

Geometric Influence on Microstructure and Mechanics in Welded A36 Mild Steel

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Abstract

Welding is widely employed in manufacturing due to its cost-effectiveness and mechanical reliability. However, heat from welding alters the base material's microstructure, especially in the Coarse Grain Heat-Affected Zone (CGHAZ). This study investigates the effect of plate geometry on the microstructural evolution and mechanical properties of A36 mild steel welded under constant heat input. Specifically, two sets of welded plates with identical thicknesses (6 mm) but different lengths (Set A: 109mm, Set B: 198mm) were subjected to mechanical and microstructural analysis. The key tests included tensile testing, hardness testing, and optical microscopy. Results showed significant variation in cooling rates and mechanical performance due to geometric differences. Set A exhibited higher tensile strength and hardness due to faster cooling, while Set B showed improved ductility but coarser microstructures. This research emphasizes the crucial role of plate length in thermal behavior and structural performance during welding.

1. Introduction

Welding is a widely used metal joining technique in manufacturing, particularly in construction, automotive, and structural applications. The quality of a welded joint significantly depends on thermal cycles that influence phase transformation, especially in the Coarse Grain Heat-Affected Zone (CGHAZ). Mild steel, such as A36, is commonly used due to its good weldability and mechanical balance. However, while welding parameters like voltage, current, and speed are often studied, the influence of geometric characteristics, such as plate length, remains underexplored. This study explores how different plate lengths influence the cooling behavior and ultimately the microstructure and mechanical properties of welded A36 steel under fixed heat input.

Many studies have focused on heat input and welding parameters, but limited attention has been given to the geometric influence of the welded plates. The effect of plate length on cooling rate may result in non-uniform mechanical behavior in joints even when heat input is controlled. Thus, it is essential to investigate how geometry, specifically length, affects microstructural development and mechanical performance under consistent welding conditions. The research aims to evaluate the influence of plate geometry on cooling rate during welding. It also focuses on comparing mechanical properties, including tensile strength, hardness, and Young's modulus, between shorter and longer welded plates. At the same time, analysing the resulting microstructure in the welded joint across different regions.

Welding introduces complex thermal cycles that affect material properties across different zones. CGHAZ is particularly susceptible to grain coarsening, which reduces mechanical strength [1]. Heat input, calculated as:

$$\text{Heat Input} = \frac{V \times I \times 60}{S \times 1000} \quad (1)$$

depends on voltage (V), current (I), and welding speed (S). However, even under constant heat input, plate length can influence the cooling rate due to differences in thermal mass and surface-area-to-volume ratio [2]. Shorter plates tend to dissipate heat more rapidly, promoting the formation of finer grains and potentially improving strength, while longer plates retain heat longer, resulting in coarser microstructures and increased ductility [3].

Microstructural development significantly influences hardness and tensile properties. Rapid cooling typically fosters the formation of bainite and martensite, which enhance strength but may reduce ductility. In contrast, slower cooling promotes ferrite and pearlite formation, improving ductility while lowering strength [4]. The impact of geometry on cooling behavior has also been confirmed in past studies, which have shown varied microstructural phases across plates of different sizes welded under identical parameters [5].

While many studies have evaluated welding process variables, less attention has been given to the effect of workpiece geometry. It has been observed that shorter plates cool faster due to their lower thermal mass and greater surface exposure, leading to refined grain structures and increased hardness. In contrast, longer plates tend to cool more slowly, promoting coarser grain growth and reduced hardness but improved ductility [6]. These variations influence the temperature gradient across the HAZ and ultimately affect the mechanical integrity of the weld [7].

The microstructure within the welded joint plays a major role in determining mechanical performance. Faster cooling promotes structures like acicular ferrite and bainite, which contribute to greater strength and toughness, while slower cooling results in polygonal ferrite and pearlite that enhance ductility at the cost of strength [8]. Mechanical testing techniques such as tensile and Vickers hardness tests are vital in assessing strength, ductility, and surface hardness across the weld and HAZ. Understanding the relationship between plate geometry, cooling rate, and microstructure is crucial to ensuring consistent weld quality in industrial applications.

2. Methodology

This study aims to evaluate the impact of plate geometry under constant heat input on the microstructure and mechanical properties of welded A36 mild steel. Two sets of samples with the same thickness but different lengths were used to investigate how geometric differences affect cooling behavior and structural performance.

2.1 Material Selection and Plate Preparation

The base material used was A36 mild steel with a thickness of 6 mm. Two sets of specimens were prepared:

- Set A (A1,A2,A3): 109 mm (length) × 10 mm (width) × 6 mm (thickness)
- Set B (B1,B2,B3): 198 mm (length) × 10 mm (width) × 6 mm (thickness)

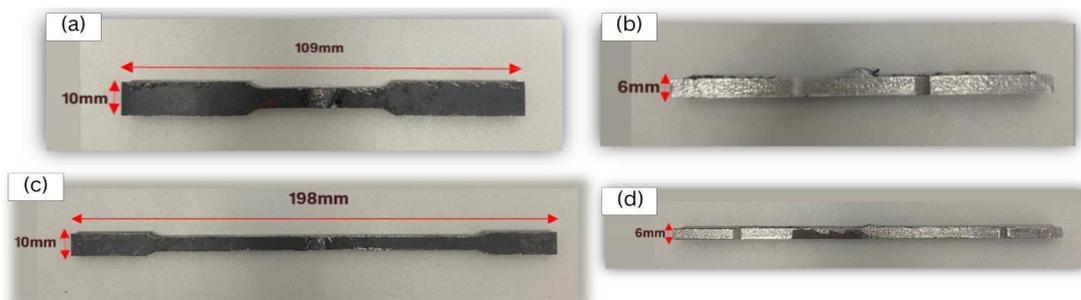


Figure 2.1 Dimension for sample (a)(b) Set A; (c)(d) Set B

Each set consisted of three samples. The plates were cut using:

- Hydraulic Swing Beam Shears Machine for Set B
- CNC milling cutter or manual cutting tools for Set A

2.2 Welding Process

The welding was performed using Shielded Metal Arc Welding (SMAW) with a V-butt joint configuration. The same welding parameters were maintained for both Set A and Set B to ensure consistent heat input:

Table 1 Welding Parameters

Voltage (V)	24
Current (A)	200
Welding Speed (S)	250mm/min

2.3 Tensile Test

Tensile testing was performed on both specimen sets to assess their mechanical features and ascertain how cooling rate affected strength parameters. The ultimate tensile strength, yield strength, and elongation properties were measured using standard protocols in the tensile tests, which yielded quantitative information on the effects of specimen geometry on the mechanical performance of welded joints.

2.4 Hardness Test

Hardness tests were conducted using the Vickers hardness testing machine to evaluate the surface hardness across the welded specimens. A load of 20 kg was applied with a dwell time of 10 seconds at 13 specific test points distributed along the transverse cross-section of the weld area, covering the Weld Metal (WM), Heat-Affected Zone (HAZ), and Base Metal (BM). Each indentation left by the diamond indenter was measured optically to calculate the Vickers Hardness Number (VHN), allowing for comparison of hardness variations influenced by thermal exposure during welding.

2.5 Microstructure Observation

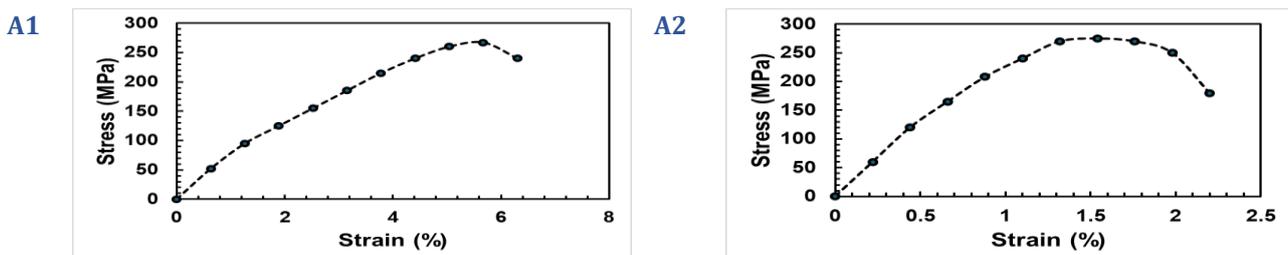
Samples for optical microscopy were sectioned from each welded plate (Set A and Set B) at three critical regions: Weld Metal (WM), Heat-Affected Zone (HAZ), and Base Metal (BM). The specimens underwent surface preparation, beginning with grinding using abrasive papers ranging from 240 to 1200 grit, followed by polishing with alumina suspension to achieve a smooth finish. Etching was then performed using a 2% Nital solution (2% nitric acid in ethanol) for 10–15 seconds to reveal the microstructure. The prepared samples were examined under an optical microscope at magnifications up to 100x to analyze grain structures and phase distribution, enabling comparison of microstructural changes influenced by varying cooling rates between the two sets.

3. Results and Discussion

3.1 Tensile Test Analysis

The mechanical performance of the welded joints was evaluated through tensile testing to understand the influence of plate geometry on strength and ductility. The stress-strain curves and summarized results are presented in Table 2 and Table 3, respectively.

Table 2 Stress-Strain curve for all specimens



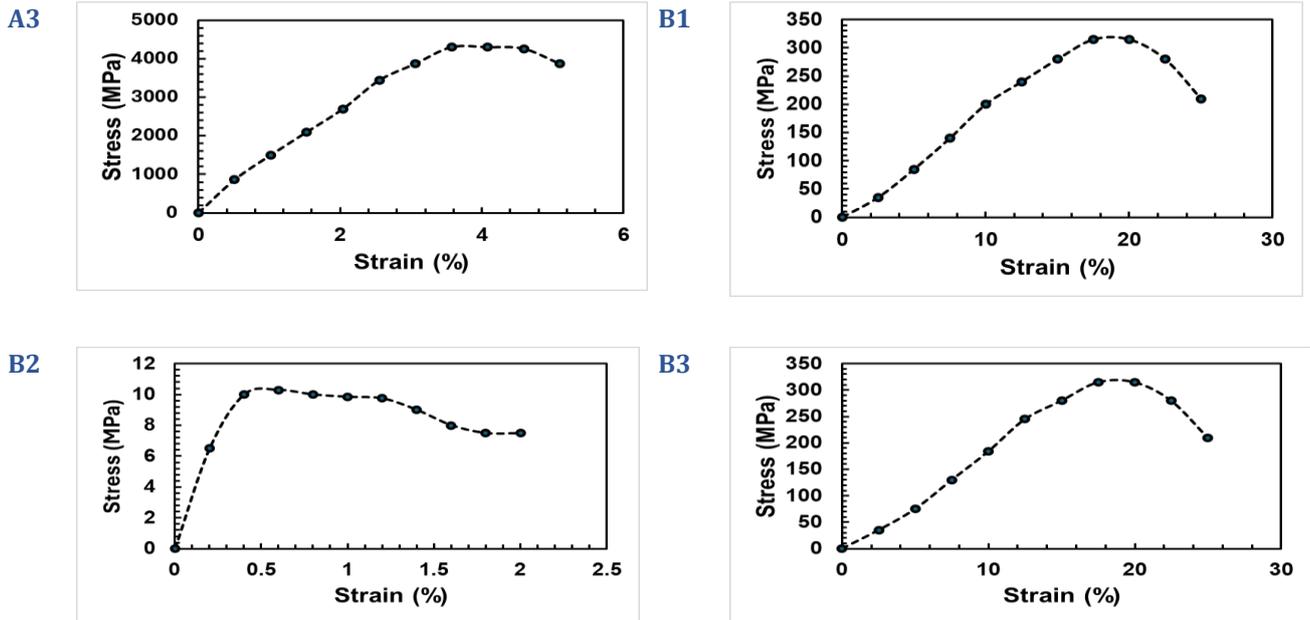


Table 3 Tensile results for all specimens

Specimen	Max Load (kN)	Young's Modulus (MPa)	Yield Strength (MPa)	Max Stress (MPa)	Max Strain (%)	UTS (MPa)
A1	9.29	57870.00	252.18	258.09	5.519	285.05
A2	9.95	21043.77	275.02	276.44	1.623	276.39
A3	0.15	49603.17	3.75	4.26	4.343	4.17
Average	6.46	42838.98	176.98	179.60	3.828	188.54
B1	11.56	73099.42	259.04	321.22	18.197	321.11
B2	0.41	15603.37	11.19	11.31	0.195	11.39
B3	11.20	69435.00	257.00	311.00	18.0	311.11
Average	7.72	52709.28	175.74	214.51	12.40	214.54

It is clear from the stress-strain curves in Table 2 and the corresponding tensile test results in Table 3, that the welded plate's geometry, especially its length, significantly affects how A36 mild steel behaves mechanically when exposed to continuous heat input. With its longer plates, Set B demonstrated superior ductility with a significantly higher average maximum strain (12.40%) than Set A (3.828%). Because longer plates have more thermal mass and a smaller surface-area-to-volume ratio, they cool more slowly, which is consistent with this result. In the heat-affected zone (HAZ), slower cooling gives grain growth and the development of softer, more ductile microstructures like pearlite and coarse ferrite more time.

On the other hand, Set A showed somewhat greater ultimate tensile strength (UTS) (188.54 MPa) and average yield strength (176.98 MPa). Faster cooling during the welding process, which promotes the formation of finer microstructures such as acicular ferrite and fine bainite, particularly in the weld metal and HAZ regions, is likely the cause of these higher strength values. Although they sacrifice ductility, finer grains increase the material's strength by preventing dislocation movement. This finding aligns with research by Suwandi et al. and Fan et al. [1,9], who found that refined microstructural development, brought about by rapid cooling, increases hardness and tensile strength.

Two specimens, A3 from Set A and B2 from Set B, displayed noticeably lower maximum load and stress values. These abnormalities could be caused by inconsistent testing, like misalignment or surface imperfections, or weld flaws, including absence of fusion, porosity, or notches. These flaws have the potential to concentrate stress, which could result in early failure and decreased mechanical performance.

Overall, the findings show that the cooling rate during welding is influenced by the geometry of the plate, particularly its length, which in turn controls the mechanical characteristics and microstructure evolution. Longer plates have better ductility but marginally lower strength because they cool more slowly, while shorter plates cool more quickly and have higher strength but less ductility. Optimizing welding parameters and joint design, particularly in structural applications where strength and toughness are crucial, requires an understanding of this relationship.

3.2 Hardness Test Analysis

To further investigate the influence of geometry on localized strength, Vickers hardness measurements were taken across the welded joint. The resulting hard distribution of hardness is illustrated in Fig. 1.

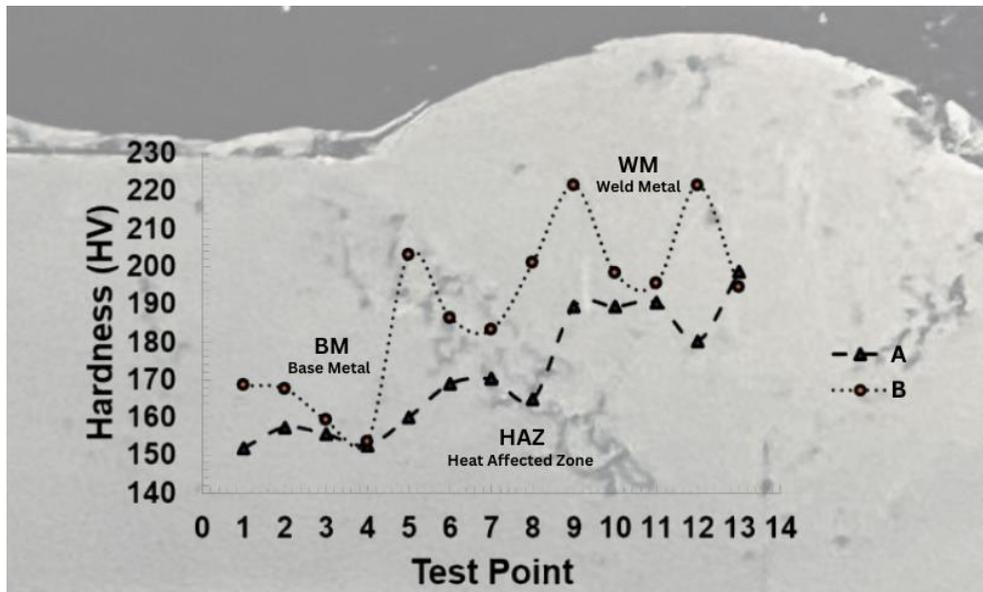


Fig. 1 Hardness profile across a welded joint

Vickers Hardness (HV) values throughout the welded joint, as shown in Figure 3.1, clearly show the variations between Set A (shorter plate) and Set B (longer plate). Set B continuously reported higher hardness values than Set A, particularly in the heat-affected zone (HAZ) and weld metal (WM). This difference can be attributed to the effect of thermal mass on cooling rate — longer plates tend to retain heat for a longer duration, allowing the formation of bainitic and martensitic structures, which are inherently harder and stronger [4,6]. These phases form through diffusion-controlled transformations during slower cooling, increasing hardness at the expense of ductility [1].

Meanwhile, Set A showed somewhat lower hardness values, likely due to the development of finer ferrite and pearlite microstructures caused by its faster cooling rate and smaller size. According to the Hall-Petch relationship, finer grains increase strength but do not necessarily result in higher hardness if softer phases such as ferrite dominate [7]. Faster cooling in smaller plates suppresses carbon diffusion, producing refined but softer microstructures that lower the overall hardness [5].

Set B displayed notable peaks above 200 HV at test points 5 to 11, corresponding to the HAZ and WM, whereas Set A stayed between 160 and 190 HV. These results agree with the findings of Suwandi et al. and Ramesh et al. [2,9], who reported that variations in specimen geometry alter heat dissipation and cooling gradients, thereby affecting microstructural evolution and local hardness. As anticipated, both sets exhibited the lowest hardness in the base metal (BM) zones, represented by points 1–4 and 12–13, where thermal influence from welding was minimal. Nevertheless, Set B still displayed slightly higher hardness even in the BM region, indicating partial heat retention effects due to its greater thermal mass.

3.3 Microstructure Examination

Fig. 2 shows below the microstructure of the Coarse Grain Heat Affected Zone (CGHAZ) on samples Set A and B that has been taken using an Optical Microscope (OM) with a magnification of 100X.

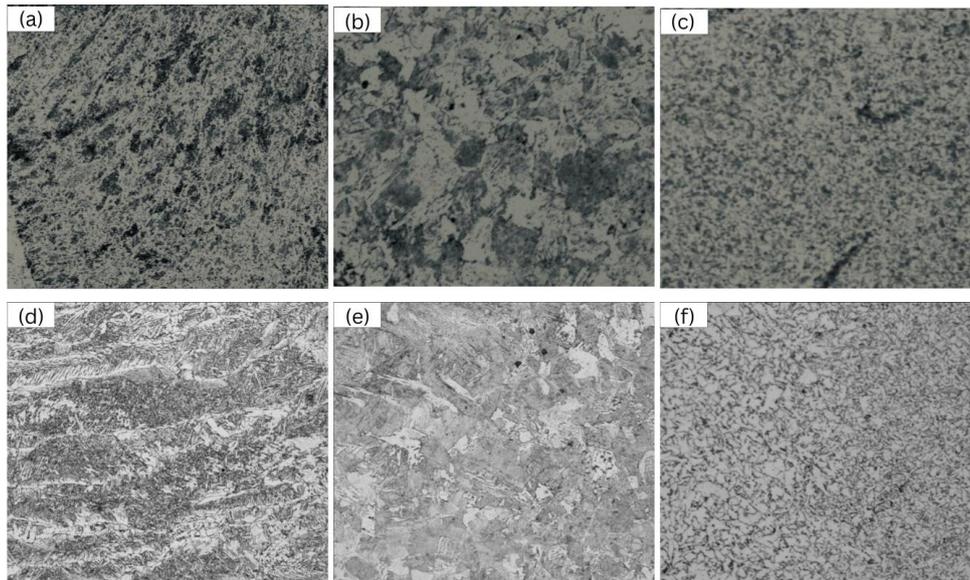


Fig. 2 Microstructure of the Coarse Grain Heat Affected Zone (CGHAZ); (a)(b)(c) Set A, (d)(e)(f) Set B

3.3.1 Set A Microstructural Characteristics (Images a, b, c)

According to Fig. 2, the weld metal region (a) shows a fine dendritic structure with well-defined grain boundaries, indicating controlled solidification during the welding process. The heat-affected zone (b) displays a mixed microstructure with moderately sized grains and clear phase boundaries between ferrite and pearlite regions. The base metal (c) exhibits the original fine-grained ferrite-pearlite structure typical of mild steel, with uniform grain distribution and no evidence of thermal alteration.

The presence of finer grains and clear phase boundaries in Set A suggests a higher cooling rate, which restricted grain growth during solidification. According to the Hall-Petch relationship, smaller grains increase the resistance to dislocation movement, thereby improving strength and toughness [4]. This behavior aligns with previous findings by Zhang et al. and Fan et al. [1,6], who observed that faster cooling during welding promotes the formation of acicular ferrite and fine bainitic structures, enhancing mechanical strength. Furthermore, Qi et al. reported that smaller specimens with reduced thermal mass cool more rapidly, leading to refined microstructures with improved uniformity and reduced grain coarsening [3]. These metallurgical mechanisms explain the higher tensile strength and moderate hardness values observed in Set A.

3.3.2 Set B Microstructural Characteristics (Images d, e, f)

Fig. 2 shows that the weld metal region (d) demonstrates a coarser dendritic structure with larger solidification patterns compared to Set A, suggesting slower cooling rates during solidification. The heat-affected zone (e) shows significantly larger grain sizes with more pronounced grain boundaries, indicating extensive grain growth due to prolonged exposure to elevated temperatures. The base metal (f) maintains the original microstructure like Set A, confirming that thermal effects were contained within the expected heat-affected zone boundaries.

The coarser dendritic and ferritic-pearlitic structures observed in Set B are consistent with slower cooling and longer heat retention. According to Ramesh et al. and Ismail et al., slower cooling allows for greater grain coarsening in the CGHAZ, which decreases strength but increases ductility due to reduced dislocation density [2,5]. Additionally, Kah et al. found that extended exposure to elevated temperatures during welding promotes grain boundary migration and phase growth, leading to the formation of softer yet less refined microstructures [7]. These phenomena collectively contribute to the higher hardness, but lower tensile strength exhibited by Set B compared to Set A.

The microscope images in Fig. 2 clearly demonstrate how cooling rate influences grain morphology and, consequently, mechanical performance. Set A, which cooled faster, contains smaller and finer grains in both the weld metal and heat-affected zone, resulting in higher strength and toughness, consistent with the grain refinement principle described by Zhang et al. [6]. In contrast, Set B cooled more slowly due to its greater length and thermal mass, producing coarser grains, especially in the HAZ. Larger grains are typically associated with higher hardness but reduced ductility, as confirmed by Suwandi et al. and Patel & Deshmukh [9,10].

Simply put, faster cooling (Set A) produced finer grains and better overall strength, while slower cooling (Set B) resulted in coarser grains and higher hardness but increased brittleness. These microstructural differences explain the contrasting mechanical behaviours of both sets, despite identical welding parameters.

4. Conclusion

This study demonstrated that plate geometry, particularly length, significantly influences the cooling rate, microstructure, and mechanical behavior of welded A36 mild steel under constant heat input. Set A exhibited higher tensile strength and hardness due to faster cooling, while Set B displayed improved ductility because of slower cooling. These findings confirm that geometric factors can alter heat distribution and subsequently affect mechanical properties even under identical welding parameters. Thermal behavior during welding is therefore highly dependent on the dimensional characteristics of the plate, emphasizing the need to consider geometry in joint design and process control to achieve the desired balance of strength and ductility.

It is recommended that future work includes real-time temperature monitoring using thermocouples or infrared cameras to validate cooling rate assumptions, expand the number of specimens tested, and apply advanced characterization methods, such as scanning electron microscopy (SEM), for detailed phase analysis. Additionally, the use of finite element thermal simulations can provide predictive insight into temperature gradients and structural performance across different geometries.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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