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Penetration and microstructure of steel joints by ultrasonic-assisted gas metal arc welding

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Abstract

This work investigates the application of ultrasonic vibration to steel joints formed by gas metal arc welding. Welding is done using a metal active gas welding source with welding current of 120–160 A, 0.8-mm-diameter welding wire and 10 L/min CO_2 flow. The distance from the torch to the ultrasonic horn is 120 mm. Ultrasonic vibration most affects the weld when ultrasonic vibration position is 120 mm from torch and increases the penetration when welding speed is 190 (275) mm/min for a 5-mm-thick (10-mm-thick) plate. Moreover, weld width increases when welding speed is 190 mm/min for 10-mm-thick plate. Although ultrasonic vibration does not affect the hardness of welding zones, it modifies the microstructure of the diffusion and welding-pool zones.

Keywords: Ultrasonic vibration, U-GMAW, penetration, hardness, microstructure

1. Introduction

Gas metal arc welding (GMAW) is a common consumable-electrode welding method. Due to its wide range of energy and easy automation, GMAW is used to weld most types of ferrous and non-ferrous metals [1-3]. To achieve good quality welds and minimal loss of material, GMAW requires testing the process parameters, such as arc length, voltage, current and electrode speed [4, 5]. In addition, ultrasonic vibration may also be applied to GMAW (U-GMAW) to improve weld quality. Ultrasonic vibration modifies the form of metal droplets produced in GMAW, thereby improving the mechanical properties of the weld [6-8]. Many studies have investigated the application of ultrasonic vibrations to GMAW. For example, Fan et al. [7, 9] used ultrasonic vibrations to improve metal transfer and considered how the distance between the ultrasonic vibrator and the welding position affects weld quality. Ultrasonic vibration only improves the weld quality when the ultrasonic vibrator is positioned a 3/4λ (where λ is the ultrasound wavelength in the material) from the welding torch [10]. In addition, ultrasonic vibrations dramatically modify the arc properties, such as metal droplet transmission [7, 9], change the

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microstructure [11-14] and improve the mechanical properties [15-17].

The results of Fan et al. [7] for 24 V arc voltage indicate that U-GMAW should be done in short-circuit mode. The application of an ultrasonic field during GMAW welding transfers smaller metal droplets into the weld pool, thereby producing a high-quality weld [18]. Moreover, the droplets transferred to the weld pool are relatively small, which increases the stability and weld quality [4, 5].

Other authors have studied how ultrasonic vibrations affect metal droplet geometry. The results show that the diameter of the liquid-metal droplets becomes larger than the electrode diameter. U-GMAW increases the aspect ratio of the elliptical droplets, decreases the arc oscillation and restores the balance more quickly than conventional GMAW. The arc in U-GMAW thus becomes brighter and shorter, and operation at 20 kHz and 45 μm vibration amplitude produces shorter arc lengths than traditional GMAW [19].

The research on liquid-metal drops is accompanied by the studies of wettability and weld penetration: one of the advantages of ultrasonic vibration is increased wettability [20],[21]. Upon applying ultrasonic oscillation, the welding arc shortens, producing negative arc bonding [22]. Furthermore, weld penetration increases and grain sizes become finer [23]. Increasing the weld penetration requires a larger amplitude of the reflected vertical-shear wave [24].

The GMAW weld structure and grain fineness both increase significantly upon applying ultrasonic oscillation [25, 26]. Previous studies report improved voltage range and arc stability upon using U-GMAW. When the ultrasonic vibration is applied directly to the workpiece, the grain fineness of the weld increases significantly [27, 28].

Further, the hardness of aluminium near the weld surface decreases when using U-GMAW. For stainless steel, the hardness decreases in areas approximately 2 mm from the weld surface but increases by approximately 20% near the surface to be welded [29].

Most previous investigations focus on the metal displacement mechanism, arc length, penetration and wettability. The present study instead investigates the distance between the ultrasonic vibrator and the welding position. In addition, we compare and analyse the weld penetration and profile with and without ultrasonic vibration and measure the hardness of characteristic regions of the weld, such as the base metal zone, the heat-affected zone, the diffusion zone and the liquid-metal zone. Finally, the microstructure of these characteristic regions with and without ultrasound is analysed.

2. Materials and experimental methods

2.1. Specimen design

Figure 1 shows a schematic drawing of a steel plate used for the GMAW experiment. The specimen measured 300 mm × 160 mm, and was either 5 or 10 mm thick. The plates were milled to form a U-shaped groove. The base material was C45 carbon steel, whose chemical composition is given in Table 1.

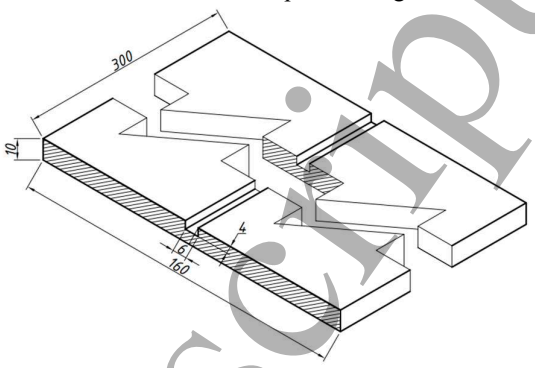

Figure 1: Specimen for GMAW experiment.

Table 1: Chemical composition of base metal and filler metal (wt%).

%	C	Mn	Si	P	S	Cr
Filler	0.12	1.85	1.15	0.025	0.025	0.40

2.2. Ultrasonic system

The ultrasonic generator used in this experiment was manufactured by the Viet Nam Ultrasonic Equipment Co., Ltd. and was operated at 20 kHz, 1000 W. The simulation of the ultrasonic system and heat treatment of the horn can be found in [30-32].

2.3. Metal active gas source

The experiment used a metal inert gas/metal active gas (MIG/MAG) welding machine (model MONOGYS 250-4CS) that uses a single-phase power supply with a four-roller wire-feeding system, which works well with soft wires such as aluminium and steel. The wire speed was automatically set given the wire type, wire diameter and welding mode. The welding current was 120–160 A, the welding-wire diameter was 0.8 mm, the wire feed speed was 1–15 m/min and the CO_2 flow was 10 L/min.

2.4. Principle of ultrasonic-assisted welding

The workpiece was welded as shown schematically in Figure 2. The soldering torch was placed in the centre of the U-groove and at a specified distance from the surface of the workpiece. Wire and shielding gas were supplied to ensure proper and repeatable welding conditions for all tests. The wire feed speed was 12 m/min, and the CO_2 flow rate was 10 L/min. Welding produced an arc that melted the welding wire, forming liquid-metal droplets that transferred to the U-groove on the workpiece. The ultrasonic vibrator was located below the torch, in direct contact with the lower surface of the workpiece. During welding, ultrasonic waves were incident directly on the underside of the workpiece, transmitting vibrations into the liquid metal in the U-groove.

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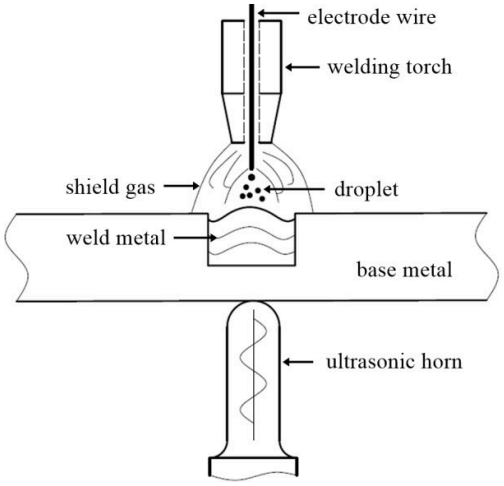

Figure 2: Principle of ultrasonic-assisted GMAW.

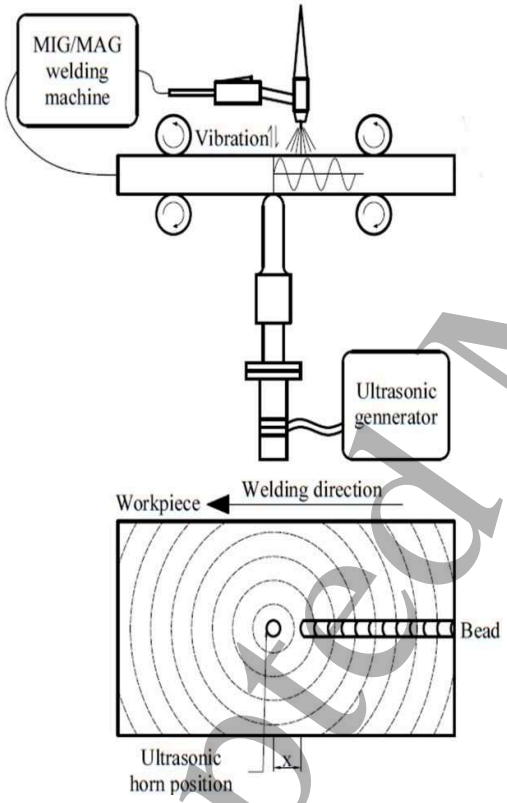

Figure 3: Schematic of ultrasonic-assisted GMAW method.

To investigate how ultrasonic vibration affects the weld, we varied the distance between the ultrasonic vibrator and the torch (see *x* in Figure 3). Krajewski et al. [10] report that x = ¾λ is optimal, where λ denotes the ultrasound wavelength in the material. In this study, we used a 20 kHz ultrasonic vibration, which propagated at 3240 m/s as a transverse wave in the C45 carbon steel material. The wavelength is given by $C = \lambda f$, which gives λ = 162 mm. Thus, $x = \frac{3}{4}\lambda \approx 120$ mm. In addition, we investigated an arbitrary value of *x* (10 mm) to produce the control data.

2.5. Experimental setup

Figure 4 shows the jig constructed to implement ultrasonic-assisted MAG welding on 300 mm × 160 mm panels. The billet was supported by two rollers below and clamped by two rollers above. The torch was mounted from above to ensure a fixed position relative to the workpiece surface. The fixed spherical ultrasonic vibrator R20 pushed up against the lower surface of the workpiece. The distance between the torch and the ultrasonic vibrator was varied by changing the torch position. The roller system was driven by a motor connected via a gearbox. The roller speed determined the movement speed of the sheet workpiece, which was adjusted by using an inverter. The MAG welding source and the ultrasonic source were placed in the advanced position for automatic testing.

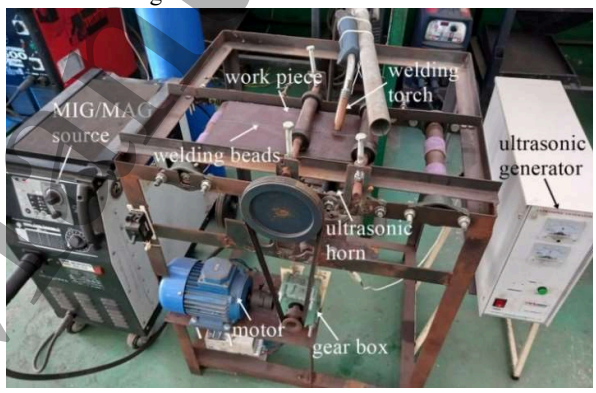

Figure 4: Apparatus for GMAW ultrasonic-assisted welding.

In this test, the workpiece was 10 mm thick, and the control sample was 5 mm thick, Table 2. The distance between the torch and the ultrasonic vibrator was 120 mm. The moving speed of the workpiece was 190 and 275 m/min, as determined by the U-groove size, wire diameter, amperage and number of layers.

Table 2: Experimental parameters.

Case	Welding speed (mm/min)	Specimen thickness (mm)	Position of ultrasonic horn (mm)
1	190	10	10
2	275	10	10
3	190	5	120
4	190	10	120
5	275	10	120

3. Results and discussion

3.1. Welding shape

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Figure 5(a) and 5(b) show the appearance of the weld line with and without ultrasound, respectively, for a 10-mm-thick workpiece travelling at 190 m/min with the vibrator 10 mm from the torch. Although the weld seam is nonuniform in both cases, ultrasonic vibration produces fish scales of more even width and height.

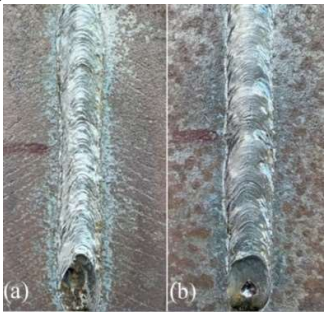

Figure 5: Photographs of weld line for 10-mm-thick plate travelling at 190 m/min and with vibrator 10 mm from torch: (a) with ultrasonic vibration and (b) without ultrasonic vibration.

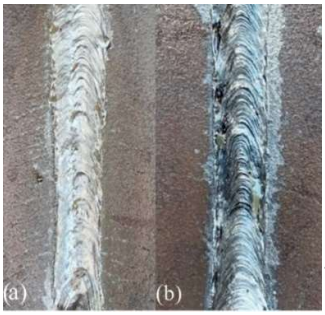

Figure 6: Photographs of weld line for 10-mm-thick plate travelling at 275 m/min and with vibrator 10 mm from torch: (a) with ultrasonic vibration, (b) without ultrasonic vibration.

Figure 7: Photographs of weld line for 5-mm-thick plate travelling at 190 m/min and with vibrator 120 mm from torch: (a) with ultrasonic vibration, (b) without ultrasonic vibration.

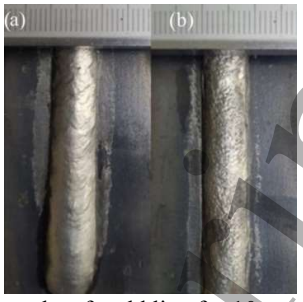

Figure 8: Photographs of weld line for 10-mm-thick plate with vibrator 120 mm from torch and with ultrasonic vibration. Welding speed is (a) 190 m/min and (b) 275 m/min.

Figure 6(a) and 6(b) show the weld line with and without ultrasound, respectively, with the workpiece travelling at 275 m/min, the vibrator 10 mm from the torch and a workpiece thickness of 10 mm. In both cases, the weld seam is rough and uneven.

Figure 7(a) and 7(b) show the weld seam with and without ultrasound, respectively, for a 5-mm-thick plate travelling at 190 m/min with the vibrator 120 mm from the torch. In both cases, the weld is of high quality; however, with ultrasonic vibration, the width and height of the weld are more uniform.

Figure 8(a) and 8(b) show the weld line for a 10-mm-thick plate with the vibrator 120 mm from the torch and a welding speed of 190 and 275 m/min, respectively. When the welding speed of the workpiece is 275 m/min, the width and height of the weld vary significantly. In contrast, when the welding speed is 190 m/min, the weld is much more uniform: the width and height of the weld remain relatively even over the entire length of the weld.

3.2. Weld cross section

Without ultrasonic vibration, the weld metal does not penetrate significantly into the base metal. Figure 9 shows weld cross sections for Case 3. Without (with) ultrasonic vibration, the metal penetrates the base metal to a depth of 0.87 mm (2.6 mm).

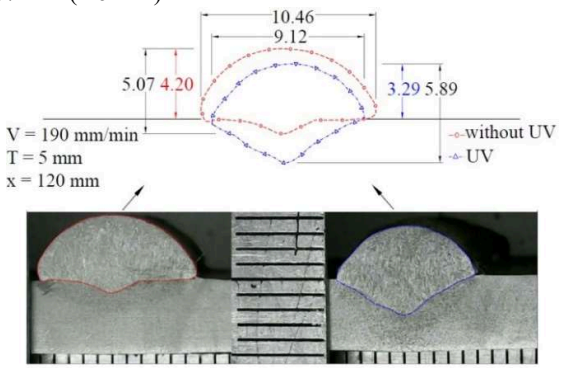

Figure 9: Cross section of welds without (left) and with (right) ultrasonic vibration (Case 3). Scales are in mm.

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Figure 10 shows that, for Case 4, the weld width and weld-metal penetration increase when using ultrasonic vibration. Without ultrasonic vibration, the penetration of the weld metal is minimal and the shape of the U-groove remains essentially unchanged. In contrast, the shape of the U-groove changes significantly when using ultrasonic vibration.

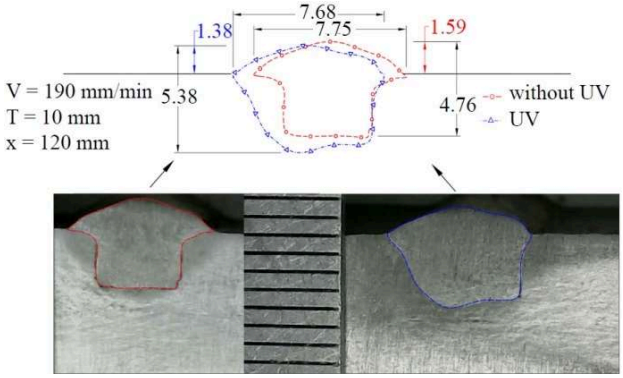

Figure 10: Cross section of welds without (left) and with (right) ultrasonic vibration (Case 4). Scale is in mm.

Figure 11 shows the cross sections for Case 5 with and without ultrasonic vibration. In both cases, the weld penetrates the base metal uniformly in width and depth, but the width and depth of the welds with ultrasonic vibration are greater than without ultrasonic vibration.

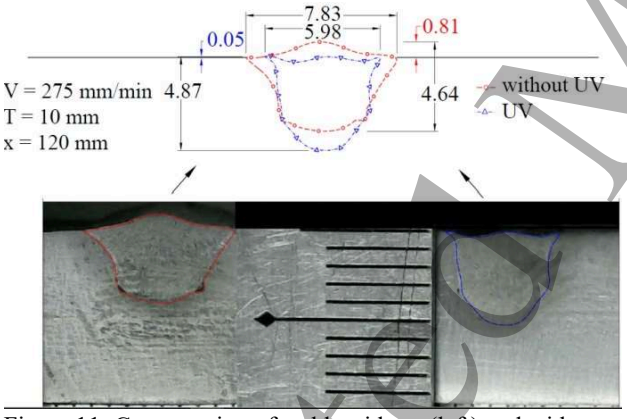

Figure 11: Cross section of welds without (left) and with (right) ultrasonic vibration (Case 5). Scale is in mm.

3.3. Hardness

Figure 12: Photograph showing result of hardness measurements of weld cross section.

Figure 12 shows the results of Rockwell hardness tests on the weld cross section. The four positions correspond to (a) the base metal, (2) the heat-affected zone, (3) the diffuse zone and (4) the welding-pool region.

In general, the hardness decreases slightly after ultrasonic vibration welding (see Figures 13 and 14). For all cases, the hardness increases from zone 1 to zone 4. The base metal position (1) is the least hard, and the solidified liquid-metal position (4) is the hardest. With and without ultrasound, the change in hardness due to ultrasonic vibration ranges from 0.5 to 2 HRA. The hardness at the base metal position (1) changes by about 0.5 HRA, whereas the hardness at the position of the solidified liquid metal (4) changes by about 2 HRA. However, the measurement error is in the range of 2 HRA. Therefore, the utrasonic vibration affects on the hardness unclearly during solidification of metals.

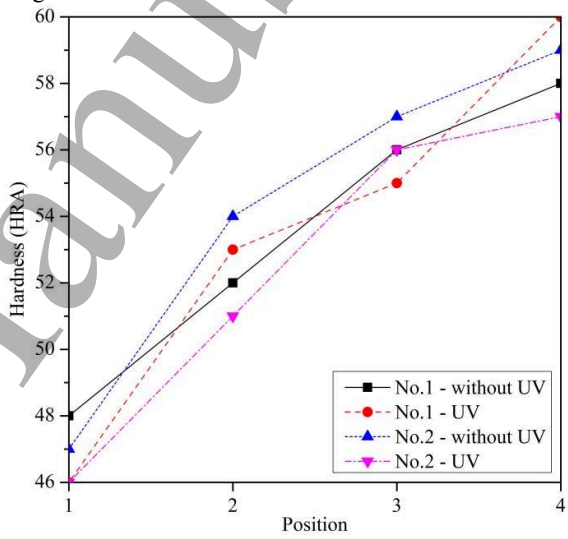

Figure 13: Hardness of weld cross section for Cases 1 and 2.

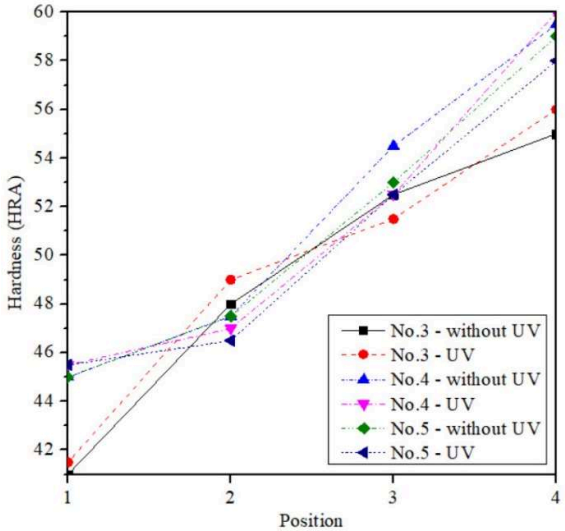

Figure 14: Hardness of weld cross section for Cases 3–5.

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3.4. Microstructure

Figure 15 shows the microstructure of the carbon steel of the base metal region. The results show that ultrasonic vibration does not affect the microscopic morphology of this region.

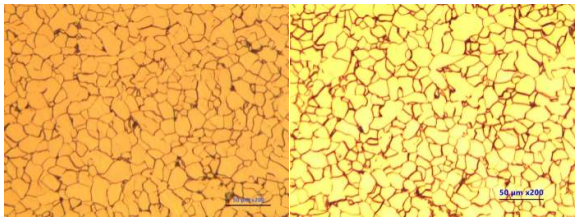

Figure 15: Microstructure of base metal without (left) and with (right) ultrasonic vibration.

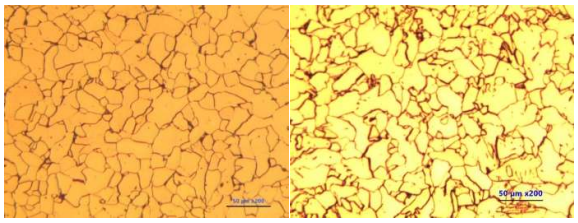

Figure 16: Microstructure of heat-affected zone without (left) and with (right) ultrasonic vibration.

Figure 16 shows the heat-affected zone. Microscopic examination shows that the heat-affected zone is smaller and more uniform for the ultrasonic-assisted weld. Although this region retains the chemical composition of the base metal, the heat during the welding process affects this area by inducing residual thermal stress and recrystallisation.

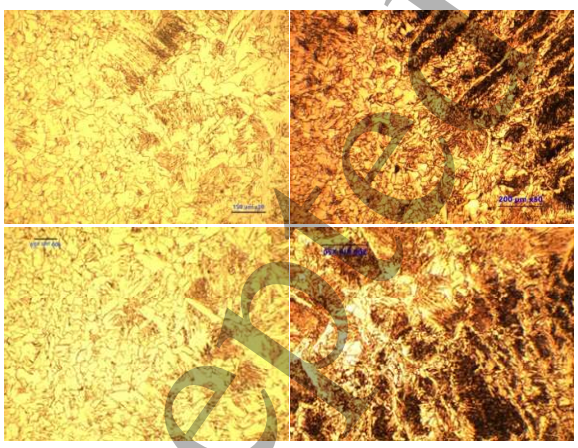

Figure 17: Microstructure of diffusion zone without (left) and with (right) ultrasonic vibration.

Figure 17 shows the diffusion zone, which is between the welding-pool and the heat-affected zone. Welding without ultrasonic vibration results in a clear distinction between the welding-pool and the heat-affected zone (cf. Figures 16 and 17). Welding with ultrasonic vibration results partial mixing of these zones, which leads to finer organisation.

The diffusion zone is characterised by coarse grains and a dendrite structure. However, the energy delivered by ultrasonic waves creates a vacuum shadow, leading to the micro-vortex phenomenon, which significantly reduces the tree branch structure.

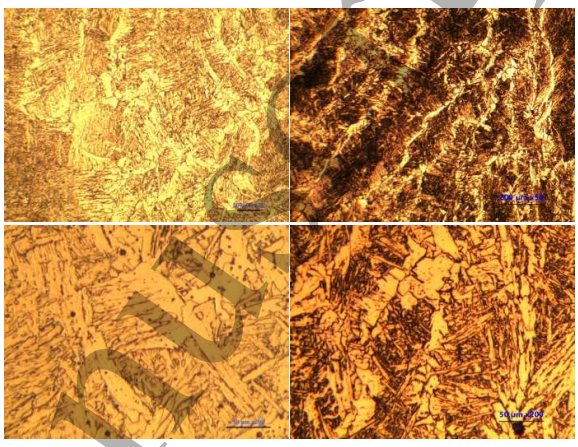

Figure 18: Microstructure of welding pool without (left) and with (right) ultrasonic vibration.

Figure 18 shows the microstructure of the weld pool area. This region is characterised mainly by a dendritic structure, which has poor mechanical properties and numerous defects, thereby degrading the quality of the weld. When welding without ultrasonic vibration, the branch organisation in the weld pool area remains coarse, large and clearly oriented (right image), whereas the branch organisation with ultrasonic vibration is still small but smooth, with branches growing in all directions (left image).

4. Conclusion

The results show that, to obtain the highest-quality weld, the distance between the torch and the ultrasonic vibrator should be three-quarters of the ultrasound wavelength in the material, which in the present work is 120 mm. Ultrasonic vibration increases weld penetration when the welding speed is 190 (275) mm/min and the plate thickness is 5 (10) mm, and increases weld width when the welding speed is 190 mm/min and the plate thickness is 10 mm. However, ultrasonic vibration has minimal effect on the stiffness of the typical weld zones (i.e. base metal, heat-affected, diffusion and welding-pool zones).

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