

Impact of Wire Feed Speed and Heat Input on Microstructure and Mechanical Properties in the Coarse-Grain Heat Affected Zone of Low Carbon Steel

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Abstract

This study investigates the impact of wire feed speed and heat input on the microstructure and mechanical properties in the coarse-grain heat-affected zone (CGHAZ) of low carbon steel, specifically focusing on applications in automotive engineering. Utilizing Gas Metal Arc Welding (GMAW), various welding parameters were examined to optimize the structural integrity and performance of welded joints. The research involved preparing low-carbon steel samples and subjecting them to different wire feed speeds (4 m/min, 6 m/min, and 8 m/min) and heat inputs (1.69 kJ/mm, 1.87 kJ/mm, and 2.05 kJ/mm). Microstructural analysis and mechanical testing, including tensile and hardness tests, were conducted to evaluate the effects of these parameters. The results indicated that increasing the wire feed speed from 4 m/min to 8 m/min led to a 17.4% reduction from Sample 1 to Sample 3 in average grain size in the CGHAZ, resulting in a 13.8% improvement in hardness. Additionally, higher heat input, increasing from 1.69 kJ/mm in Sample 1 to 2.05 kJ/mm in Sample 7, led to a 12.9% decrease in impact toughness. Furthermore, the flexural modulus of the optimal sample (Sample 3) was 155.84% higher than the sample with the lowest flexural modulus (Sample 2). The findings demonstrate that optimizing wire feed speed and minimizing heat input are crucial for enhancing the mechanical properties and safety of welded low-carbon steel components in automotive applications. This study bridges the gap between theoretical knowledge and practical applications, providing valuable insights for improving welding practices in the industry.

1. Introduction

Gas Metal Arc Welding (GMAW) is a widely used welding technique in the automotive industry for joining low-carbon steel components, such as the crash box and frame. The quality and integrity of these welded joints are crucial for ensuring the structural soundness and safety of vehicles. The Coarse-Grained Heat-Affected Zone (CGHAZ) is a critical region in welded joints, as it undergoes significant microstructural changes due to the heat generated during welding [4]. These changes can affect the mechanical properties of the material, potentially leading to reduced strength, toughness, and ductility

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[1]. The current study aims to investigate the effects of wire feed speed and heat input on the microstructure and mechanical properties of the CGHAZ in low-carbon steel. By understanding the relationship between these welding parameters and the resulting microstructural and mechanical changes, we can optimize welding procedures to achieve desired material properties and improve the overall performance of welded joints in automotive applications.

2. Methodology

2.1 Welding Parameters

To investigate the effect of wire feed speed and heat input on the microstructure and mechanical properties of low carbon steel, the GMAW welding method was employed. Nine distinct samples were prepared, each with a unique combination of wire feed speed (4 m/min, 6 m/min, and 8 m/min) and heat input (1.69 kJ/mm, 1.87 kJ/mm, and 2.05 kJ/mm). These parameters were systematically varied to assess their individual and combined effects on the CGHAZ. Various tests were conducted on the weld zone and the microstructure of the samples. The tests include optical microscopy, Charpy impact testing, and 3-point bending tests. Table 1 shows the categorisation of the 9 samples.

Table 1 *Categorization of specimens*

	Heat Input, kJ/mm	Wire Feed Speed, m/min
Sample 1	1.69	4
Sample 2	1.69	6
Sample 3	1.69	8
Sample 4	1.87	4
Sample 5	1.87	6
Sample 6	1.87	8
Sample 7	2.05	4
Sample 8	2.05	6
Sample 9	2.05	8

2.2 Sample Preparation

Following the welding process, the welded specimens were meticulously prepared for microstructural and mechanical testing. This involved sectioning, mounting, grinding, polishing, and etching procedures to reveal the microstructure of the CGHAZ.

2.3 Microstructural Observation

Optical Microscopy (OM) was utilized to examine the microstructure of the CGHAZ in each sample. The average grain sizes in both the CGHAZ and the Fine-Grained Heat-Affected Zone (FGHAZ) were measured using ImageJ software. This analysis provided insights into how variations in wire feed speed and heat input influenced grain growth and overall microstructural characteristics.

Energy-dispersive X-ray spectroscopy (EDX) analysis was employed to determine the elemental composition of the base metal, weld zone, and heat-affected zone (HAZ). X-ray diffraction (XRD) analysis was conducted to investigate the crystalline structure and phase composition of the base metal and weld surface.

2.4 Vickers Hardness Test

The Vickers Hardness Test was employed to assess the hardness of the CGHAZ and weld zone in each sample. A consistent test force of 4.903 N (HV0.5) was applied, adhering to ASTM E92-17 standards [1]. The resulting hardness values were correlated with the microstructural observations to understand the relationship between grain size and hardness.

2.5 Charpy V-Notch Test

The Charpy V-Notch test was conducted to evaluate the impact toughness of the CGHAZ in each sample. Standard Charpy V-notch specimens were prepared according to ASTM E23 specifications [1]. The test was performed at room temperature with a constant impact velocity of 4.5 meters per second. The absorbed energy during the test served as an indicator of the material's toughness.

2.6 3-Point Bending Test

The 3-point bending test was performed to assess the flexural strength and deformation properties of the welded specimens. This test involved applying a bending force to the samples while maintaining a constant bend radius and angle, as specified in ASTM E290 standards [1]. The loading rate was set at 2 mm/min, and the resulting flexural modulus was calculated for each sample.

3. Results and Discussion

3.1 Microstructure of the Coarse-Grain Heat Affected Zone

The microstructures of the CGHAZ and FGHAZ of each sample were taken at 200x zoom. Figure 1 shows the CGHAZ of 9 successful samples, while Figure 2 shows the average grain size obtained. In conclusion, Sample 3 has better mechanical qualities and is more appropriate to be used in the automotive field due to its smaller grain size. Sample 1 exhibited relatively homogenous grain sizes in both CGHAZ (7.132 μm) and FGHAZ (7.02 μm), suggesting a consistent heat input during the welding process. Grain sizes for Sample 2 were 6.401 μm in CGHAZ and 5.39 μm in FGHAZ. Sample 3 exhibited reduced grain sizes in CGHAZ (5.99 μm) and FGHAZ (4.3 μm), indicating a potential reduction in heat input or acceleration of cooling. Grain sizes in Sample 4 were moderate in FGHAZ (5.92 μm) and CGHAZ (6.342 μm). Sample 5's grain size was smaller in FGHAZ (5.392 μm) and larger in CGHAZ (9.188 μm). A balanced heat input was indicated by Sample 6's somewhat large CGHAZ (7.504 μm) and smaller FGHAZ (5.202 μm) grains. Sample 7 had a moderately large grain size (7.008 μm) in FGHAZ and the largest grain size (13.544 μm) in CGHAZ. Large grains were seen in Sample 8's CGHAZ (12.218 μm) and FGHAZ (6.73 μm). Sample 9 exhibited reasonable CGHAZ (7.384 μm) and FGHAZ (5.546 μm) grain sizes, indicating a well-balanced welding process.

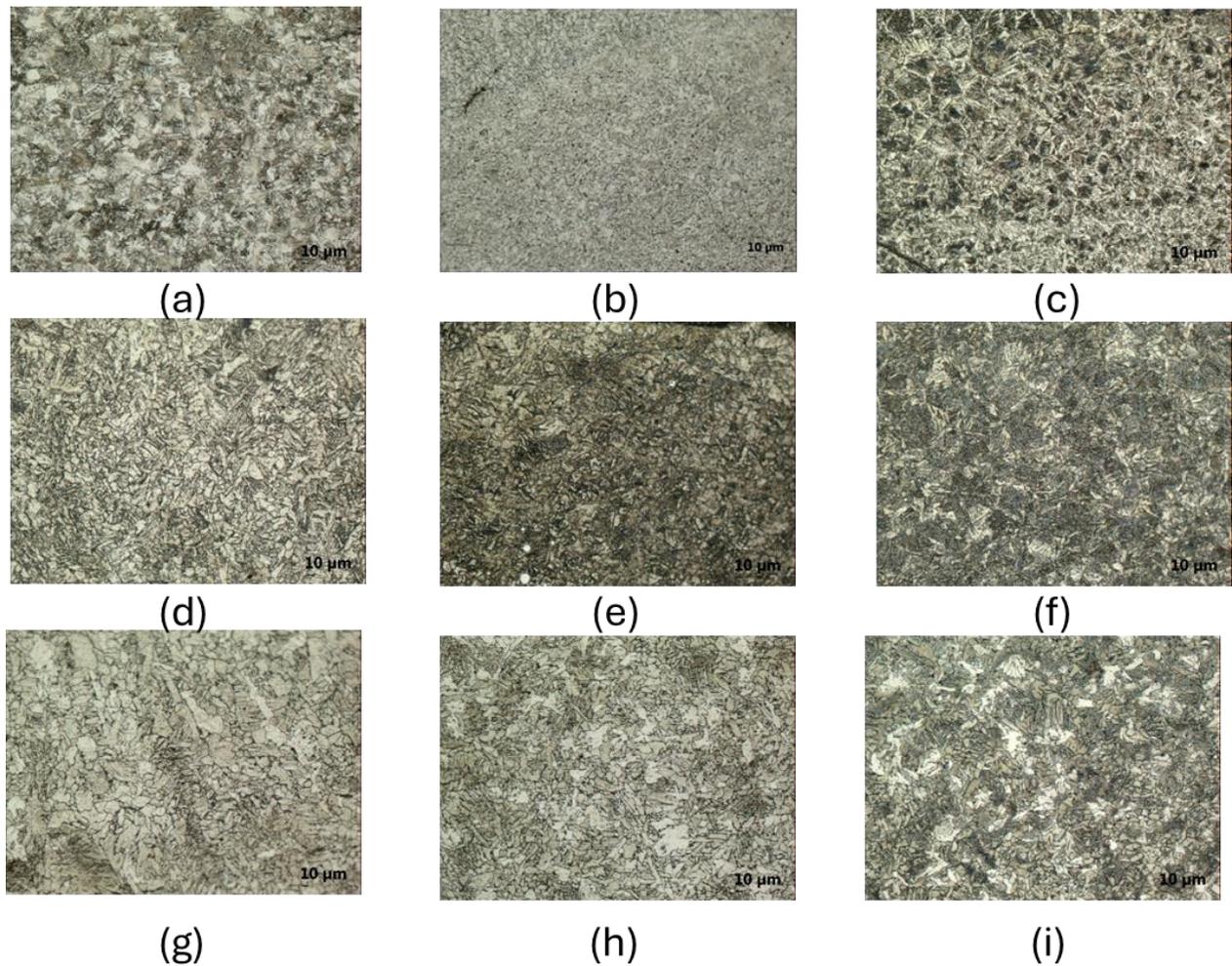


Fig. 1 CGHAZ of (a) Sample 1; (b) Sample 2; (c) Sample 3; (d) Sample 4; (e) Sample 5; (f) Sample 6; (g) Sample 7; (h) Sample 8; (i) Sample 9

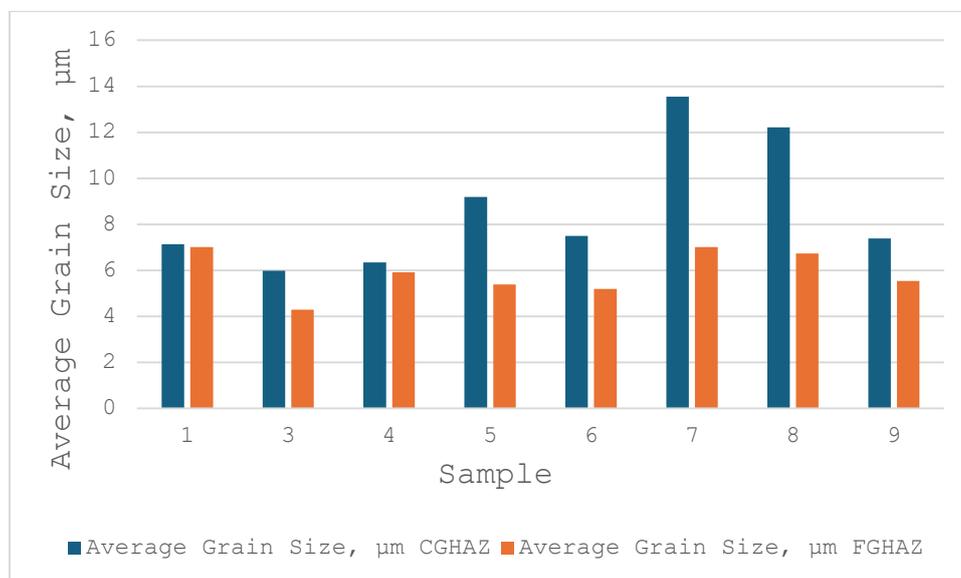


Fig. 2 Average grain size of each sample

3.2 EDX and XRD Analysis

Energy-dispersive X-ray spectroscopy (EDX) analysis was employed to determine the elemental composition of the base metal, weld zone, and heat-affected zone (HAZ). The base metal was confirmed to be low-carbon steel, primarily composed of iron (Fe) with small amounts of carbon (C) and silicon (Si). The weld zone also consisted mainly of iron, with higher carbon and silicon content compared to the base metal, likely due to the welding filler material or diffusion during welding. Notably, copper (Cu) was absent in the weld zone, as the copper plating on the welding wire vaporizes at high temperatures. The HAZ composition was similar to the base metal, with a slightly higher carbon content, possibly due to diffusion from the weld zone.

X-ray diffraction (XRD) analysis revealed the phase composition of the base metal and weld surface. The base metal consisted of iron (Fe), fayalite (Fe_2SiO_4), and manganese carbide (Mn_2C). The weld surface exhibited iron (Fe), manganese silicon ($\text{Fe}_3\text{Mn}_2\text{Si}_3$), and hausmannite (Mn_3O_4). The presence of these phases influences the mechanical properties of the welded joint, with iron contributing to strength and ductility, while other phases like fayalite and hausmannite can affect hardness and brittleness.

3.3 Effect of Wire Feed Speed and Heat Input on Hardness

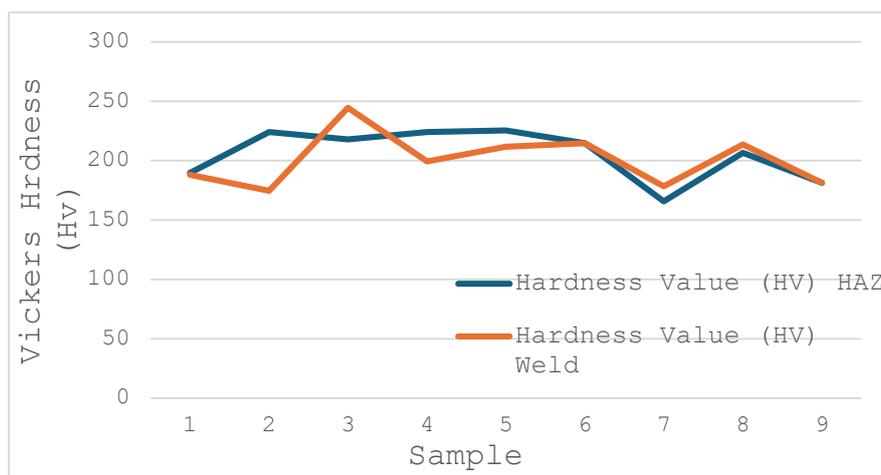


Fig. 3 Hardness values on HAZ and Weld Zone

The Vickers Hardness Test results, as presented in Figure 3, revealed a clear correlation between welding parameters and hardness [1]. Samples with finer grain structures, resulting from lower heat input and higher wire feed speed, generally exhibited higher hardness values. This is consistent with the Hall-Petch relationship, which predicts an inverse relationship between grain size and hardness [3]. Conversely, samples with coarser grains due to higher heat input showed lower hardness values. For instance, sample 3, welded with 1.69 kJ/mm heat input and 8 m/min wire feed speed, exhibited the highest hardness values in both the HAZ (217.718 HV) and weld zone (244.489 HV), indicating a strong and wear-resistant weld. On the other hand, sample 7, welded with 2.05 kJ/mm heat input and 4 m/min wire feed speed, displayed the lowest hardness values in both the HAZ (165.644 HV) and weld zone (178.151 HV), suggesting a softer and potentially less wear-resistant weld.

3.4 Effect of Wire Feed Speed and Heat Input on Toughness

The Charpy Impact Test results, as shown in Table 2, demonstrated the impact of welding parameters on the toughness of the CGHAZ. Samples with finer grain structures and balanced phase distributions, achieved through lower heat input and higher wire feed speed, exhibited superior toughness [2]. This is attributed to the ability of finer grains to impede crack propagation and dissipate energy more effectively during impact loading [5]. For example, sample 3, welded with 1.69 kJ/mm heat input and 8 m/min wire feed speed, showed the highest impact energy absorption (142 J), indicating excellent

toughness. In contrast, sample 2, welded with 1.69 kJ/mm heat input and 6 m/min wire feed speed, exhibited the lowest impact energy absorption (112 J), suggesting reduced toughness.

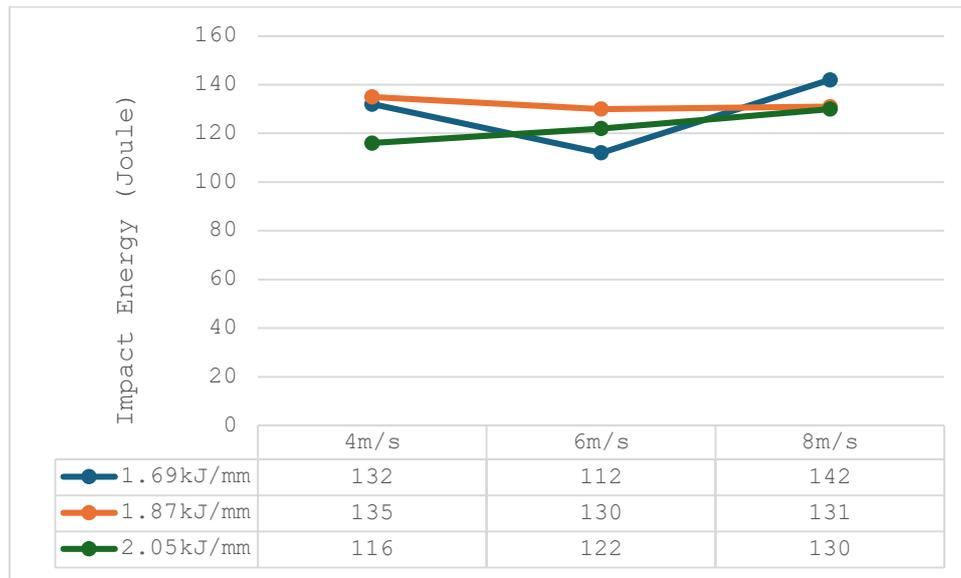


Fig. 4 Charpy impact test results

3.5 Effect of Wire Feed Speed and Heat Input on Flexural Properties

The 3-point bending test provided valuable insights into the mechanical behavior of the samples under bending conditions. Results of the bending test are tabulated as shown in Table 2 below.

Table 2 Results of bending test

Sample	Max Force (N)	Max Disp (mm)	Max Stress (N/mm ²)	Max Strain (%)
1	1702.81	1.045	425.703	1.045
2	275.625	1.203	68.9063	1.203
3	1995.94	1.081	498.984	1.081
4	3014.06	7.0475	753.516	7.0475
5	2647.19	2.149	661.797	2.149
6	1549.38	2.682	387.344	2.682
7	4528.44	11.287	1132.11	11.287
8	4958.75	10.965	1239.69	10.965
9	4820.94	11.313	1205.23	11.313

Meanwhile, the flexural modulus is determined using the equation below.

$$E_f = \frac{L^3 F}{4wh^3d} \quad (1)$$

Flexural modulus is used to determine the stiffness of a material. Figure 5 shows the result of flexural modulus that is obtained through the formula.

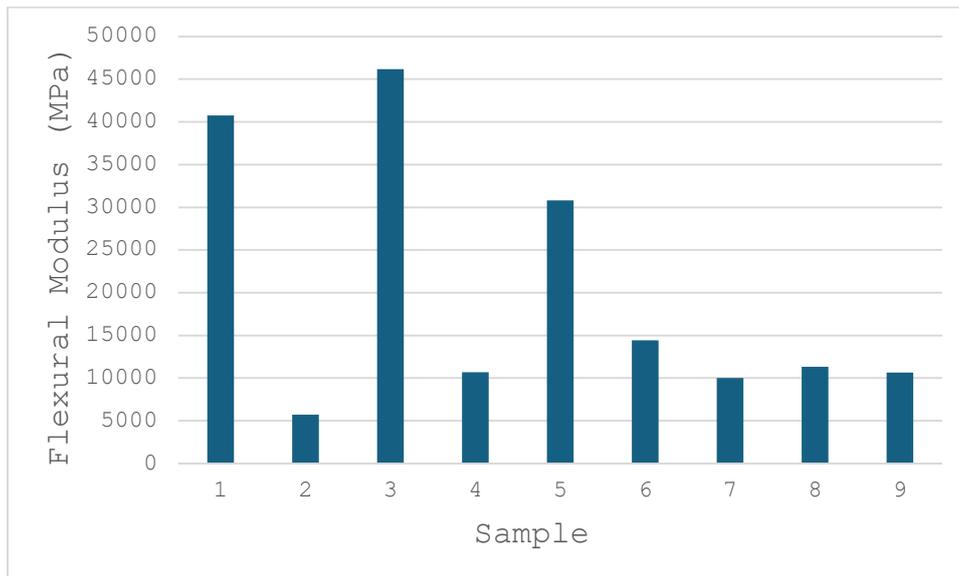


Fig. 5 Flexural modulus for each sample

The 3-point bending test results highlighted the influence of welding parameters on the flexural modulus, stress, and strain of the welded specimens. Samples with finer grain structures and balanced phase distributions, resulting from lower heat input and higher wire feed speed, generally exhibited higher flexural modulus values, indicating greater stiffness and resistance to deformation under bending loads. Notably, sample 3, welded with 1.69 kJ/mm heat input and 8 m/min wire feed speed, demonstrated the highest flexural modulus (46160 MPa), suggesting superior stiffness compared to other samples. These observations collectively indicate that Sample 3 exhibited the stiffest and strongest response to bending. This characteristic is crucial for structural components that need to maintain their shape under stress, such as car frames and crash boxes. The impressive maximum stress reading of Sample 3 further underscores its ability to withstand significant loads before yielding. Finally, the minimal displacement experienced by Sample 3 during bending reinforces its exceptional stiffness and resistance to bending deformation.

3.6 Correlation between Microstructure and Mechanical Properties

The combined analysis of microstructural observations and mechanical test results revealed a strong correlation between microstructure and mechanical properties which is shown in Figure 6. Finer grain structures, achieved through optimized welding parameters, were associated with improved hardness, toughness, and flexural properties. This correlation underscores the importance of controlling the microstructure through careful selection of welding parameters to achieve desired mechanical performance in automotive applications.

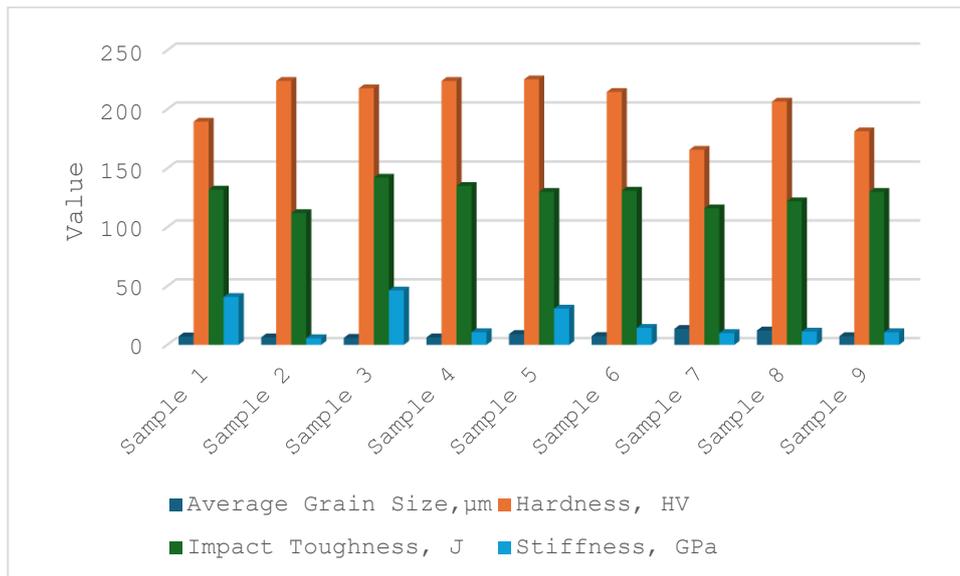


Fig. 6 Correlation between Microstructure and Mechanical Properties

Grain size plays a critical role in determining the hardness of a material. This relationship is governed by the Hall-Petch equation, which states that smaller grain sizes result in higher hardness and yield strength due to the increased grain boundary area, which impedes dislocation movement. In the context of the provided data, it can be observed that samples with smaller average grain sizes tend to have higher hardness values. For instance, Sample 3 (low heat input, 1.69 kJ/mm, and high wire feed speed, 8 m/min) has the smallest average grain size (5.99 μm) and a high hardness value (217.718 HV), whereas Sample 7 (high heat input, 2.05 kJ/mm, and low wire feed speed, 4 m/min) with the largest average grain size (13.544 μm) shows the lowest hardness (165.644 HV). This inverse relationship is consistent across the samples and highlights the importance of grain refinement in enhancing material hardness.

While hardness is an indicator of a material's resistance to deformation, it often inversely correlates with impact toughness, which measures the ability to absorb energy during fracture. Materials with higher hardness tend to be more brittle, exhibiting lower impact toughness. This trend is evident in the low heat input samples, where Sample 2, with the highest hardness (223.973 HV), demonstrates the lowest impact toughness (112 J). Conversely, Sample 3, which maintains a high hardness (217.718 HV) but not the highest, shows the highest impact toughness (142 J) among the low heat input samples. This suggests that an optimal hardness level, rather than the highest possible, may be more beneficial for achieving better toughness.

The amount of heat input during welding significantly affects the microstructure, particularly the grain size [4]. Higher heat input generally results in larger grains due to prolonged exposure to elevated temperatures, allowing more time for grain growth. In the provided data, high heat input samples such as Sample 7 (13.544 μm) and Sample 8 (12.218 μm) exhibit larger grain sizes compared to low and medium heat input samples. This increase in grain size with higher heat input correlates with a decrease in hardness and impact toughness, emphasizing the need for precise control of heat input to avoid excessive grain growth and consequent deterioration of mechanical properties.

The interplay between heat input, grain size, and mechanical properties reveals that optimal welding conditions are crucial for balancing hardness and toughness. Medium heat input samples (e.g., Sample 6) show a good balance, with moderate grain size (7.504 μm), high hardness (214.657 HV), and good impact toughness (131 J). This suggests that medium heat input provides sufficient thermal energy to refine the grain structure without excessive grain growth, maintaining both hardness and toughness. On the other hand, high heat input samples exhibit a significant drop in both properties due to larger grain sizes.

4. Conclusion

The study's findings provide valuable insights into the effects of wire feed speed and heat input on the microstructure and mechanical properties of the CGHAZ in low-carbon steel GMAW welds. The results

highlight the importance of optimizing welding parameters to achieve a balance between strength, toughness, and ductility, crucial for ensuring the safety and reliability of welded joints in automotive applications.

Specifically, the study found that lower heat input and higher wire feed speed generally lead to finer grain structures, resulting in improved hardness, toughness, and flexural properties. Conversely, higher heat input and lower wire feed speed tend to produce coarser grains, leading to reduced mechanical performance.

These findings have practical implications for the automotive industry, where the optimization of welding parameters can lead to the production of stronger, more durable, and safer welded joints. By understanding the relationship between welding parameters and material properties, manufacturers can tailor their welding processes to achieve specific performance goals, ultimately contributing to the development of more reliable and efficient automotive structures.

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