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Effect of welding angle variation on impact strength, micro and macrostructural characteristics of SMAW joints in AISI 1020 steel

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Abstract

Welding parameters strongly influence the mechanical integrity and metallurgical quality of welded joints. Shielded Metal Arc Welding (SMAW) is valued for its ease of use and versatility across various materials. This study investigates the effect of welding angle variations on the impact strength, microstructure and macrostructure of AISI 1020 steel joints welded using SMAW technique. Welding was performed at angles of 45° and 70° using currents of 80, 90, and 100 A. Charpy impact testing was conducted in accordance with ASTM E23, while macrostructural and microstructural observations were used to evaluate weld quality and the Heat-Affected Zone (HAZ). Impact testing evaluated the internal toughness of the welded joints, while structural observations provided insights into the weld quality and integrity. Results indicated that higher welding currents and larger angles significantly improved impact resistance. The highest impact energy (56 J/cm²) was obtained at 100 A and a 70° welding angle, showing the best impact resilience. The macro and microstructural analysis supported this, with fewer cracks and more evenly distributed martensite, indicating better weld quality.

Keywords:
SMAW, AISI 1020, welding angle, impact toughness, macrostructure, Charpy test.

1 Introduction

Welding is an important process in the manufacturing industry that is used to join materials, especially metals, by local heating that causes the parts of the material to fuse without involving external connecting materials [1]. One of the welding techniques often used is Shielded Metal Arc Welding (SMAW), which is known for its ease of operation and ability to work on various types of materials, including low-carbon steel such as AISI 1020. The strength of the welded joint in the SMAW method is influenced by various factors, including the welding angle [2]. Variations in welding angle can affect the stress distribution, porosity, and mechanical strength of the welded joint, which in turn affects the impact strength and microstructure of the joint [3]. Several previous studies have shown that smaller welding angles can produce stronger joints by enabling better control of heat distribution and deeper weld penetration [4]. In addition, variations in welding angles can affect the macrostructure of the joint, leading to the formation of cavities and pores that can reduce joint quality [5]. Welding angles that are too large can increase distortion and reduce the strength of the welded joint, whereas welding with a more optimal angle can improve the performance of welded joints in low-carbon steel [6]. Therefore, a thorough understanding of the influence of welding angle on the impact strength and macrostructure of the joint is essential to maximize the performance of welded joints in industrial applications.

Several previous studies have examined the effect of welding angle on the mechanical properties of welded joints in various types of steel. A 45° angle produces the maximum tensile strength in AISI 1045 steel welded joints, while larger angles cause a decrease in joint quality [7]. Meanwhile, sharper welding angles tend to increase the risk of pores forming in the weld joint, which can reduce impact strength [8]. In addition, the influence of welding angle on the microstructure of low carbon steel welded joints and found that variations in welding angle can change the grain distribution and cause changes in the microstructural phase formed, which ultimately affects the resistance of the joint to dynamic loads [9]. Although many studies have examined the influence of welding angle on the quality of welded joints, there are still several aspects that have not been discussed in depth, especially regarding the influence of welding angle on the impact strength and macrostructure of AISI 1020 steel using the SMAW method.

A research gap identified in previous studies is the lack of focus on the relationships among welding angle, impact strength, and the macrostructure of welded joints in AISI 1020 steel, particularly with the SMAW method. Several studies have assessed the effect of welding angle on tensile strength or joint microstructure [10]. However, few have explored its influence on impact strength, which is crucial for dynamic load applications in this material. Existing studies have also focused more on medium- or high-carbon steels [11], while AISI 1020 steel, a low-carbon steel, exhibits different characteristics in terms of welding behavior and resistance to damage from impact loads. Therefore, more specific research on the effect of welding angle on impact strength and macrostructure in AISI 1020 steel with the SMAW method is urgently needed to close this knowledge gap.

Although the effect of welding angle on the microstructure and mechanical properties of welded joints has been studied extensively, there is a lack of focused research on its influence on the impact strength and macrostructure of AISI 1020 steel welded joints, especially when using the SMAW technique [12]. While several studies have investigated the relationship between welding angle and tensile strength, fewer have examined impact strength, which is essential for materials subjected to dynamic loading [13].

This research aims to bridge this gap by systematically analyzing the effect of welding angle variations on both the impact strength and the macrostructure of SMAW-welded joints in AISI 1020 steel. The study will evaluate how different welding angles affect the joint's ability to resist dynamic loads and the resulting microstructural and macrostructural changes.

2 Methods and materials

This study used AISI 1020 steel, a low-carbon steel with a relatively low carbon content and a ferrite-pearlite microstructure. This steel was chosen for its good mechanical properties, such as ductility and optimal weldability, making it an ideal material for testing welded joints under impact conditions. The primary material used was cut into test plates according to ASTM standard dimensions and joined using SMAW process. In this study, the welding parameters were systematically varied.

Welding current: three current levels were used: 80 A, 90 A, and 100 A. The welding current directly affects heat input, weld bead size, and penetration depth, which in turn influence the mechanical properties of the weld.

Welding angle: two welding angles were used: 45° and 70°. These angles were chosen because they significantly affect heat distribution and weld quality. The welding angle influences the flow of molten metal and the cooling rate, both of which affect the resulting microstructure and impact toughness. The theoretical aspects of the influence of welding angle on metallurgical phenomena are: (1) heat input distribution: the welding angle plays a critical role in determining how heat is distributed across the weld zone. At smaller welding angles, the heat is more concentrated, which leads to deeper penetration and potentially a finer Heat-Affected Zone (HAZ). This is because a focused welding arc results in more localized heat, leading to more precise heat input control [14]. In contrast, larger welding angles cause the heat to disperse more widely, resulting in a shallower weld pool and a broader HAZ. This can reduce the mechanical properties of the weld by increasing the likelihood of grain coarsening within the HAZ [15]; (2) molten pool flow: the angle at which the welding arc is applied also affects the flow of the molten pool. Smaller angles yield a more focused molten pool, enhancing fusion and reducing the risk of defects such as cold laps or incomplete fusion. A larger welding angle, however, causes the molten metal to flow away from the weld joint, reducing fusion quality and increasing the chances of porosity and other defects [16]; (3) HAZ formation: the welding angle influences the HAZ formation by controlling the thermal gradient during welding. A smaller welding angle results in a more concentrated thermal cycle, promoting rapid cooling in the weld pool and HAZ, which can result in a finer microstructure. A larger welding angle, however, results in a wider and more diffuse heat distribution, leading to a larger HAZ with coarser grain structures that may reduce the weld's overall mechanical properties [17].

Electrode type: E6013 electrodes were used for all welds. This type of electrode is commonly used for general welding applications and provides stable arc characteristics suitable for the SMAW process.

Polarity: Direct Current Electrode Positive (DCEP) polarity was used. DCEP is known for providing deeper weld penetration, which benefit weld strength and the HAZ in steels like AISI 1020.

Welding speed: the welding speed was kept constant at 10 cm/min across all trials. This speed ensures uniform heat distribution and consistent weld quality. A stable welding speed is crucial to minimize defects such as excessive spatter or poor fusion.

Welding technique: the stringer bead technique was used for all welds. This technique ensures that the welding arc remains steady, helping maintain better control of heat input and preserving the structural integrity of the welded joint.

Variations in these parameters were intended to affect heat distribution, the cross-sectional shape of the weld metal, and the HAZ. After the welding process, impact test specimens were prepared with V-shaped notches according to ASTM E23 standards and tested using the Charpy method to measure the energy absorbed until fracture occurs [18]. All tests were conducted using a pendulum type impact testing machine with a pendulum mass of approximately 21.4 kg and an arm length of 62 cm. The results of this test are expressed in impact energy values in joules, which reflect the toughness of the welded joint under dynamic loading.

The AISI 1020 steel used in this study was cut into plates according to ASTM standard dimensions and then assembled into butt joint configurations with welding angle variations of 45° and 70°. Each specimen was welded with an E6013 electrode at welding currents of 80 A, 90 A, and 100 A. The impact test specimens had a V-shaped notch with a depth of 2 mm and an angle of 45°, as per ASTM E23, see Fig. 1.

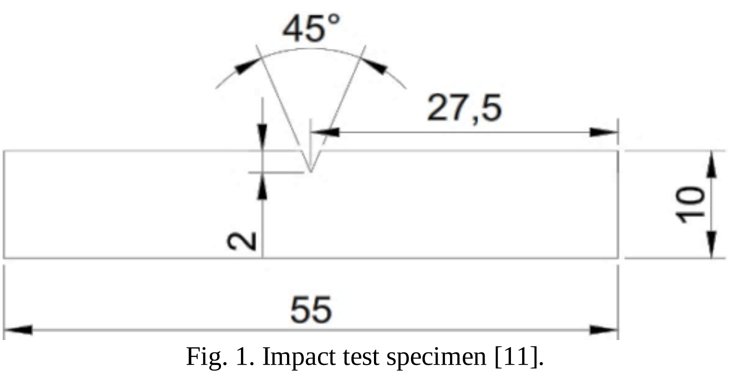


Fig. 1. Impact test specimen [11].

Impact testing was performed to measure the energy absorbed until fracture, which was then analyzed to evaluate the toughness of the welded joint at various combinations of welding parameters. In addition, a portion of the weld plate was cut transversely through the joint for macrostructural observation, allowing the morphology of the weld metal and the HAZ to be examined and correlated with the impact test results obtained. After welding, the specimens were tested using the Charpy method according to ASTM E23 (Fig. 1). Macrostructural observation was performed by photographing the fracture surface under uniform illumination. In addition to macrostructural and impact testing, microstructural analysis conducted to evaluate changes in the internal structure of the welded joint. Observations were made using an optical microscope at 3000× magnification to examine the grain size, phase distribution, and differences between the weld metal structure and the base material.

3 Results

While welding current is widely recognized as a critical parameter influencing weld quality, the welding angle is often overlooked in standard welding practices, such as those described by AWS or ASME. However, in this study, the welding angle was selected as a primary variable because it plays a significant role in the distribution of heat within the weld pool, the geometry of the weld bead, and the formation of the HAZ. Understanding how the welding angle affects these factors is essential for optimizing weld quality, particularly in low-carbon steels such as AISI 1020, which are often subject to dynamic loading conditions.

Heat distribution: the welding angle influences the concentration of heat during the welding process. A smaller angle directs the heat more vertically, resulting in more concentrated heating and deeper penetration. This, in turn, can lead to better fusion and reduced porosity in the weld. In contrast, larger angles tend to disperse heat over a broader area, reducing heat concentration and potentially affecting the microstructure of the welded joint. This aspect is particularly crucial for ensuring that the joint can withstand high dynamic loads, such as those encountered in industrial applications [19].

Weld bead geometry: the angle of the welding torch directly affects the the weld bead geometry, which is critical in determining the joint’s strength and durability. With a more optimal angle, the weld bead can be more uniform, reducing the likelihood of defects such as undercutting or incomplete fusion. In this study, the selected angles (45° and 70°) were specifically chosen to represent both typical and more extreme welding configurations to assess their impact on the joint's mechanical properties.

Formation of HAZ: the welding angle affects the thermal gradient across the joint, which in turn influences the formation and characteristics of the HAZ. Smaller angles, which concentrate the heat, result in a narrower HAZ, whereas larger angles lead to a broader HAZ with potentially coarser grain structures. The HAZ's size and microstructure are crucial in determining the joint's mechanical properties, especially its resistance to dynamic loading conditions [20].

Given that the welding angle can significantly impact these metallurgical phenomena, it was deemed essential to investigate its role in improving the mechanical properties of AISI 1020 steel joints. Previous studies have highlighted that optimizing the welding angle can improve the weld's impact resistance, particularly in low-carbon steels used in critical applications [21].

3.1 Impact test results

Table 1 shows the relationship between the combination of welding current and welding angle on the impact energy measured on AISI 1020 welded joints using the SMAW method. The impact test results showed that the impact energy before welding was 96 J/cm² [22]. Impact energy is measured in Joules per square centimeter (J/cm²), which indicates the extent to which the welded joint can withstand impact loads.

Table 1. Impact testing results

Current-angle combination	Collision energy (J/cm²)
80 A – 45°	25
90 A – 45°	29
100 A – 45°	36
80 A – 70°	34
90 A – 70°	47
100 A – 70°	56

The test results show that increasing the welding current and welding angle simultaneously significantly affects the durability of the welded joint. The lowest impact energy (25 J/cm²) was observed at a welding current of 80 A and a welding angle of 45°. This result correlates with the macrostructural observations, where the fracture surface displayed shallow indentation and a tortuous crack path, reflecting poor energy absorption and low impact resistance. Such behavior is characteristic of a welding configuration that does not provide sufficient heat input for optimal fusion and penetration, which in turn compromises the mechanical properties of the joint [23].

Increasing the welding current to 90 A at a 45° angle led to a modest increase in impact energy to 29 J/cm², with macrostructural showing a rougher crack morphology and more pronounced plastic deformation prior to fracture. This improvement suggests that higher welding currents enhance the energy absorption capacity of the weld, likely due to improved fusion and a finer microstructure resulting from increased heat input [24].

At a welding current of 100 A and a 45° angle, the impact energy increased further to 36 J/cm². This indicates a clear improvement in the weld's resistance to impact, with the macrostructure revealing a more uniform grain distribution and fewer signs of porosity or defects. These findings support the notion that increasing welding current enhances the heat input, which promotes a better-quality weld with increased resistance to dynamic loading [25].

In contrast, when the welding angle was increased to 70°, even with the same welding current of 80 A, the impact energy increased to 34 J/cm². This suggests that a larger welding angle positively influences the weld's performance by facilitating more even heat distribution, reducing thermal stress, and preventing excessive distortion [26]. As the welding current was increased to 100 A with a 70° angle, the highest impact energy of 56 J/cm² was achieved, demonstrating the synergistic effect of both higher current and larger welding angle in improving weld quality. This combination allows for deeper penetration and a larger molten pool, thereby improving mechanical properties and impact resistance [24].

These results align with previous studies, which have demonstrated that both welding current and angle significantly affect the mechanical properties of welded joints. Higher currents increase weld penetration and heat input, while larger welding angles improve heat distribution, thereby improving overall weld strength [25].

Fig. 2 shows a relatively consistent increase in absorbed energy with increasing current, but no drastic changes. The influence of welding parameters, especially welding current and welding angle, on the mechanical properties of welded joints has a significant impact on the structural integrity of the weld material.

Fig. 2 shows three different data sets, each representing a different welding condition. The first data set, at a welding angle of 45°, shows that the impact energy increases with increasing welding current, with values ranging from 25 J/cm² at 80 A to 36 J/cm² at 100 A. This trend is consistent with typical welding behavior, where higher currents generally produce stronger welds. The second data set, at a welding angle of 70°, shows that the impact energy at this angle is consistently higher than at 45°, ranging from 34 J/cm² at 80 A to 56 J/cm² at 100 A. This indicates that the welding angle significantly influences the impact strength, with a larger angle providing better resistance to impact forces.

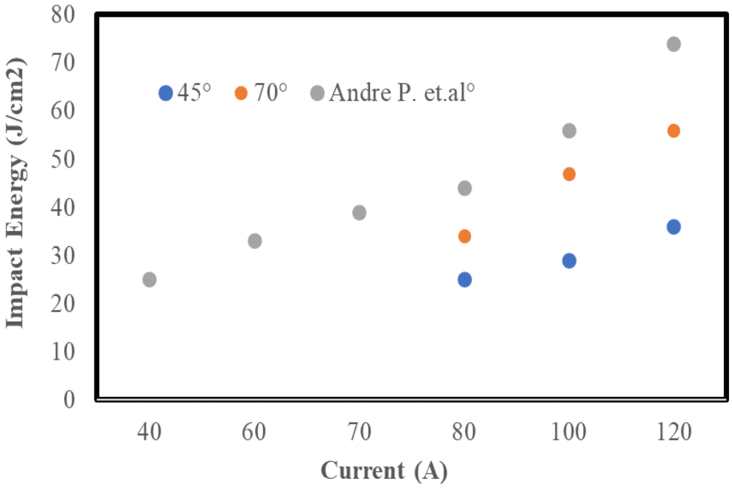


Fig. 2. Relationship welding current versus impact energy at various welding angles when compared with research by Andre P. et al.

Besides that, when compared to AISI 4340 steel at a 45° welding angle [27]. The impact energy for AISI 4340 was consistently higher than that for AISI 1020 at both welding angles, especially as the welding current increased. For example, at 100 A, AISI 4340 showed an impact energy of approximately 60 J/cm², which was higher compared to 56 J/cm² measured for AISI 1020 at the same current. This indicates that AISI 4340 has better impact resistance, making it a more suitable material for applications requiring higher strength and durability [28].

The results of this study show that welding with a higher current combined with a 70° angle significantly increases impact strength, making this configuration ideal for applications where impact resistance is critical. Furthermore, a comparison with AISI 4340 highlights the influence of material selection on weld joint performance, with AISI 4340 offering better impact resistance under comparable welding conditions.

3.2 Macrostructure test results

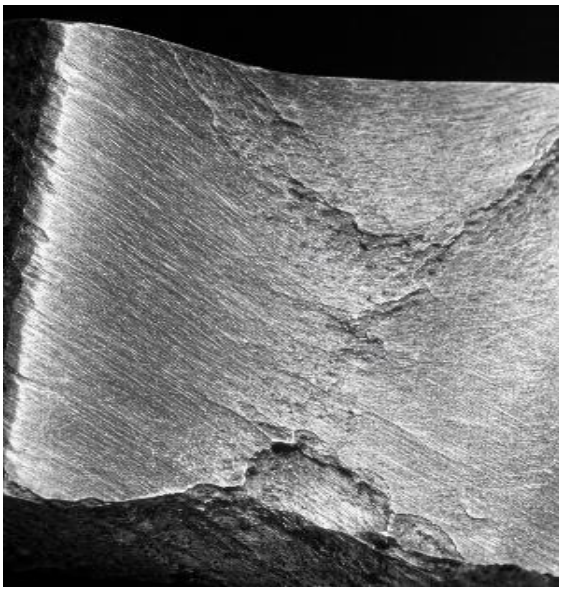
Fig. 3 shows various macrostructure results of the cracked surface after impact testing on welded joints with varying welding currents and angles. Each macrostructure exhibits different characteristics, reflecting differences in the resistance of welded joints to impact based on welding conditions.

The fracture surface of AISI 1020 steel in Fig. 3 exhibits predominantly ductile characteristics with minor localized brittle features. The surface appears rough with wavy patterns and some “cup and cone” regions, indicating significant plastic deformation prior to fracture. With an impact energy of 65 J/cm², the steel absorbs a considerable amount of energy, reflecting good material toughness. The granular morphology with small dimples is consistent with a ductile fracture mechanism, where micro-voids form, grow, and coalesce. Some fine lines on the surface suggest localized brittle contributions at grain boundaries or inclusions. Overall, the fracture reflects the behavior of low-carbon AISI 1020 steel, showing ductility and the capacity to withstand high-impact energy before failure.

The macrostructural result of the welded joints after impact testing provides further insights into the effects of welding parameters on weld quality. At the combination of 80 A and 45°, the macrostructure exhibited shallow indentation and winding cracks, consistent with the lowest impact energy observed in the corresponding impact test results. This suggests that the weld produced under these conditions was prone to failure under dynamic loading due to inadequate heat input and a suboptimal welding angle [29].

When the welding current was increased to 90 A at the same 45° angle, the macrostructure showed a more homogeneous crack path, with signs of plastic deformation. This indicated an improvement in the joint's ability to absorb impact energy, which was corroborated by the increased impact energy of 29 J/cm². The observed plastic deformation indicates improved material flow and fusion, which increases the strength and toughness of the welded joint [30].

At 70°, the increased welding angle contributed to a more uniform macrostructure with fewer visible defects. The combination of 100 A and 70° resulted in a high-quality weld with reduced porosity and a more even crack morphology. This indicates that a larger welding angle not only improves heat distribution but also enhances the mechanical properties of the weld by allowing for a more controlled cooling rate and reducing the risk of distortion and porosity [31].



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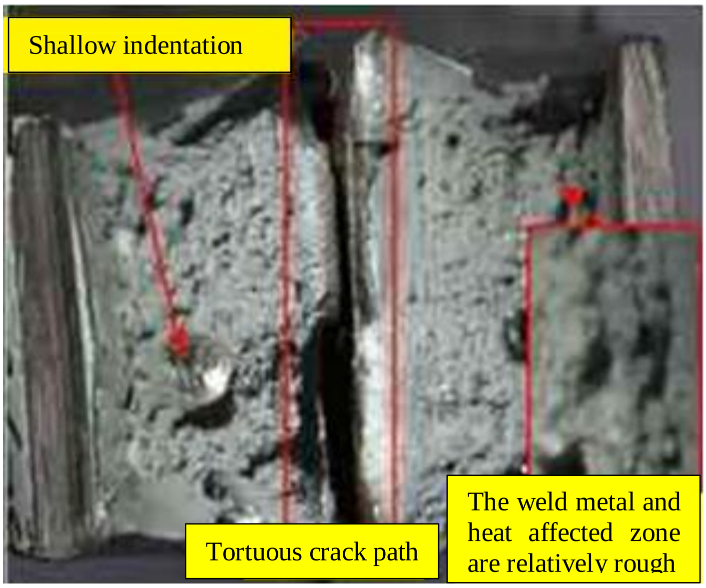
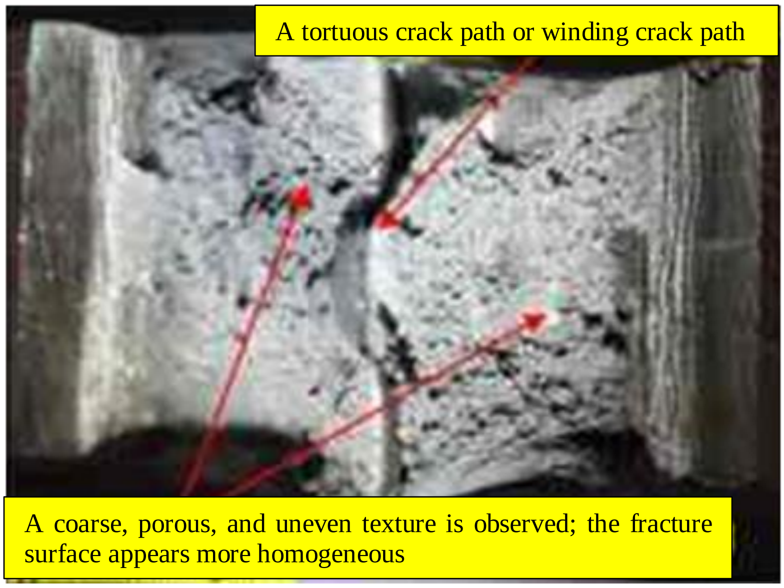
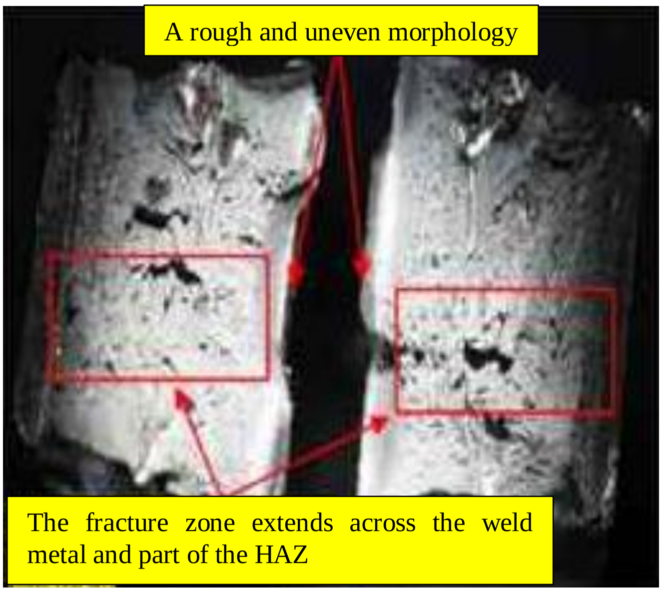


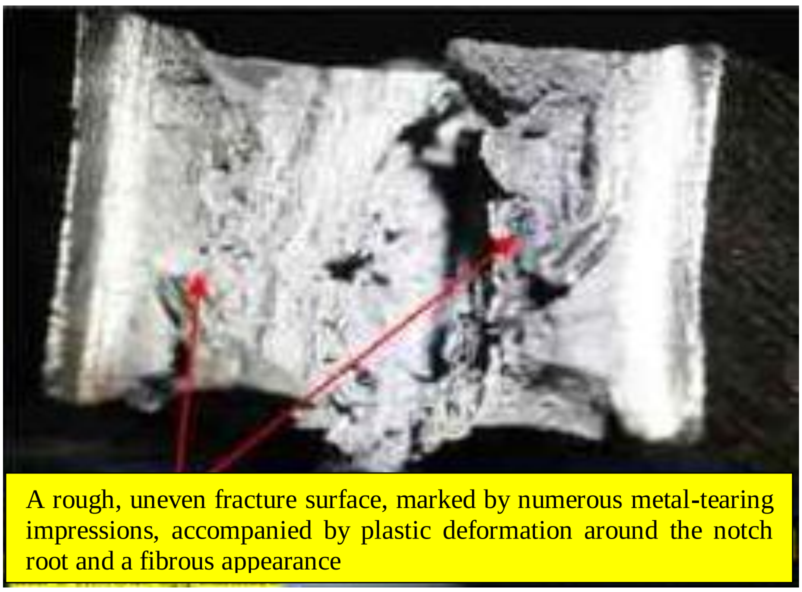
80 A 45º



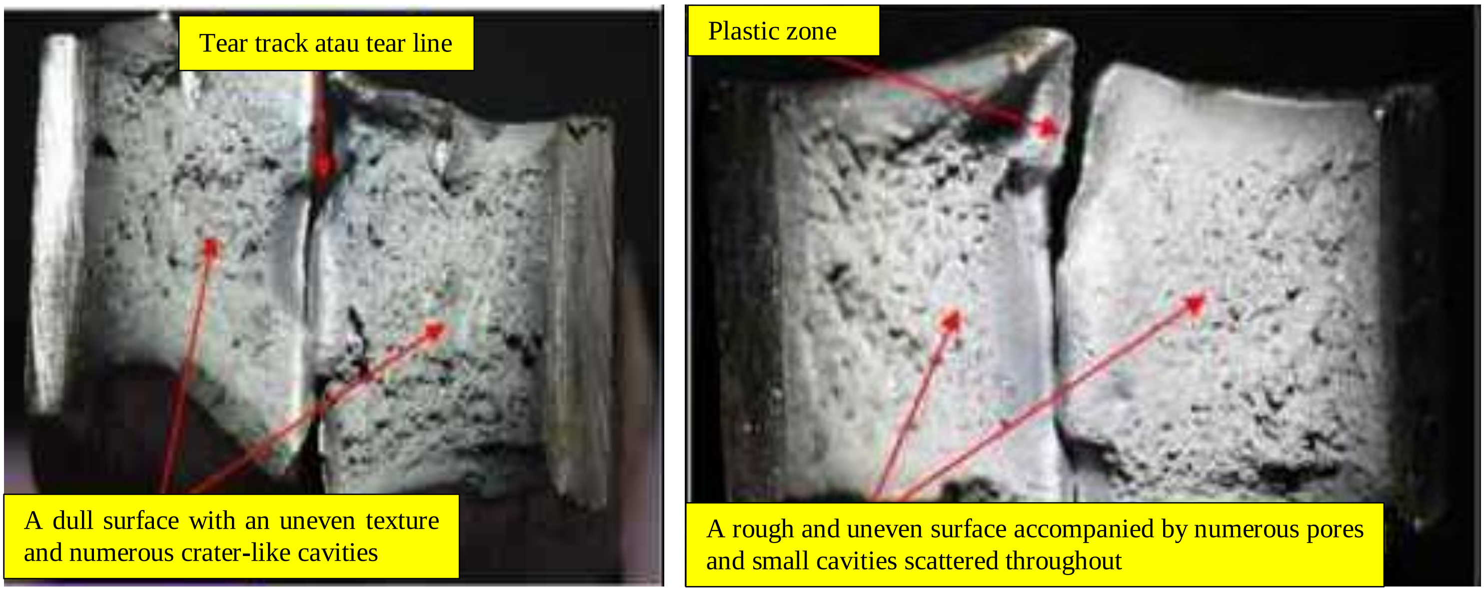
80 A 70º



90 A 45º



90 A 70º



100 A 45º 100 A 70º

Fig. 3. Macrostructure impact test results at a welding current of variation amperage and a welding angle.

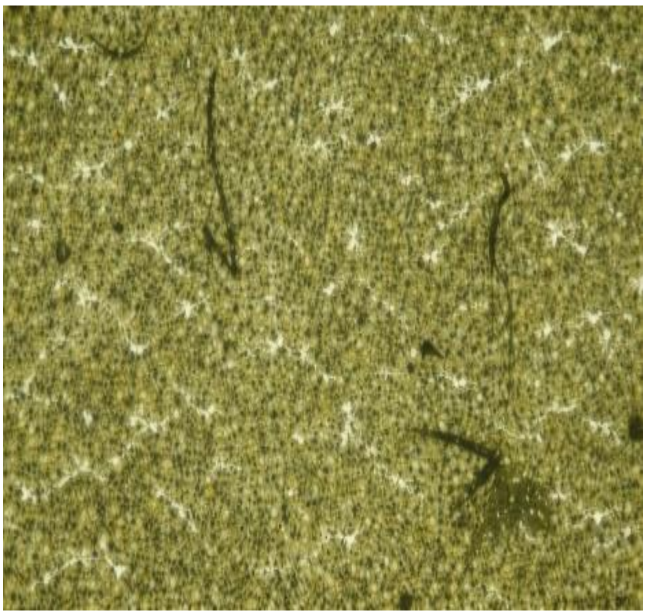
3.3 Microstructure test results

Fig. 4 shows the HAZ microstructure at various current and angle welding conditions, with a current of 80 A and an angle of 45° welding. The dominant visible structure is grains of rough martensite formed by fast cooling in the weld zone and the HAZ, visible indentation, shallow and lane winding cracks, indicating that this welding joint has low impact resistance.

The microstructure of the AISI 1020 steel fracture, untreated, observed after an impact test with an energy of 65 J/cm², is predominantly composed of ferrite with finely distributed pearlite, which is typical for low-carbon steel. The bright ferritic regions contrast with the darker pearlitic areas, creating a relatively uniform structure. Dark lines and traces on the surface indicate the paths of crack propagation, often following grain boundaries and pearlitic regions. This pattern is consistent with predominantly ductile fracture, where plastic deformation is significant. Small microvoids likely form around inclusions or at grain boundaries, coalescing and promoting crack growth. Overall, the microstructure reflects a ductile failure mode, demonstrating that AISI 1020 steel can absorb substantial impact energy before fracturing, with only minor localized brittle features.

This is in accordance with the impact test results in Table 1, which show a marked impact energy of 25 J/cm², which is the lowest. This shows that welded joints with this condition are not capable of absorbing enough energy during a collision before fracture occurs, with a wider crack zone seen in the HAZ area.

At the welded joint with current 90 A and 45° angle welding, the visible structure is more microhomogeneous compared to the picture first, with a little difference between the weld zone and the HAZ. The dominant structure is a mixture of martensite and perlite, which shows a greater number of more plastic deformations compared to the picture previously. The fracture that occurred shows a rough morphology with a number of signs of separation and shifting of materials, which are related to a higher impact energy, tall, which is 29 J/cm². This shows that with an improvement in current to 90 A, the welded joint is more capable of absorbing energy during collision, although there are still morecracks. Microstructure welded joints with 100 A current at a 45° angle. The more dominant structure seen here is more martensite stable with a little involvement of phase bainite, which provides greater resilience against fracture. In the picture, the fracture appears more homogeneous with a little material reduction and low porosity. The recorded impact test results are 36 J/cm², thigher than the combination previously, showing that welded joints in this condition are stronger and more resistant to collision. This is also seen in the picture macrostructure, which shows welded joints with amore uniform structure and greater plastic-deformation, indicating improved impact resistance with increasing current.



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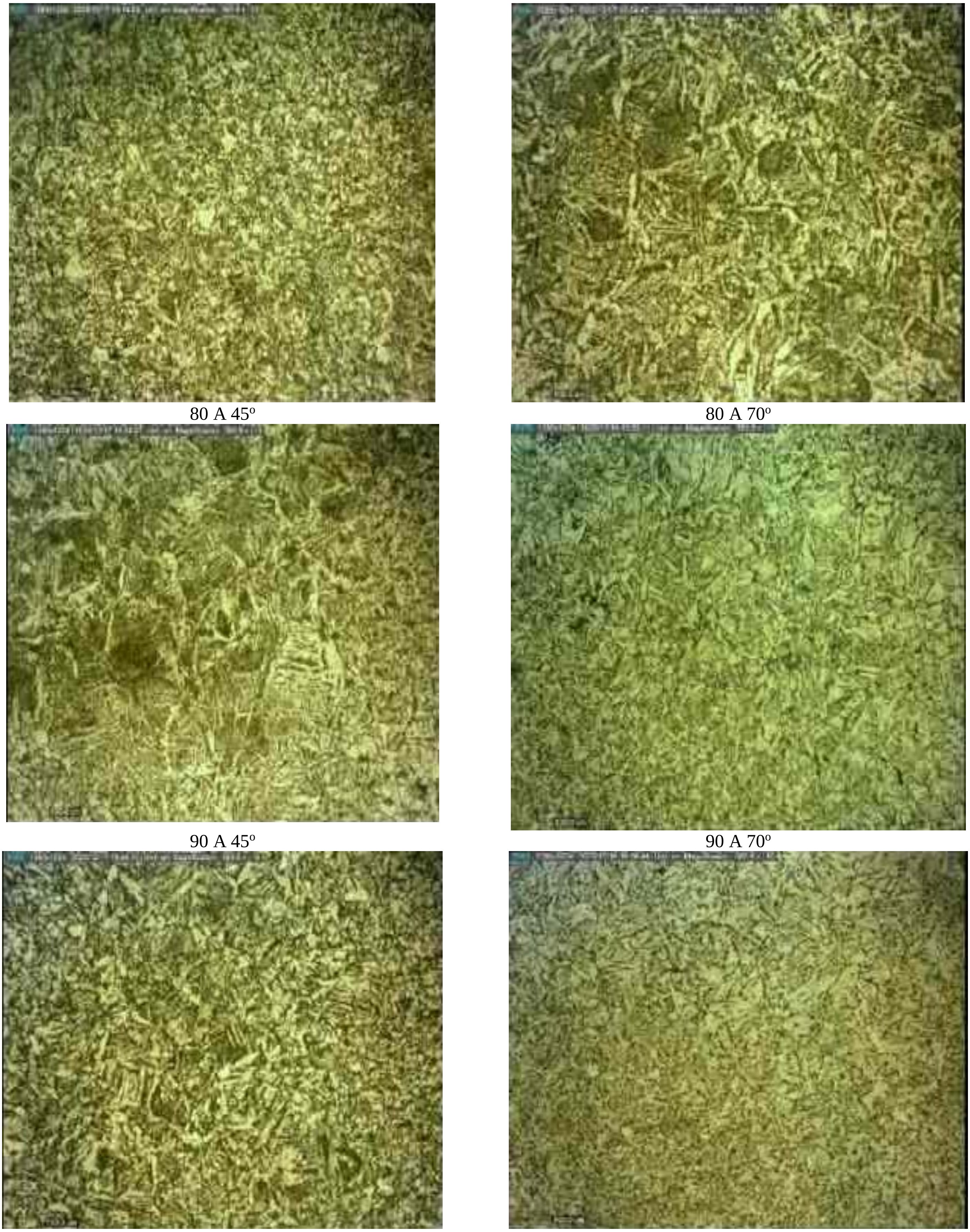

Fig. 4. Microstructure HAZ area at various welding currents and angles.

At the welded joints in the combination current 80 A and angle 70° welding, the structure is more microhomogeneous compared to the combination current and angle previously, with a more even distribution of martensite. This Fig. 4 shows more fractures uniform with more cracks, smooth, reflective, and resilient to impact. Impact test results for the combination are 34 J/cm², which is taller than the combination with a 45° angle, indicating that change corner welding also affects the strength of the connection. In the picture macrostructure, visible deformation is more plastic and larger around the weld zone, which indicates that the influence of corner welding can increase the resilience of the connection to collision.

At the welded joints in combination current 90 A and angle 70° welding, there is a visible improvement in the homogeneity of the microstructure, with more martensite uniform throughout the weld zone and HAZ. The fracture shows more surface roughness and more significant signs of plastic deformation. The impact energy recorded in the combination is 47 J/cm², which is higher than the combination previously, indicating that improvements in current and angle welding produce stronger and more stand-up welded joints. The macrostructural results show that the weld area is more homogeneous and contains less porosity, indicating better weld quality.

At the welded joints in the combination current of 100 A and angle of 70°, indicating a structure-dominant micro with more martensite, smooth and durable. Structure this gives more resilience against fractures, with more fracture surfaces homogeneous and deformed more plastic large, indicating that this welding joint can absorb energy from collisions better. The recorded impact test result is 56 J/cm², which is the highest in the series testing, indicating that the combination of current height and angle produces the strongest and most collision-resistant welded joints. Structure more macro fine with a little disabled or porosity support findings; this shows improvement in quality and durability of welded joints in condition welding.

3.4 Discussion

This is the result of impact, macrostructure, and microstructure tests. AISI 1020 welded joints with variation in welding current and angle welding show a significant relationship between both parameters, and resistance welded joints against impact. At a combination of 80 A – 45°, the measured impact energy is 25 J/cm², which is the lowest in this testing. In the results, related macrostructures, visible surface cracked with indentation shallow and lane winding cracks. Structure surface this show that welded joints in condition this own low impact resistance, with more cracks significant in the weld zone and HAZ. The microstructural results show the presence of coarse martensite grains formed due to rapid cooling in the weld zone and HAZ, which also indicates low impact resistance [32]. These results in accordance with data in Table 1 showing that welded joints with combination this not enough capable absorb energy before fracture occurs.

With the current improved to 90 A at an angle of 45° welding, impact energy increases to 29 J/cm², and at 100 A – 45°, it reaches 36 J/cm². This changes show that improvement in welding current contributes to an increase in the resilience of welded joints against collisions. In the results macrostructure, the visible morphology of the crack surface is more rough and uneven, with a number of signs of separation and shifting of materials, which reflect the existence of plastic deformation before the occurrence of cracks. Microstructural results in the combination show an existence of a mixture between martensite and perlite, with alittle difference between the weld zone and the HAZ, which shows the improvement in homogeneity structure and durability against fractures. This shows that improvements in welding current repair quality welding joints, making them more capable of absorbing energy impacts. Previous research also supports this finding, showing that increasing the welding current is often associated with increased material resistance to impact, due to improved homogeneity and material structure [33].

In combination with 70° corner welding, the results obtained show a significant improvement in impact energy compared with 45° angle. For example, in the 80 A – 70° combination, the impact energy increases to 34 J/cm², and at a combination of 100 A – 70°, the impact energy reaches the highest, namely 56 J/cm². This result shows that change corner welding gives a significant contribution to the resilience of welded joints against impact, even at higher currents. Macrostructure results show more uniform fracture surfaces and fewer defects, indicating that changing corner welding reduces the formation of defects such as porosity or cracks, which can influence resilience to impact. Microstructural results show that the distribution phase has more martensite evenly distributed in the weld zone and HAZ, providing greater resilience Good against fracture. This is in line with previous studies showing that larger welding angles allow for more even heat distribution, reducing thermal stress and improving the quality of the welded joint, which leads to increased impact resistance [34].

This study has several limitations, such as testing only low-carbon AISI 1020 steel, so the results may not be fully applicable to steels with different chemical compositions or mechanical properties. Furthermore, this study focused only on variations in welding current and angle during the SMAW process, without considering other variables such as welding speed or electrode type. Impact testing was limited to joint toughness testing, while other tests, such as tensile or fatigue testing, could provide more comprehensive information about joint performance under different conditions. These results should be considered as preliminary guidelines that require further verification.

The results of this study provide practical implications in the selection of welding parameters for AISI 1020 steel, particularly by using a welding angle of 70°, which has been proven to increase joint toughness. Increasing the current, although increasing penetration, does not always result in a stronger joint. Theoretically, these findings enrich understanding of the influence of welding parameters on the microstructure and mechanical properties of welded joints, and pave the way for further research on welding process optimization by considering other variables.

4 Conclusions

This study demonstrates that welding current and welding angle significantly affect the impact performance and structural quality of SMAW joints in AISI 1020 steel. The results show that the combination of 100 A and a 70° welding angle yields the highest impact energy of 56 J/cm², which is a 124% increase over the lowest combination. The increase in welding current improves fusion quality, while the larger welding angle enhances heat distribution, resulting in better weld strength and impact resistance. Microstructural analysis confirms that higher current and larger angles result in a more uniform distribution of martensite, improving joint toughness. These results suggest that a welding current of 100 A and a 70° welding angle are favorable parameters for AISI 1020 steel requiring good impact resistance. This study provides valuable insights into optimizing welding practices, though future research should examine additional variables, such as travel speed, electrode type, and multi-pass welding conditions to further optimize weld performance.

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