

Strain gradient plasticity in AISI A36 plain carbon steel weldment: Comparison of butt and lap joint configurations

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ABSTRACT

Strain gradient plasticity phenomenon in the parent material (PM), heat affected zone (HAZ) and fusion zone (FZ) of butt and lap joint of shielded metal arc welded AISI A36 steel is studied. The deformation mechanisms of the weldment were explained using mechanistic and phenomenological plasticity and dislocation models. The hardness of the FZ and HAZ of the lap weldment were 1.83 GPa and 1.56 GPa, which were slightly higher than the 1.63 GPa and 1.49 GPa of the FZ and HAZ of the butt. Tensile strengths of the butt joint was ~384 MPa and that of lap was ~361 MPa, which were higher than the parent material of ~290 MPa. The difference in strength between the butt and lap joint were due to the weld configuration and the limited fusion of the single build of the lap joint. The material length scale parameters varied due to microstructural transition from the PM to the FZ as a function of temperature. Length scales of ~34.37 μm and 22.75 μm were observed for the fusion zones of the lap and butt joints, whereas the lowest of 14.76 μm was for the as-received A36 steel. The geometrically necessary and statistically stored dislocations densities were higher in the lap weldment than for the butt. The average shear strain estimations were used to elucidate the underlying dislocation structures and densities. Grain refinement and localised stress and strain states at the HAZ and FZ led to variations in the mechanical properties. The implications of the results for robust design of welds for structural applications are discussed.

1. Introduction

Welding is at the heart of the industrial revolution and for designing and manufacturing massive structural components [1–9]. As the backbone of modern infrastructure development, it is the linchpin for fabrication and modernization of structures. Typical examples include landmarks (Eiffel Tower), monuments, tall buildings and skyscrapers, bridges, energy infrastructure (power plants and dams), oil rigs, industrial machinery, and transportation systems (megaships, yachts, railways, airplanes and automotive). Welding processes provide efficient, low cost and flexible approaches for fabricating structural and functional components [4,6,9–11].

Increasing population growth, need for low carbon emission strategies and global urbanization require massive infrastructural design and development. Most of these infrastructural (structural and functional)

developments are driven by metallic materials with great strength – toughness combinations [12]. For all structural and functional components, steels accounts to ~80% of all metallic materials [13,14]. Advancement in technologies and design in transportation, aviation, automotive, mining, oil and gas exploration and manufacturing industries have placed significant demand on the quality and structural integrity of welded joints [10,11,15]. This has direct implication on operating expenses (OPEX) as unplanned downtime can be minimized, which reduces repair, thus contributing to the structural integrity of these components. Furthermore, structural failures of welds are functions of the weld design and material selection [10,11,15–18]. Hence, understanding of material selection and the design of the welding processes is paramount.

Shielded Metal Arc Welding (SMAW) is the most mechanized and widely used welding process for fabrication of mechanical components

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[2,4,5,7,9,19]. The inherent advantages of deep-penetration, smooth welding beads and mechanical reliability enhance structural integrity [2,4,5,20]. It is also cost-effective with enhanced material deposition rates for high productivity [21]. However, the quality of welds in SMAW is highly dependent on process parameters such as weld speed, voltage, electrode feed, weld current and type of joint [5,22–24]. High heat inputs during SMAW welding have adverse effects on mechanical properties of the weldment of structural steels [25]. Thus, when the optimized process parameters are not selected for the welding process, weld defects such as porosity, inclusions, lack of fusion, cracks, undercuts and burn-through are inevitable and can compromise structural integrity [10,11,15,26–30]. The welding process irrespective of type and method induce residual stresses which has tremendous effects on functional and structural properties as well as structural integrity [31–33].

Weld joint design is vital for permanent joint development of two or more pieces of metals. The process affects the quality and overall cost of the process. The five main types of joints design for welds are butt, tee, corner, lap, and edge. The butt and lap joints are used in this study. The joint configurations and the microstructural features of the fusion zone (FZ) and heat affected zone (HAZ) affect the overall structural performance of the weld. Irrespective of the welding method (fusion or solid-state), the weld quality is affected by compositional dilution, mechanical properties of the fusion zone (FZ) and heat affected zone (HAZ) [34]. Apart from the fusion zone, the HAZ is categorized based on the grain size and the microstructural features induced by the processing parameters [35]. These are coarse-grained HAZ, fine-grained HAZ, and intercritical HAZ [35]. The peak temperature, which is a function of heat input during welding is the main contributing factor to the difference of the weld and fusion zones [2,36]. This is observed for low-alloyed carbon steels with martensite-austenite microstructures at different heat input [15,36]. The difference in grain sizes and other microstructural features are contributing factors to the desired and designed mechanical properties [10,11,15,31,32,37–39].

The AISI A36 carbon steel is a general-purpose structural alloy due to its low-cost, easy to weld, easy to form and machine [2]. It has 0.22–0.30 wt% hypoeutectoid carbon composition with ~1 wt% Mn contributing to malleability and ductility. This steel grade compares with other high performing alloys. It is paramagnetic making it good conductor of magnetic fields, thus impervious to electromagnetic pulses. Most applications are in automotive, construction (buildings and bridges), heavy machinery, and oil and gas industries. The AISI A36 steel have generated some research interests on mechanical behaviour of its weld and defects [1,2,40–44], tribological and corrosion properties [45–49]. However, little have been done to understand the effect of joint configuration on mechanical behaviour and strain gradient plasticity of the weldment.

Structural components subjected to stress and strains are explained using classical and strain gradient plasticity models [50–53]. Typical continuum plasticity model assumes uniform strains during the deformation process. In the case of strain gradient plasticity, there are variations of strains within the material during the deformation at the microstructural level. In welding metallurgy, there are different zones such as parent metal (PM), heat affected zone (HAZ) which can be subdivided based on grain sizes) and the fusion zone (FZ) due thermal cycling. These zones have variation in strains hence the continuum plasticity model is inadequate. Thus, a size-dependent behaviour of the weldment can be assessed and quantified based on geometrically necessary and statistically stored dislocations [51,52,54–57].

Welding and strain gradient plasticity have tremendous effects on the mechanical behaviour of welded structures [51,58–61]. The welding process introduces significant changes to the non-homogenous microstructure at the heat affected zone (HAZ) and the fusion zone [10,58]. This leads to localized variation in stress concentration and deformation mechanisms. Under these localized variations and non-homogeneous microstructure, the relevance of strain gradient plasticity is justified

[59–61]. The localised deformation and microstructural changes are associated with welding amplify strain gradients. Hence, assessing the size effects and the microstructural variations at the weld joint where stress and strains are highly concentrated is crucial [59–61]. Thus, gradation of microstructural features from welding is better analysed using strain gradient plasticity models. This is to account for any non-conformity in the deformation at the varying material length scales. The correlation between welding and strain gradient plasticity is evident for crack prediction and crack formation [15,62–65]. The localised effects of welding on material behaviour, combined with the ability of strain plasticity models to capture size-dependent phenomena, make these models valuable in assessing the integrity of welded structures [59–62,65]. The cumulative effects of statistically stored and geometrically necessary dislocations and their interactions with varying microstructural features need to be understood [51,58–65].

The SGP models have been used to elucidate bulk and surface modified alloys, composite and verified with simulations [51,53,60,61, 66–70]. Emphasis has been on bulk materials with heterogenous microstructures. Three distinct microstructural zones have been established showing defined indentation size effects [66,71]. However, the SGP technique has not been applied to joining technologies such as brazing, soldering, and welding of structural components. These are essential manufacturing techniques that requires critical assessment of the structural integrity. Hence, in-depth comprehension of mechanistic and phenomenological strain gradients and size effects as a function of the microstructure and phase transformation as applied to fusion welded components are required. This is vital in understanding the nature of dislocations (statistically stored and geometrically necessary) and their interactions with microstructural features driving the mechanical behaviour of welded structural components. This has essential implication for the design of components at the micro and nano scale [17,72]. The strain gradient plasticity model has not been applied to the different weld joint configurations of typical structural steel such as the AISI A36 steel. The aim of this work is to provide detailed analyses of strain gradient plasticity phenomenon on weldment of A36 steel with butt and lap joints. This is a useful tool to aid the design of weldments and how to assess the effects of dislocations and other defects during deformation.

In this work, strain gradient plasticity phenomenon and the tensile strength of butt and lap joints of SMAW welded AISI A36 was studied. Optical and scanning electron microscopy were used to resolve microstructural variations prior to tensile and hardness testing. An in-depth indentation size effect study using strain gradient plasticity theories was carried out on the welded samples. The samples with lap joint configuration had the highest retained average shear strain and hardness at both the heat affected zone and the fusion zone. The underlying dislocation microstructure for plastic deformation is elucidated. The butt welded samples had the highest ultimate tensile strength with reduced toughness. The variations in the mechanical properties of the samples are discussed with their microstructural differences. The impact of the results on welding joint design is also discussed.

2. Materials and methods

2.1. Materials

The A36 low carbon steel plates was procured from Sethi Brothers Ltd (Kumasi, Ghana). The compositions of the as-received samples were verified using spark analysis with a SpectroMaxx LMM-14 Glow Discharge Optical Emission Spectroscopy (GDOES) (Kleve, Germany). The spark analysis was done in triplicated and averaged shown in Table 1 and the balance being (iron) Fe. The plates, dimensioned as 609.6 mm × 1219 mm × 5 mm were sectioned using a plasma cutting machine (AVIC INTL, China) to 5 mm × 40 mm × 100 mm for the welding, mechanical and microstructural characterization. The samples were metallographically prepared (grinding and polishing) before welding, microstructural and mechanical characterization.

Table 1
Compositional analysis of As-received A36 low carbon steel.

Element	C	Cu	Mn	P	Si	S	Fe
Amount (wt%)	0.25 ±0.006	0.20 ±0.005	1.03 ±0.006	0.040 ± 0.003	0.280 ± 0.002	0.05 ±0.003	98.0 ±0.008

2.2. Welding process

Butt and lap weld joint designs are used. For the butt weld, the two plates of the A36 steels were placed in the same plane and welding was then carried-out between them. For the lap weld joint, the two plates were place on top of each other in an overlapping manner. Electrodes were used for the fabrication process. The E6013 electrode with a diameter of 3.2 mm was used, and the compositions are given in Table 2. A current of 90 A and arc voltage of 22–25 V were applied to induce melting and fusion of the parts. The shielded metal arc welding (SMAW) process was done with a single pass on the prepared A36 low carbon steel plates. The schematics of the butt and lap joint configurations and how the samples were sectioned are schematically shown in Fig. 1. Samples of dimensions 40 mm × 100 mm were prepared for the lap joint with an overlap of 20 mm.

2.3. Hardness tests

The micro-indentation test was done using a Wilson VH3300 hardness tester (Lake Bluff, IL, USA). The Vickers micro-hardness indenter had a conical diamond tip and loads from 2 - 20 N were applied for a dwell time of 10s. The experiments were done according to the ASTM E2546-15 standards. The hardness values were obtained at the three distinct zones; base metal, heat affected zone (HAZ) and the fusion zone (FZ). The values were converted to SI units. The microscopic hardness H of the specimens were determined using Equation (1).

$$H = \frac{F}{A}, \quad (1)$$

Where F is the applied force and A represents the indented area.

The Hall-Petch relation was used to analyse the variations in hardness of the base metal and the weldment as the microstructure changes. This theory has been modified to relate hardness to grain diameter. The Hall-Petch relationship for the micro-hardness (H) of the specimens were determine using Equation (2).

$$H = H_o + k_H d^{-\frac{1}{2}}, \quad (2)$$

where k_H and H_o are material constants determined from experiments and d represents the grain size of the microstructures.

2.3.1. Mechanistic/strain gradient plasticity theories

The mechanistic strain gradient plasticity models were used in this work [60,61]. The hardness (H) to indentation depth (h) was estimated using the Nix and Gao model in Equation (3).

$$H^2 = H_o^2 \left(1 + \frac{h^*}{h} \right), \quad (3)$$

where, H_o is the macroscopic hardness of the material that is resulting from the statistical stored dislocations (SSDs) and h^* represents the characteristics depth which is independent of the indenter geometry or indented material. Fig. 2 shows the contributions of geometrically necessary dislocations in hardening of the material during indentation.

Table 2
Composition of the E6013 filler rod.

Element	C	Mn	Cr	Si
Amount (wt%)	0.08	0.5	0.06	0.3

A linear curve is obtained for the plot of H^2 versus $1/h$. The square root of the intercept gives the macro hardness of the material as H_o and the gradient of the line is equivalent to h^* . The SSD density ρ_s is linked to the H_o as shown in Equation (4). The material length scale ($\hat{\gamma}$) was used to assess whether the strain gradient is large enough for the GNDs to contribute significantly to the hardening effect and the flow stress [73, 74], it was calculated using Equation (5).

$$H_o = 3\sqrt{3} \alpha \mu b \sqrt{\rho_s}, \quad (4)$$

$$\hat{\gamma} = b \left(\frac{\mu}{\sigma_o} \right)^2, \quad (5)$$

Where μ is the shear modulus, b is the Burgers vector, α is the Taylor factor and where σ_o represents the flow stress in the absence of strain gradient.

Generally, the flow stresses and behaviour are crucial in understanding the microstructural mechanisms [16,38]. At very high flow stresses, the material length scale becomes negligible. To contain the displacing volume of material during indentation, the average shear strain (γ) is in the order of the average density of the geometrically necessary dislocations (ρ_G) [50]. This is formulated using the local length scale (indent depth, h), and the Burgers Vector (b) as given in Equation (6) [58]. The total dislocations density is then linked to the hardness of the material as shown in Equation (7). A maximum curve fitting of the plot of experimental values (using equation (7)) is then used to determine the average shear strain in the system. The spacing (L) in between the dislocations is estimated (Equation (8)).

$$\rho_G \approx \frac{4\gamma}{bh}, \quad (6)$$

$$H \approx \mu b \left[\rho_s + \frac{4\gamma}{bh} \right]^{\frac{1}{2}}, \quad (7)$$

$$L = \frac{1}{\sqrt{\rho_G}}, \quad (8)$$

2.4. Tensile test

The universal tensile testing machine was used. The welded and unwelded samples were machined and dimensioned according to the ASTM E8 standards. The samples were prepared transverse to the direction of the welding as shown in Fig. 1(c). The samples were mounted firmly in the jaw heads and tensile tests were done at a strain rate of 0.8 mm/s.

2.5. Microstructural characterization

The welded and unwelded samples were metallographically prepared (coarse and fine gridding, and diamond polishing to 2 μ m). The polished samples were etched in 2% Nital for 12 s. The SMZ800 N optical microscopy (Melville, NY, USA) was used to observe the microstructure of the samples. Scanning electron images were taken with 5 kV voltage using a JEOL JSM – 7000F Field Emission Scanning Electron Microscope (Golden, Co, USA) equipped with energy dispersive spectroscopy (EDS) and electron backscatter diffraction (EBSD) detectors. The EBSD of the FZ and HAZ was done with 20 keV and a step size of 5 μ m. The analysis was performed at a plane 70° to the welding direction

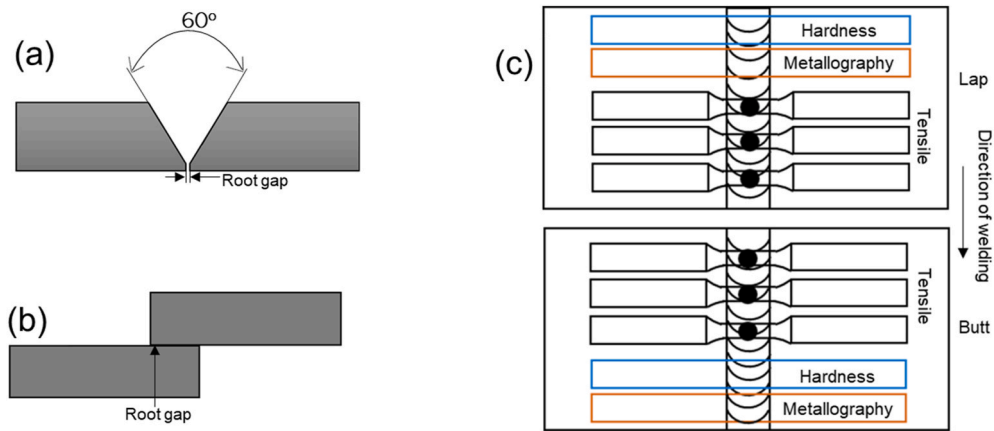


Fig. 1. Schematics of welding joint sampling and joint configurations (a) Sketch of A36 low carbon steel plate sampling, (b) lap joint and (c) butt joint.

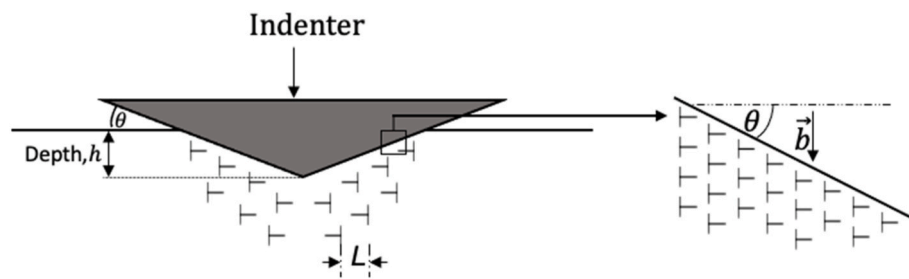


Fig. 2. Schematic showing geometrically necessary dislocations under an indenter, where L is the spacing between dislocations, “ h ” is the depth of penetration, b is the Burgers vector, and θ is the angle between the plane of the indented surface and conical surface of the indenter.

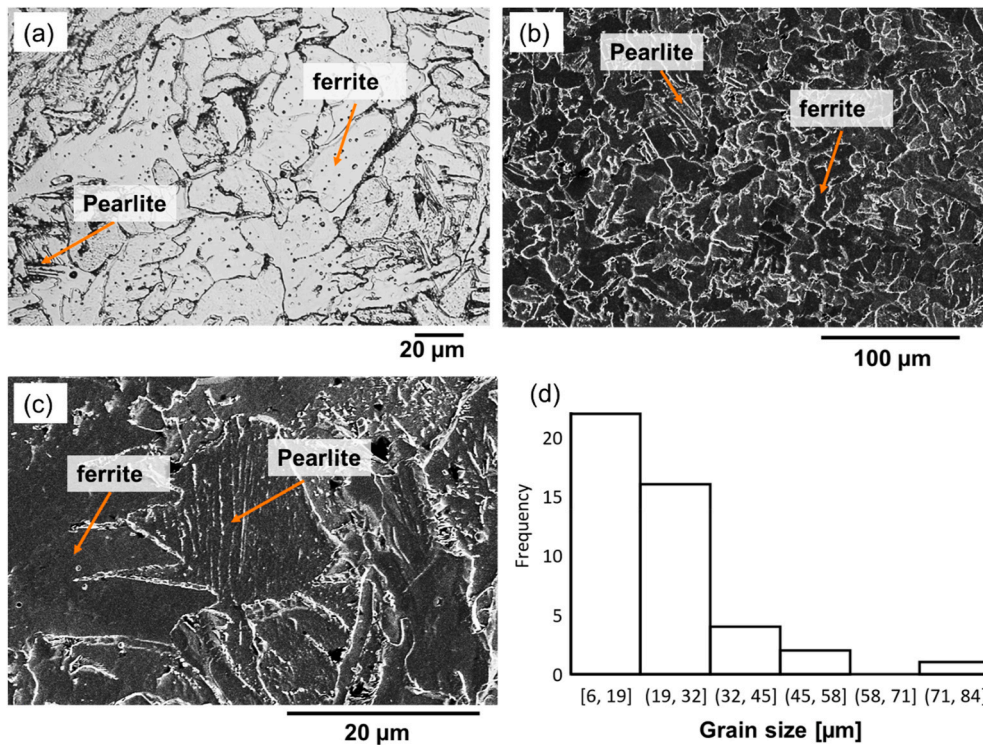


Fig. 3. The as-received A36 low carbon steel showing: (a) optical image with high volume fraction of ferrite, ((b) and (c) are the SEM images of characteristic ferrite and pearlite and (d) grain size distribution.

in the transverse section of the welded joint. Data on phase distribution, grain size, crystal orientation maps and phase content in the zones were collected.

The fracture surfaces of the tested tensile specimens were ultrasonically cleaned using ethanol for two to 3 min. This was done to remove any contaminants and rust from the surface prior to SEM analyses. Fractographic images were acquired using the SEM in the secondary electron mode. The failure mode and fracture mechanisms were examined from the fractographs.

3. Results and discussion

3.1. Microstructure characterization of the parent metal

The as-received A36 low carbon steel had proeutectoid ferrite – pearlite with grain size distribution is given in Fig. 3. This is characteristic microstructure for most carbon steels [39,66,75,76]. The grain size distribution is given in Fig. 3(d) with the average grain size estimated as $21.54 \pm 12 \mu\text{m}$ showing differences between the fine and coarse grains which are statistically significant. The lamellar spacing for the pearlite colonies was determined to be $\sim 0.3 \mu\text{m}$.

3.2. Visual inspection of the butt and lap welded A36 steel

The weldment of the A36 steel showing the butt and lap joints is given in Fig. 4. The butt welded joint is shown in Fig. 4 (a) and that of the lap joint configuration, Fig. 4 (b). The need for the visual and physical examination of the weldment is to ensure that there are no macro defects that could compromise the structural integrity of the weldment. These macro defects reduce the aesthetic quality of the weld, reduce load-bearing capacity resulting in poor mechanical properties which could lead to premature failure. When macro defects are observed on the weldment, the sample is discarded. Thus, the visual and physical examination of the weldment showed no macro defects such as incomplete penetration, incomplete fusion, undercutting, overlap, weld spatter, cracking, and porosity. These defects are generally associated with shielded metal arc welding and easily compromise structural integrity.

3.3. Microstructure characterization of the heat affected zone and weldment

3.3.1. Heat affected zone

The optical images of the HAZ of the lap and butt joint configurations are given in Figs. 5 and 6. For the two configurations, three distinct zones based on the grain sizes were observed for the HAZ. These are the coarse grain heat affected zone (CGHAZ), fine grain heat affected zone (FGHAZ) and inter critical heat affected zone (ICHAZ). The grain size distribution of the zones is given in Fig. 5(a)–(c). There was temperature gradient experienced in the HAZ of the lap welded joint. This decreased

away from the weld. Although, there was no temperature profile determination, the HAZ underwent thermal cycling at temperatures below the melting temperature. The highest temperature within the HAZ was near the weld bead. However, due to thermal cycling and slow rate of cooling from the weld bead to the parent material, the characteristic gradient microstructure was observed (Fig. 5 (g)). Generally, there was no thermal cracking due to the carefully controlled interpass temperature.

For the lap joint (Fig. 5), the CGHAZ (Fig. 5(d)) showed elongated and coarse ferrite, due to high and sustained heat inputs. The associated average grain size was $31.19 \pm 14.04 \mu\text{m}$ with an estimated zone width of $\sim 796.05 \mu\text{m}$ and a hardness of $1.57 \pm 0.18 \text{ GPa}$. Fine grains HAZ of the lap welded joint formed after the coarse grain heat affected zone as shown in Fig. 5 (d). The width of FGHAZ was estimated to be $\sim 554.14 \mu\text{m}$ with the corresponding average grain size of $5.58 \pm 2.62 \mu\text{m}$ and hardness of $1.52 \pm 0.15 \text{ GPa}$. The hardness was higher than the parent material due to the strengthening mechanisms from the grain refinement according to Hall Petch relationship.

The inter critical heat affected zone of the lap welded joints formed between the FGHAZ and the parent material. The average grain size of the intercritical HAZ was $12.23 \pm 6.02 \mu\text{m}$ which was lower than that for the CGHAZ and FGHAZ. The hardness of $1.44 \pm 0.22 \text{ GPa}$ was measured for the intercritical HAZ which was also higher than the parent material as expected. This is due to the overall grain refinement resulting from the heat input from the welding process. The width of the intercritical HAZ was $\sim 390 \mu\text{m}$. Considering hardness is proportional to strength and inversely proportional to tensile ductility, the differences in hardness values were due to changes in microstructural features such as varying grain sizes. Grain size refinement correlated well with tensile property and ductility.

The microstructural variation due to thermal gradient of the butt welded joint is given in Fig. 6. In the HAZ, the three distinct zones (CGHAZ, FGHAZ and ICHAZ) were observed. This is similar to those of the lap welded joints. The average grain sizes of the CGHAZ, FGHAZ and ICHAZ were $32.46 \pm 23.93 \mu\text{m}$, $8.99 \pm 3.63 \mu\text{m}$ and $16.44 \pm 7.08 \mu\text{m}$, respectively. The corresponding hardness values are $1.579 \pm 0.056 \text{ GPa}$, 1.51 ± 0.058 and $1.471 \pm 0.068 \text{ GPa}$. For the width, the CGHAZ and FGHAZ of the butt were comparable, which are ~ 611 and ~ 652.41 . However, the intercritical HAZ was about twice that of the CGHAZ and FGHAZ which was $\sim 1224.56 \mu\text{m}$. The intercritical HAZ was characterized by ferrite, pearlite, and some retained austenite. Based on the butt configuration and the groove design, high heat input was observed contributing to the very high intercritical HAZ. The multi - pass welding and the slow cooling rate were contributing factors.

The thickness of the A36 steel was also a contributing factor necessitating observed microstructural and mechanical properties in the butt welded joints. The HAZ experienced thermal cycling which affects the microstructural features during the welding process due to phase transformation. The variation in the width of the HAZ was attributed to

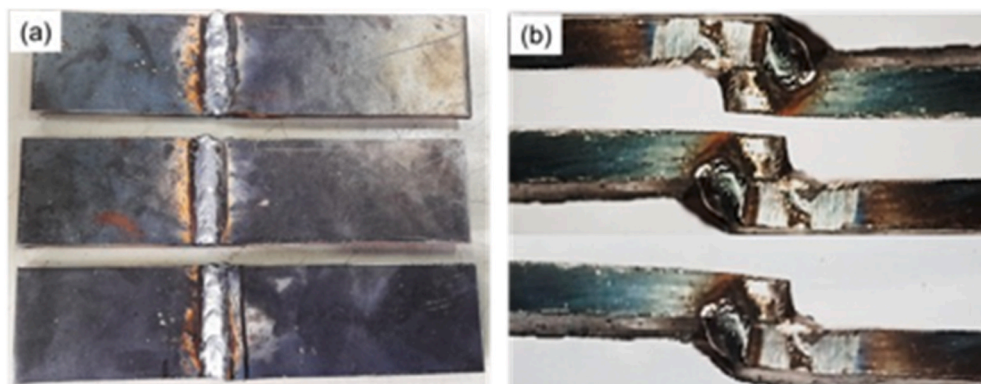


Fig. 4. Stereo images of the weldment of A36 steel showing (a) butt and (b) lap joints.

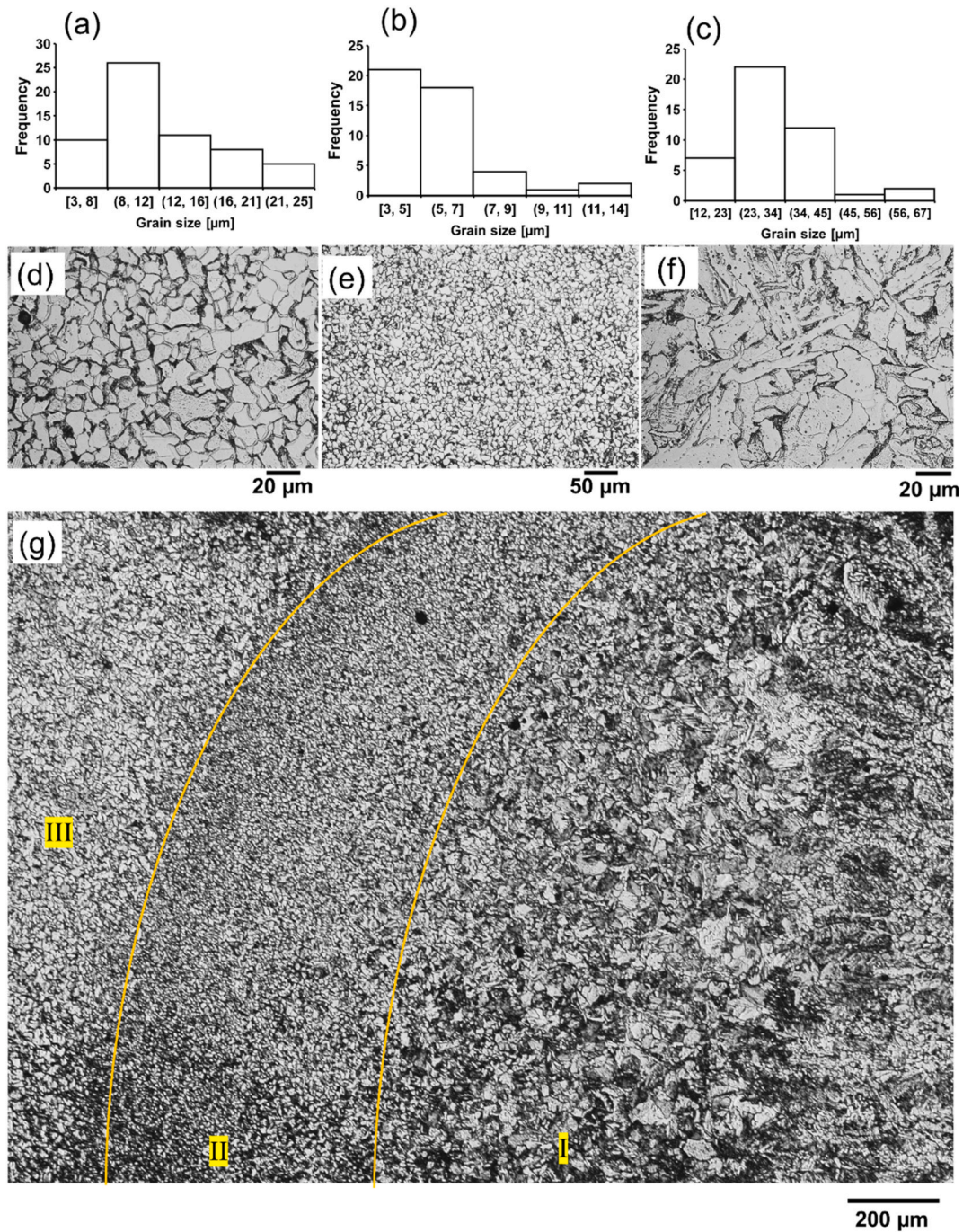


Fig. 5. Grain size distribution of the lap welded joint showing: (a) of the intercritical HAZ, (b) FGHAZ, (c) CGHAZ and the corresponding optical images: (d) intercritical HAZ, (e) FGHAZ, (f) CGHAZ and (g) low magnification of the zones: (I) as CGHAZ, (II) as FGHAZ and (III) as intercritical HAZ.

rate of heating and cooling cycling after welding [77]. The intercritical zones also showed banded ferrite after the recrystallization, which contributes to the overall mechanical properties. Banding is characteristics of hot-rolled carbon steels and the overall effects of the alloying elements [78,79].

3.3.2. Fusion zone

The microstructure of the fusion zone of the butt joint and lap joint welded samples are shown in Figs. 7 and 8 respectively. The microstructure of the fusion zone of both joint configurations showed elongated ferrite grains that were oriented towards the welding direction. The pearlite colonies formed within the elongated ferrite matrix (Fig. 7 (a)–(d)). The volume fraction of pearlite in the fusion zone were small

(Fig. 7(a)). Fig. 7(b) shows the grain size distribution of the FZ of the butt samples to be predominantly lower than 35 μm. Generally, the ferrite – pearlite volume fraction is a function of the thermal history and the heat input during the welding process.

The microstructure of the lap weldment showed distinct structures for the upper (above the dark line in Fig. 8 (a)) and lower lap configuration (below the dark line in Fig. 8 (b)). The dark line extending into the microstructure is the unwelded part of the two plates. This is due to the lap joint configuration and configuration applied, single fillet lap weld joint was used (Fig. 1). This is one of the main approaches used for welding tanks that are oriented in vertically [80]. The justification for using the single fillet lap joint was due to its simplicity, minimized welding defects generally associated with more than one fillet design,

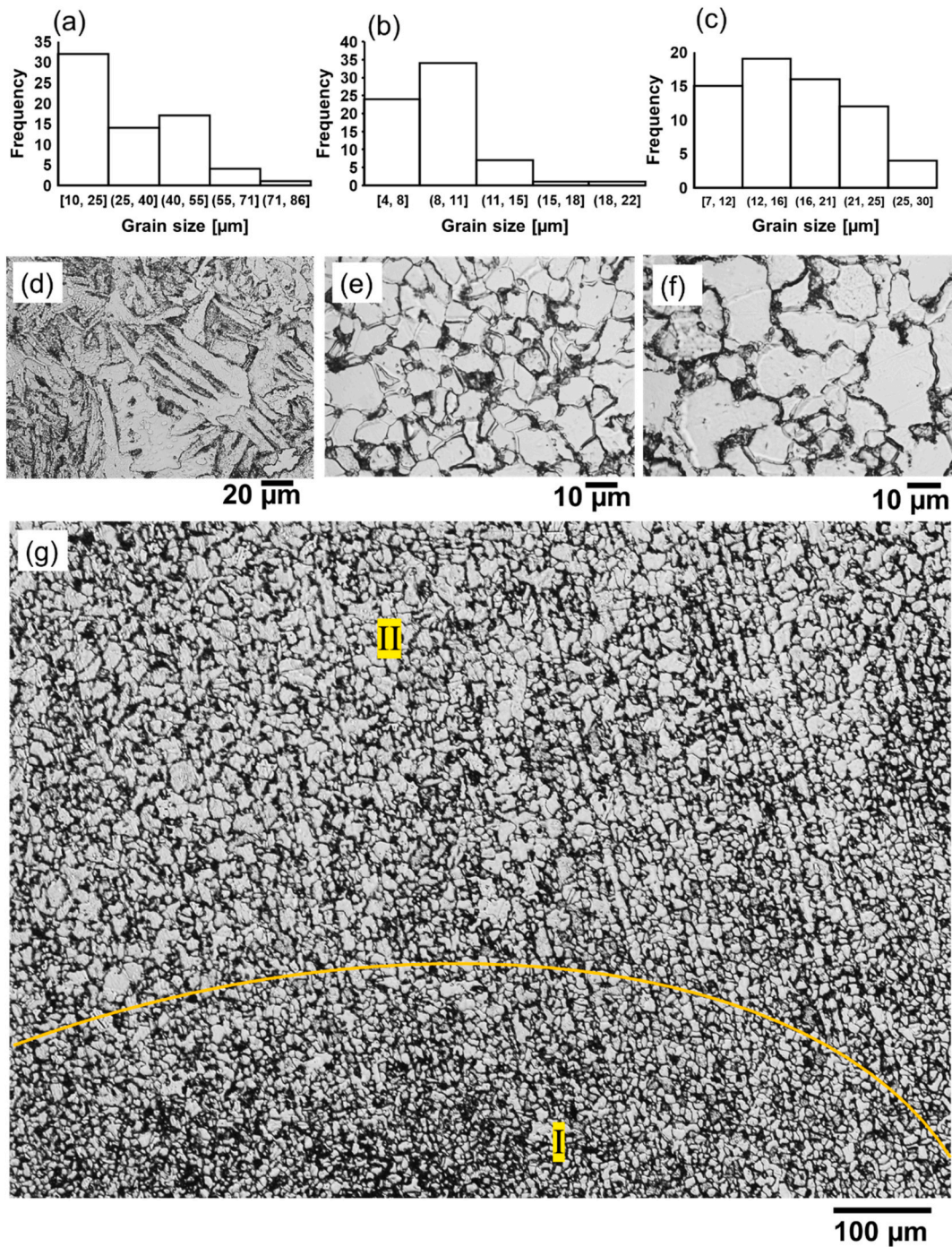


Fig. 6. Grain size distribution of butt weldment showing (a) CGHAZ, (b) FGHAZ, (c) intercritical HAZ and corresponding optical images of (d) CGHAZ, (e) FGHAZ, (f) intercritical HAZ and (g) banded microstructure at the intercritical HAZ with FGHAZ and intercritical HAZ labelled as (I) and (II).

reduced welding time and decreased distortions. However, it is important to highlight possible structural integrity challenges associated with single fillet lap joint [81–83]. These could have resulted in the fit-up being poor and not precise leaving gaps and misalignment between the edges of the two plates being welded. In the first instance, it could serve as a stress concentration for the initiation of cracks or pre-existing crack under monotonic and dynamic loading. There could be insufficient penetration during the welding process and the two pieces not adequately fused together [81].

Above the dark line, elongated ferrite grains with pearlite are oriented towards the welding direction with small grain sizes (Fig. 8(c)). Below the dark line, the microstructural features were mainly coarse

ferrite with pearlite extending into the FGHAZ beneath (Fig. 8(d)). The differences were attributed to thermal variation in the welded joint. For the single fillet lap weld design, the difference in the microstructures is also attributed to phase transformation, which is driven by the rate of cooling at the fusion zone. As the parent metals melt together with the electrode material, there are structural and compositional changes driving the observed microstructures. Hence the ferrite is seen as elongated like a typical dendritic structure associated with solidified cast structures, which are also influenced by the localized rate of cooling.

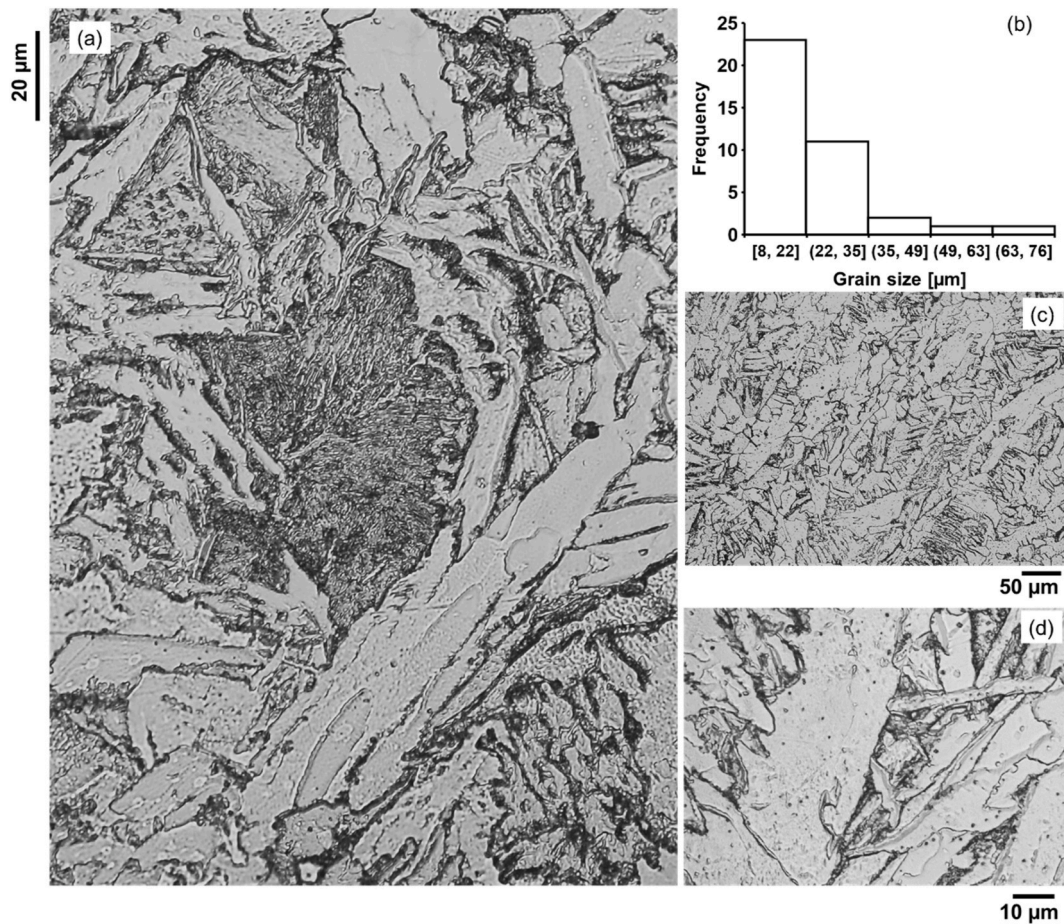


Fig. 7. Optical micrographs and grain size distribution of the fusion zone of the butt welded samples: (a) elongated ferrite - pearlite, (b) grain size distribution of the FZ and (c)–(d) critical features of ferrite-pearlite in the welding direction.

3.4. Crystallographic and phase mapping of weld microstructure

The EBSD mapping given in Fig. 9(a and c) show randomly oriented grains from the FZ and HAZ. The grains oriented towards the [001] are in red, those in [111] in blue and [101] planes in green. Most of the elongated grains are in the x – direction, which is along the welding direction. The EBSD phase mapping confirms a high content of ferrite, estimated at $\sim 94.85\%$, with the blue colour coding in Fig. 9(b) in the HAZ. This was also the case for the FZ, with a high ferrite content of 93.33% , represented in red colour coding in Fig. 8(d). The cementite phase which forms the pearlite phase in the microstructure was low, about 4.8% in the HAZ and 5.83% in the FZ. This phase was mainly located at the grain boundaries around the ferrite grains, as represented in yellow in Fig. 9(b and d). A small amount of the prior austenite phase was retained in the microstructure, also along the grain boundaries with red colour coding in Fig. 9 (d) and blue in Fig. 9(d).

3.5. Hardness

The hardness of the parent material was $\sim 1.40 \pm 0.02$ GPa. Fig. 10 (a) is a plot of hardness versus distance, that were taken 10 mm from the centre of the fusion zone towards the parent metal. The hardness of the HAZ of the butt welded samples was 1.49 ± 0.03 GPa, which was slightly higher than the parent material. In the fusion zone of the butt weldment, the hardness of the butt welded sample was 1.68 ± 0.11 GPa, which was about 17% higher than for the parent metal and $\sim 11\%$ higher than the HAZ. This is mainly driven by the microstructural features resulting in an overall decreased grain size. For the lap joint, the hardness of the fusion zone was 1.83 ± 0.13 GPa, which is higher than the

HAZ of 1.56 ± 0.25 GPa. Generally, hardness of the lap joint design was better than the butt joint. This was attributed to the different joint configurations and the heat sinking variations in them. This led to the observed differences in hardness between the lap and butt joint, which is partly due to Hall-Petch effects - grain size strengthening mechanism. However, grain sizes are not always the overarching effects as the weld quality and microstructural variation in the HAZ has been observed to sometimes have opposite effect [84,85].

Retained shear strain or prestrain is another contributing factor to observed trends in mechanical properties (i.e., hardness). These trends are further analysed using strain gradient plasticity and dislocation theories. The effect of hardness to indentation depths are given in Fig. 10(b) and (c). In Fig. 10 (c), an increase in hardness with decreasing indentation depth is observed for the two weld joint configurations. The size effect commenced at a depth of ~ 40 µm and then vary below ~ 20 µm. These differences are due to the changes in the material length scale parameters due to the heat input during welding process. The size effect was stronger at the FZ than for the HAZ, followed by the parent material. Table 3 highlights the changes in the material length scale parameters from the parent material through the HAZ to the FZ.

The Nix and Gao relation (Equation (3)) was used to interpret the hardness data for the samples (Fig. 10 (d)). The relationship between the hardness squared (H^2) and the reciprocal of the indentation depth ($1/h$) for all samples were linear. This is characteristic of the contributions from grain boundary dislocations, which are predominantly geometrically necessary dislocations [51,53,66]. The characteristic length h^* , which is the gradient of the curves for the plots were 34.37 µm (FZ lap), 22.73 µm (FZ butt), 17.39 µm (HAZ butt), 15.57 µm (HAZ lap) and 14.76 µm for the base or parent material. The characteristic length is the

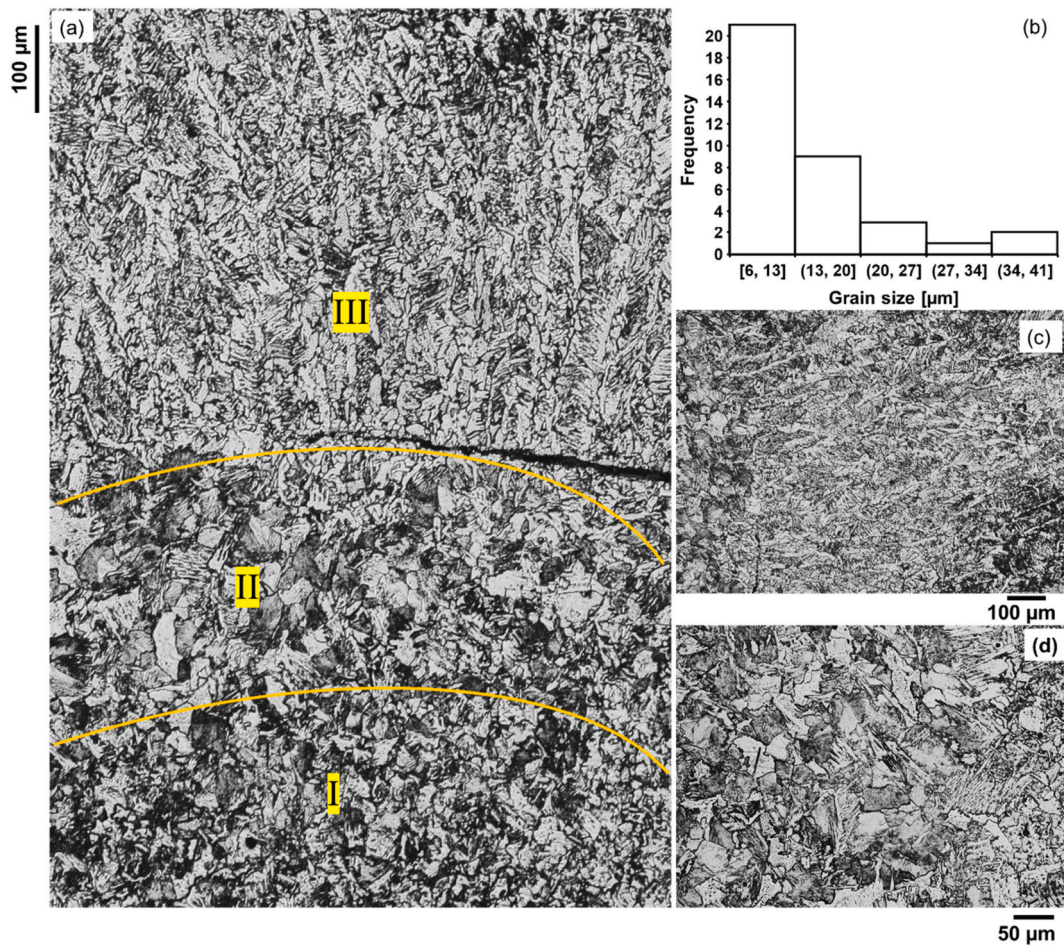


Fig. 8. Optical micrographs and grain size distribution of the fusion zone of the lap welded samples: (a) ferrite – pearlite variations in grain sizes and morphologies with I) fine grain heat affected zone, II) coarse grain heat affected zone and III) elongated fusion zone grains (b) grain size distribution of the FZ and (c) critical features of ferrite-pearlite in the welding direction and (d) coarse grains zone in the lower lapped metal.

local length scale parameter below which the size effect will occur. The results show that this parameter is highest in the FZs, followed by HAZs and the parent material respectively.

The macroscopic hardness (H_o), which is the square root of the intercept of the curves for the various zones were 1.499 GPa (FZ lap), 1.448 GPa (FZ butt), 1.321 GPa (HAZ lap), 1.306 GPa (HAZ butt) and 1.152 GPa for the parent material. The H_o value is an estimation of the bulk hardness of the material, and it is shown by the model to be highest at the FZ for both weld configuration. The electrode material and the solidification of the fusion zone with grain refinement contributed to the observed high hardness. Although, the hardness of the fusion zone of the lap was comparable to the fusion zone of the butt, with 0.051 MPa difference hence can be considered negligible. Considering there was no precipitates observed in the fusion zones of the two weldments, the structural integrity is adequate to support the intended applications.

The average shear strain (γ) is a determining component of the residual stress in the material. This was estimated by fitting the curve using Equation (7) for statistically stored dislocation values in Table 4 for the various zones [50]. The Burgers vector of 0.3 nm and shear modulus of 80 GPa were used for the average shear strain estimations. The values of the average shear strain at FZ lap, FZ butt, HAZ lap, HAZ butt and PM samples were 8.04%, 6.58%, 5.1%, 4.58% and 3.8%, respectively (Fig. 11(a)). The average shear strains estimated at the FZ zones were higher than those for the HAZs and PM. They were also higher in the lap welded samples than in the butt welded samples at their respective zones. The change in average shear strain plot in Fig. 11 (e) shows an increase in average shear strain with distance from the PM to

the FZ. This relationship was consistent for both butt and lap weld configurations. This provides a useful theory for molecular and atomistic simulations for weldment in structural materials.

A linear relationship was obtained when the GND densities were plotted against the inverse of the indentation depths. The differences in the position of the curves were linked to the changes in the average shear strain in the system. The curves moved upwards and towards the left as the average shear strain in the material increased. This variation in dislocation responds as the material is subjected to uneven heat distribution and input is significant for welding joint design.

The estimated average shear strains were then used to calculate the geometrically necessary dislocations densities for the indentation depths using Ashby's theory (Equation (6)) [58]. Fig. 11 (b) is a plot of the GND densities versus indentation depths. A similar trend as obtained for the average shear strain estimations was established for this plot. The densities of the GNDs increased as the indentation depth decreased for all the sample. The rise in GND densities is stronger below indentation depths of 20 μm, which is in the range of the average grain sizes of the material (Fig. 10(b)). This is attributed to the superimposition of the dislocation volume under the indenter on the already existing grain boundary GNDs in the material [66,73]. The grain boundary GNDs are therefore captured for the extra hardening effect noticed in the calculations [58]. The GND densities were highest in the lap welded samples than for the butt welded samples and the parent material in their respective zone. The dislocation spacing for the GNDs as shown in Fig. 11(d) had a reversed trend as compared to the trends established for the average shear strain and GND densities. This was attributed to the

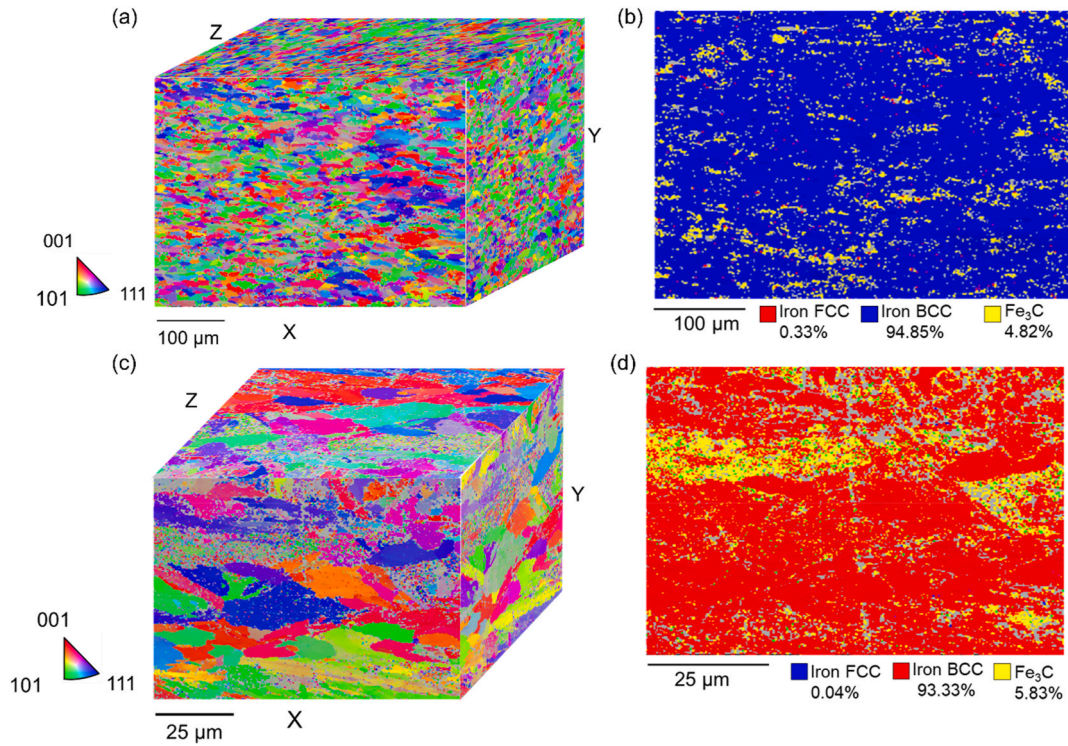


Fig. 9. EBSD maps of the butt weld showing: (a) 3D grain orientation of the HAZ with red representing [001], blue for [111] and green for [101], and (b) phase distribution at the HAZ with predominantly ferrite (blue), randomly dispersed retained austenite (red), and Fe₃C (yellow), (c) 3D grain orientation of weld with red representing [001], blue for [111] and green for [101], (d) phase distribution at the weld with predominantly ferrite (Red), low retained austenite (blue), and intermittent Fe₃C (yellow).

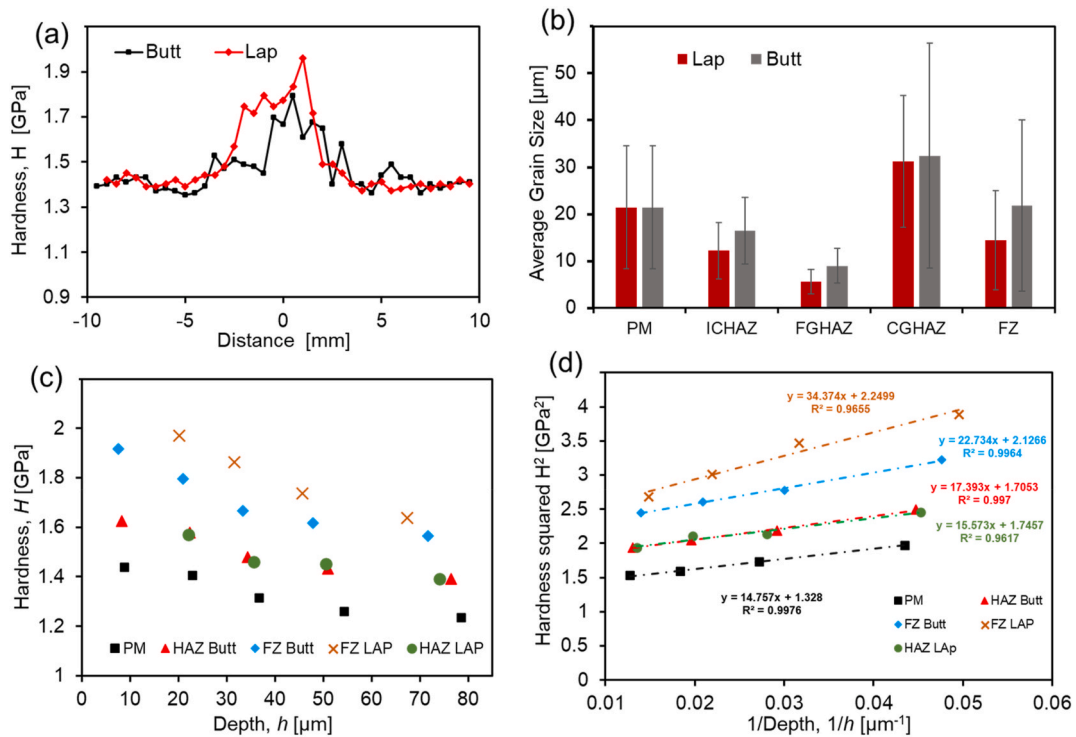


Fig. 10. Specific relationship plotted for the butt and lap joint configurations showing: (a) hardness trends as a function of the distance from the parent material across the fusion zone (b) average grain size comparison (c) hardness as a function of indentation depth (d) Nix and Gao model (relationship between squared of the hardness and the inverse of indentation depth).

Table 3

Length scale parameters for the PM, FZ lap, FZ butt, HAZ lap and HAZ butt.

Zone	H_0 [GPa]	h^* [μm]	Length scale, λ [μm]	$Y(\text{ave})$ [%]	ρ_s spacing -L [m]	ρ_G spacing -L [m]
PM	1.1524	14.76	1.30×10^{-5}	3.801398	2.49×10^{-8}	3.01×10^{-8}
FZ butt	1.4583	22.73	8.13×10^{-6}	6.579282	1.96×10^{-8}	2.68×10^{-8}
FZ Lap	1.5	34.37	7.68×10^{-6}	8.035513	1.91×10^{-8}	2.53×10^{-8}
HAZ butt	1.3059	17.39	1.01×10^{-5}	4.581584	2.20×10^{-8}	2.17×10^{-8}
HAZ Lap	1.3242	15.57	9.85×10^{-6}	5.101658	2.17×10^{-8}	1.92×10^{-8}

Table 4

Dislocation density values for the PM, FZ lap, FZ butt, HAZ lap and HAZ butt.

Zone	ρ_s [m^{-2}]	ρ_G [m^{-2}]	ρ_T [m^{-2}]
PM	1.29×10^{15}	1.61×10^{15}	2.91×10^{15}
FZ butt	1.63×10^{15}	2.58×10^{15}	4.21×10^{15}
FZ Lap	1.81×10^{15}	2.73×10^{15}	4.55×10^{15}
HAZ butt	2.47×10^{15}	2.07×10^{15}	4.54×10^{15}
HAZ Lap	3.16×10^{15}	2.13×10^{15}	5.29×10^{15}

changes in the dislocations microstructural volume and total dislocation densities.

3.6. Tensile properties

The tensile test results as given in Fig. 12(a) and (b) show changes in the tensile properties as a function of the weld joint configuration. The yield strength of the as-received A36 low carbon steel was 202 ± 15 MPa (Fig. 12(a)), that for the butt welded samples was 272 ± 18 MPa (Fig. 12(b)), whereas that for the lap welded samples was 268.95 ± 16 MPa (Fig. 12(b)). The differences in the yield and tensile strengths of the butt and lap weldments were attributed to the effect of the joint configuration, varying heat input and uneven heat distribution in the material during the welding process [86,87]. The structural integrity of the fusion zone of the butt joint was better due to the high welded zone compared to the narrow one of lap joint. This is mainly attributed to the weld design which has high concentration of plastic strains induced under the tensile loads. From a microstructural point, the AISI A36 has ferrite-pearlite microstructure with the volume fraction of proeutectoid ferrite (soft) phase higher than the pearlite, which is a composite of ferrite and cementite.

The alloy is tough with ultimate tensile properties not above 430 MPa. In this work, the UTS of the as-received A36 steel was 290.54 ± 22 MPa, whereas that of the butt and lap welded steels were, 384.48 ± 38 MPa and 361.52 ± 25 MPa respectively. The general trend of the tensile properties agrees with literature and those of the weldment are not far from the parent material. This suggests that the welding technique is ideal, but the joint configuration should be chosen in ways that address the structural integrity and design requirements. The lap joint could be used in applications that do not require high stresses to prevent premature failure and localization of stresses. The variations in the strength properties were attributed to the grain refinement that occurred due to the heat input and nonuniform thermal distribution in the material. The FZ of the weldment serves as crack initiation sites for failure under tension.

The material closest to the welded joint absorbed the excess heat and transmitted it through the entire material. This created a temperature gradient that resulted in changes in the microstructure from the fusion zone to the parent material are given in Figs. 7 and 8. This contributed to the grain size variations across the heat affected zones. The optical

microscopy image of the fusion zone of the lap welded samples as shown in Fig. 8(a) shows an unwelded interface in between the upper and lower plates.

Generation of thermal and transformation induced pre - and shear strains are contributing factors to changes in UTS in weldments [88–90]. There are large variations in the UTS of welded materials than the unwelded under conditions of pronounced thermally and transformation induced prestrains [88–90]. Thermal induced pre- or shear strains are attributed to restrictions in the expansion and contraction near the weld zone. This is correlated with the temperature gradient during the welding process inducing thermal elastic and plastic strains [88–90]. Under acute conditions, this phenomenon often introduces residual distortions in welds [91,92] but this was not observed in this instance. Volumetric variations during phase transformation of low carbon steels are also responsible for transformation induced pre - and shear strains in welded steels [93]. As shown in Fig. 10 (b), the grain sizes of the material are different in the various zones. The differences in lattice parameters between the high temperature face-centered cubic and the low temperature body-centered tetragonal or body-centered cubic structures lead to expansion in volume at the heat affected and fusion zones.

The prestrains and shear strains generated due to factors and mechanisms discussed above results in differences in the mechanical properties of welded steel [90,94]. By using Ashby's dislocations theory as modified by Ma and Clark [50,58], the average shear strain for the zones were estimated. The trend indicated that the average shear strain in the material is highest at the FZ, followed by the HAZ and the parent material. The variations in the tensile properties in Fig. 12(a and b) is attributed to the changes in weld joint configurations. Parameters like groove configuration, welding velocity, heat input and welding procedure lead to the generation of prestrains and defects which affect the mechanical properties of welded joints [95]. Changes in the groove configuration in this work resulted in an increase in ultimate tensile and yield strengths of the material.

The fracture analyses of the tensile test specimens of the butt and lap joint are given in Fig. 13. The failure was mainly at the weld zone for the two joint configuration. Although there are comparable hardness and strength properties, there was discernible trend in fractographic images. Typical ductile fracture was observed, indicative of the sustained plastic deformation with characteristic dimples and microvoid coalescence [12, 96–99]. For the butt joint, there were small, inhomogeneous and patches of elongated dimples skewed in different directions. The lap joints had large and numerous dimples and slip markings around the coalesced voids. This shows a correlation between the grain sizes and the dimple sizes [96]. The presence of dimples in both joints strongly correlate with strong crack resistance behaviour [97]. Similarly, the local stress state is at an angle with some slip deformations in shear.

3.7. Implication and novelty statement

In this work, the changes in microstructural features and mechanical properties of the welded with different joint configurations are established. The effect of welding parameters on the quality of weld joints is critical for joint design. This has serious implications for the structural integrity of welded components. The hardness to ductility trade-offs inspired by changes in average shear strain, dislocation microstructural evolution and material length scale bring new understanding to the response of the material to heat treatment and deformation. The use of indentation size effect and strain gradient plasticity theories to estimate average shear strain and residual stresses in welded joints is discussed. This approach offers a fundamental and low-cost method of estimating residual stresses and prestrains in welded materials.

Strain gradient plasticity analyses of welded components provide insights for robust design of next generation structural and functional weldment. Particularly, the novelty is in understanding the material length scale and its effects on deformation mechanisms and welding

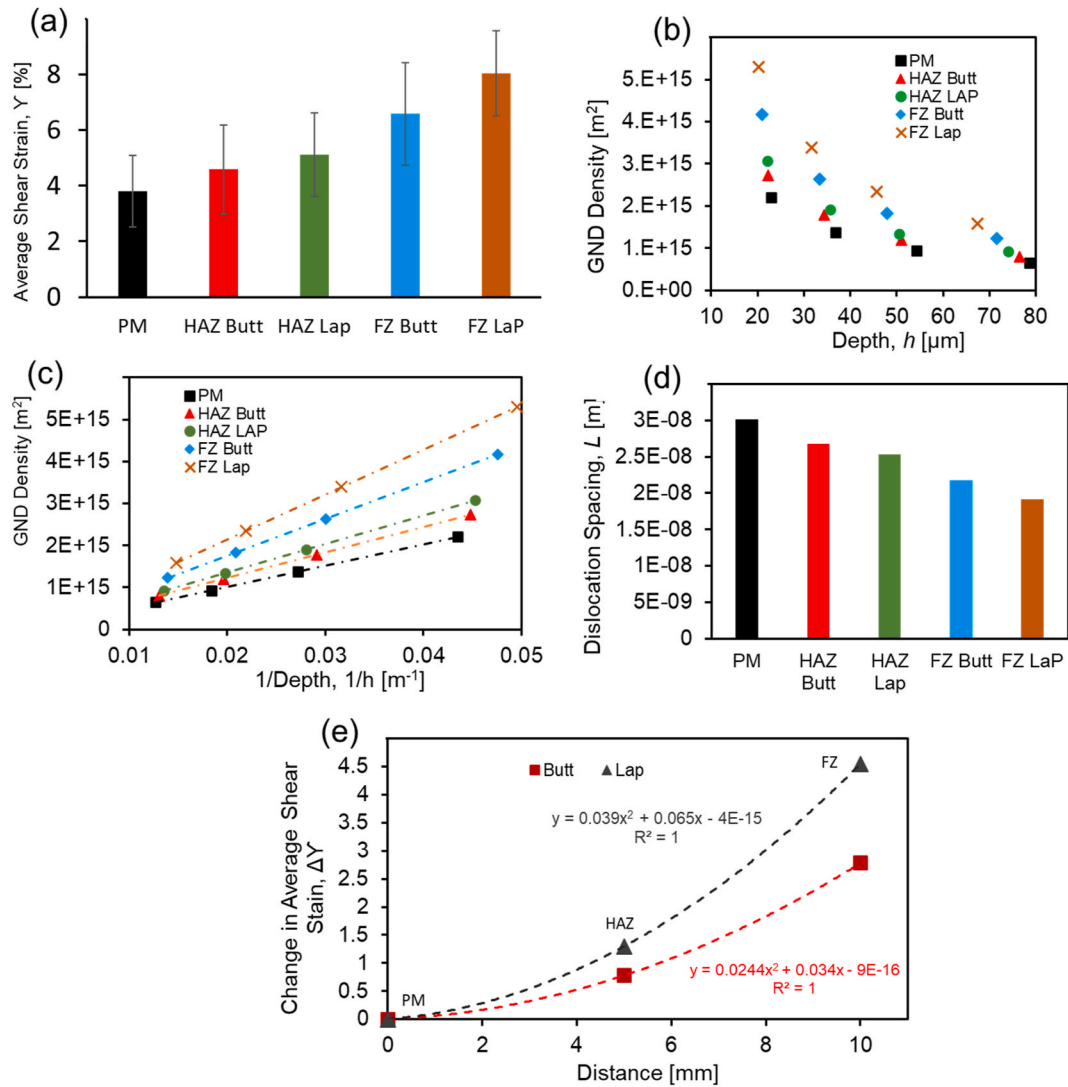


Fig. 11. (a) Average shear strains for the PM, HAZ butt, HAZ lap, FZ butt and FZ lap samples, (b) plot of geometrically necessary dislocation densities with depth (c) geometrically necessary dislocation densities versus inverse of depth plot showing variations in response to changes in the average shear strains and (d) dislocations spacing estimations for the weldments.

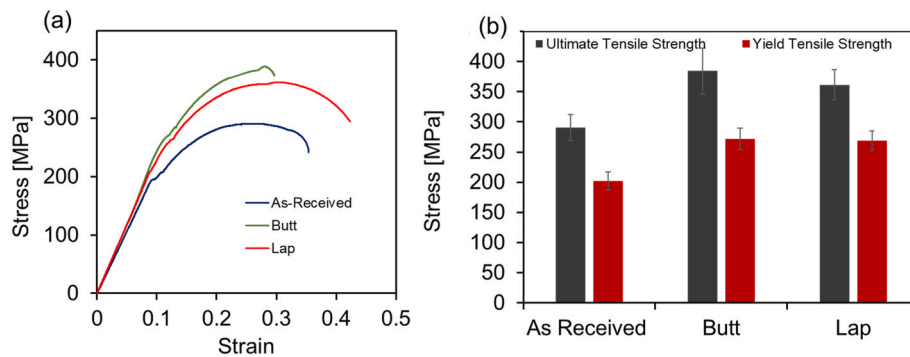


Fig. 12. Stress-strain curves of AISI A36 low carbon steel showing: (a) as-received condition, butt joint and lap joint and (b) comparison of the yield and tensile strengths.

metallurgy in HAZ and FZ. These are critical regions susceptible to crack initiation, contributing to a more accurate and nuanced understanding of the mechanical behaviour of welded structures. The effects of statistically stored and geometrically necessary dislocations and their interactions with defects in the HAZ and FZ are explained, which is rarely

done in weld metallurgy. Thus, mechanistic strain gradient plasticity models are used to explain the joint design configurations in the weldment.

The synergy between welding and strain gradient plasticity has innovative industrial applications. These insights are of importance to

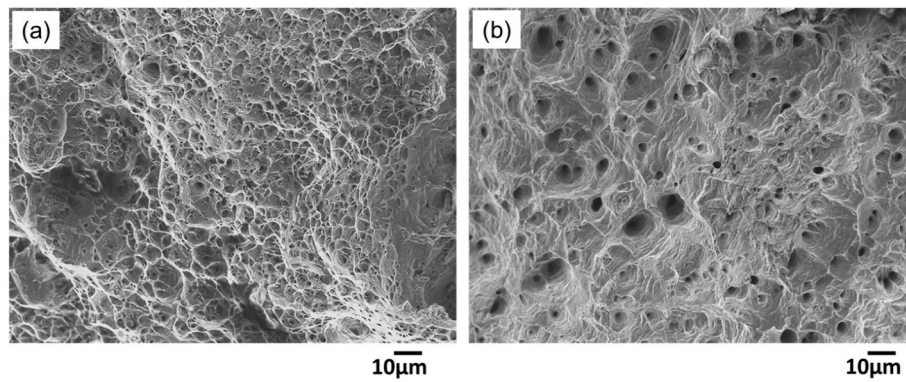


Fig. 13. The SEM images of fracture surface of tensile specimen showing (a) the butt joint with inhomogeneous and some elongated dimple colonies and (b) lap joint showing microvoid coalescence and slip markings.

material joining technology, structural integrity, performance, and reliability. The SGP models provides avenues for the optimization of weld quality which could reduce defects and improve structural integrity for the automotive, shipbuilding, aerospace, and infrastructure development. Analyses of strain gradient effects during welding contributes to better microstructural control over the welded joint and across the microstructural length scale. It contributes to improved hardness, toughness, strength, and corrosion resistance, crucial for mega structures and industries.

The SGP models provide relevant data for modelling, simulation and predication of residual stresses and mitigation factors in welded components. By predicting residual stresses, pressurized vessels for various structural applications can be designed for optimized and long fatigue lives. The comprehension of size-dependent behaviour influences the material and welding design criteria for lightweighting in the aerospace and automotive industries. The SGP analysis is essential for structural integrity and performance in highly stressed components where welding is an integral part of the design considerations. The application of SGP in analyses of welding phenomena can inspire the design and development of new welding techniques. This could be critical for the automotive industry where lightweight structural alloys are crucial. With the increasing drive for electric and autonomous vehicles, thus, innovative, and new welding methods could be critical for structural integrity. Similarly, the analyses of SGP models and welding phenomena could inspire the design and development of new materials for additive and metamorphic manufacturing processes. It will also drive the next generation of failure analyses techniques to elucidate failure modes and crack initiation in welded structures. This has implications for applications across diverse fields in oil and gas sector, manufacturing, construction, biomedical advances, aerospace, automotive and energy.

4. Conclusions

Based on the results and discussion, the conclusions are.

- The shielded metal arc welding of the A36 low carbon steel was successfully carried out using both joint configurations. The welding process led to microstructural changes contributing to the slight differences in the mechanical properties.
- The grain sizes of the A36 low carbon steel varied with distance from the fusion zone to the parent material with a discernible trend. The difference in grain sizes at the different zones were functions of the process temperature and the rate of cooling.
- The hardness of the fusion zones of the welded joints was higher than for the heat affected zones which was also higher than the parent material. This was driven by the microstructure and the varied differences in grain sizes which are statistically significant.

- The weldment with lap joint configuration had the highest retained average shear strain and hardness at both the heat affected zones and the fusion zones.
- The butt weldment had the highest ultimate tensile strength with reduced toughness which makes it suitable for relatively high strength and hardness structural applications. This was attributed to the grain refinement as a function of the structural integrity of the butt weld joint configuration.
- The material length scale parameters changed with changing microstructural features of the zones. The overall dislocations around the indentation which were statistically stored dislocations (SSDs), and geometrically necessary dislocations (GNDs) were accounted for. The strain gradient plasticity model provided reasonable and acceptable ways of estimating these line defects in the weldment. The densities associated with the GNDs were higher in the lap welded joints than the butt weldment and the parent material in their respective zones. There were more dislocations in the lap welded joints than for the butt for equivalent depths during indentation.
- The fracture surfaces mainly show ductile fracture indicative of plastic deformation. The characteristic inhomogeneous dimples which were skewed in different direction and microvoid coalescence are the distinctive features. The local stress states were at different angular direction with some slip deformation in shear.
- The implication for strain gradient plasticity models for the analyses of welded structures for structural integrity and novel approaches to understanding material length scale across microstructural length scale has become apparent. Innovative pathways for the design and analyses of welded structures have been discussed and highlighted.

CRedit authorship contribution statement

B. Addai: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **K.O. Gyimah:** Writing – review & editing, Supervision, Project administration, Conceptualization. **T.K. Asumadu:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **M. Anto:** Writing – review & editing, Supervision, Project administration, Conceptualization. **D.E.P. Klenam:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **W.O. Soboyejo:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Data availability

Data will be made available on request.

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