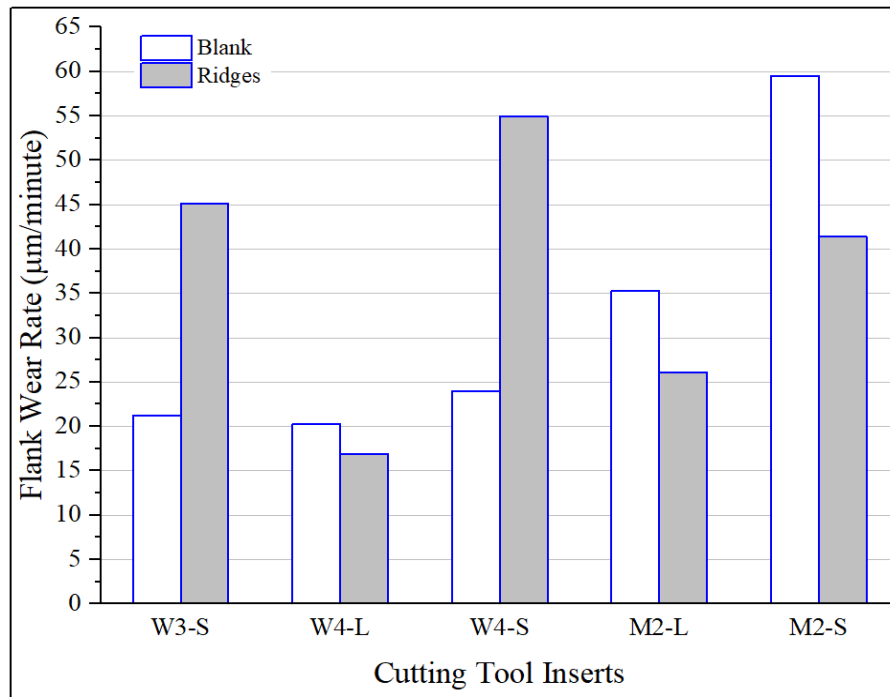


Figure 5.29. Comparison of flank wear rates for cutting tool inserts during milling at vc of 60m/minute and ap of 1mm.

5.3.2 Analysis of tool wear at cutting of 75m/minute

Increased vc from 60m/minute to 75m/minute, ap at 1mm resulted in higher flank wear rates for all the cutting tool inserts (Table 5.12 and Figure 5.30). In the blank category, the W3-L-B insert had the lowest FWR of 40.28 $\mu\text{m/minute}$, followed by the W4-L-B with a flank wear rate of 50.15 $\mu\text{m/minute}$ (Table 5.12).

At vc from 75m/minute and ap of 1mm, the W3-S-B and W4-S-B inserts had higher flank wear rates than their LPS counterpart (Figure 5.31). All the cutting tool inserts experienced higher FWR with the introduction of ridges (Table 5.12). The only exception was the W4-L-R insert which had the lowest FWR of 45.94 $\mu\text{m/minute}$ in the ridges category (Table 5.12

and Figure 5.31). Apart for the M2-S-R insert, all the SPS - ridges inserts had had higher flank wear rates compared to their LPS counterparts (Figure 5.31).

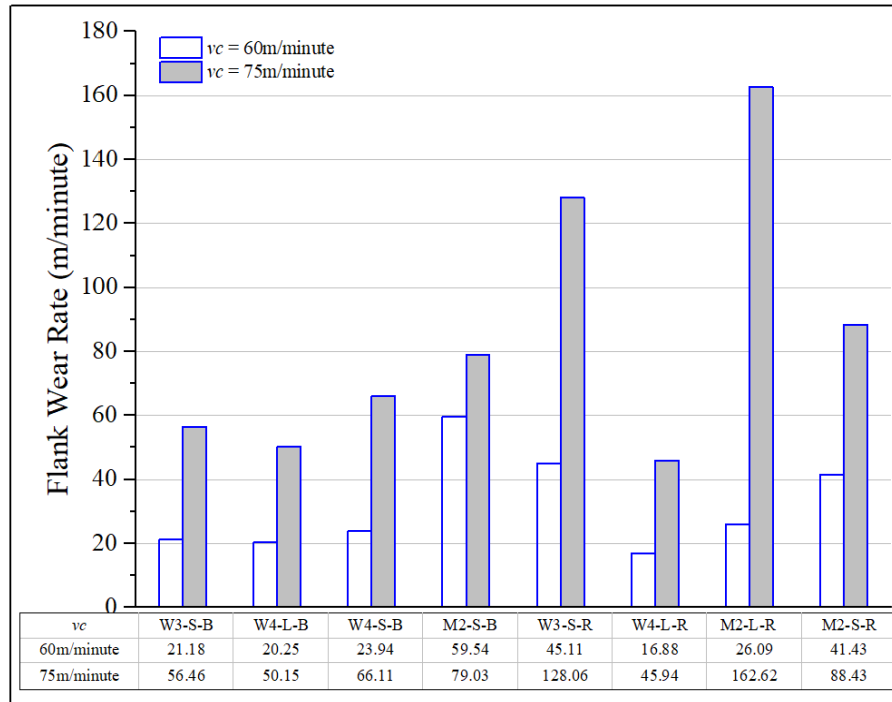


Figure 5.30. Variation in flank wear rate for cutting tool inserts with increase in vc from 60m/minute to 75m/minute, at ap of 1mm.

Table 5.12. Experimental results of flank wear rates during milling at vc of 75/minute

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Flank wear rate ($\mu\text{m}/\text{min}$)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	75	1	40.28	-	73.71	-
2	W3-S	75	1	56.46	-	128.06	-
3	W4-L	75	1	50.15	-	45.94	-
4	W4-S	75	1	66.11	-	138.30	-
5	M2-L	75	1	71.43	-	162.62	-
6	M2-S	75	1	79.03	-	88.43	-
7	W3-L	75	0.5	Negligible	25.30	Negligible	Negligible
8	W3-S	75	0.5	50.15	31.60	Negligible	24.08
9	W4-L	75	0.5	27.05	29.13	Negligible	31.75
10	W4-S	75	0.5	43.44	25.70	49.52	64.82
11	M2-L	75	0.5	41.80	34.95	39.24	20.32
12	M2-S	75	0.5	33.03	19.59	26.35	-

* L = liquid phase sintering, S=spark plasma sintering, vc = Cutting speed (m/minute),
 ap = Depth of cut (mm).

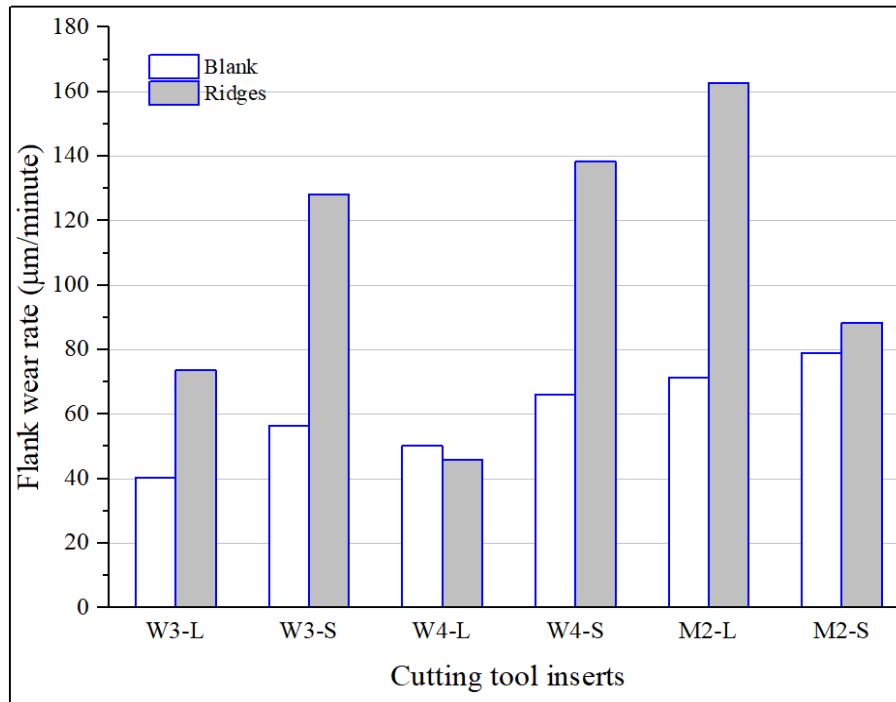


Figure 5.31. Comparison of flank wear rates for cutting tool inserts during milling at v_c of 75m/minute and a_p of 1mm.

All the cutting tool inserts had lower FWR with reduction in a_p from 1mm to 0.5mm, at v_c of 75m/minute (Table 5.12 and Figure 32). In the blank category, the W3-L-B insert had a negligible FWR, while the W4-L-B and M2-L-B inserts had lower FWRs of 27.05 $\mu\text{m/minute}$ and 41.80 $\mu\text{m/minute}$ respectively (Table 5.12). Apart from the M2-S-B insert, all the SPS – blank inserts had higher FWRs than their LPS counterparts (Figure 5.33). In the laser peened category, the W3-L-LP insert had a slightly lower FWR than the W4-L-P and M2-L-P insert (Figure 5.33). The FWRs for the spark plasma sintered W4-S-LP and M2-S-LP were lower than that of their LPS counterparts (Figure 5.34), with the M2-S-LP having the lowest FWR of 19.59 $\mu\text{m/minute}$ in the blank category (Table 5.12). A Comparison of FWR between the blank and LP inserts shows that the M2-S-LP, M2-L-LP and W4-S-LP had lower FWR than their blank counterparts (Figure 5.33). The effect of ridges on flank wear could clearly be seen from the negligible flank wear rates of the W3-L-R, W3-S-R and W4-L-R

inserts (Table 5.12). The highest FWR of 49.52 $\mu\text{m}/\text{minute}$ in the ridges category was experienced by the W4-S-R insert (Table 5.12). A comparison of FWR between the ridges and blank inserts shows that the M2-L-R and M2-S-R had lower flank wear rates (Figure 5.33).

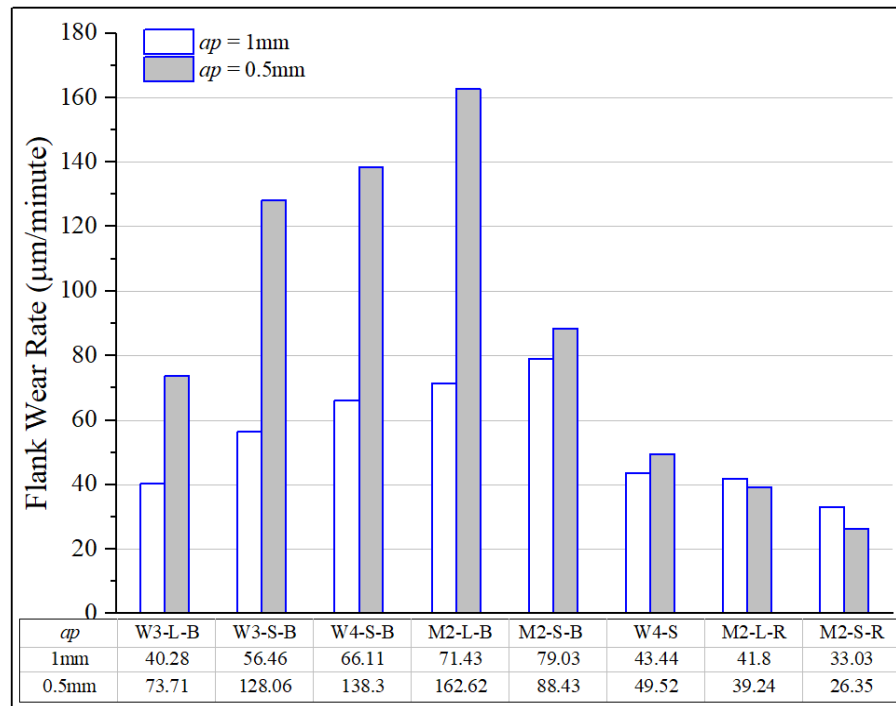


Figure 5.32. Variation in flank wear rate for cutting tool inserts with decrease in ap from 1mm to 0.5mm at vc of 75m/minute.

In the chip breaker category, the W3-L-C insert maintained a negligible FWR (Figure 5.34), while the W3-S-C and M2-L-C insert also had lower FWR of 24.08 $\mu\text{m}/\text{minute}$ and 20.32 $\mu\text{m}/\text{minute}$ respectively (Table 5.12). The effect of sintering could also be seen in the chip breaker category with the LPS inserts having lower FWR than their SPS counterparts (Figure 5.33).

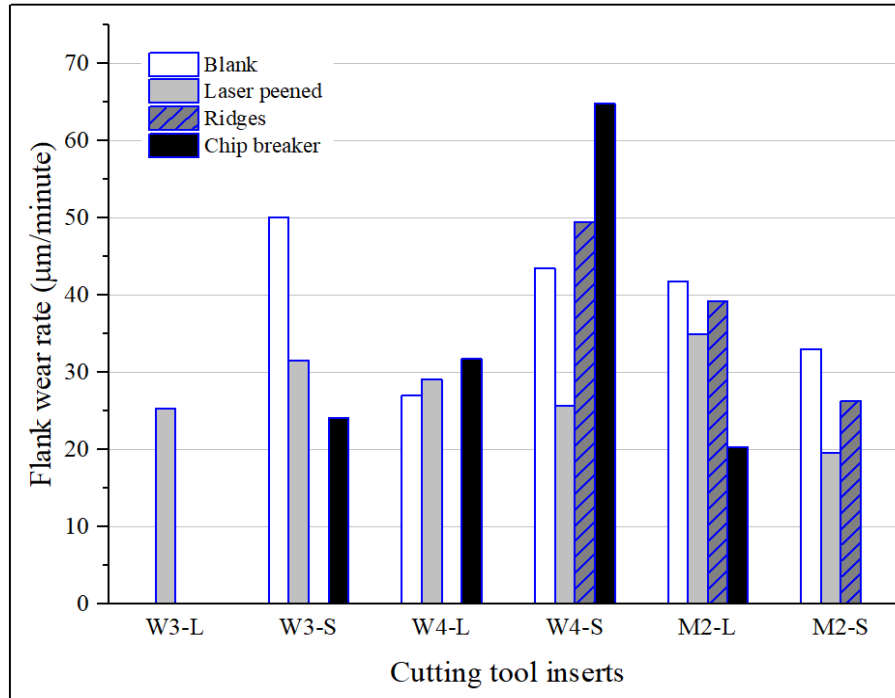


Figure 5.33. Comparison of flank wear rates for cutting tool inserts during milling at v_c of 75m/minute and a_p of 0.5mm.

5.3.3 Analysis of tool wear at cutting of 100m/minute

The cutting tool inserts generally had higher FWRs with increased v_c from 75m/minute to 100m/minute at a_p of 0.5mm (Table 5.13 and Figure 5.34).

Table 5.13. Experimental results of flank wear rates during milling at v_c of 100m/minute

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Flank wear rate ($\mu\text{m/min}$)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	100	0.5	Negligible	Negligible	Negligible	45.14
2	W3-S	100	0.5	55.47	41.80	87.18	77.96
3	W4-L	100	0.5	64.45	115.59	20.46	Negligible
4	W4-S	100	0.5	59.49	105.37	82.86	65.47
5	M2-L	100	0.5	56.27	31.71	41.03	-
6	M2-S	100	0.5	73.85	63.59	68.38	-

* L = liquid phase sintering, S=spark plasma sintering, v_c = Cutting speed (m/minute), a_p = Depth of cut (mm).

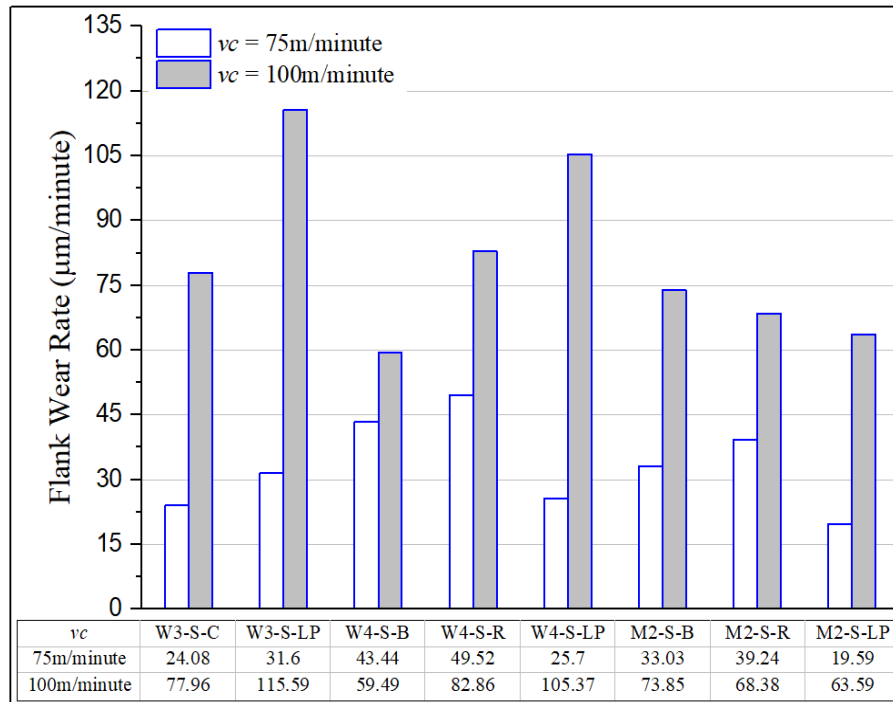


Figure 5.34. Variation in flank wear rate for cutting tool inserts with increase in vc from 75m/minute to 100m/minute, at ap of 0.5mm.

Although the W3-L-B insert had a negligible FWR (Table 5.13), significantly higher FWRs of $64.45\mu\text{m/minute}$ and $56.27\mu\text{m/minute}$ were observed for the W4-L-B and M2-L-B inserts respectively (Table 5.13). The spark plasma sintered W3-S-B and M2-S-B inserts had slightly higher FWRs compared to their LPS counterparts (Table 5.13). In the laser peened category, the W3-L-LP maintained a negligible flank wear rate, while the W4-L-LP insert had the highest FWR of $115.59\mu\text{m/minute}$ during milling at vc of 100m/minute and ap of 0.5mm (Figure 5.35). Apart from the W4-S-LP, the spark plasma sintered - LP inserts had significantly higher flank wear rates compared to their LPS counterparts (Table 5.13 and Figure 5.36). In comparison to their blank counterparts the W3-S-LP, M2-L-LP and M2-S-LP inserts had slightly lower flank wear rates (Figure 5.36).

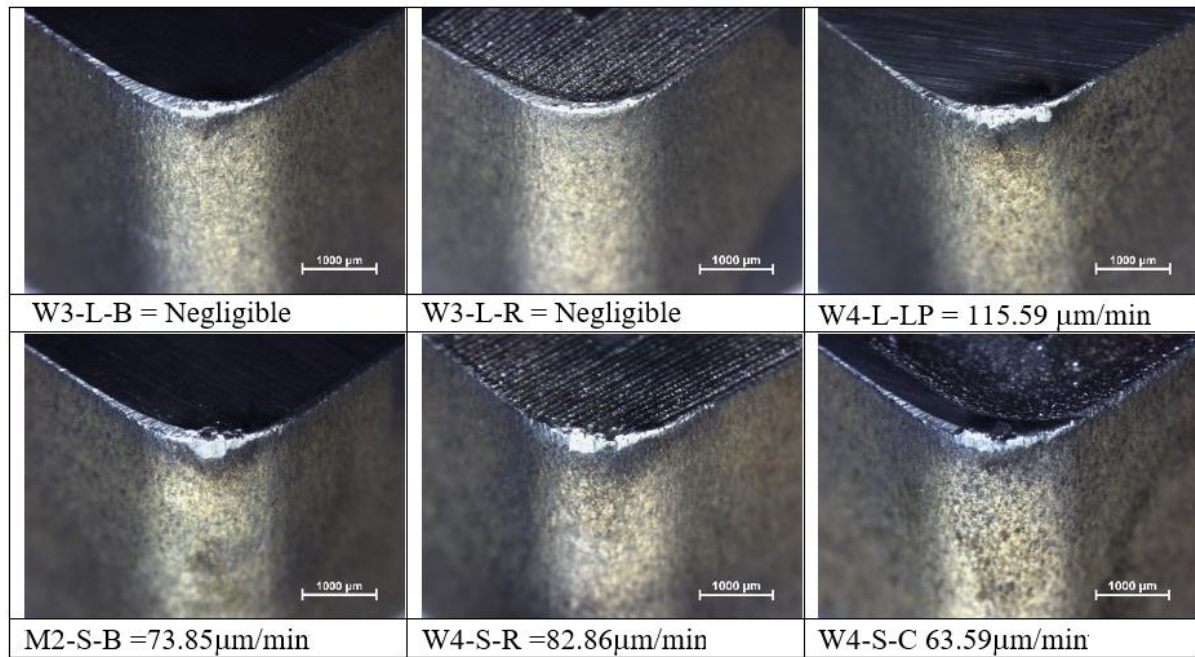


Figure 5.35 Micrographs of the W3-L-B, W3-L-R, W4-L-LP, M2-S-B, W4-S-R, and W4-S-C cutting tool inserts after milling at v_c of 100m/minute and a_p of 0.5mm.

It was noticed that the introduction of ridges resulted in significantly lower flank wear rates for the liquid phase sintered inserts (Figure 3.36). The W3-L-R insert maintained a negligible FWR (Table 5.13), while the W4-L-R and M2-L-R insert inserts had slightly lower FWRs of 20.46µm/minute and 41.03µm/minute respectively (Table 5.13). This was not the case for the spark plasma sintered – ridges inserts as their flank wear rates significantly increased (Figure 3.36). Apart from the W4-L-C insert which had a negligible flank wear rate (Table 5.13), all the chip breaker inserts had slightly higher FWR compared to their blank counterparts (Table 5.13 and Figure 5.36).

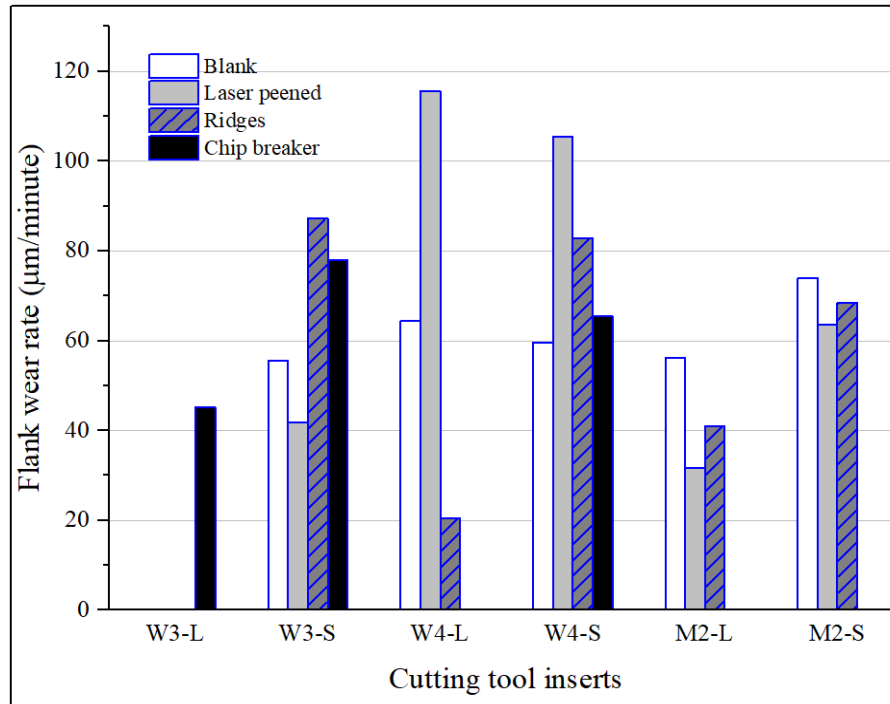


Figure 5.36. Comparison of flank wear rates for cutting tool inserts during milling at v_c of 100m/minute and a_p of 0.5mm.

5.3.4 Analysis of tool wear at cutting of 120m/minute

At v_c of 120m/minute and a_p of 0.5mm, the W4-L-B insert had a slightly lower FWR than the W3-L-B and M2-L-B insert (Table 5.14 and Figure 5.37). The effect of SPS on the performance of the cutting tool inserts could be clearly seen on the W4-S-B and M2-S-B inserts, as they both had higher flank wear rates compared to their LPS counterparts (Figure 5.37). Apart from the W3-L-R insert which had the lowest FWR of 41.85µm/minute during milling at v_c of 120m/minute and a_p of 0.5mm, all the ridges inserts had higher flank wear than their blank counterparts (Table 5.15 and Figure 5.37).

5.3.5 Analysis of tool wear at cutting of 300m/minute

The cutting tool inserts had significantly higher flank wear rates with increase in cutting speed from 120m/minute to 300m/minute (Table 5.15 and Figure 5.38). The W4-L-B insert

had the lowest FWR of 304.72 $\mu\text{m}/\text{minute}$, followed by the W3-L-B inserts with a FWR of 341.62 $\mu\text{m}/\text{minute}$ at v_c of 300m/minute and a_p of 0.5mm (Table 5.15 and Figure 5.38).

Table 5.14. Experimental results of flank wear rates during milling at v_c of 120m/minute

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Flank wear rate ($\mu\text{m}/\text{min}$)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	120	0.5	51.70	-	41.85	-
2	W3-S	120	0.5	53.39	-	72.04	-
3	W4-L	120	0.5	46.16	-	54.78	-
4	W4-S	120	0.5	80.42	-	94.39	-
5	M2-L	120	0.5	47.87	-	55.13	-
6	M2-S	120	0.5	69.76	-	71.39	-

* L = liquid phase sintering, S=spark plasma sintering, v_c = Cutting speed (m/minute),
 a_p = Depth of cut (mm).

Table 5.15. Experimental results of flank wear rates during milling at v_c of 300m/minute

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Flank wear rate ($\mu\text{m}/\text{min}$)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	300	0.5	341.62	-	-	-
2	W4-L	300	0.5	304.72	-	-	-
3	M2-L	300	0.5	561.61	-	-	-

* L = liquid phase sintering, S=spark plasma sintering, v_c = Cutting speed (m/minute),
 a_p = Depth of cut (mm).

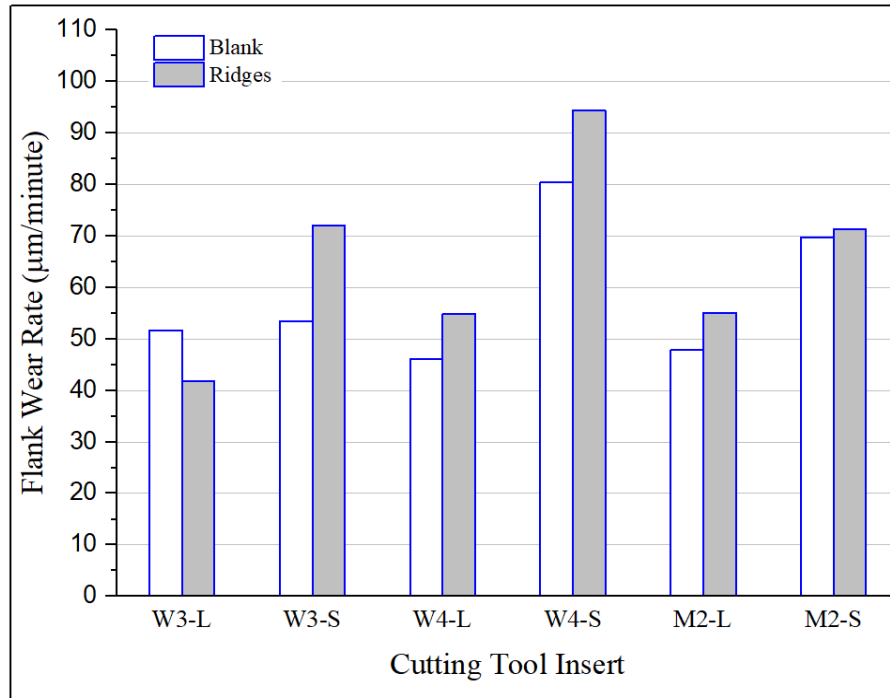


Figure 5.37. Comparison of flank wear rates for cutting tool inserts during milling at vc of 120m/minute and ap of 0.5mm.

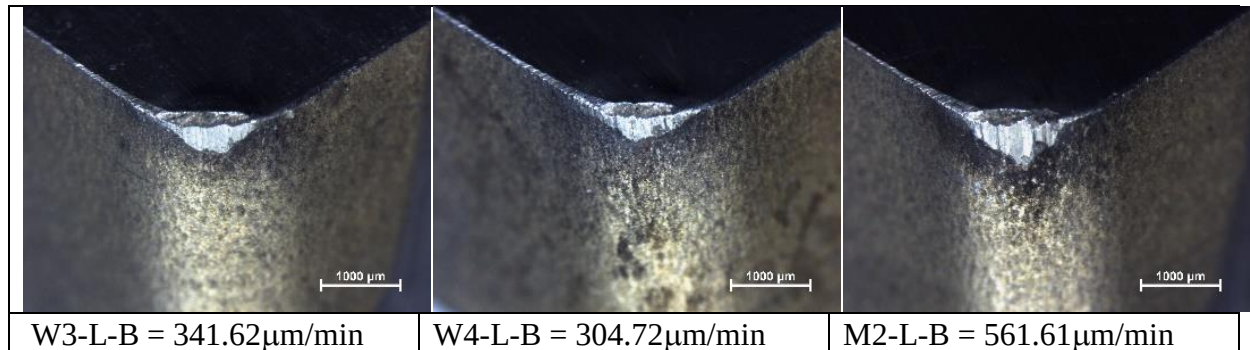


Figure 5.38. Micrographs of cutting tool inserts after milling at a vc of 300m/minute and ap of 0.5mm

Cutting edge – workpiece interface energy-dispersive x-ray spectroscopy (EDS) analysis of the cutting tool flanks after milling at vc of 300m/minute and of 0.5mm identified the occurrence of diffusive wear through the evolution of the chemical composition at the interface between the cutting tool and workpiece material (Figure 5.9). Diffusion profiles were obtained along the line located in the adhesion zone and inside the worn cutting tool.

The EDS analysis of these profiles (Figure 5.39 and 5.40) shows that chemical species evolved from the interface between the Ti-6Al-4V workpiece and the tool surface. This confirmed that diffusive wear occurred between the machined titanium alloys and cutting tool inserts.

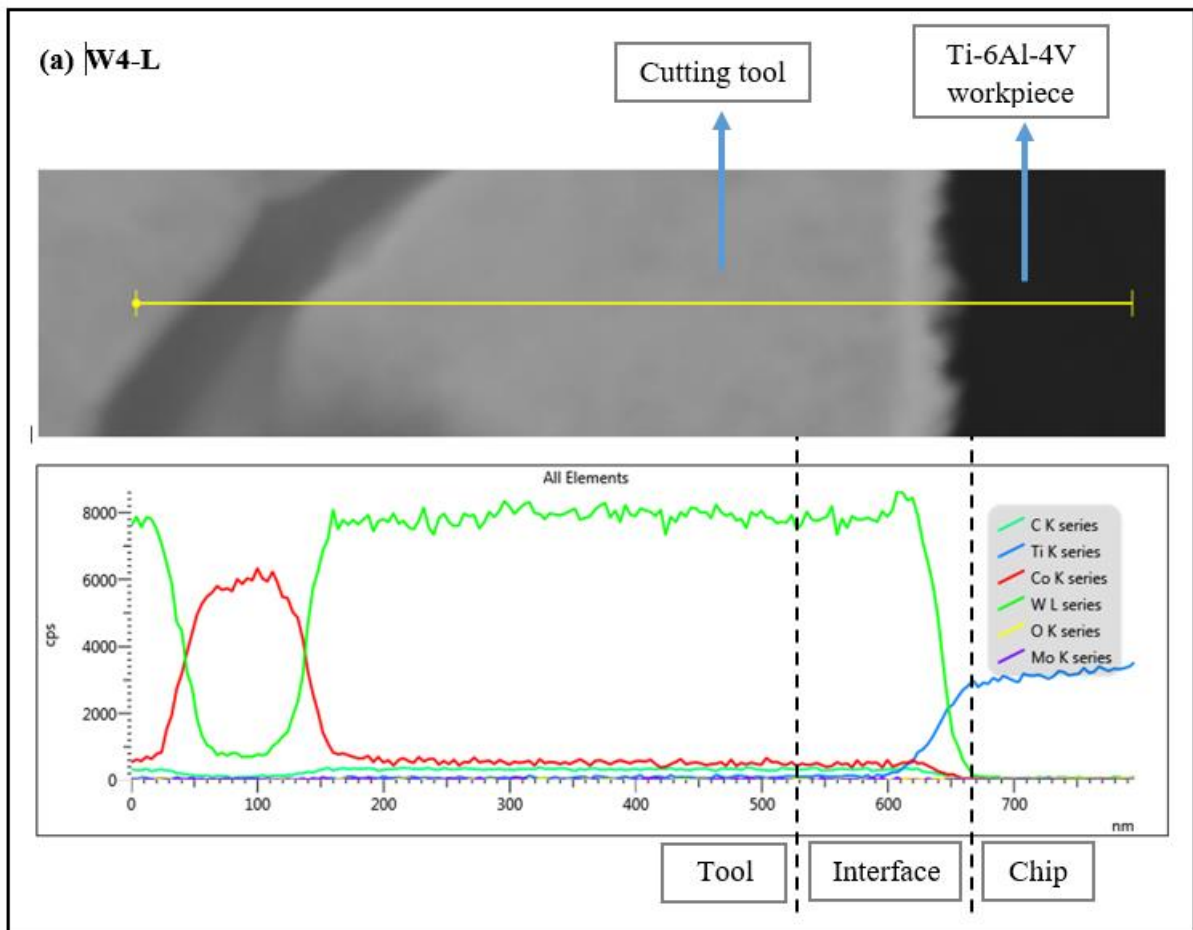


Figure 5.39 Diffusion profiles obtained at the tool-chip interface by EDS surface analysis along lines in the tool-chip interface and inside the cutting tool after milling at v_c of 300m/minute and a_p of 0.5mm with the W4-L insert

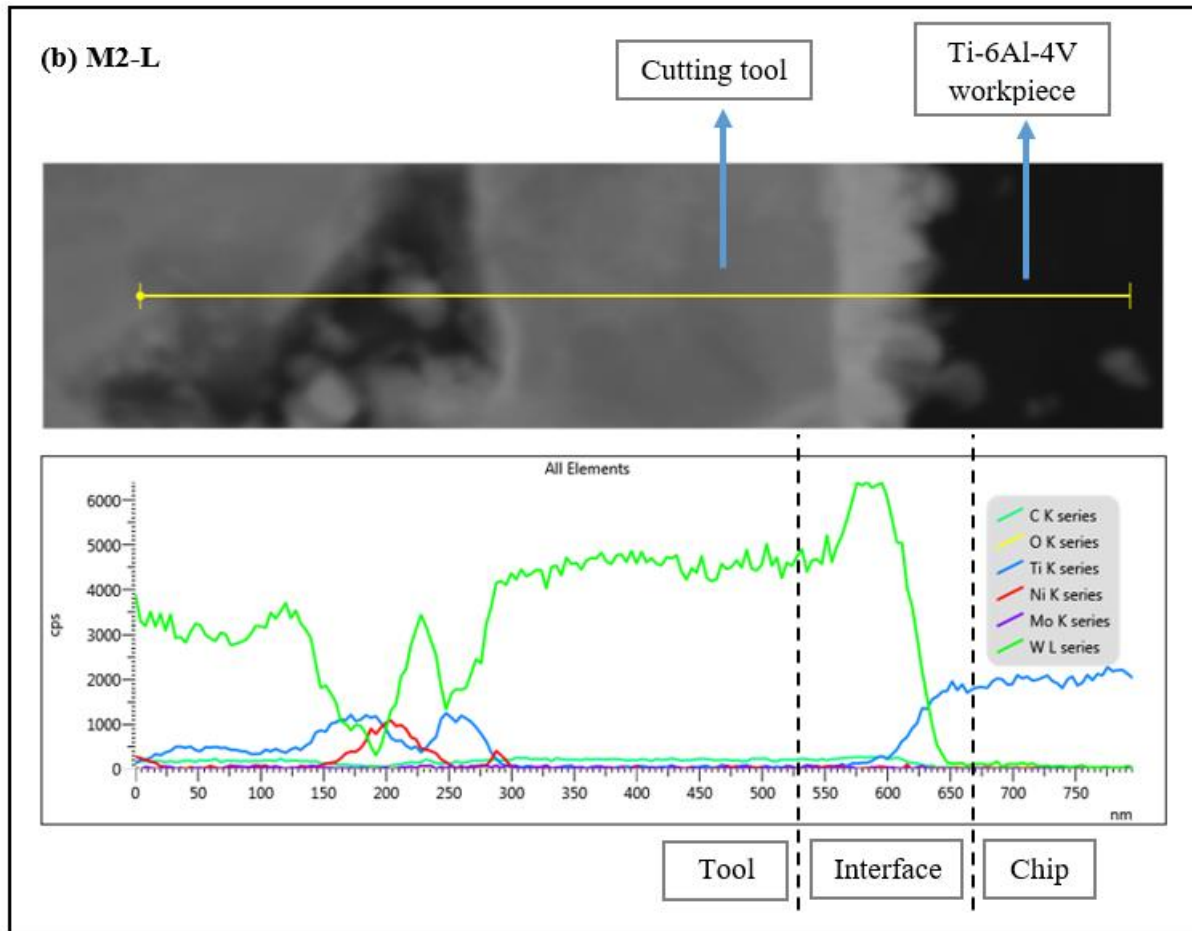


Figure 5.40 Diffusion profiles obtained at the tool-chip interface by EDS surface analysis along lines in the tool-chip interface and inside the cutting tool after milling at vc of 300m/minute and ap of 0.5mm with the M2-L insert

5.4 Chip Formation

To determine the nature of chips produced by the different cutting tool compositions and the various cutting tool edges, chips were collected during each machining trial. However, optical analysis was only carried out on the following process parameters; at vc of 60m/minute and ap of 1.5mm, at vc of 75m/minute and ap of 0.5mm, and at vc of 100m/minute and ap of 0.5mm. This is because all the tool types and cutting edges were utilised at these parameters.

5.4.1 Analysis of milling chips at v_c of 60m/minute and a_p of 1.5mm

At v_c of 60m/minute and a_p of 1.5mm, all the blank cutting tool inserts, with exception of the M2-S-B and W4-S-B inserts produced snarled ribbon chips (SNR) (Table 5.16 and Figure 5.41). The spark plasma sintered M2-S-B and W4-S-B inserts produced snarled tubular chips (SNT) (Table 5.16 and Figure 5.41). The laser peening of the inserts resulted in various chip forms (Figure 5.41). The W3-L-LP and M2-L-LP inserts produced SNT, while the W4-L-LP insert produced concentrated arc chips (CA) (Table 5.16). All the spark plasma sintered - laser peened inserts had SNR (Table 5.16 and Figure 5.41). The chip forms were also different for the ridges inserts (Figure 5.41), with the W3-L-R insert producing CA and the W4-L-R, W4-S-R and M2-S-R inserts all producing SNR (Table 5.17 and Figure 5.41). The introduction of chip breakers resulted in CA chips for the M2-S-B insert and SNR for the W3-L-C, W3-S-R and W4-S-R inserts (Table 5.16 and Figure 5.41). Only the W4-L-C insert produced long ribbon chips at v_c of 60m/minute and a_p of 1.5mm (LR) (Table 5.16 and Figure 5.41).

Table 5.16. Experimental results of chip form at v_c of 60m/minute and a_p of 1.5mm

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Chip form			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	60	1.5	SNR	SNT	CA	SNR
2	W3-S	60	1.5	SNR	SNR	SNT	SNR
3	W4-L	60	1.5	SNR	CA	SNR	LR
4	W4-S	60	1.5	SNT	SNR	SNR	SNR
5	M2-L	60	1.5	SNR	SNT	SNT	SNT
6	M2-S	60	1.5	SNT	SNR	SNR	CA

*LR = Long Ribbon Chips; SNR=Snarled Ribbon Chips; SNT = Snarled Tubular Chip
CA = Concentrated Arc Chips

5.4.2 Analysis of milling chips at v_c of 75m/minute and a_p of 1.5mm

At a higher cutting speed of 75m/minute and lower depth of cut of 0.5mm, all the blank inserts produced SNT chips (Table 5.17). Apart from the M2-L-LP and W4-L-LP inserts, all

the laser peened inserts also produced SNT (Table 5.17). The M2-L-LP insert produced flat conical chips (FC), while the W4-L-LP insert produced SNR chips (Table 5.17). The introduction of ridges resulted in snarled ribbon chips for the W4 inserts and snarled tubular chips for the W3 and M2 inserts (Table 5.17). In the chip breaker category, the W3 inserts had snarled tubular chips, while the W4-L-C and W4-S-C inserts produced short ribbon chips and concentrated arc chips respectively (Table 5.17).

Table 5.17. Experimental results of chip form at v_c of 75m/minute and a_p of 0.5mm

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Chip Form			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	75	0.5	SNT	SNT	SNT	SNT
2	W3-S	75	0.5	SNT	SNT	SNT	SNT
3	W4-L	75	0.5	SNT	SNR	SNR	SR
4	W4-S	75	0.5	SNT	SNT	SNR	SNR
5	M2-L	75	0.5	SNT	FC	SNT	-
6	M2-S	75	0.5	SNT	SNT	SNT	-

* SR = Short Ribbon Chips; SNT = Snarled Tubular Chips; CA = Concentrated Arc Chips; FC = Flat Conical Chips

5.4.3 Analysis of milling chips at v_c of 100m/minute and a_p of 0.5mm

At v_c of 100m/minute and a_p of 0.5mm, all the blank cutting tools with exception of the W4-L-B insert produced snarled tubular chips (Table 5.18 and Figure 5.42).

Table 5.18. Experimental results of chip form at v_c of 100m/minute and a_p of 0.5mm.

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Chip Form			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	100	0.5	SNT	FC	SNT	SNR
2	W3-S	100	0.5	SNT	SNT	SNT	SNT
3	W4-L	100	0.5	SNR	SNT	SNT	SNR
4	W4-S	100	0.5	SNT	SNT	SNT	SNT
5	M2-L	100	0.5	SNT	SNT	SNT	-
6	M2-S	100	0.5	SNT	FC	SNT	-

* SR = Short Ribbon Chips; SNR=Snarled Ribbon Chips; SNT = Snarled Tubular Chips; FC = Flat Conical Chips

The chip form for the laser peened cutting tool inserts were varied (Table 5.18). The W3-L-LP and M2-L-LP inserts which produced SNT (Table 5.18 and Figure 5.42), while the W3-L-LP and M2-S-LP inserts produced flat conical (FC) chips (Table 5.18 and Figure 5.42). Snarled tubular chips was produced by all the ridges inserts (Table 5.18 and Figure 5.42). The liquid phase sintered chip breaker tools produced SNR while their spark plasma sintered counterparts produced SNT (Table 5.18 and Figure 5.42).

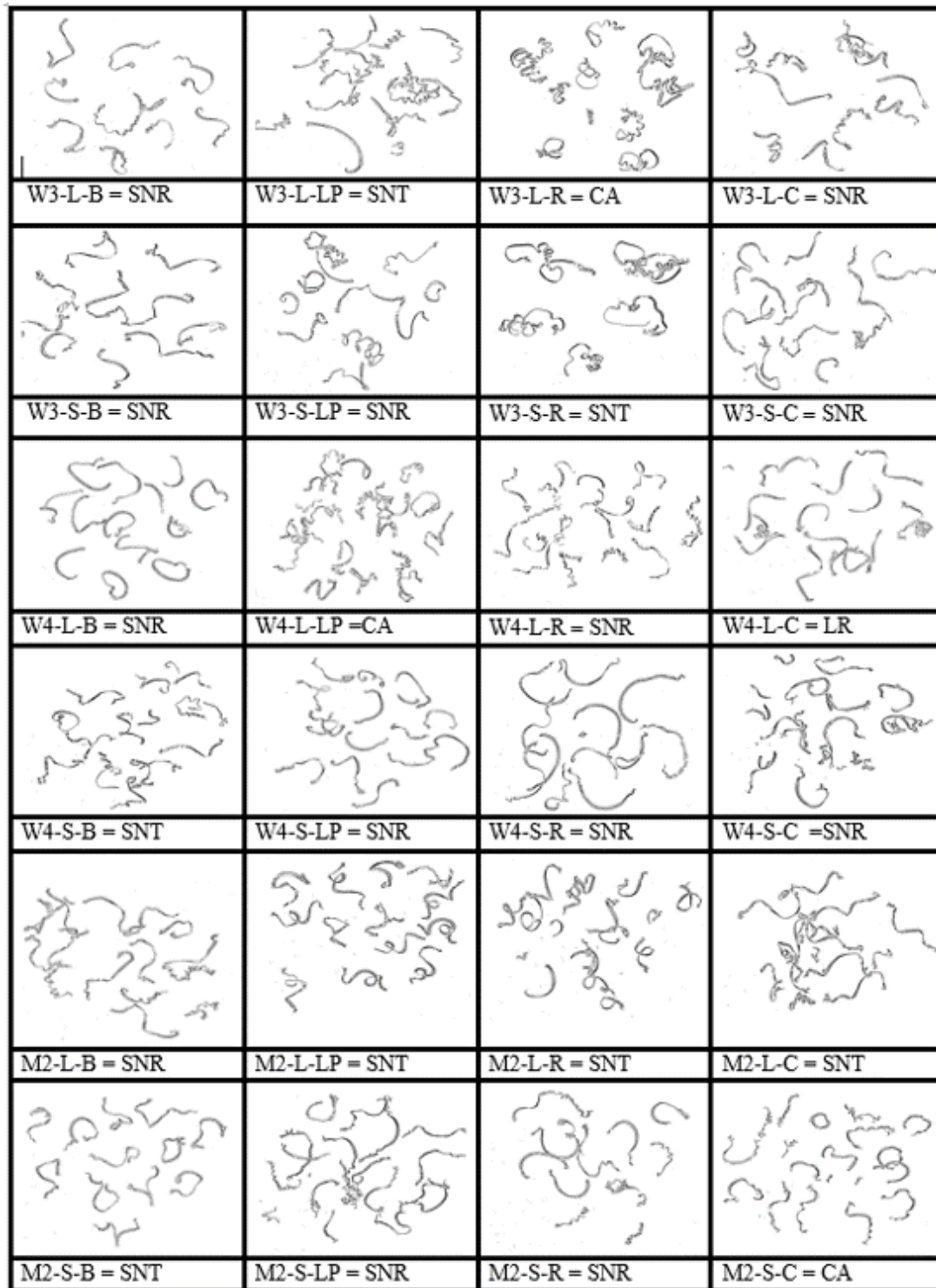


Figure 5.41. Micrographs of chips obtained during milling at vc of 60m/minute and ap of 1.5mm.

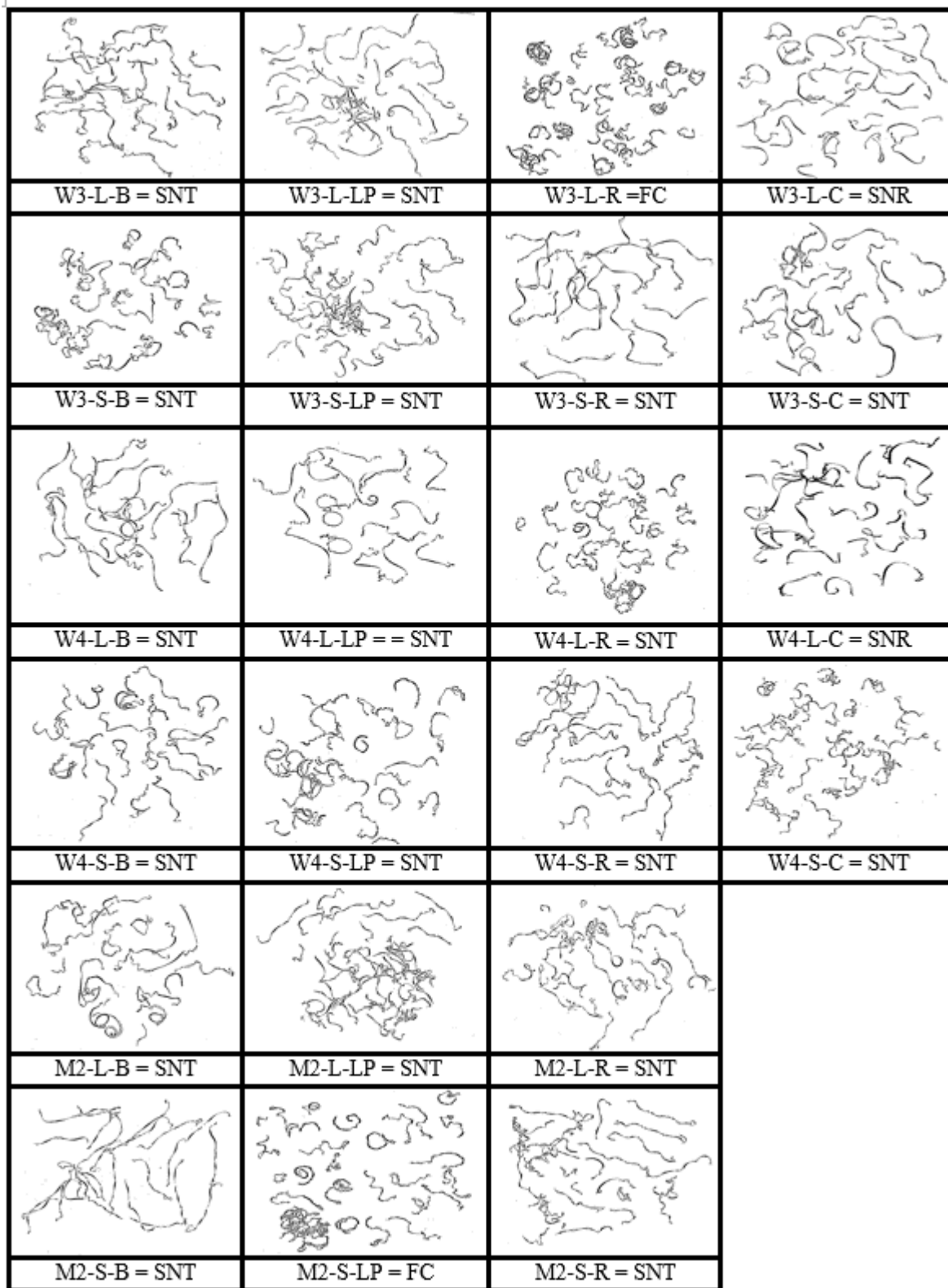


Figure 5.42. Micrographs of chips obtained during milling at v_c of 100m/minute and a_p of 1.5mm.

5.5 Surface Roughness

The surface finish of the workpiece material is an important parameter during machining, as it influences both the performance of the material and as well as production cost. Various failure mechanisms can also be attributed to poor surface finishing. As a test of productivity, it was important to investigate the influence of milling parameters and cutting tool inserts on the surface roughnesses of the Ti-6Al-4V workpieces during semi-finishing and finishing milling trials. The qualifying standard of measuring the Ti-6Al-4V workpiece surfaces remained the average roughness (Ra) which is widely used in industry.

5.5.1 Analysis of surface roughness at *vc* of 75m/minute and *ap* of 0.5mm

At *vc* of 75m/minute and *ap* of 0.5mm, the W3-L-B and W4-L-B inserts produced very similar surface roughness of $0.92 \pm 0.02\mu\text{m}$ and $0.83 \pm 0.05\mu\text{m}$ respectively (Table 5.19 and Figure 5.43). The surface roughness produced by the SPS inserts were lower compared to that of their LPS counterparts (Figure 5.43). The M2-S-B insert produced the lowest surface roughness of $0.49 \pm 0.02\mu\text{m}$ during milling at *vc* of 75m/minute and *ap* of 0.5mm (Table 5.19). The laser peening of the inserts generally resulted in slightly higher surface roughnesses (Figure 5.43). The surface roughnesses for the W3-S-LP and M2-S-LP inserts were lower than that of their liquid phase sintered counterparts (Figure 5.43). The effect of ridges on roughness was clearly seen with the liquid phase sintered - ridges inserts producing significantly lower surface roughnesses than their blank counterparts (Figure 5.43). In the ridges category, the LPS inserts had lower surface roughnesses than their SPS counterparts, with the W3-L-R having the lowest surface roughness of $0.58 \pm 0.03\mu\text{m}$ (Table 5.19 and Figure 5.43). The effect of chip breaker on roughness was also noticed with lower surface roughnesses produced by all the chip breaker cutting tool inserts except the W4-S-C (Table 5.20 and Figure 5.43). No trend could be established between the roughness of the chip

breaker inserts and their sintering technique. The W3-S-C had the lowest roughness of $0.60 \pm 0.05\mu\text{m}$ in the chip breaker category (Table 5.20 and Figure 5.43).

Table 5.19. Experimental results of surface roughnesses at v_c of 75m/minute and a_p of 0.5mm

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Surface roughness (μm)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	75	0.5	0.92 ± 0.02	1.02 ± 0.02	0.58 ± 0.03	0.76 ± 0.05
2	W3-S	75	0.5	0.78 ± 0.06	0.95 ± 0.05	0.76 ± 0.03	0.60 ± 0.05
3	W4-L	75	0.5	0.83 ± 0.05	0.85 ± 0.05	0.73 ± 0.06	0.75 ± 0.04
4	W4-S	75	0.5	0.56 ± 0.06	1.36 ± 0.01	0.83 ± 0.05	1.17 ± 0.06
5	M2-L	75	0.5	1.06 ± 0.05	1.20 ± 0.04	0.84 ± 0.10	0.82 ± 0.02
6	M2-S	75	0.5	0.49 ± 0.02	0.65 ± 0.03	0.97 ± 0.03	-

* L = liquid phase sintering, S=spark plasma sintering, v_c = Cutting speed (m/minute), a_p = Depth of cut (mm).

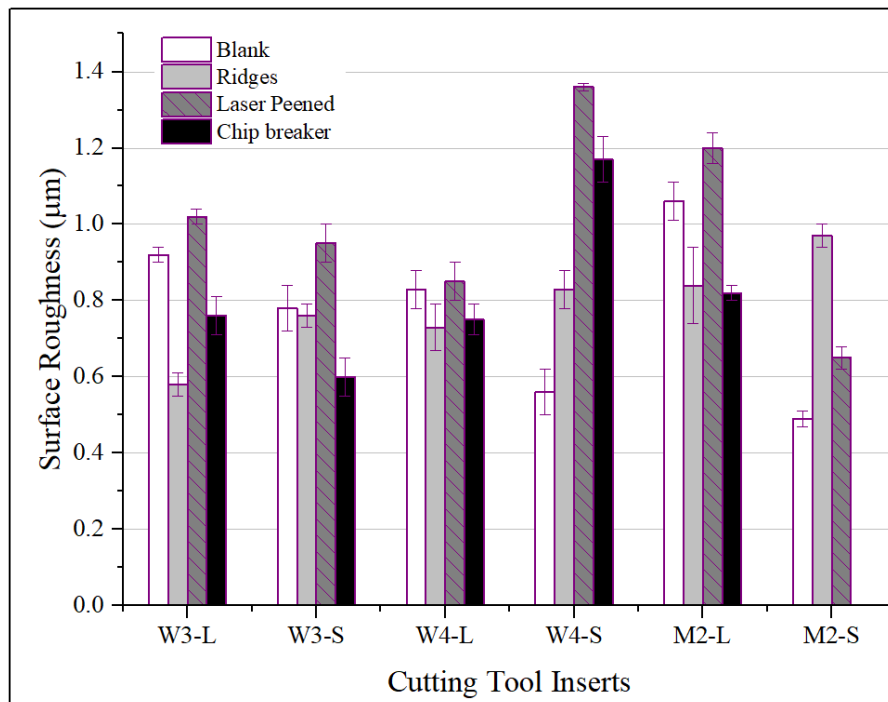


Figure 5.43. Comparison of surface roughness produced by cutting tool inserts during milling at v_c of 75m/minute and a_p of 0.5mm.

5.5.2 Analysis of surface roughness at v_c of 100m/minute and a_p of 0.5mm

Increased cutting speed from 75m/minute to 100m/minute at depth of cut of 0.5mm resulted in slightly lower surface roughnesses for the liquid phase sintered – blank inserts (Table 5.19 and 5.20). The surface roughness for W4-L-B insert was slightly lower than that of the W3-L-B and M2-L-B inserts (Figure 5.44). Apart from the W3-S-B insert, all the SPS inserts produced lower surface roughness than their LPS counterparts (Figure 5.44). The W4-S-B produced the lowest surface roughness of $0.43 \pm 0.02\mu\text{m}$ during milling at v_c of 100m/minute and a_p of 0.5mm (Table 5.21). In the laser peened category, the W3-L-LP insert produced a slightly lower surface roughness than the W4-L-LP and M2-L-LP inserts (Figure 5.44). Except for the M2-S-LP insert which had the lowest surface roughness of $0.52 \pm 0.05\mu\text{m}$ in the laser peened category, the surface roughness for the spark plasma sintered - LP inserts were generally higher than that of their LPS counterparts (Figure 5.44). The effect of ridges on the W3 inserts was clearly seen with decreased surface roughnesses (Figure 5.44). All the other ridges inserts had higher surface roughnesses compared to their blank counterpart (Figure 5.44). Contrary to the behavioural trends exhibited by the ridges inserts, the introduction of chip breakers increased the surface roughnesses produced by the W3-L-C insert (Figure 5.44). Although other chip breaker inserts followed suit with higher surface roughnesses, the W3-S-C was the only exception with a lower surface roughness of $0.53 \pm 0.05\mu\text{m}$ (Table 5.20 and Figure 5.44). Figure 4.45 shows the best and worst surface roughness per cutting tool category after milling at v_c of 100m/minute and a_p of 0.5mm.

Table 5.20. Experimental results of surface roughnesses at v_c of 100 m/minute and a_p of 0.5 mm

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Surface roughness (μm)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	100	0.5	0.83 ± 0.02	0.76 ± 0.07	0.73 ± 0.03	1.45 ± 0.06
2	W3-S	100	0.5	1.65 ± 0.06	1.28 ± 0.05	0.75 ± 0.03	0.53 ± 0.05
3	W4-L	100	0.5	0.64 ± 0.02	1.04 ± 0.04	1.05 ± 0.02	0.81 ± 0.01
4	W4-S	100	0.5	0.43 ± 0.04	1.11 ± 0.07	1.36 ± 0.05	1.24 ± 0.08
5	M2-L	100	0.5	0.79 ± 0.04	1.21 ± 0.06	0.76 ± 0.04	-
6	M2-S	100	0.5	0.57 ± 0.02	0.52 ± 0.05	1.33 ± 0.03	-

* L = liquid phase sintering, S=spark plasma sintering, v_c = Cutting speed (m/minute),
 a_p = Depth of cut (mm).

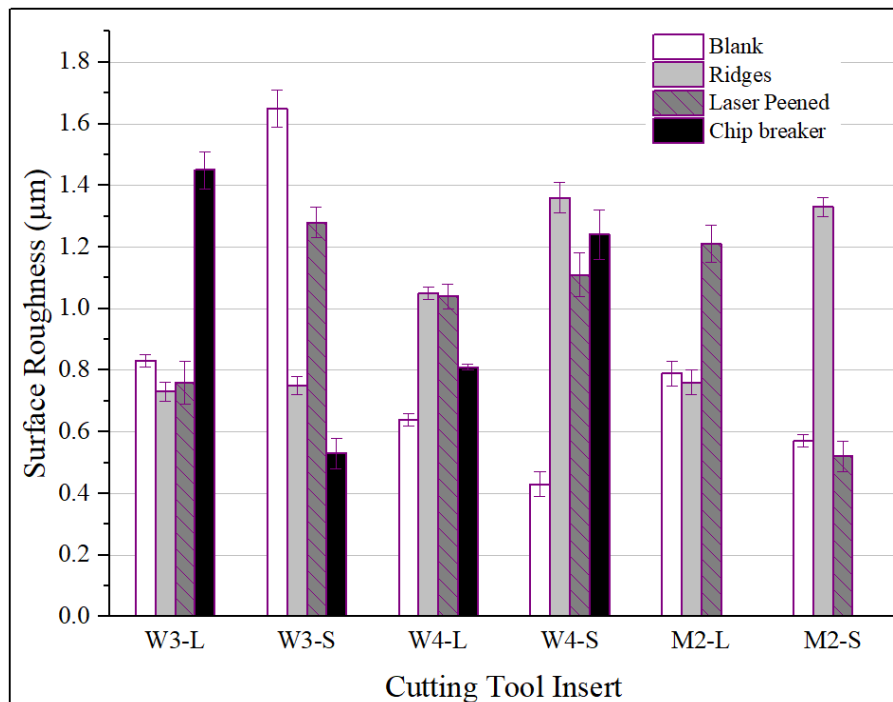


Figure 5.44. Comparison of surface roughness produced by cutting tool inserts during milling at v_c of 100m/minute and a_p of 0.5mm.

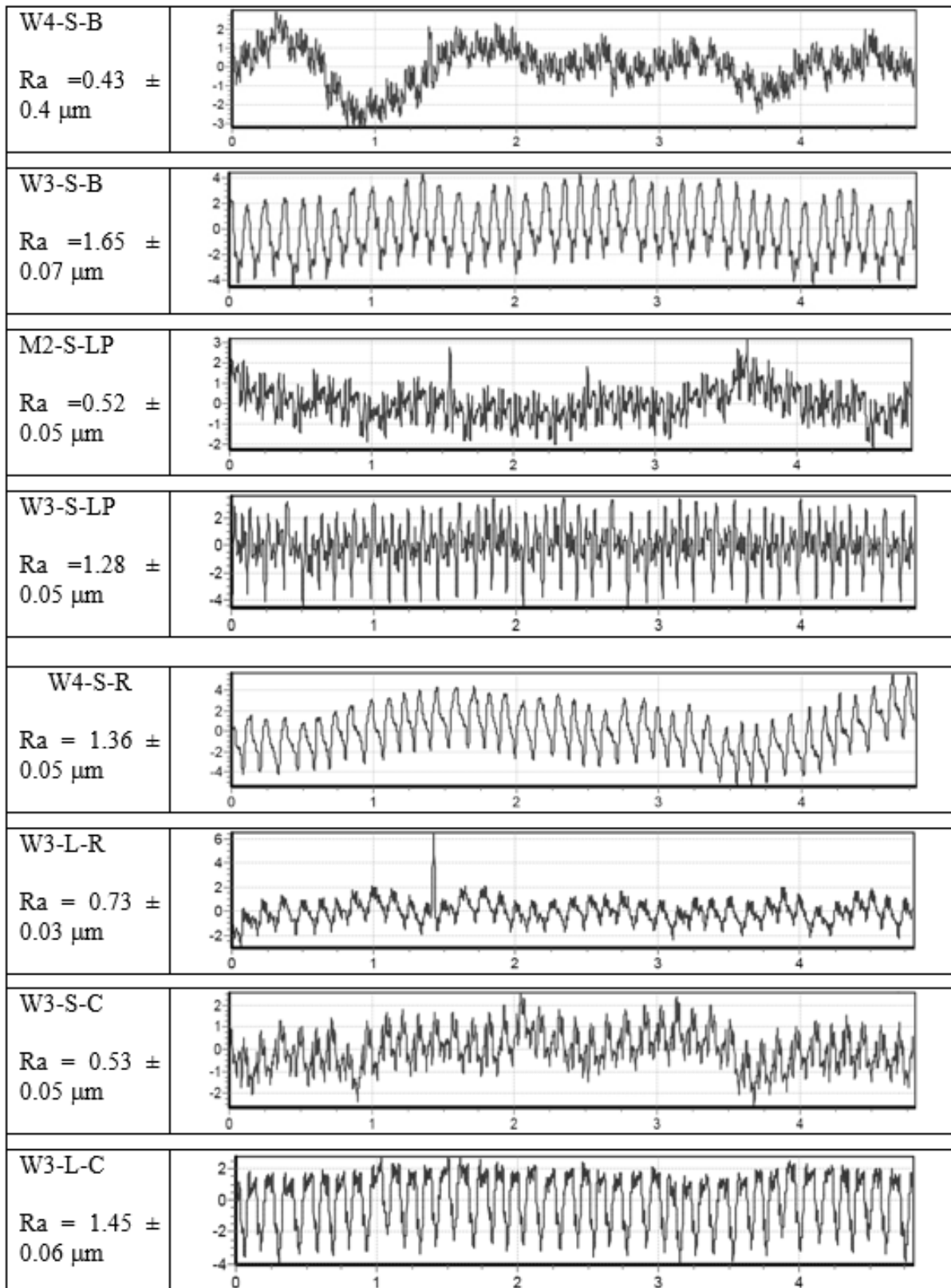


Figure 5.45 Best and worst roughness profiles for Ti-6Al-4V workpieces after face milling at vc of 100 m/minute and ap of 0.5 mm.

5.5.3 Analysis of surface roughness at v_c of 120m/minute and a_p of 0.5mm

Increased v_c from 100m/minute to 120m/minute generally resulted in higher surface roughnesses for the cutting tool inserts (Table 5.21 and Figure 5.46). The samples machined by the W3-L-B and W4-L-B insert produced similar surface roughnesses of $1.15 \pm 0.08\mu\text{m}$ and $1.11 \pm 0.08\mu\text{m}$ respectively, while the M2-L-B insert produced a slightly higher surface roughness of $1.39 \pm 0.03\mu\text{m}$ (Figure 5.47). The lowest surface roughness of $0.48 \pm 0.01\mu\text{m}$ during milling at v_c of 120m/minute and a_p of 0.5mm was produced by the M2-S-B insert (Table 5.21). The introduction of ridges led to significantly lower surface roughnesses for the W3-L-R, W3-S-R and W4-L-R inserts (Figure 5.47). All the other inserts produced higher surface roughnesses with the introduction of ridges (Table 5.21 and Figure 5.47).

Table 5.21. Experimental results of surface roughnesses at v_c of 120 m/minute and a_p of 0.5 mm

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Surface roughness (μm)			
				Blanks (B)	Laser peened (LP)	Ridges (R)	Chip breaker (C)
1	W3-L	120	0.5	1.15 ± 0.08	-	0.59 ± 0.02	-
2	W3-S	120	0.5	1.36 ± 0.01	-	0.95 ± 0.02	-
3	W4-L	120	0.5	1.11 ± 0.08	-	1.00 ± 0.02	-
4	W4-S	120	0.5	0.54 ± 0.06	-	1.29 ± 0.03	-
5	M2-L	120	0.5	1.39 ± 0.03	-	1.60 ± 0.03	-
6	M2-S	120	0.5	0.48 ± 0.01	-	1.81 ± 0.07	-

* L = liquid phase sintering, S=spark plasma sintering, v_c = Cutting speed (m/minute),
 a_p = Depth of cut (mm).

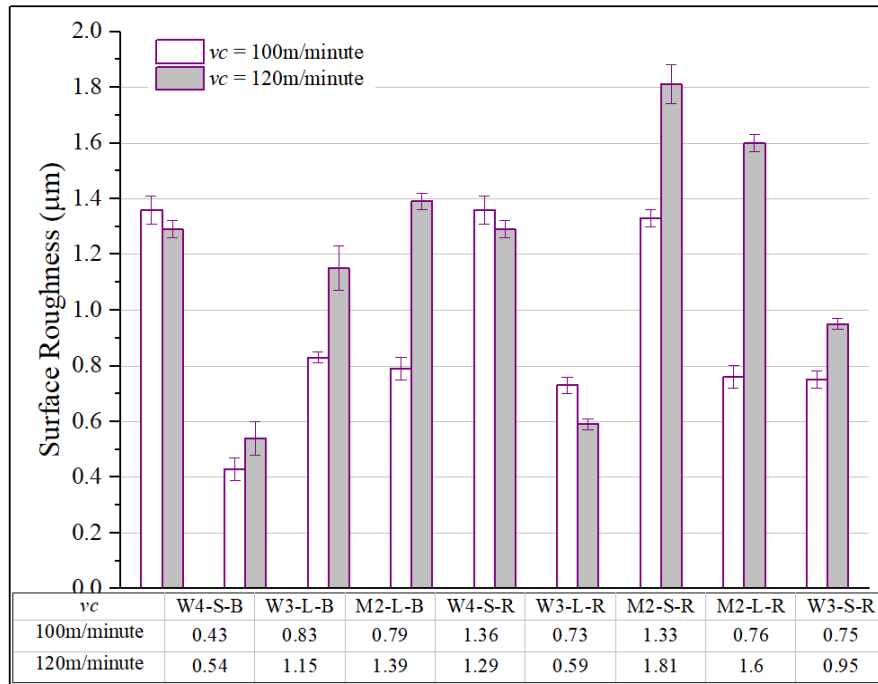


Figure 5.46. Comparison of surface roughness produced by cutting tool inserts with increase in vc from 100m/minute to 120m/minute, at ap of 0.5mm.

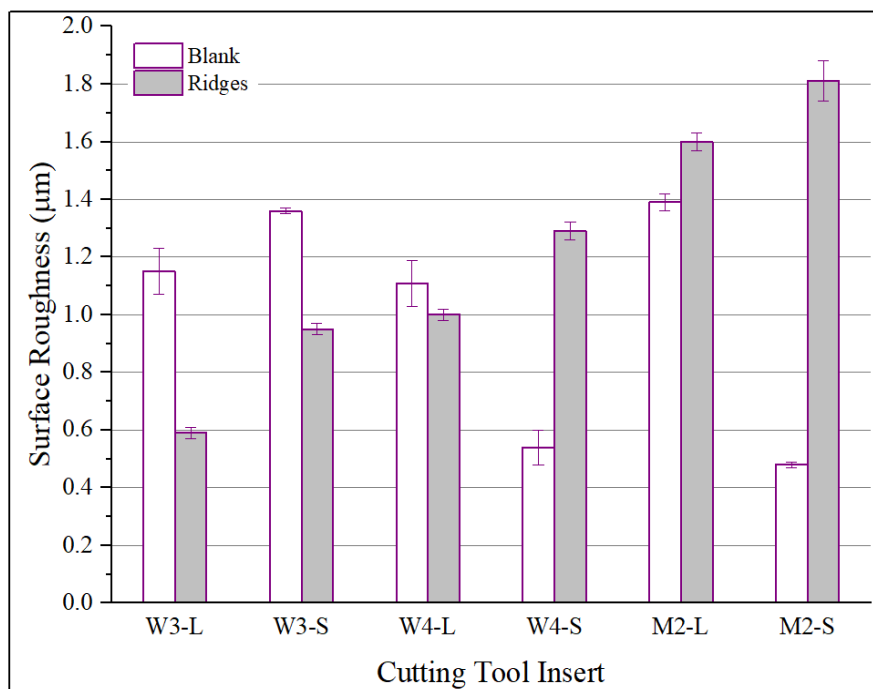


Figure 5.47. Comparison of surface roughness produced by cutting tool inserts during milling at vc of 120m/minute and ap of 0.5mm.

5.5.4 Analysis of surface roughness at v_c of 300m/minute and a_p of 0.5mm

A further increase in v_c to 300m/minute resulted in higher surface roughness for all the cutting inserts (Table 5.22). The M2-L-B insert had the lowest surface roughness of $1.19 \pm 0.01\mu\text{m}$ followed by the W4-L-B with a surface roughness of $1.33 \pm 0.03\mu\text{m}$ (Table 5.22).

Table 5.22. Experimental results of surface roughnesses at v_c of 300 m/minute and a_p of 0.5 mm

Trial	Sample Abbreviation	v_c [m/min]	a_p [mm]	Surface roughness (μm)			
				Blanks (B)	Ridges (R)	Laser peened (LP)	Chip breaker (C)
1	W3-L	300	0.5	1.56 ± 0.04	-	-	-
2	W4-L	300	0.5	1.33 ± 0.03	-	-	-
3	M2-L	300	0.5	1.19 ± 0.01	-	-	-

* L = liquid phase sintering, S=spark plasma sintering, v_c = Cutting speed (m/minute), a_p = Depth of cut (mm).

6 Discussion

6.1 Microstructure of WC cemented carbides

The spark plasma sintered WC-0.5Cr₃C₂-10Co (wt%) had smaller WC grains compared to their liquid phase sintered counterparts (Table 4.1 and Figure 4.1). This was due to the shorter sintering time and lower sintering temperature which reduced Ostwald ripening and coalescence (Table 3.3) [1998Upa]. Contrariwise, the liquid phase sintered WC-0.5Cr₃C₂-10Co (wt%) had larger WC grains because of the higher sintering temperature and longer sintering time (Table 3.3), thus promoting Ostwald ripening and coalescence [1998Upa, 2005Cha]. The addition of Mo₂C (wt%) to WC-0.5Cr₂C₃-10Co (wt%) inhibited grain growth, resulting in finer WC grain (Table 4.1 and Figure 4.3). This is because Mo₂C (wt%) has a very low solubility in WC resulting in difference in interfacial free energies and precipitation of inhibitor at the WC grains interface [2002Gil, 2008Guo]. The spark plasma sintered WC-0.5Cr₃C₂-Mo₂C-10Co (wt%) had smaller grain sizes because of the shorter sintering time and lower sintering temperature [Table 3.3]. During cemented carbide production, increased sintering temperature and longer sintering times result in increased Ostwald ripening, and coalescence which promotes grain growth [1998Upa, 2005Cha]. The smallest grain size of $0.45 \pm 0.02 \mu\text{m}$ for the spark plasma sintered WC-0.5Cr₃C₂-Mo₂C-10Ni (wt%) (Table 4.1 and Figure 4.4) was due to the better wettability of WC by Ni with Mo₂C (wt%) additions [2008Guo]. Laser shock peening of the sintered samples had negligible effect on grain sizes (Figure 4.1). This contradicts reports presented by Hong and Chengye in experiments with aluminium alloys where grain refinement was evident after laser peening [1998Hon].

6.2 Mechanical properties of WC cemented carbides

6.2.1 Hardness:

The spark plasma sintered samples had higher Vickers hardness than their liquid phase sintered counterparts in all compositions (Table 4.3). This was because the SPS inserts had more refined WC grains (Figure 4.1 and Figure 6.1), as a result of their shorter sintering times and lower sintering temperatures (Table 3.2) [1975Bro]. This trend confirms the Hall-petch effect which upholds that as grain size decreases, hardness and yield strength increases [1998Upa]. Also, for smaller grains, a small repulsion stress is felt by a grain boundary dislocation, and a higher stress is required to propagate dislocations through the material [2002Ste].

The addition of 3.5Mo₂C (wt%) to the WC-0.5Cr₃C₂-10Co (wt%) increased hardness for both the LPS and SPS samples (Table 4.3 and Figure 4.7). This is because Mo₂C (wt%) is a good grain growth inhibitor which reduces average WC grain size and shape [1998Upa, 2019Gra]. Additionally, the hardness and transverse rupture strength of cemented carbides primarily depends on their average grain size, with finer WC grains possessing higher hardness and transverse rupture strength [2003Zha]. Binder substitution of 10Co (wt%) with 10Ni (wt%) resulted in a lower hardness for the liquid phase sintered WC-0.5Cr₃C₂-Mo₂C-10Ni (wt%), and a slightly similar hardness for the spark plasma sintered WC-0.5Cr₃C₂-Mo₂C-10Ni (wt%) (Table 4.3 and Figure 4.7). This conforms to findings by Penrice [1987Pen]; that WC-Ni (wt%) alloys are appreciably lower in strength and hardness than WC-Co (wt%) of similar composition.

Generally, laser peening slightly increased the hardness of the sintered samples (Table 4.4 and Figure 4.8). This was attributed to strain hardening [2013Pra]. Liu et al, Gomez et al Sano et al have also attributed increase in hardness with laser peening to plastic deformation

and increased twinning [2009 Liu, 2010Gom and 1997San]. In addition, the hardness of the laser peened samples also increased because of the increase in dislocation density and non-uniform load distribution [1976Cla, 1996Pey]. Results also showed that the M2-L-B which had the lowest hardness in its blank state experienced the highest increase in hardness after laser peening (Table 4.3 and Figure 4.8). This is because the poor hardness of the M2-L-B insert allowed for more plastic deformation during LP, resulting in highly induced compressive residual stresses. As revealed in the submitted patent on laser peening of cemented carbide [2018PCT]; the increase in hardness and toughness of cemented carbides through laser peening depends on a certain hardness and toughness threshold.

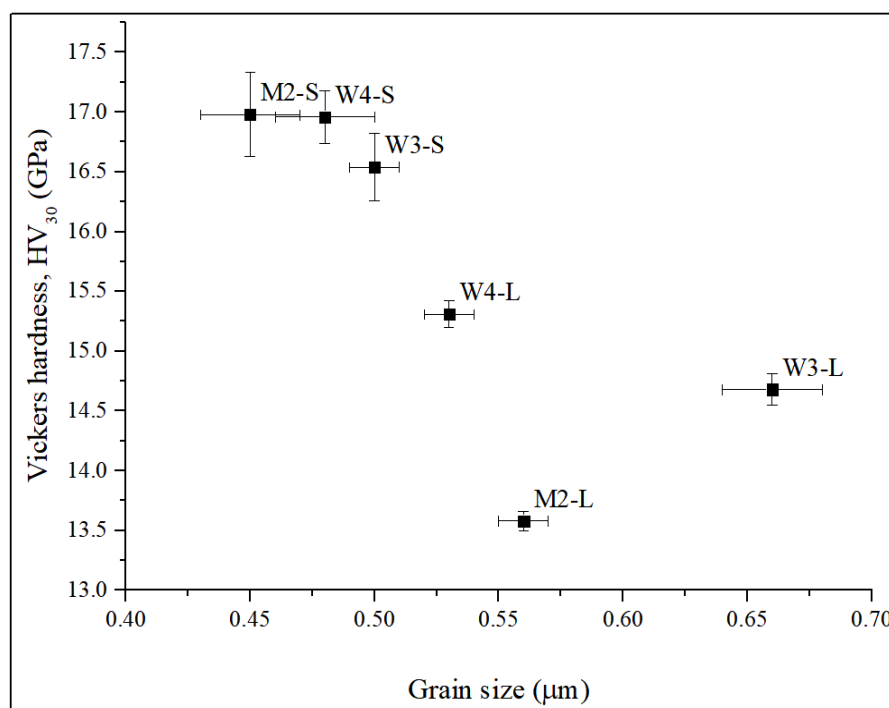


Figure 6.1. Effect of WC grain size on hardness of sintered samples.

6.2.2 Fracture toughness

The liquid phase sintered samples had higher fracture toughness than their spark plasma sintered counterpart in all compositions (Table 4.4 and Figure 4.9). This was because the LPS samples had larger WC grain sizes and more homogenously distributed binder pool (Table

4.1 and Figure 4.1). Fracture toughness in cemented carbide increases with increased mean carbide grain size (Figure 6.2), binder phase volume fraction, and binder phase mean free path [1987Dus, 1983Bol]. The addition of 3.5Mo₂C (wt%) to the WC-0.5Cr₃C₂-10Co (wt%) resulted in slightly lower fracture toughnesses (Table 4.4 and Figure 4.9). This was due to grain growth inhibition by the 3.5Mo₂C (wt%), since the K_{1C} of cemented carbides decreases with decrease in grain size (Figure 6.2) [1983Bol]. The binder substitution of 10Co (wt%) with 10Ni (wt%) led to the lowest fracture toughnesses for both the LPS and SPS samples (Table 4.4 and Figure 4.9). This was because of the smaller grain sizes for the WC-0.5Cr₃C₂-Mo₂C-10Co (wt%) (Figure 6.2). As earlier mentioned, fracture toughness of cemented carbides decreases with decrease in mean carbide grain size and binder phase mean free path [1998Upa].

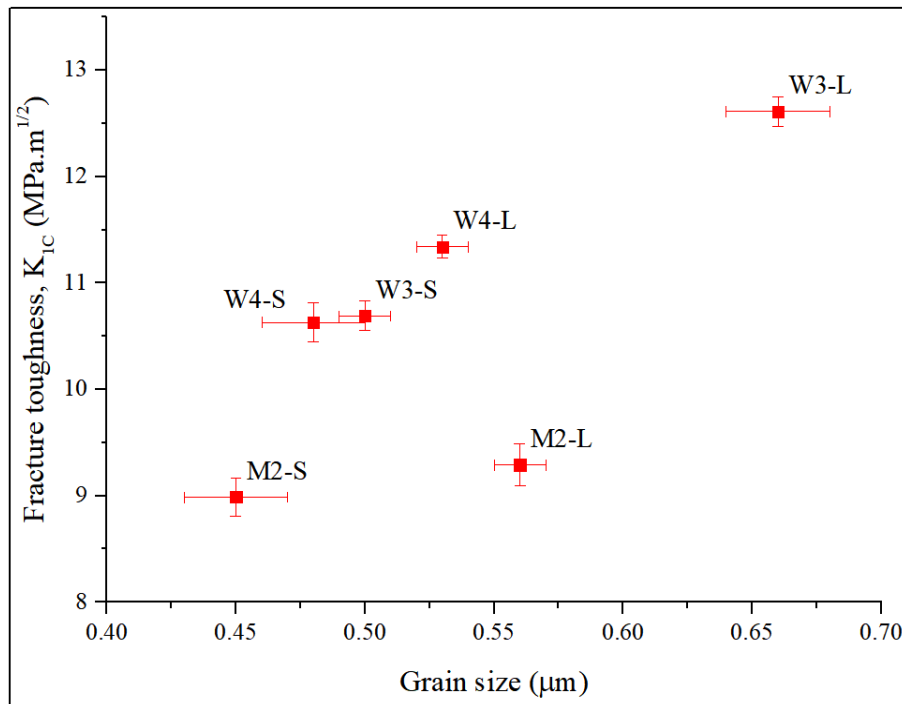


Figure 6.2. Effect of WC grain size on fracture toughness of sintered samples.

The laser peening of the sintered samples increased their fracture toughnesses (Table 4.4 and Figure 4.10). This was due to work hardening of the surface layer of the cermets [2013Pra].

The improvements in mechanical properties after laser peening are mainly connected to laser peened induced plastic deformations causing compressive residual stresses closer to the processed surface of metallic components [1996Cla, 1998Cla]. Compared to other laser peened inserts, the M2-L-B inserts had the most increased K_{IC} (Table 4.4 and Figure 4.10). This could be because of its significantly lower fracture toughness value in its blank state (Table 4.3 and Figure 4.10), giving more room for increase in fracture toughness.

6.3 **Cutting force and Temperature**

At lower cutting speed of 60m/minute and higher depth of cut of 1.5mm, the W4-L-B insert had better resistance to impact forces (Figure 5.2) because of its better combined mechanical properties (Figure 4.7 and Figure 4.9). Although the laser peened inserts had better mechanical properties compared to their blank counterparts (Figure 4.8 and Figure 4.10), they experienced higher resultant forces (Figure 5.2). This could be due to the higher compressive residual stresses and deep deformation layer after laser peening [2016Wan]. The lower resultant forces for the W4-L-LP could either be due to its better mechanical properties (Figure 4.7 and Figure 4.9), or the higher milling temperatures (Figure 5.14) which reduced the strength and modulus of the workpiece, thus; making it easier to machine [2009Sun]. The lower resultant forces for the W3-L-R, W3-L-C, W4-L-R and W4-L-B inserts (Figure 5.3) was due to their higher fracture toughnesses (Table 4.4). This confirms that higher K_{IC} is required for thermal and impact resistance of cemented carbides [2014Gen, 2016Ofe]. The slightly lower resultant forces experienced by the cutting tool inserts with decreased depth of cut from 1.5mm to 1mm at cutting speed of 60m/minute (Figure 5.3), was as a result of the reduced effective area of shear per tooth [2013Pat], and the reduced amplitude variation of the high-frequency cyclic force [2009Sun]. The lower resultant forces for the W3-L-B, W4-L-B and W3-S-B inserts were due to their higher fracture toughnesses (Figure 4.9 and Table 5.2), which improved their impact resistance [2014Gen]. In the laser peened category, the

general trend of decreased cutting forces withThe lower resultant force for the W3-L-R insert compared to other ridges inserts (Figure 5.2) was because of its higher fracture toughness (Figure 4.10) and better heat dissolution. During milling, lower temperatures and thermal stresses results in reduced micro-chipping and flank wear [2014Zhu].

At v_c of 75m/minute and ap of 1mm, the W3-L-R insert had a lower average resultant force (Figure 5.6) because of its higher fracture toughness and better heat dissipation forces (Figure 4.9 and Figure 4.10) [2005Sha, 2014Gen, 2005Raj], which made it more resistant to impact forces and thermal stresses [2005Sha, 2005Raj]. A reduction in depth of cut from 1mm to 0.5mm at v_c of 75 m/minute resulted in lower resultant forces and temperatures (Figure 5.7 and Figure 5.18). This was because at lower depth of cut the effective area of shear per tooth is reduced [2013Pat].

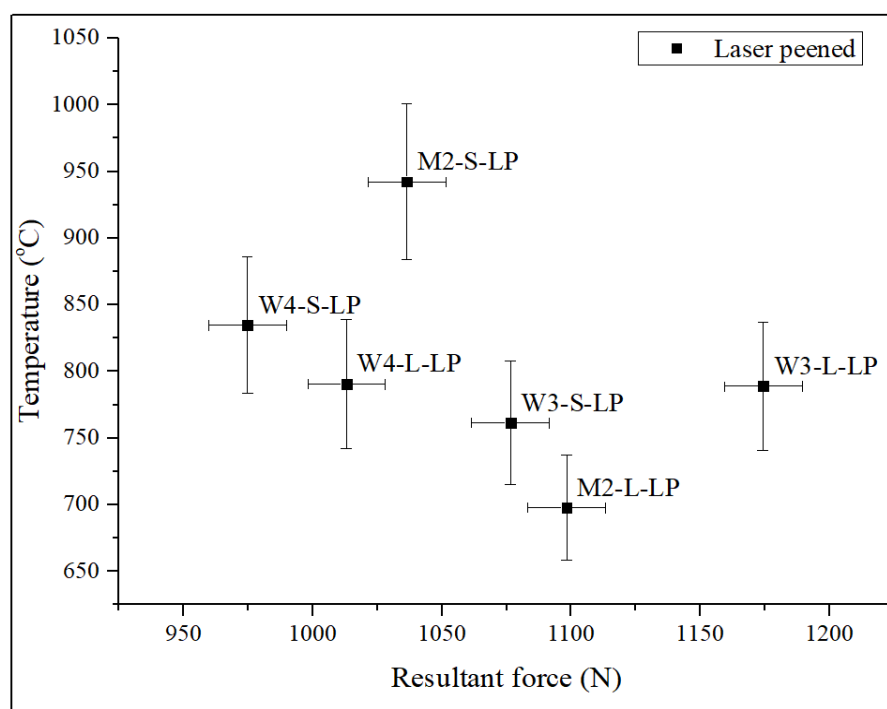


Figure 6.3. Effect of temperature on resultant forces of laser peened inserts during milling at v_c of 60m/minute and ap of 1mm

The hardness of the cutting tool inserts was critical at higher cutting speed of 75m/minute and lower depth of cut of 0.5mm [1967Wes]. The W4-S-B, M2-S-B and W3-S-B inserts which had higher Vickers hardnesses and finer WC grains experienced significantly lower resultant forces (Figure 6.4). The lower resultant forces for the laser peened inserts was also due to better mechanical properties (Figure 5.8, Figure 4.8 and Figure 5.10). The lower resultant forces for the ridged inserts (Figure 5.8) was due to their improved heat dissipation feature. This was because the conduction of heat from the secondary deformation zone to the cutting tool insert was reduced as a result of the reduced surface area of contact between the chip and the cutting tool [2005Raj] with the introduction of ridges. Furthermore, the ridges in the cutting tool inserts also acted as heat exchangers, where the ambient air which acted as a cutting fluid [1998Chi] cycled through dissipating most of the cutting heat conducted through the ridges walls. The significantly lower resultant forces and temperature for the W3-S-C inserts was due to its better combined mechanical properties (hardness and toughness) (Figure 5.8, Figure 4.7 and Figure 4.9). This has also been pointed out by Shaw and Genga [2005Sha, 2014Gen].

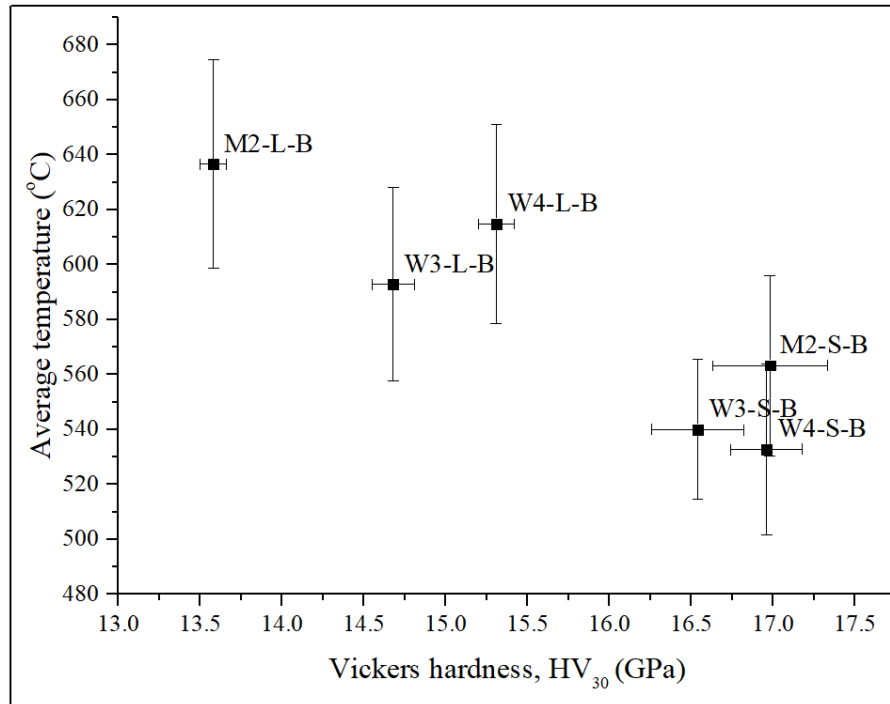


Figure 6.4. Effect of Vickers hardness on temperature of blank inserts during milling at vc of 75m/minute and ap of 0.5mm

The lower resultant forces experienced by the cutting tool inserts at vc of 100m/minute and ap of 0.5mm (Figure 5.9) was due to the drop in shear strength in the flow zone as the tool-chip temperature increases with increasing cutting speed [2009Dem]. This results in thermal softening and decreased yield stress of the cutting tool [2010Elh, 2009Sun]. The W3-L-B inserts had slightly lower resultant forces than the W4-L-B and M2-L-B inserts because of its higher fracture toughness (Table 5.4 and Table 4.4) [2014Gen]. This has also been pointed out by Genga [2014Gen]. At cutting speed of 120m/minute and depth of cut of 0.5 mm, the cutting tool inserts experienced lower resultant forces because of the higher milling temperature which thermally softened the workpiece material and aided grain boundary dislocation (Figure 5.11 and Figure 5.22) [2009Sun]. The lower temperatures and resultant forces for the W3-S-B insert (Table 5.5 and Figure 5.12) was due to its better combined mechanical properties (Figure 4.7 and Figure 4.9). The lower resultant force for the M2-L-R insert was due to the combined effect of high hardness (Figure 4.7) and reduced heat

conduction from the secondary deformation zone to the cutting tool insert. [2005Raj]. The Ti-6Al-4V debris which act as coating on the cutting tool ridges could be another factor. At cutting speed of 300m/minute and depth of cut of 0.5mm, the lower resultant force for the W4-L-B insert was attributed to their better combined mechanical properties (Figure 4.7 and Figure 4.9) (Table 5.11) [2009Sun, 2005Sha].

6.4 **Wear**

Optical images of the cutting tool inserts after milling at cutting speed of 60m/minute and depth of cut of 1.5mm, shows that the major tool failure mechanisms were abrasive wear of the flank, adhesion, mechanical wear and chipping (Figure 5.25 and Figure 5.26). This has also been reported by Che-Haron [2001Che] and Ezugwu [1997Ezu]. The M2-S-B, M2-S-LP, M2-S-R, W4-S-B and W4-S-C inserts which had higher hardnesses and poor fracture toughnesses (Figure 4.9, Figure 4.7 and Table 4.1) experienced high thermo-mechanical and cyclic stresses resulting in severe wear (Figure 5.25 and Figure 5.27) [2005Ezu, 2005Sha, 2014Pau]. This is because tools with higher hardness cannot withstand wide variations in cutting forces, which is typical of rough-machining operations [2005Sha]. The severe chipping of the inserts cutting edges was due to higher cutting loads at higher depth of cut under intermittent cutting process [2000Chi]. This has also been reported by Ezugwu [1997Ezu]. The occurrence of adhesion wear was due to the higher milling temperatures (above 700 °C) in the presence of normal tool contact pressure [1995Sad]. The repeated damage of the tool material by the high heat consequently resulted in adhesion wear, as the welded tool particles were detached by the flow of the chip over the rake face (welding and tearing action) [2014Pau]. The lower flank wear rate for the liquid phase sintered inserts (Figure 5.27) was attributed to their high fracture toughness which made them more resistant to impact forces and temperatures (Figure 4.9 and Figure 5.2) [2014Gen, 2005Sha]. At higher milling temperatures (over 600 °C) the hardness of cemented carbide tools decreases

[1998Upa]. Contrarily, elevated temperature results in increased toughness for cutting tool inserts, thus improving their resistance to impact forces [2005Sha]. The negligible wear for the W3-L-B and W4-L-B inserts was also due to their significantly higher fracture toughnesses (Table 5.12 and Figure 4.9) [1998Upa, 2005Sha]. Although the laser peened inserts had higher mechanical properties compared to their blank counterparts, their flank wear rates were higher as a result of their poor resistance to impact forces (Figure 4.8, Figure 4.10 and Figure 5.14). This could be attributed to the varying stress concentrated in the cutting tool edge after peening [2006Tan], since large tensile residual stresses which may be caused by the thermal effect of the laser pulse are generated in the centre of the spot, while compressive residual stresses are generated around the spot and adjacent to the peened area [2006Tan, 1996Cla]. Tensile residual stresses leads to crucial damage [2004Kus]. Similarly, tensile surface residual stresses which may have deleterious effects on component performance are likely to be generated outside the peened area [1996Cla]. The negligible wear for the W3-L-C, and W4-L-R inserts was due to their higher fracture toughnesses (Figure 4.7), which gave them better resistance to impact forces (Figure 5.2) [2005Sha, 2014Gen]. The spark plasma sintered inserts had higher flank wear rates because of their poor fracture toughnesses and lower hardnesses at elevated temperatures (Figure 5.27 and Figure 4.7) [2005Sha]. The accelerated tool wear at higher temperature during Ti-6Al-4V machining can be attributed to the high strain hardening ability and high chemical reactivity of Ti-6Al-4V with cutting tool materials at higher temperatures [2014Pau]. The lower flank wear rate for the cutting tool inserts with decreased depth of cut from 1.5mm to 1mm, at cutting speed of 60m/minute (Figure 5.28) was due to the reduced cutting forces (Figure 6.5) [2009Sun]. Furthermore, at lower depth of cuts, flank wear decreases due to decreased frictional resistance [2015Sha]. In the blank category, the fracture toughness of the cutting tool insert

was vital towards wear resistance (Figure 6.6). The negligible flank wear rate for the W3-L-B insert was due to its higher fracture toughness (Table 5.12 and Figure 4.9).

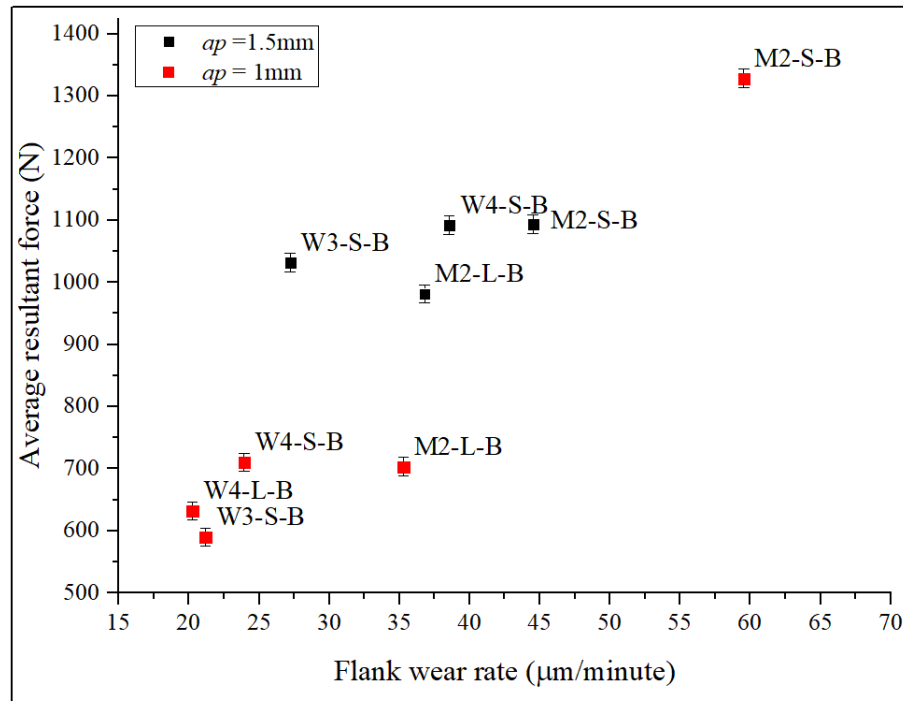


Figure 6.5. Effect of depth of cut on flank wear rate of cutting tool inserts during milling at v_c of 60m/minute

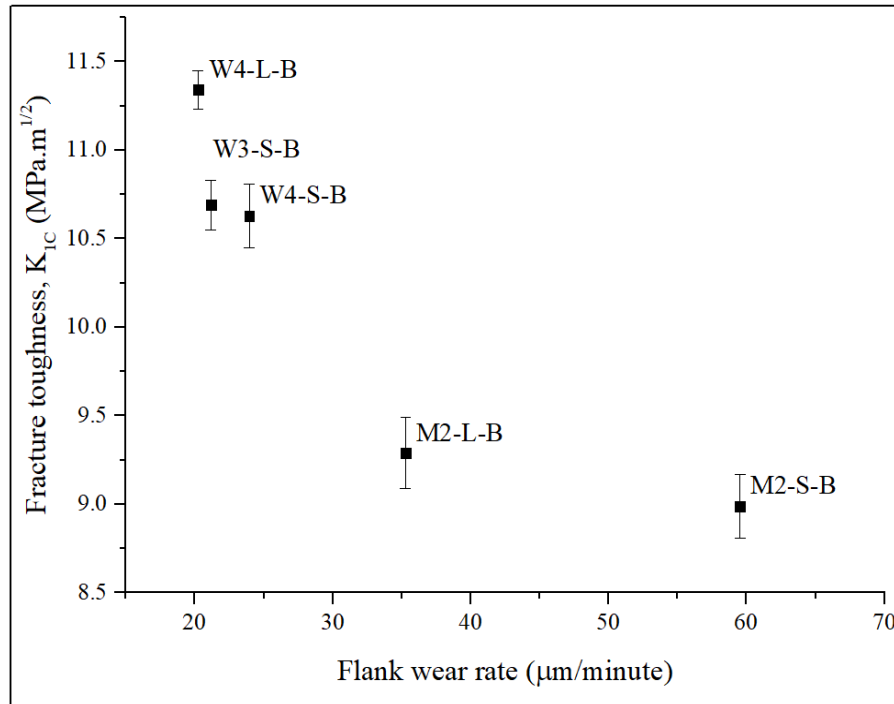


Figure 6.6. Effect of fracture toughness on flank wear rate of blank inserts during milling at v_c of 60m/minute and a_p of 1mm

In the ridges category, tool wear was influenced by the cutting forces experienced. The liquid phase sintered inserts which had better resistant to impact forces due to their higher fracture toughnesses experienced lower flank wear rates (Figure 4.9, Figure 5.4 and Figure 5.29). The lower flank wear rates for the liquid phase sintered ridged inserts compared to their blank counterparts (Figure 5.29), was due to their better resistance to impact forces. This has also been pointed out by Shaw [2005Sha]. As shown in Figure 6.7, the introduction of ridges acted as a coating, thereby reduced the conduction of heat entering the cutting tool from the secondary deformation zone. This was because the tool-chip contact area was reduced resulting in lower plastic deformation, sticking-sliding friction [2017Man]. The rate of heat transfer through a homogenous solid is directly proportional to the surface area in contact [2005Raj]. Furthermore, the temperature distribution in the cutting tool insert influences its deformation. This has also been pointed out by Eisen [1941Eis]. The ridges on the rake of the cutting tools also served as channels for trapping strips of Ti-6Al-4V chips, which later acted

as a coating on the cutting tool rake. Since Ti-6Al-4V is a poor heat conductor, the heat concentrated at the secondary deformation zone was reduced, thereby minimising tool wear and increasing tool life.

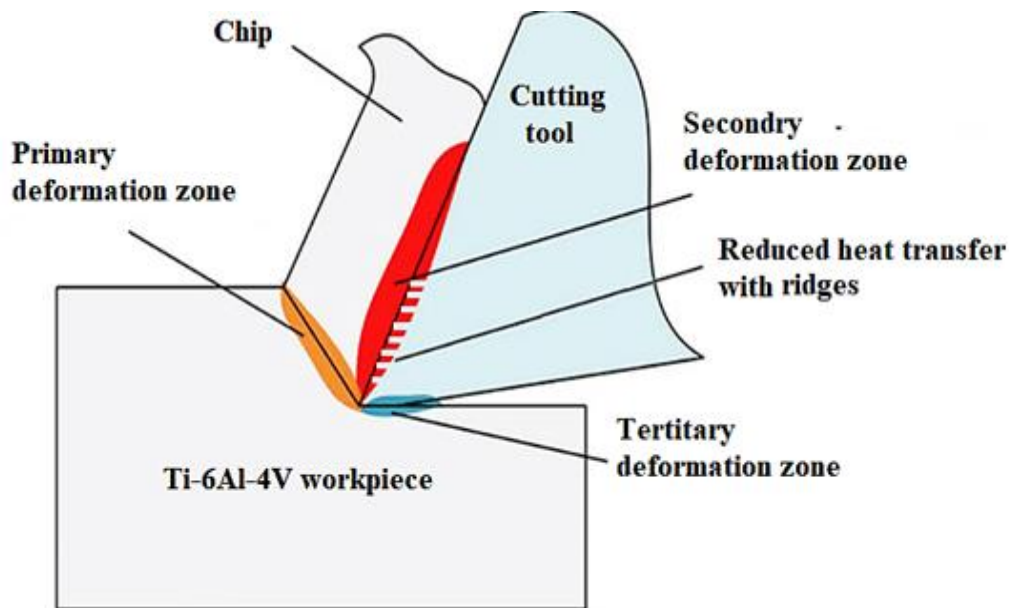


Figure 6.7. Schematics showing reduced conductive heat transfer in the secondary deformation zone with introduction of ridges.

The high wear rate for the laser peened inserts despite their higher hardness and fracture toughness could be due to the unwanted side effect of laser peening, as the originally sharp ground cutting edge surfaces were partially damaged.

Increased cutting speed from 60m/minute to 75m/minute at a depth of cut of 1mm resulted in higher flank wear rates (Figure 5.30). This was because the rubbing area per unit time and impact forces were increased [2015Elk, 1987Sol]. The liquid phase sintered inserts had lower flank wear rates (Figure 5.32) because of their higher fracture toughnesses which improved their resistance to impact forces and wear (Figure 6.8 and Figure 6.9). This has also

been pointed out by Genga [2014Gen]. The higher thermal stresses experienced by the ridges inserts at vc of 75m/minute and ap of 1.5mm (Figure 5.17) resulted in accelerated flank wear rate (Figure 5.32). Shaw has mentioned that elevated temperature in the cutting zone increases cutting tool deformation [2005Sha]. In addition, cutting tool deformation increases at higher temperatures because of the increased friction temperature [1941Eis, 2005Sha].

At cutting speed of 75m/minute and depth of cut of 0.5mm, the W3-L-B inserts had a negligible flank wear rate (Table 5.13) despite its higher milling resultant forces and temperatures (Figure 5.8 and Figure 5.19). This could be due to its increased fracture toughness at elevated temperature [2005Sha]. The lower flank wear rates for the laser peened inserts (Table 5.13) was because of their improved mechanical properties (Figure 4.8 and Figure 4.10) which made them better resistant to milling temperatures and thermal stresses (Figure 5.19) [2005Sha]. The negligible flank wear rates for the W3-L-R, W3-S-R, W3-S-C and W4-L-R inserts was due to their higher fracture toughness (Figure 4.9) which resulted in better resistance to impact forces (Figure 5.8) [2005Sha, 2014Gen]. Furthermore, the fcc-hcp transition of binder cobalt made the cutting tool inserts more ductile and formed a lubricating film on the surface [1998Upa]. The increased FWR for the cutting tool inserts with increase in cutting speed from 75m/minute to 100m/minute at depth of cut of 0.5mm (Figure 5.34), was because of the increase in rubbing area per unit time [2015Elk]. This results in higher cutting temperatures leading thermal fatigue for the cutting tool (Figure 5.20) [2015Elk]. The poor thermal conductivity of Ti-6Al-4V is another factor, as the workpiece material becomes more strain-hardened and most of the cutting heat is transferred to the cutting tool insert [2003Ezu, 1986Dea]. Tool wear in machining of titanium alloys is due to high stresses and high temperatures near the cutting tool edge [2005Ezu, 1993Sub].

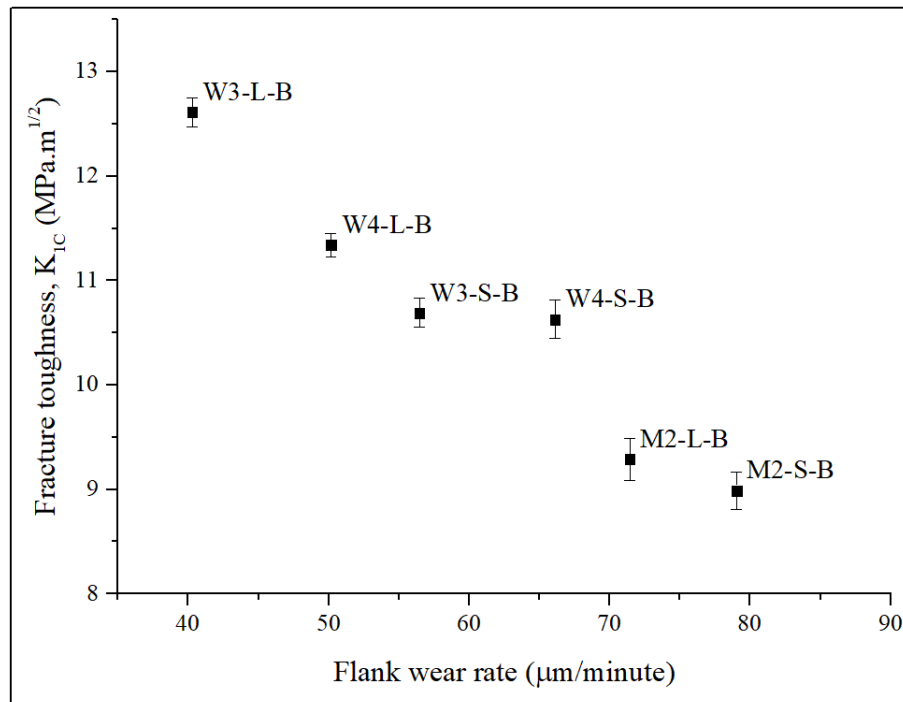


Figure 6.8. Effect of fracture toughness on flank wear rate of cutting tool inserts during milling at v_c of 75m/minute and a_p of 1mm

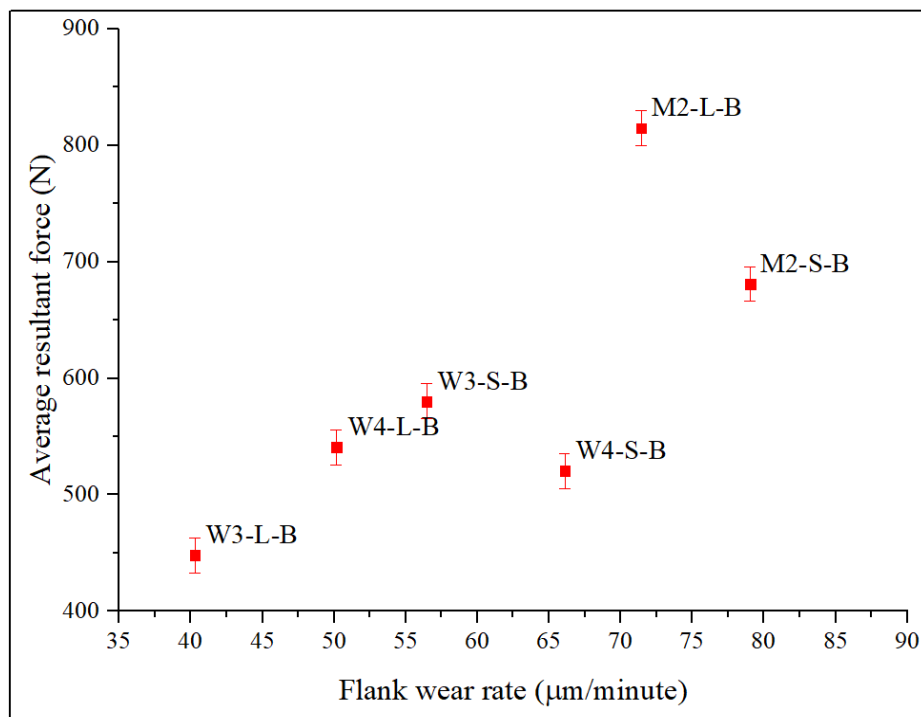


Figure 6.9. Effect of resultant forces on flank wear rate of cutting tool inserts during milling at v_c of 75m/minute and a_p of 1mm.

At v_c of 100m/minute and ap of 0.5mm, the negligible flank wear rates for the W3-L-B, W3-L-LP, W3-L-R and W4-L-C inserts (Table 5.14) was because of their higher fracture toughnesses (Figure 4.8). The high k_{1c} made the inserts more resistant to impact forces (Figure 5.10) [2014Gen]. The lower FWR for the M2-L-LP and M2-S-LP inserts was due to their higher hardness (Figure 4.8) which made them more resistant to impact forces [2014Gen]. The high wear rate suffered by the laser peened inserts could be because the increased mechanical properties imparted by laser shock peening were torn down as a result of the relatively low stability of the compressive residual stresses during cyclic loading [2012Che]. At cutting speed of 120m/minute and depth of cut of 0.5mm, the milling temperatures influenced the flank wear rate of the blank inserts (Figure 6.10). The W4-L-B insert which experienced the lowest temperature in the blank category had the lowest flank wear rate (Figure 6.10). The higher milling temperatures for the W4-S-B and M2-S-B inserts (Figure 5.23) were principal to their accelerated flank wear rate (Figure 5.37). This is because at elevated cutting zone temperature of 600–700 °C and above, oxygen and nitrogen molecules in the air diffuse into the titanium workpiece and harden its surface layer [1985Zha]. Ti-6Al-4V maintains its strength at elevated temperature, while carbide tool undergo plastic deformation due to intense heat [1982Don, 1986Dea]. The W3-L-R had the lowest resultant force at v_c of 120m/minute and ap of 0.5mm due to the combined effect of higher fracture toughness and better heat dissipation which made it more resistant to impact forces and thermal stresses (Figure 5.12 and Figure 5.37) [2005Raj and 2005Sha]. At a higher cutting speed of 300m/minute and depth of cut of 0.5mm, the flank wear rate for the cutting tool inserts significantly increased (Table 5.16). This was due to the higher temperature generated (Table 5.11). At elevated temperature above the optimum value, flank wear increases due to higher rates of diffusion wear [2014Ami]. The W4-L-B insert had the lowest flank wear rate (Table 5.16 and Figure 5.38) because of its better resistance to cutting forces

(Table 5.6). Additionally, during high speed dry machining where temperature is elevated, Mo₂C oxidises form MoO₃ and MoO₂ oxides. The MoO₃ oxide serves as a solid lubricant, and therefore reduces the frictional coefficient between cutting edge and the workpiece was decreased [2013Bro]. It can be clearly seen from the cutting edge – workpiece interface EDS analysis (Figure 5.39) that diffusion wear occurred during milling at 300m/minute. The diffusion wear occurred between the Ti-6Al-4V workpieces and the cutting tool inserts. In the W4-L-B insert, the diffusion profile clearly showed that the W and Co atoms inside the W4-L-B insert diffused towards the Ti atoms in the workpiece and vice versa under the influence of thermal energy (Figure5.39a) resulting in the formation of TiC [2003Ezu]. The diffusion of cobalt led to loss in the WC strength and the WC crystals which were now brittle fractured away on exposure [2005Hua, 2003Ezu].The WC grains could then be pulled out by the flowing chips (Figure 6.11a). The diffusive wear significantly influenced the hardness and wear resistance of the W4-L-B cutting tool insert [2003Hua]. The diffusive profile for the M2-L-B inserts also showed minor diffusion between the Ni atoms from the cutting tool to the Ti atoms in the workpiece (Figure 5.39b). The diffusion of Nickel binder could also lead to a slight loss in the WC strength and the brittle WC crystals fractured from the chip action (Figure 6.11b) [2017Ram, 2007Kum]. The W4-L-B had higher diffusive wear (Figure 6.11) because of its lager WC grains (Table 4.1). Coarser WC grains are more susceptible to be pulled off when the chip slides over the rake face [1993Edw].

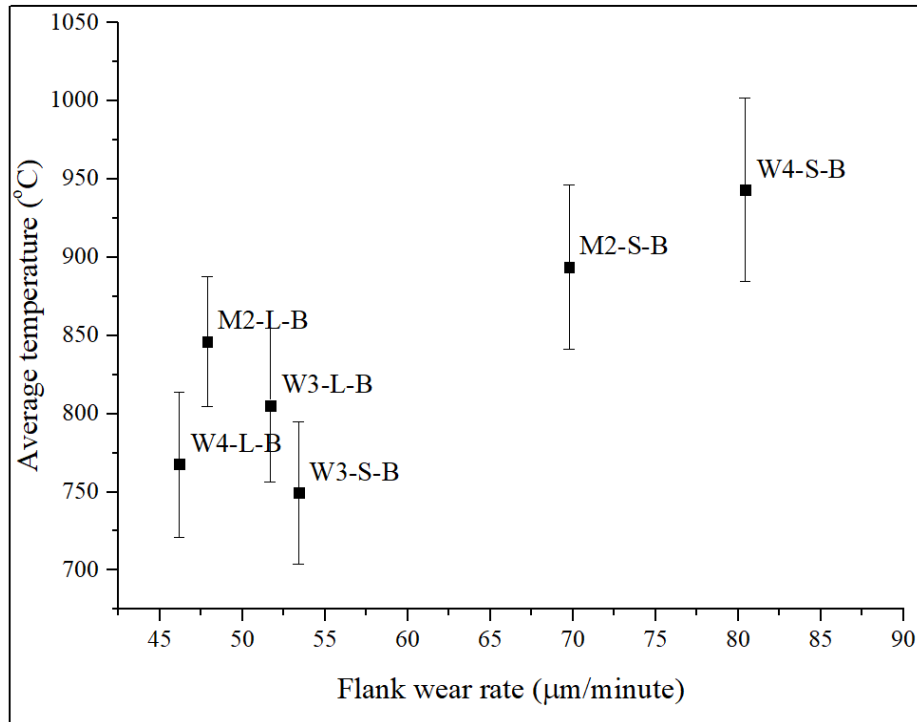


Figure 6.10. Effect of temperature on flank wear rate of cutting tool inserts during milling at v_c of 120m/minute and a_p of 0.5mm

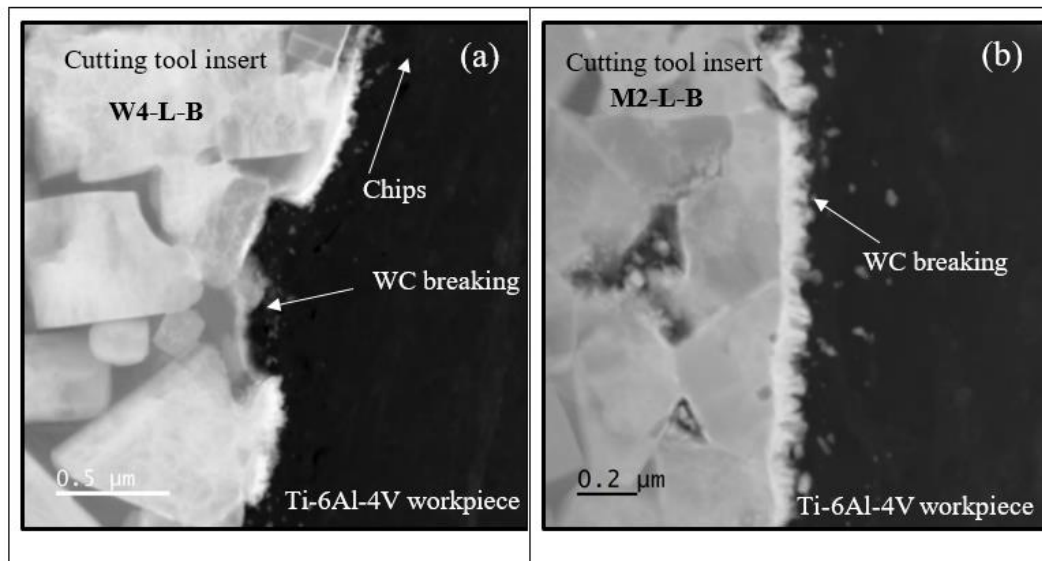


Figure 6.11. SEM-BS images of W4-L-B and M2-L-B inserts showing grain pull out mechanism during face milling of Ti-6Al-4V.

6.5 **Chips formation.**

The different cutting edges, tool composition and process parameters had minimal effect on chip formation. Discontinuous snarled ribbon chips (SNR) and snarled tubular chips (SNT) were predominant during the machining trials (Figure 5.40 – 41). This type of chips are typical during titanium machining. This has been mentioned by Sun [2009Sun], and is believed to originate either by growth of crack from the outer surface of the chip [1995Vya] or adiabatic shear formation due to localized shear deformation resulting from thermal softening over strain hardening [1981Kom].

6.6 **Surface roughness:**

At v_c of 75m/minute and ap of 0.5mm, the surface roughness produced by cutting tool inserts was influenced by the milling temperatures as well as the hardness of the cutting tool inserts. The spark plasma sintered blank inserts which had higher hardnesses and finer WC grains (Figure 4.7) produced lower surface roughnesses compared to their liquid phase sintered counterparts (Figure 6.12). This was because the SPS inserts with higher hardness had better abrasive property [1998Upa]. The poor surface roughness for the LPS inserts was due to their larger WC grains and poor hardness [1998Upa]. This is because abrasive particles with poor hardness are not capable of indenting the workpiece surface, but rather sliding over the surface under considerable load and with substantial frictional force [1998Upa]. A general trend in roughness was established from Figure 6.12, as surface roughness generally increased with decrease in hardness of the cutting tool inserts. This was however different for the laser peened inserts, as they produced higher surface roughnesses despite their higher hardnesses (Figure 5.43 and Figure 4.8). This could be due to their varying residual stress concentrations after peening [2006Tan], since large tensile residual stresses which may be caused by the thermal effect of the laser pulse are generated in the centre of the spot, while compressive residual stresses are generated around the spot and adjacent to the peened area

[2006Tan, 1996Cla]. Tensile residual stress negatively influence the performance of a material [2004Kus]. The lower surface roughness for the W3-L-R and W3-L-C inserts compared to the W3-L-B and W3-L-LP inserts was because of their better chips/heat expulsion features (Figure 3.5). The M2-S-B and W4-S-B insert which had lower milling temperatures and higher Vickers hardness produces the lower surface roughnesses (Figure 6.12 and Figure 6.13). The M2-S-LP insert produced the lowest surface roughness due to its significantly higher hardness (Figure 4.7) and better abrasion property [1998Upa]. The low surface roughness for the W3-L-LP and W3-L-R inserts was due to their lower flank wear rates (Table 5.13).

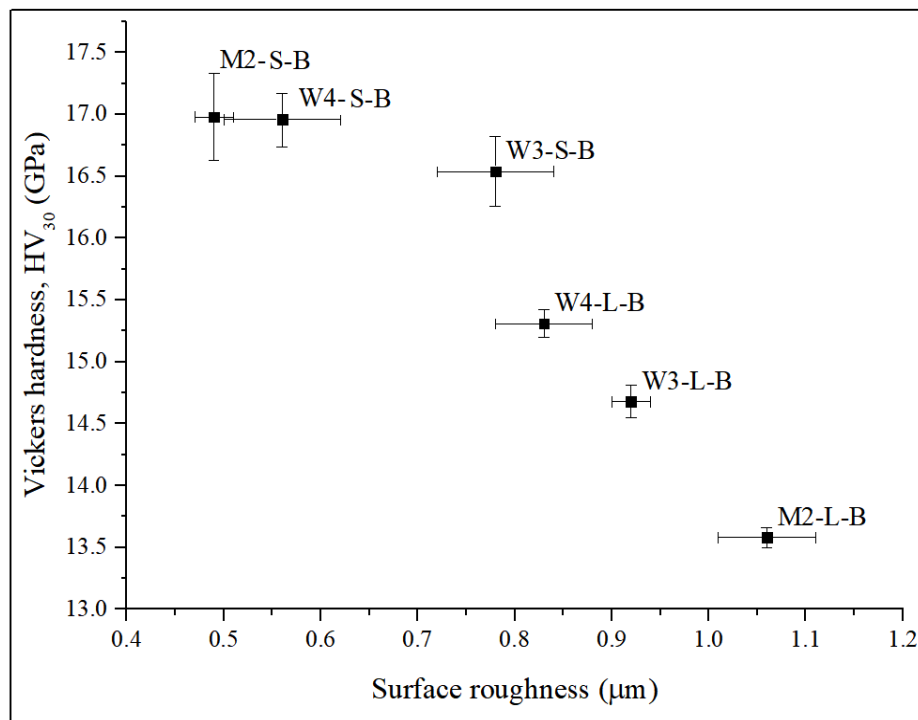


Figure 6.12. Effect of Vickers hardness on surface roughness produced by blank inserts during milling at vc of 75mminute and ap of 0.5mm

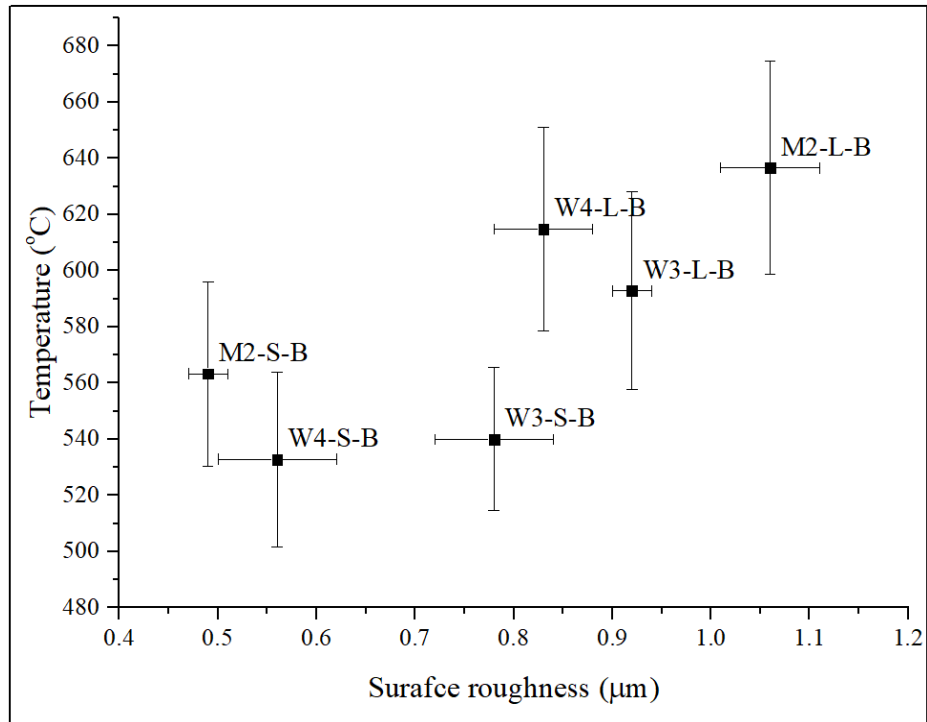


Figure 6.13. Effect of temperature on surface roughness produced by blank inserts during milling at vc of 75m/minute and ap of 0.5mm

Notwithstanding the higher resultant forces, temperatures and flank wear rates experienced by the M2-S-B and W4-S-B inserts at vc of 120m/minute and ap of 0.5mm (Figure 5.12, Figure 5.23 and Figure 5.37), their surface roughnesses were significantly lower compared to other blank inserts in the same milling condition (Figure 5.46). This could likely be due to their higher cutting edge hardness which made them better abrasers (Figure 4.7) [1198Upa], as the trend in Figure 6.14 and Figure 6.15 shows a decrease in surface roughness with increase in hardness of the cutting tool inserts [1998Upa]. The lower surface roughness for the W3-L-R inserts (Figure 5.46) was due to its significantly lower flank wear (Figure 3.7) and better heat expulsion.

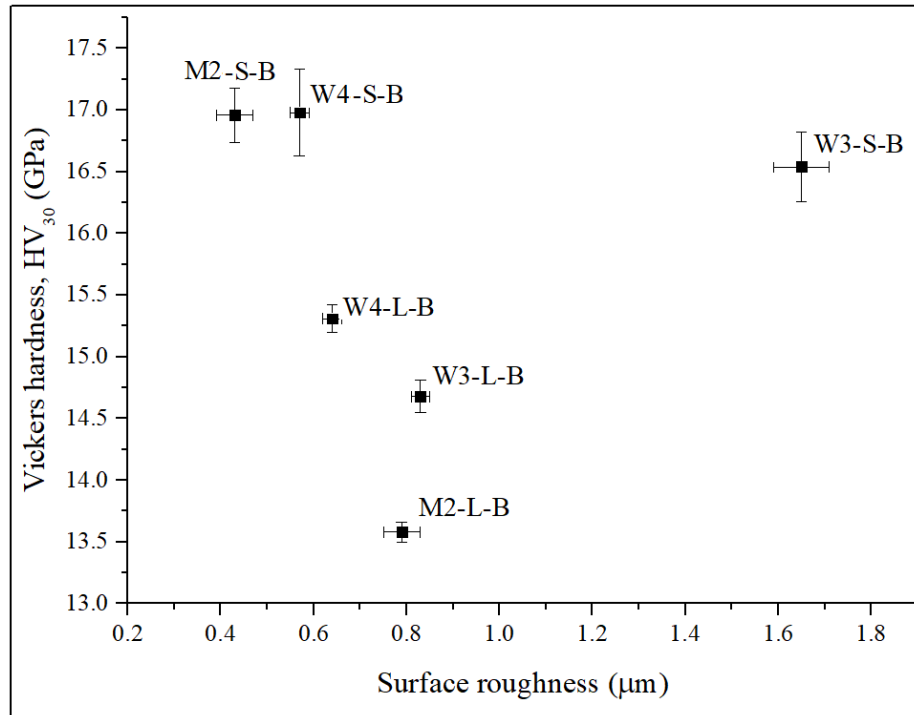


Figure 6.14. Effect of Vickers hardness on surface roughness of blank inserts during milling at vc of 100m/minute and ap of 0.5mm

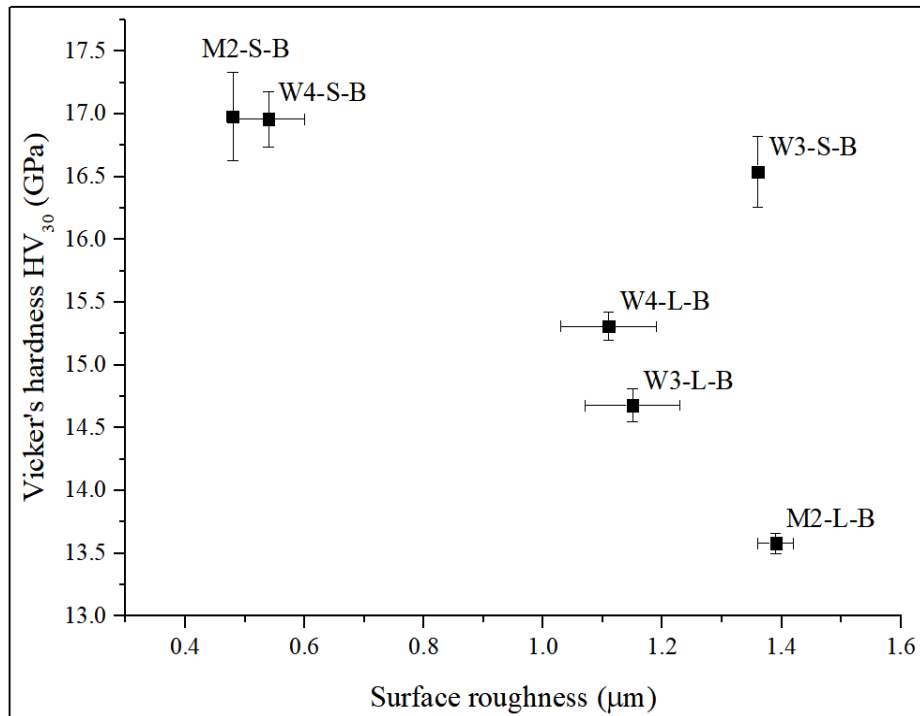


Figure 6.15. Effect of Vickers hardness on surface roughness produced by blank inserts during milling at vc of 120m/minute and ap of 0.5mm.

At v_c of 300m/minute and ap of 0.5mm, the surface roughnesses produced by W3-L-B, W4-L-B, and M2-L-B inserts were significantly higher compared to those produced at lower cutting speeds of 120m/minute, 100m/minute and 75m/minute (Table 5.23). This was because they experienced higher temperatures and flank wear rates (Table 5.11 and Table 5.16).

7 Conclusion and Recommendations

7.1 Conclusion

In this research work, a detailed experimental approach for developing and improving the performance of cemented carbide tools for Ti-6Al-4V machining has been presented. From the above results and discussion a conclusion can be drawn as follows. All the sintered samples had good densification (>99% theoretical density). The addition of Mo₂C to WC-Cr₃C₂-10Co (wt%) inhibited grain growth resulting in finer grains for both LPS and SPS samples. Binder substitution of 10Co (wt%) with 10Ni (wt%) resulted in finer WC grains because of the improved wettability of WC by Ni with the addition of Mo₂C (wt%). The samples produced by spark plasma sintering had higher hardness than their liquid phase sintered counterparts because of their finer grains. Nonetheless, the liquid phase sintered samples had higher fracture toughness because of the homogenous distributed binder and larger WC grains. Laser peening of the samples slightly increased mechanical properties (hardness and fracture toughness) for both the liquid phase sintered and spark plasma sintered samples due to increased compressive residual stresses and work hardening. The cutting tool inserts with higher fracture toughnesses had lower flank wear rates, due to their better resistance impact forces, while the SPS inserts which had smaller grains and lower fracture toughnesses experienced higher flank wear rates. The laser peened samples which had better mechanical properties experienced accelerated wear during the machining trials, this could be attributed to their varying residual stresses. In principle it is possible to improve the near surface mechanical properties of cemented carbides, but there are limitations to this, given the chipping of the cutting edge.

The ridges inserts outperformed other cutting tool inserts because of their better heat dissipation, which was achieved through the reduced conduction of heat from the secondary deformation zone to the cutting tool insert and the ambient air cooling of the cutting tool insert walls. The surface roughness of the Ti-6Al-4V workpieces was mostly influenced by the cutting temperatures and hardness of the cutting tool inserts, with the harder inserts producing better surface roughness due to their better temperature resistance.

In summary, the W3-L and W4-L inserts outperformed other cutting tools because of their higher fracture toughnesses which made them better resistant to impact forces and thermal stress. Nonetheless, the performance of these cutting tool inserts varied with respect to their cutting edges and process parameters. The W3-L-B and W4-L-B inserts are more suitable for roughing operations as they are better resistant to impact forces and thermal stress at slower cutting speeds and higher depth of cuts. On the other hand, the higher fracture toughnesses, better heat dissipation and stronger cutting edges for the W3-L-R and W4-L-R inserts makes them suitable for semi-finishing and finishing operations where milling temperatures are elevated. In machining operations where the surface integrity of the workpiece is of primary interest the M2-S-B insert which is harder and more brittle should be utilised.

7.2 Recommendations

7.2.1 Due to time constraint, further analysis could not be carried out to fully understand the effect of cutting tool edge profiles and sintering technique on the residual stresses of the cutting tool inserts and workpiece materials. Further research is therefore recommended in this area, as it would be vital for understanding the behavioural pattern of the laser peened cemented carbides.

7.2.2 Further research should also be carried out to understand why the hardness for the M2-L-B insert significantly increased after laser peening.

7.2.3 To fully understand the influence of the different cutting edges on chip forms, more in-depth analysis should be carried out on the chips using high resolution equipment.

7.2.4 To further study the effect of friction on chip formation and wear, the feed rate should be varied at constant speed. Further investigations should also be carried out on the chips collected during machining, as this could provide additional information on cutting performance

7.2.5 For clearer disparity in performances, face milling test at higher cutting speeds exceeding 300m/minute should be carried out using these cutting tool inserts.

7.3 **Research contributions**

7.3.1 **Publications**

This research is contributing the following papers which are still in preparation:

- Effect of WC-Based Cutting Tool Composition Manipulation and Laser Shock Peening on Face Milling of Ti-6Al-4V
- Effect of Laser Processed Chip Breakers and Ridges on Wear of WC Cemented Carbide tools during Ti6-Al-4V Machining.

7.3.2 **Conferences**

Part of this work has been presented at the Aeronautical Society of South Africa (AESSA), South Africa. (2018) annual conference.

N Lekam, J Branjer, P Zeman, C Polese and R Genga, Effect of WC-based Cutting Tool Composition Manipulation and Laser Surface Modification on Face-milling of Ti-6Al-4V, AeSSA 2018, Hoogeind Manor, Somerset West, 24-26 October, 2018. AeSSA2018-14 <http://www.aessa.org.za/index.php/programme/submissions-summaries-2018>

7.3.3 **Patents**

This work is contributing to the developmental work for the provisional patent C. Polese, D. Glaser, L. Cornish, R. Genga, South Africa Provisional Patent Application METHOD AND SYSTEM FOR IMPROVING THE ABRASIVE RESISTANCE OF BRITTLE MATERIALS, AND A CUTTING TOOL PRODUCED BY SUCH METHOD been filed in collaboration with Wits Enterprise, International Application No.: PCT/IB2018/053772, Pub. No.: WO/2018/215996, published 29 November 2018.

REFERENCES

- [1932AST] ASTM E18-03E1, Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials (1932).
- [1934Sch] K. Schroter, The Inception and Development of Hardmetal Carbides, The Iron Age, 3 (1934), 27-29.
- [1941Eis] S.U. Eisen, "Study of Wear of Cemented Carbides" vol. 61, p. 210.
- [1949Lee] E.H Lee, B.W Shaffer; Brown University. Providence, R.I : Division of Applied Mathematics, Brown, 1949.
- [1953Coo] N. Cook, Proceeding of Son Machining and Grinding of Titanium, Watertown, Arsenal, (1973), pp. 1-7.
- [1953Sha] M.C. Shaw, N.H. Cook, and I. Finnie., "The Shear-Angle Relationship in Metal Cutting/" Trans. ASMS, 1953, pp. 273-288.
- [1954Gur] J. Gurlans, Trans. Amer. Inst. Min. Met. Eng., 1954, 200, 285
- [1957Nak] K. Nakayama, Bull. Fac. Engng. Yokohama Natn. Univ. 6. (1957).
- [1959Kin] W.D. Kingery, Densification during Sintering in the Presence of a Liquid Phase, J. Applied Phys., 30(3) (1959) 301-306.
- [1959Pal] W.B Palmer and P.L Oxley, "Mechanics of Orthogonal Machining," Proc. Inst. Mech. Engrs., Vol. 1733 19595 p. 623.
- [1957Boc] G. Bockstiegel, Iron Powder Handbook, section E, chapter 20, (1957).

- [1959Kin] W.D. Kingery, Densification during sintering in the presence of a liquid phase. I. Theory, J Appl. Phys. 30 (1959), 301–306.
- [1960Sch] Schwarzkopf, P., and Kieffer, R., Cemented Carbides, MacMillan, New York, p. 188(1960).
- [1961Oxl] P. L. B. Oxley, "A Strain-Hardening Solution for the 'Shear Angle' on the Orthogonal Metal Cutting/" International J. Mech. Sci. Vol. 3, 196.1, pp. 68-79.
- [1963Whi] R.M White, Elastic wave generation by electron bombardment or electromagnetic wave absorption. Journal of Applied Physics, 34, (1963) 21234.
- [1964Kub] H. Kubota, R. Ishida, and A. Hara, Sumitomo Elect. Tech. Rev., 1965,6, 87; Trans. Indian Inst. Metals, 1964, 17, (5), 132.
- [1967Boo] G. Boothroyd, J.M. Eagle, W.J. Chisholm, Advances in Machine Tool Design and Research 1967, Proceedings of the 8th International M.T.D.R. Conference (Incorporating the 2nd International CIRP Production Engineering Research Conference), the University of Manchester Institute of Science and Technology, September 1967, Pages 667-680.
- [1967Wes] J. H. Westbrook, and E. R. Stover, High Temperature Materials, and Technology, (I. E. Campbell, and E. M. Sherwood, eds.), John Wiley, and Sons, Inc., N. Y., (1967). p. 312.
- [1968Att] C.R. Attaway, An Analysis of the Orthogonal Metal Cutting Process, Thesis for Doctor of Philosophy, Georgia Institute of Technology, 1968

- [1970And] N.C. Anderholm, Laser-generated stress waves. Applied Physics Letters, 16, (1970), 113–14.
- [1970Exr] H. E. Exner and J. Gurland A Review Of Parameters Influencing Some Mechanical Properties Of Tungsten Carbide–Cobalt Alloys. Powder Metallurgy, 1970, Vol. 13, N0. 25
- [1970Woo] G.A. Wood, Powd. Met., Vol. 13, p. 338 (1970).
- [1970Zal] N. Zaltin, Modern Machine Shop, 42 (1970), pp. 139-144.
- [1975Bro] K.J.A. Brookes, Hardmetal and other Hard Materials, International Carbide Data, Hertfordshire, UK (1975).[
- [1975Fre] R. Freeman, Ph.D. Thesis, University of Birmingham (1975)
- [1976Cla] A.H. Clauer, B. P. Fairand, and B.A. Wilcox. Laser shock hardening of weld ` zones in aluminium alloys. Metallurgical Transactions A, 8A, 1871–6. (1976).
- [1976Sih] G. C. Sih, Fracture Toughness Concept, Properties related to fracture toughness, ASTM 605, American society for testing materials, 1976, pp. 3-15.
- [1977BS] BS 5447, Methods of Test for Plain Strain Fracture Toughness (KIC) of Metallic Materials, (1977).
- [1978Cha] H.E. Chandler, Metals Handbook, 1978, pp. 845-852.
- [1978Exn] H.E. Exner, A. Walter, P. Walter and G. Petzow, Sintering of WC-12 wt% Co Cemented Carbide with Different Binder Phase Composition, Planseeber Pulvermet, 26 (1978) 90-104.

- [1978Kon] W. Konig, Proc. 47th Meeting of AGARD Structural and Materials Panel, Florence, Sept. 1978, AGARD, CP256, London, 1979, pp. 1.1-1.10.
- [1978Lee] H.C. Lee and J. Gurland, Hardness and Deformation of Cemented Tungsten Carbide, Mater. Sci. Eng. 33 (1978) 125–133.
- [1979Fai] A.H. Fairand, B.P. Clauer, Interaction of laser-induced stress waves with metals. In Proceedings of the ASM Conference Applications of Lasers in Materials Processing, Washington, DC, USA, 18–20 April 1979; ASM International: Materials Park, OH, USA, 1979.
- [1982Kom] R. Komanduri, Some clarifications on the mechanics of chip formation when machining titanium alloys, Wear, 76: 15–34.
- [1982Sor] E. L. Sorice, Selecting milling cutters, in: B. K. Lambert, Ed., Milling Methods and Machines, SME, Dearborn, MI, 1982, pp. 62–63.
- [1982Suz] H. Suzuki, K. Hayashi, Y. Taniguchi and H. Matsubara, The Bend Deformation of WC-Co Cemented Carbides at Temperatures up to 1273 K, Trans. Jap. Inst. Met., 23 (1982) 77-84.
- [1982Tip] V. J. Tipnis, The working face mill, in: B. K. Lambert, Ed., Milling Methods and Machines, SME, Dearborn, MI, 1982, pp. 64–67.
- [1983Bo1] J. D. Bolton and R.J. Kee, Fibre Sci. and Tech., Vol. 19, p. 36 (1983).
- [1983Exn] H.E. Exner and E. Artz, Sintering processes, Physical Metallurgy, Third edition, Elsevier Science Publishers, Amsterdam, (1983) 1885–1912.

- [1983Has] Z. Hash, Analysis of Composite Materials - A Survey, J. Appl. Mech., 1983, vol.50, pp.481-505.
- [1984Mye] H. Bomberger, F. Froes, Processing Titanium and Their Alloys, J.O.M, (1984), pp. 50-60.
- [1984Sub] B.K. Subhas, R.A. Katti, Mech. Eng. 106 (8) (1984) 84
- [1984War] R. Warren, and B. Johansson, Sintered Metal Ceramic Composites, Elsevier, Amsterdam, Netherlands (1984).
- [1985Ger] R.M. German, Liquid Phase Sintering, Plenum Press, New York, 1985.
- [1985Kha] J.F. Kahles, M. Field, D. Eylon, F.H. Froes, J. Met. 37 (4) (1985) 27-35.
- [1985Zha] H. G. Zhang, Experimental investigations of the surface integrity of broached titanium alloy. CIRP Ann-Manuf Technol 34(1):491–494 (1985).
- [1986Cha] Y. Chaochen, Horizons in Powder Metallurgy, Verlag-Schmid, Freiburg, Germany (1986).
- [1986Dea] P. Dearnley, A. Grearson, Evaluation of principal wear mechanisms of cemented carbides and ceramics used for machining titanium alloy IMI 318. Mater Sci Technol 2(1):47–58 (1986).
- [1987Dus] J. Dus, L. Par, and M. Sle., Ceramic International, Vol. 13, No. 3, p. 133 (1987).
- [1987Hof] J. Hoffman et al. “Thermal Relaxation of Shot Peened Residual Stress in the Differently Heat-treated Plain Carbon Steel ICK45”. In: Shot Peening-Science,

Technology, Application. Ed. by H. Wohlfahrt, R. Kopp, and O. Vohringer. Oberursel, Germany: Informationsgesellschaft Verlag, Deutsche Gesellschaft fur Metallkunde, 1987, pp. 239–246.

- [1987Mot] S. Motonishi, Y. Hara, S. Isoda, H. Itoh, Y. Tsumori, Y. Terada, Study on machining of titanium and its alloys. *Kobelco Technology Review* (1987) (2), 28–31.
- [1987Pen] T.W. Penrice, Alternative Binders for Hard Metals, *J. Mat. Shaping Technol.*, 5 (1987) 35-39.
- [1988Ezu] E.O. Ezugwu, Technical Report, University of Warwick, 1988.
- [1988Wan] M. Wang, Y.Z. Zhang, *Mater. Sci. Technol.* 4 (1988) 548-553
- [1989Boo] G. Boothroyd, *Fundamentals of Machining and Machine Tools, Manufacturing Engineering and Materials Processing*, Marcel Dekker, Inc. (1989).
- [1990Ban] G. Banas, J. Lawrence, J. Rigsbee, E. Elsayed-ali, Laser shock hardening of welded maraging steel. *Surface Engineering*, (1990b). 67, 280–90.
- [1990Mac] A.R. Machado, and J. Wallbank, Machining of titanium and its alloys- A Review, *Proceedings Institution of Mechanical Engineers, Journal of Engineering Manufacturing*, (1990), Vol. 204, pp. 53–60.
- [1991Bal] P. Ballard, J. Fournier, R. Fabbro, and J. Frelat. Residual stresses induced by laser-shocks. *Journal de Physique IV*, C3, 487–94.(1991).

- [1991Jen] I. Jenkins and J.V. Woods, *Powders Metallurgy - An Overview*, Brookfield, The Intitute of Metals, USA (1991).
- [1992Vac] J.A. Vaccari, Laser shocking extends fatigue life. *Laser Technology*, Vaccari J.A. (ed.), *American Machinist*, 62–4 (1992).
- [1993Edw] R. Edwards, *Cutting tools*. Institute of Materials, London, (1993).
- [1993Hon] H. Hong, A. Riga, J. Cahoon, and G. Scott, “An Experimental Study of Wire EDM on Ti-8Al-4V, *Tribology International*, (1993), 34-39.
- [1993Saw] S. Sukvittayawong and I. Inasaki, Detection of Built-up Edge in Turning Process. *Internal Journal on Machine Tools and Manufacture*, 6 (33) (1993), pp. 829 – 840.
- [1994Zen] Zener, C., Hollomon, J. H., *Journal of Applied Physics* 15 (1), p 22-32, (1944) Isostatic Pressing. Australian Nuclear Science and Technology Organisation, 1997.
- [1995Ban] D. Banerjee, G.K. Lal and S.G. Upadhaya, Effect of Binder-Phase Modification and the Cr₃C₂ Addition on the Properties of WC-10Co Cemented Carbide, *JMEPEG*, 4 (1995) 563-72.
- [1995Bay] A.E. Bayoumi, J.Q. Xie, Some metallurgical aspects of chip formation in cutting Ti-6wt.%Al4wt.%V alloy. *Materials Science and Engineering*, (1995), 190: 173–180.
- [1995Sad] M.I. Sadik, B. Lindström, The effect of restricted contact length on tool performance. *J Mater Process Technol.* 48(1), (1995): 275–282.

- [1996Cas] D.A. Casarcia, W.D. Cowie and S. Mannava, Laser Shock Peened Bearings. US Patent 5584586, General Electric Company. (1996).
- [1996Cla] A.H. Clauer, J.K. Gregory, H.J. Rack and D. Eylon, Laser shock peening for fatigue resistance. Proceedings of Surface Performance of Titanium, (1996).
- [1996Hum] A.M. Human and H.E. Exner, Electrochemical Behaviour of Tungsten-Carbide Hardmetals, Mater. Sci. Eng., A 209(1–2) (1996) 180–191.
- [1996Joh] M. John, Structural Alloys Handbook, Technical Ed, Purdue University, West Lafayette, IN, (1996).
- [1996Lal] G.K. Lal, Introduction To Machining Science, New Age International, 1996
- [1996Man] S Mannavas and D. Cowie. Techniqueto Prevent or Divert Cracks. US Patent 5569018, General Electric Company. (1996).
- [1996Pey] P. Peyre et al, “Laser Shock Processing of Aluminium Alloys: Application to High Cycle Fatigue”. In: Materials Science and Engineering A210 (1996), pp. 102–113.
- [1996Qui] D. Quinto, Technology Perspective on CVD and PVD Coated Metal-Cutting Tools. International Journal of Refractory Metals & Hard Materials, 14 (1996), pp. 7-20.
- [1997Dan] C.B. Dane, L.A. Hackel, J. Daly, and J. Harrison, High laser power for peening of metals enabling production technology. Advanced Aerospace Materials and Processes Conference '98, Tysons Corner, Virginia, June 15–18, 1997.

- [1997Ezu] E.O. Ezugwu, Z.M. Wang, Titanium alloys and their machinability—A review. *Journal of Materials Processing Technology*, (1997), 68: 262–274.
- [1997Man^a] S. Mannava and S.J. Ferrigno, Laser Shock Peening for Gas Turbine Engine Vane Repair. US Patent 5675892, General Electric Company. (1997).
- [1997Man^b] S. Mannava, A.E. Mcdaniel, W.D. Cowie, H. Halila, J.E. Rhoda, and J.E. Gutknecht j.e. (1997). Laser Shock Peened Gas Turbine Engine Fan Blade Edges. US Patent 5591009, General Electric Company.
- [1997San] Y. Sano, N. Mukai, K. Okazaki, M. Obata, Residual stress improvement in metal surface by underwater laser irradiation. *Nucl. Instrum. Methods Phys. Res. B*. 1997;121:432–436. doi: 10.1016/S0168-583X(96)00551-4.
- [1997Zha] Y.K. Zhang, S.Y. Zhang, X.R. Zhang, L. Cal, J.C. Yang, N.F. Ren, Investigation of the surface qualities of laser shock-processed zones and the effect on fatigue life of aluminum alloy. *Surface and Coatings Technology*. (1997). 92, 104–9.
- [1998Ano] Anon., *Productive Metal Cutting*, Sandvik Coromant, Fair Lawn, NJ, 1998.
- [1998Cha] H.E. Chandler, Machining of reactive metals, *Metals Handbook volume 16: machining*, (1998) pp. 844-857.
- [1998Chi] D.R. Chichili, K.T. Ramesh, K.J. Hemker, The high-strain-rate response of alpha-titanium: Experiments, deformation mechanisms and modelling. *Acta Materialia* (1998). 46: 1025–43.

- [1998Ezu] E.O. Ezugwu, A.R. Machado, 1st Int. Conf. Behaviour of Materials in Machining. Stratford-upon-Avon, England, Inst. Met., 1988, Paper 3.
- [1998Fab] R. Fabbro, P. Peyre, I. Berthe and X. Scherpereel, Physics and applications of laser-shock processing. *Laser Application*, 10, (1998), 265–79.
- [1998Hon] Z. Hong and Y. Chengye. “Laser Shock processing of 2024-T62 Aluminium Alloy”. In: *Materials Science and Engineering A527* (1998), pp. 322–327.
- [1998Pey] P. Peyre, L. Berthe, X. Scherpereel, and R. Fabbro, Laser-shock processing of aluminium-coated 55C1 steel in water-confinement regime, characterization and application to high-cycle fatigue behaviour. *Materials Science*, 33, 1421–9. (1998).
- [1998Upa] G.S. Upahyaya, *Cemented Tungsten Carbide Production, Properties and Testing*, Noyes Publications, New Jersey, USA (1998).
- [1999Chu] J. Chu, G. Banas g. E. Elsayed-ali, Laser-shock processing effects on surface microstructure and mechanical properties of low carbon steel. *Materials Science and Engineering*, (1999) A260, 260–8.
- [1999Rus] J. Ruschau, R. John, S.R. Thompson, T. Nicholas, Fatigue crack nucleation and growth rate behavior of laser shock peened titanium. *Int. J. Fatigue* 1999, 21, 199–209.
- [1999Tok] M. Tokita, *Mechanism of Spark Plasma Sintering*, Sumitomo Coal Mining Company, Ltd., Kawasaki-shi Kanagawa, Japan (1999).

- [2000Bra] N.S. Brar, A. Hopkins, M.W. Laber, Laser shock peening of titanium 6–4 alloy. AIP Conf. Proc. 2000, 505, 435–438.
- [2000Chi] T. Childs, K. Maekawa, T. Obikawa, Y. Yamane. Metal Machining – Theory and Applications. Arnold: 2000.
- [2000Pey] P. Peyre, X. Scherpereel, L. Berthe, C. Carboni, R. Fabbro, G. Béranger, C. Lemaitre, Surface modifications induced in 316 L steel by laser peening and shot-peening. Influence on pitting corrosion resistance. Mater. Sci. Eng. A 2000, 280, 294–302.
- [2000Tre] E. Trent, “Metal cutting”, New York, Butterworth-Heinemann, 2000
- [2000Zoy] Z. Zoya, R. Krishnamurthy, The performance of CBN tools in the machining of titanium alloys. J Mater Process Technol, (2 000)100:80–86.
- [2001Che] C. H Che-Haron, Tool life and surface integrity in turning titanium alloy. J Mater Process Technol. 118:231–237. (2001).
- [2001Cla] A.H. Clauer, D. F. Lahrman, Laser shock processing as a surface enhancement process. Engineering Materials, (2001), 197, 121–44.
- [2001Ezu] E.O. Ezugwu, Z.M. Wang, Titanium alloys and their machinability a review, School of Engineering Systems and Design, South Bank University, London SE1 OAA, UK, 2110
- [2001Fer] S.J. Ferrigno, K.G. Mcallister and S. Mannava, Laser Shock Peened Gas Turbine Engine Seal Teeth. US Patent 6200689, General Electric Company. (2001).

- [2001Sha] Y. Shane, Y. Hong, D. Yucheng and W. Jeong, Friction and Cutting Forces in Cryogenic Machining of Ti-6Al-4V, *International Journal of Machine Tools and Manufacture*, Vol.41, (2001), pp.2271-2285.

- [2002Bör] A. Börger, P. Supancic and R. Danzer, The Ball on Three Balls Test for Strength Testing of Brittle Discs -Stress Distribution in the Disc, *J. Eur. Ceram. Soc.*, 22 (2002) 1425-1436.

- [2002Des] J. Destefani, Cutting tools geometries, *Manuf. Eng.* 133:5 (2002) 41–49.

- [2002Gil] G. Gille, B. Szensy, K. Dreyer, H. Van den Berg, J. Schmidt, T. Gestrich, Submicron and ultrafine grain hardmetals for micro drills and metal cutting inserts. *Int J Refract Hard Mat* 2002;20 (1)3:22

- [2002Mam] V. Mamedov, Spark Plasma Sintering as an Advanced PM Sintering Method, *Powd. Metall.*, 45(4) (2002) 322-328.

- [2002Ste] D. M. Stefanescu, *Science and engineering of casting solidification*, Springer, (2002), p. 265,

- [2002Wit] B. Wittmann, W. Schubert and B. Lux, WC Grain Growth and Grain Growth Inhibition in Nickel and Iron Binder Hardmetals, *Int. J. Refract. Met. Hard Mater.*, 20 (2002) 51-60.

- [2003Ano] Anon., Geometries at work—Optimize edge and insert placement in facemill and endmill cutters, *Cutting Tool Eng.* 55:5 (2003).

- [2003Ezu] E. Ezugwu, J. Bonney, Y. Yamane, An overview of the machinability of aeroengine alloys. *J Mater Process Technol* 134(2):233–253. (2003).

- [2003Zha] F.L. Zhang, C.Y. Wang, M. Zhu, Nonostructured WC/Co composite powder prepared by high energy ball milling, *Scripta Mater.* 49 (2003) 195 - 201

- [2004Dud] D. Dudzinski, A. Devillèz, A. Moufki, D. Larrouquere, V. Zerrouki, and J. Vigneau, A review of developments towards dry and high speed machining of Inconel 718 alloy. *Int. J. Mach. Tools Manuf.* 44 (2004), pp. 439 – 456.

- [2004Pet] A. Petersson, *Cemented Carbide Sintering: Constitutive Relations and Microstructural Evolution*, Stockholm 2004.

- [2005Ger] G. Dumitru, B. Luscher, M. Krack, S. Bruneau, J. Hermann, and Y. Gerbig, “Laser processing of hardmetals: Physical basics and applications,” *Int. J. Refr. Metals Hard Mater.* 23, 278–286 (2005).

- [2005Hua] J. Hua, A Cobalt Diffusion Based Model for Predicting Crater Wear of Carbide Tools in Machining Titanium Alloys, *Journal of Engineering Materials and Technology* 127(1) · 2005.

- [2005Raj] R. K. Rajput, *A Textbook of Engineering Thermodynamics – Heat Engineering*, Laxmi Publications, 2005.

- [2005Sha] M.C. Shaw, *Metal Cutting Principles*, Second Edition, Oxford University Press, 2005.

- [2005Wan] Z. G. Wang, Y. S. Wong M. Rahman, High-speed milling of titanium alloys using binderless CBN tools. *International Journal of Machine Tools and Manufacture*, 45(1) (2005): 105–114

- [2005Yan] H. Yan, J. Hua, R. Shivpuri, Numerical simulation of finish hard turning for AISI H13 die steel. *Sci. and Tech Adv. Mat.* (6) (2005), pp. 540.
- [2006 Din] K. Ding L.Ye. *Laser shock peening Performance and process simulation*, CRC Press, New York Washington, DC.
- [2006Har] P. M. Har, M. Henry, and M. Brownell, Laser processing of polycrystalline diamond, tungsten carbide, and a related composite material, *Journal of Laser Applications* 18, 117. 2006.
- [2006Nou] M. Nouari, A. Ginting, Wear characteristics and performance of multi-layer CVD-coated alloyed carbide tool in dry end milling of titanium alloy. *Surface and Coatings Technology*, (2006), 200(18):5663–5676.
- [2006Zoe] Z. Lin, S. Lo, “Effect of different tool flank wear lengths on the deformations of an elastic cutting tool and the machined workpiece”, *International Journal of Computer Applications in Technology*, vol. 25, no.1, pp. 30 -39, 2006.
- [2007Ezu] E.O Ezugwu, J. Bonney, R.B. Silva, O. Cakir, Surface integrity of finished turned Ti-6Al-4V alloy with PCD tools using conventional and high pressure coolant supplies, London south bank university, 2007
- [2007Kum] M. Kumar, J. R. Kumar, and B. Bas, Crater wear mechanisms of TiCN–Ni–WC cermets during dry machining. *International Journal of Refractory Metals and Hard Materials*, 25(5-6), (2007).
- [2007Lui] F. Luigino, M. Fabrizio, L. Settineri, D. Umbrello, Wear modelling in mild steel orthogonal cutting when using uncoated carbide tools. *Wear*. 2007, vol. 262, p. 545-554.

- [2007Lut]] G. Lütjering, J.C. Williams, Titanium. 2nd ed. New York, NY: Springer; 2007.
- [2007Qia] L. Qian, M. Hossan, “Effect on cutting force in turning hardened tool steels with cubic boron nitride inserts”, Journal of Materials Processing Technology, vol. 191, 274–278, 2007.
- [2008Abe] E. Abele, B. Fröhlich, High speed milling of titanium alloys. Advances in Production Engineering and Management, (2008), 3: 131–140.
- [2008Cui] Y. Cui, Tool wear monitoring for milling by tracking cutting force model coefficients, Masters Thesis, University of New Hampshire, Durham
- [2008Dav] J.P. Davim, V.P. Astakhov, Tools (Geometry and material) and tool wear. In: J.P. Davim (ed.). Machining – Fundamentals and recent advances. Springer: 2008, ISBN: 978-1-84800-212-8.
- [2008Gao] F. Gao, R.K. Leach, J. Petzing, and J.M. Coupland, Surface Measurement errors using commercial scanning white light interferometers, Measurement Science and Technology, 19 (1) (2008).
- [2008Guo] Z. Guo, J. Xiong, M. Yang, X. Song and C Jiang, , Effect of Mo₂C on microstructure and properties of WC-TiC-Ni cemented carbides, International Journal of Refractory Metals & Hard Materials 26 (2008) 601–605.
- [2008Pau] I. Davim, J. Paulo. Machining: fundamentals and recent, Springer-Verlag London Limited, (2008).
- [2008San] C. Sandvik, Application Guide: Titanium machining, Sweden, 2008.

- [2008Ran] M. Randal, P. Seong: Review of Liquid Phase Sintering, Int Journal of Material Science, Jan 2008.
- [2008Smi] P. Smid, CNC Programming Handbook (3rd ed). New York Industrial press, 2008.
- [2009Bew] A.K. Bewoor and V.A. Kulkarni, Metrology & Measurement, Tata McGrwa-Hills Education Private Limited, 2009.
- [2009Che] K. Cheng, Machining dynamics: fundamentals, applications and practices. - (Springer series in advanced manufacturing), 2009.
- [2009Dem] H. Demir, S. Gunduz, The effects of aging on machinability of 6061 aluminium alloy. Materials and Design 2009, 30, 1480–1483.
- [2009Kik] M. Kikuchi, The use of cutting temperature to evaluate the machinability of titanium alloys. Acta Biomaterialia, (2009) 5: 770–775.
- [2009Liu] K.K Liu, M.R. Hill, The effects of laser peening and shot peening on fretting fatigue in Ti-6Al-4V coupons. Tribol. Int. 2009;42:1250–1262. doi: 10.1016/j.triboint.2009.04.005
- [2009Sch] G. Schnieder, Cutting tool materials, American machinist, 2009.
- [2009Sun] S Sun, M Brandt, M Dargusch, Characteristics of cutting forces and chip formation in machining of titanium alloys. Int. J Mach Tools Manuf. 49:561–568, 2009.
- [2009Url] <http://www.custompartnet.com/wu/milling>. Accessed 03/12/2017.

- [2010Dav] J. Davim, Surface Integrity in Machining, Springer, 2010.
- [2010Elh] M. ElHossainy, T. Zoghby. Cutting Parameter Optimization when Machining Different Materials. Materials and Manufacturing Processes. 25. (2010).
- [2010Gom] G. Gomez-Rosas, C. Rubio-Gonzalez, J.L. Ocaña, C. Molpeceres, J.A. Porro, M. Morales, F.J. Casillas, Laser shock processing of 6061-T6 Al alloy with 1064 nm and 532 nm wavelengths. Appl. Surf. Sci. 2010;256:5828–5831. doi: 10.1016/j.apsusc.2010.03.043.
- [2010Tha] S.K Thandra, S.K. Choudhury, “Effect of cutting parameters on cutting force, surface finish and tool wear in hot machining”, International Journal of Machining and Machinability of Materials, vol. 7, No. 3/4, pp. 260-273, 2010.
- [2010Ye] C. Ye, Y. Liao, G.J. Cheng, Warm laser shock peening driven nanostructures and their effects on fatigue performance in aluminium alloy 6160. Adv. Eng. Mater. 2010, 12, 291–297.
- [2010Zha] Y. Zhang, J. You, J. Lu, C. Cui, Y. Jiang, X. Ren, Effects of laser shock processing on stress corrosion cracking susceptibility of AZ31B magnesium alloy. Surf. Coat. Technol. 2010, 204, 3947–3953
- [2011Mon] C. Montross, V. Florea, M. Swain, The influence of coatings on subsurface mechanical properties of laser peened 2011-T3 aluminium. J. Mater. Sci. 2011, 36, 1801–1807.
- [2011Ros] N. Rossini, M.Dassisti, K. Benyounis, and A. Olabi, Methods of measuring residual stresses in components, Materials and Design, 35 (2011), pp. 572-588.

- [2011Rub] C. Rubio-González, C. Felix-Martinez, G. Gomez-Rosas, J.L. Ocaña, M. Morales, J.A. Porro, Effect of laser shock processing on fatigue crack growth of duplex stainless steel. *Mater. Sci. Eng. A* 2011, 528, 914–919.
- [2011Wol] Krystian L. Surface deformation mechanisms in laser smoothing and micromachining of optical glasses, PhD Thesis, Heriot-Watt University, School of Engineering and Physical Sciences. 2011.
- [2011Ye] C. Ye, S. Suslov, B.J. Kim, E.A. Stach, G.J. Cheng, Fatigue performance improvement in AISI 4140 steel by dynamic strain aging and dynamic precipitation during warm laser shock peening. *Acta Mater.* 2011, 59, 1014–1025
- [2011Yul] E. Yul, M. Riza and M. Y. Ali, Cutting Force Impact to Tool Life of CT5015 in High Speed Machining by Applying Negative Rake Angles, International Conference on Applied Mechanics, Materials and Manufacturing (ICAMMM 2011), At Shenzhen, China.
- [2012Cao] Z. Cao, H. Xu, S. Zou, Z. Che, Investigation of surface integrity on TC17 titanium alloy treated by square-spot laser shock peening. *Chin. J. Aeronaut.* 2012, 25, 650–656
- [2012Che] Y. Liaoa, S. Suslov, C. Ye, Gary J. Cheng, The mechanisms of thermal engineered laser shock peening for enhanced fatigue performance, *Acta Materialia*, August 2012, Pages 4997-5009.
- [2012Mac] R. Machado, J.wallbank, Machining of Titanium and it's Alloy-A review, Warwick, 2012.

- [2012Sad] A. B. Sadat, “Surface Integrity When Machining Metal Matix Composites,” in *Machining of Metal Matrix Composites*, London, Springer-Verlag London Limited, 2012, pp. 51-61.
- [2012Tra] U. Trdan, J.A. Porro, J.L. Ocaña, J. Grum, Laser shock peening without absorbent coating (LSPwC) effect on 3D surface topography and mechanical properties of 6082-T651 Al alloy. *Surf. Coat. Technol.* 2012, 208, 109–116.
- [2012Zho] Z. Zhou, S. Bhamare, G. Ramakrishnan, S.R. Mannava, K. Langer, Y. Wen, D. Qian, V.K. Vasudevan, Thermal relaxation of residual stress in laser shock peened Ti-6Al-4V alloy. *Surf. Coat. Technol.* 2012, 206, 4619–4627.
- [2013Nev] D. Neves, A. E. Diniza, M. S. FernandesLima, Microstructural analyses and wear behavior of the cemented carbide tools after laser surface treatment and PVD coating. *Applied Surface Science*, Volume 282, 1 October 2013, Pages 680-688.
- [2013Pra] P. S. Pratik, P.T. Swanson, and C.J. Page, Laser shock peening and mechanical shot peening processes applicable for the surface treatment of technical grade ceramics: A review, *J. Engineering Manufacture* 2014, Vol. 228(5) 639–652
- [2013Tok] M. Tokita, *Spark Plasma Sintering (SPS) Method, Systems, and Applications. Handbook of Advanced Ceramics*, (2013) 1149–1177.
- [2013Url] Titanium project has global impact, Sarah Wild (<http://mg.co.za/author/sarah-wild>) 07 Jun 2013.
- [2013Ush] T. Usher, *The Modern Machinist*, N. W. Henley. (2), 2013.

- [2014Abd] H. Abdel-Gawa, Fundamentals of Machining Processes, Conventional and Nonconventional Processes. CRC Press, 2013.
- [2014Gen] R.M. Genga, Microstructure and properties of selected WC-cemented carbides manufactured by SPS method, Doctoral thesis, University of Witwatersrand, Johannesburg, (2014).
- [2014Guj] A. K. Gujba and M Medraj, “Laser Peening Process and Its Impact on Materials Properties in Comparison with Shot Peening and Ultrasonic Impact Peening”. In: Materials 7 (2014), pp. 7925–7974.
- [2014Kum] A. Kumar and S.Mohanty, A Review on the Effect of Process Parameters on Different Output Parameters during Machining of Several Materials, International Journal of Engineering Science and Research, 2014.
- [2014Pau] J. Paulo Davim, Materials Forming, Machining and Tribology, Aveiro, Portugal, 2014.
- [2014Pra] A. Pramanik, Problems and solutions in machining of titanium alloys. International Journal of Advanced Manufacturing Technology, (2014), 70 (5–8): 919–928.
- [2014Url] Mitsubishi, Functions of chip breakers, mmc.permanent.learnways.com/courses/75/functions-of-chip-breakers.html. Accessed: 14/01/2018.
- [2014Zhu] L. Zhu, S.S. Peng, C.L. Yin, Cutting temperature, tool wear, and tool life in heat-pipe-assisted end-milling operations, Int. J Adv. Manuf. Technol., (2014) 72: 995.

- [2015Cha] A. Chang, B. Zhang, Y. Wu, Q. Zhao, H. Zhang, J. Yao, P. Zhao, Spark Plasma Sintering of Negative Temperature Coefficient Thermistor Ceramics. Sintering Techniques of Materials. (2015).
- [2015Elk] E. El-Kady, A. Gaafer, M. G. Ghaith, T. Khalil¹, A. Mostafa¹, The Effect of Machining Parameters on the Cutting Forces, Tool Wear, and Machined Surface Roughness of Metal Matrix Nano Composite Material.
- [2015Lot] M. Lofti, A. Faris, H. Soleimanimehr, The effect of chip breaker geometry on chip shape, bending moment, and cutting force: FE analysis and experimental study. *Int J Adv Manuf Technol* (2015) 78: 917
- [2015Pra] A. Pramanik and G. Littlefair. Machining of Titanium Alloy (Ti-6Al-4V)—Theory to Application, *Machining Science and Technology*, (2015). 19:1, 1-49.
- [2015She] M. Sherif, The history and necessity of mechanical alloying in *Mechanical Alloying* (Second Edition), 2015.
- [2015Url] www.olympusims.com/en/knowledge/metrology/roughness/2d_parameter/ (2015): Accessed 01/06/2017.
- [2015Vei] V. P. veiko, A. M. Skvortsov, T. U. Huynh Cong, A. A Petrov. Laser ablation of monocrystalline silicon under pulsed-frequency fiber laser. *Scientific and Technical Journal of Information Technologies, Mechanics and Optics*, 2015, vol.15, no. 3, pp. 426–434.

- [2016Ofe] N.L. Ofem, Optimising the surface integrity of machined Ti-6Al-4V using advanced cemented carbide inserts and minimum quantity lubrication, Master's thesis, University of Witwatersrand, Johannesburg, (2016).
- [2016Ste] A.A. Stephenson, J.S. Agapiou, Metal Cutting Theory and Practice, CRC Press, (2016).
- [2016Url] <https://www.spilasers.com/application-ablation/what-is-laser-ablation>
Accessed: 14/01/2019.
- [2016Wan] C. Wang, C. Jiang, F. Cai, Y. Zhao, K. Zhu, and Z. Chai, Effect of shot peening on the residual stresses and microstructure of tungsten cemented carbide, (2016).
- [2016Sai] A. Saini, P. Chauhan, B. Pabla, Multi-process parameter optimization in face milling of Ti6Al4V alloy using response surface methodology, Proceedings of the Institution of Mechanical Engineers, Part B. Journal of Engineering, 2016
- [2017Url^b] Groove Type and Obstruction Type Chip Breaker - Advantages And..., <https://www.mecholic.com>› Manufacturing Technology. Accessed: 04/08/2018
- [2018Li] N. Li, Y. Chen, D. Kong Effect of cutter body geometry in Ti-6Al-4V face-milling process, The International Journal of Advanced Manufacturing Technology, 2019, Volume 100, Issue 5–8, pp 1881–189.
- [2017Url^a] <https://www.totalcarbide.com/tungsten-carbide-manufacturing-process.htm>.
Assessed: 09/03/2019.

- [2018Mas] P. Masek¹, P. Zeman, P. Kolar, and F. Holesovsky, Edge trimming of C/PPS plates. The International Journal of Advanced Manufacturing Technology. 2018
- [2018Osk] Oskar Sören, Machinability analysis of cemented carbide -A theoretical and experimental study, Masters Thesis, Department Of Mechanical Engineering Lund Institute Of Technology, 2016.
- [2017Ram] C. Ramirez, A. Idhil Ismail, C. Gendarme, M. Dehmas, E. Aeby-Gautier, G. Poulachon and F. Rossi, Understanding the diffusion wear mechanisms of WC-10%Co carbide tools during dry machining of titanium alloys, Wear, 2017.
- [2018PCT] METHOD AND SYSTEM FOR IMPROVING THE ABRASIVE RESISTANCE OF BRITTLE MATERIALS, AND A CUTTING TOOL PRODUCED BY SUCH METHOD been filed in collaboration with Wits Enterprise, International Application No.: PCT/IB2018/053772, Pub. No.: WO/2018/215996, published 29 November 2018.
- [2018Wan] X. Wang, and H. Zheng, Picosecond laser micro-drilling, engraving and surface texturing of tungsten carbide Journal of Laser Applications 30, 032203 (2018)
- [2019Gra] J. García, V. C. Ciprés, A. Blomqvist, and B. Kaplan, Cemented carbide microstructures: a review, International Journal of Refractory Metals and Hard Materials, 2019.

- [2019Hat] O. Hatamleh, A comprehensive investigation on the effects of laser and shot peening on fatigue crack growth in friction stir welded AA 2195 joints. *Int. J. Fatigue* 2009, 31, 974–988.
- [2019Sai] A. Saini, B.S. Pabla, S.S Dhani, Improvement in performance of cryogenically treated tungsten carbide tools in face milling of Ti-6Al-4V alloy, *Materials and Manufacturing Processes*, 2019.

APPENDIX A

Abstract for AESSA Conference.

EFFECT OF WC-BASED CUTTING TOOL COMPOSITION MANIPULATION AND LASER SURFACE MODIFICATION ON FACE-MILLING OF TI-6AL-4V.

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Abstract

Titanium alloys are difficult to machine primarily because of most (over 80%) of heat generated is absorbed by the cutting tool edge, accelerating tool wear. The presented study deals with the effect of insert composition manipulation and cutting edge laser modification for rapid heat dissipation during Ti-6Al-4V machining. Innovative cutting tools produced by liquid phase sintering (LPS) and pulsed electric current sintering (PECS) were used for this research, and their effect during face milling of Ti-6Al-4V was investigated under the following cutting conditions: cutting speed ranged from 60 to 300 m/min, depth of cut from 0.5 to 1.5 mm at a constant feed rate of 0.1mm/tooth. Cutting insert performance was assessed in terms of flank and crater wear, response to cutting force and temperature, and surface roughness.

APPENDIX B

Consumables and chemicals used in the production and test.

Chemical/Consumable	Sources
99% pure Ethanol	MK LABS, South Africa
Poly ethylene glycol (PEG)	BASF, Germany.
20 mm Ø WC milling media	Pilot tools (Pty) Ltd., South Africa
SPS graphite punches and dies	SGL Carbon, South Africa
SPS graphite foils	SGL Carbon, South Africa
SPS carbon protective cloth	FCT, Germany
Diamond coated cutting wheel	Struers, USA
Mounting Polyfast	Struers, USA
Grinding wheels and polishing cloths	Pilot tools (Pty) Ltd., South Africa
Polishing lubricant and diamond suspensions	Pilot tools (Pty) Ltd., South Africa
Edge honing white fused Alumina-F60	Wester Mineralien, South Africa