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ORIGINAL ARTICLE

Effects of an ultrasonically excited TIG arc on CLAM steel weld joints

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Abstract The objectives of the present study are to research the effects and mechanism of an ultrasonically excited tungsten inert gas (TIG) arc on the comprehensive mechanical properties of China Low Activation Martensitic (CLAM) weld joints. In the arc-ultrasonic process, an ultrasonic power source is coupled to the TIG power source to modulate the welding arc. The influence of various arc-ultrasonic parameters is determined through comparisons of the resulting weld microstructures, impact energy, hardness and tensile properties. The results show that the arc-ultrasonic technique effectively refines the microstructure, provides even distribution of carbides, and improves mechanical performance of the weld metal and HAZ. With increasing ultrasonic power, the impact toughness of the weld metal first increases by up to 80% and then begins to decrease while the hardness and tensile strength of the weld metal exhibit a slight decrease. The optimum matching of arc-ultrasonic excitation parameters and welding parameters improve the comprehensive mechanical properties of CLAM weld metal. Furthermore, PWHT is beneficial to weld metal mechanical properties for both standard and arc-ultrasonic TIG welding.

Keywords CLAM steel · TIG · Ultrasonic · Microstructure · Mechanical properties

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1 Introduction

The Tested Blanket Model is an essential part of International Thermonuclear Experimental Reactor manufacturing [1], structure of its first wall/covering is huge, numbers of LiPb channels and nitrogen loops inside are large [2, 3], sizes of the channels and clapboards at different position differ greatly, and their shapes are complex, all these factions make it difficult to form in integral, and dependable welding technique is needed to connect the components together. Reduced Activation Ferritic Martensitic (RAFM) steel, as the material of the first wall, has to suffer the surface thermal load from the plasma side, as well as the nuclear thermal load from the reaction between neutron and structure material, it requires good welding qualities. China Low Activation Martensitic (CLAM) steel is one of the RAFM steels, which is developed by China. The chemical composition of CLAM is slightly different from some RAFM such as F82H, Eurofer'97, and JLF-1 giving it superior or similar performance. Some work on the traditional fusion welding of CLAM steel also has been studied [4–7]. The main processes being considered for the welding of RAFM steel include fusion welding and diffusion welding. Fusion welding plays an important role in the joining process of RAFM steel because of low cost and ease of application. The fusion welding methods of RAFM steel include tungsten inert gas (TIG) welding and laser welding and others. Because of the heat input of welding, the metal in the fusion zone remelts and crystallizes and the grains in the heat-affected zone (HAZ) grow. Some Widmanstatten structures develop, which severely affect the properties of the welded joint and leads to nonuniformity between the properties of welded joints and parent metals. Therefore, many efforts have been made to try to refine the grains of weld fusion zone. These efforts include post-welding treatment, weld pool stirring, and arc oscillation. As a newer welding technique, arc-ultrasonic welding introduces ultrasonic power into the welding arc and therefore into the weld. The ultrasonic power in the weld pool results in the fine grains in final weld, which significantly improves the mechanical properties of the weld, such as the ductility and fracture toughness [8–13]. Arc-ultrasonic welding technique has been successfully used in many materials such as titanium alloy [11], Q235 and 09MnMiDR [12], the researches demonstrate that it can effectively improve weld microstructure, refine grain, and enhance mechanical properties. The paper uses arc-ultrasonic TIG welding to weld CLAM steel. The microstructure and mechanical properties under different welding and arc-ultrasonic parameters are studied. The mechanism about how the arc-ultrasonic process affects weld properties is also discussed in this paper.

2 Experiment

The base material used in the experiment is CLAM steel produced by CAS in batch no. HEAT 0912A. The normalization was performed at 980°C for 30 min and then tempering was done at 760°C for 90 min. The chemical composition is shown in Table 1. The thickness of base material is 3 mm. The square groove butt weld is achieved without filler metal by arc-ultrasonic TIG welding.

The shielding gas is Argon with a flow rate of 12 L/min. The arc is contracted at welding nozzle to reduce the width of HAZ. According to [13], resonant frequencies of arc-ultrasonic are 30, 50, and 80 kHz, preferable results can be obtained under 50 kHz. In this experiment, the frequency of 50 kHz is adopted, besides, the CLAM steels are welded under different excitation voltages. The last two groups are additional for confirmation. The welding speed is 50 mm/min. The parameters of ultrasonic-excited frequency, excited voltage, and welding current are shown in Table 2.

Table 2 The welding parameters

Sample no.	1	2	3	4	5	6
Current (A)	80	80	80	80	60	60
Ultrasonic frequency (kHz)	50	50	50	50	50	–
Excited voltage (V)	20	30	40	60	60	–

After welding, visual examination revealed no welding flaws such as cracks nor undercut on seam surface. Then selected samples were furnace heated at 760°C for 30 min followed by air cooling . Subsequently, the samples are conducted with incision, burnishing, and polishing, etched with solution of picric acid, hydrochloric acid, and alcohol until the metallographic structure can be observed clearly. After that, observe the weld microstructure of each sample with a metalloscope. The Charpy V-notch samples were 55 mm long, 10 mm wide, and 2.5 mm thick. In all cases, the notch was centered in the weld metal and excess weld metal is smoothed before impact test. Vickers micro-hardness measurements were performed on the cross-sections of the CLAM weld joints by using a Model HVS-1,000 digital micro-hardness tester. Measurements were taken from the weld center line (0 mm) toward the HAZ and base metal (8–10 mm), the test weight was 0.98 N load time was 20s. The tensile testing experiments were carried out according to Chinese standard GB/T 228–2002, i.e., metallic material stretching experiment standard.

2.1 Metallographic characterization of welding zone

Figure 1 shows representative optical micrographs of arc-ultrasonic TIG welds on the as-received base material without post-weld heat treatment (PWHT). As can be seen in Fig. 1, the weld zone of TIG-welded CLAM steel is mainly lathy martensite and the microstructural morphology of weld zone varies with different welding parameters. The data indicate that as the ultrasonic excitation voltage increases, martensite lath length decreases. Figure 2 shows SEM images of arc-ultrasonic TIG welds without PWHT. Comparison of Fig. 2a (sample 5 with ultrasonic power) and Fig. 2b (sample 6 without ultrasonic power), shows that the addition of ultrasonic power reduces martensite lath length and produces a finer and more even distribution of precipitated carbide $M_{23}C_6$ [14].

Mechanism of arc-ultrasonic power during the crystallization is not clear thoroughly, it is generally acknowledged that the main effects of arc-ultrasonic are mass transfer and heat transfer [8–13]. During the period from the melt of weld metal to its recrystallization, the effects are more obvious. In this experiment, during the solidification of weld zone, with the effect of ultrasonic cavitation and sound flow, the distribution of composition and heat at weld pool becomes homogeneous, the residual stress is reduced

Table 1 The chemical composition of CLAM steel

Composition	Cr	W	V	Ta	Mn	C	Fe
Design	9.00	1.50	0.20	0.25	0.45	0.10	Balance
Test	8.72	1.55	0.20	0.23	0.67	0.14	Balance

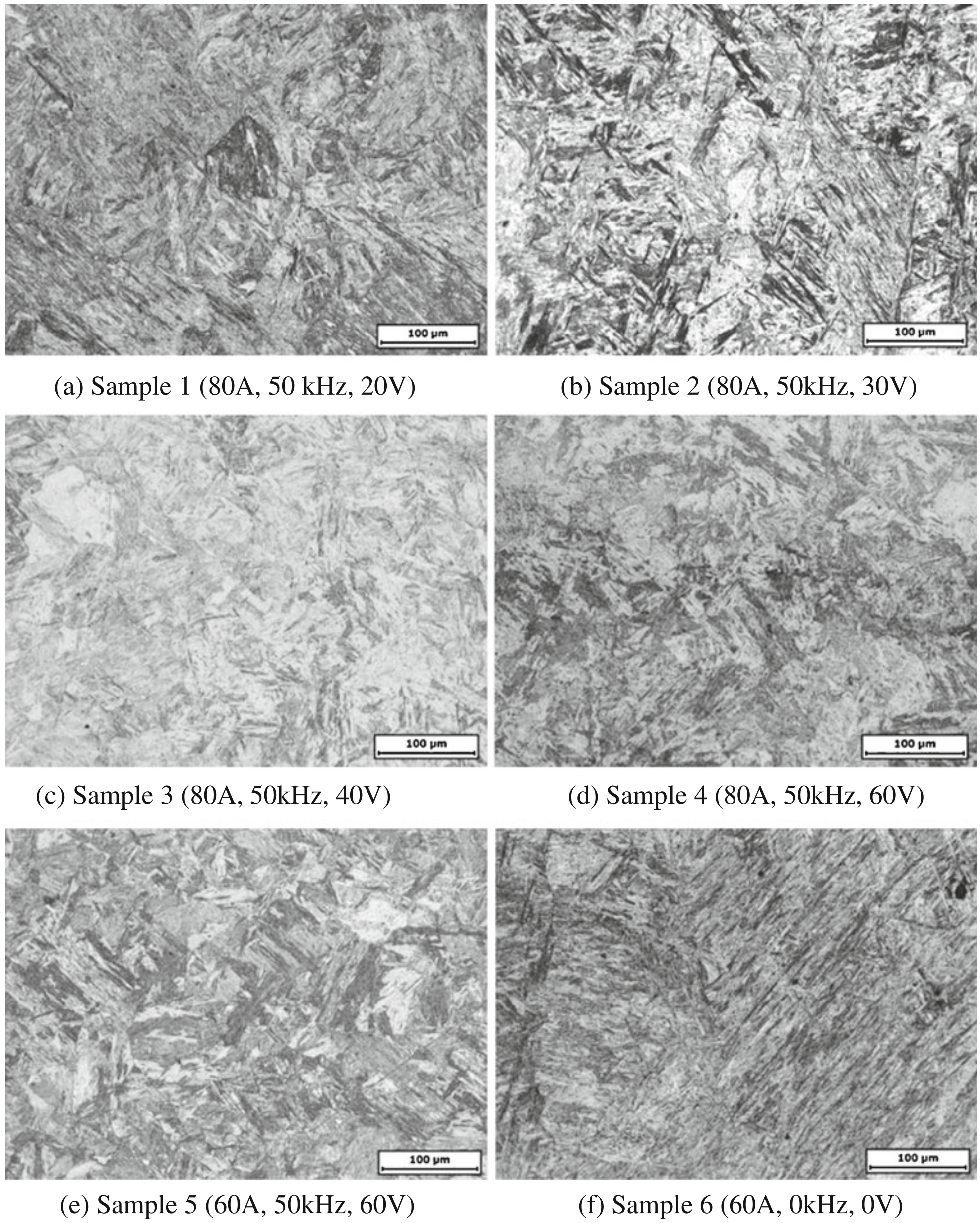


Fig. 1 Optical Micrographs of microstructure of arc-ultrasonic TIG welds without PWHT. **a** Sample 1 (80 A, 50 kHz, 20 V); **b** sample 2 (80 A, 50 kHz, 30 V); **c** sample 3 (80 A, 50 kHz, 40 V); **d** sample 4 (80 A, 50 kHz, 60 V); **e** sample 5 (60 A, 50 kHz, 60 V); **f** sample 6 (60 A, 0 kHz, 0 V)

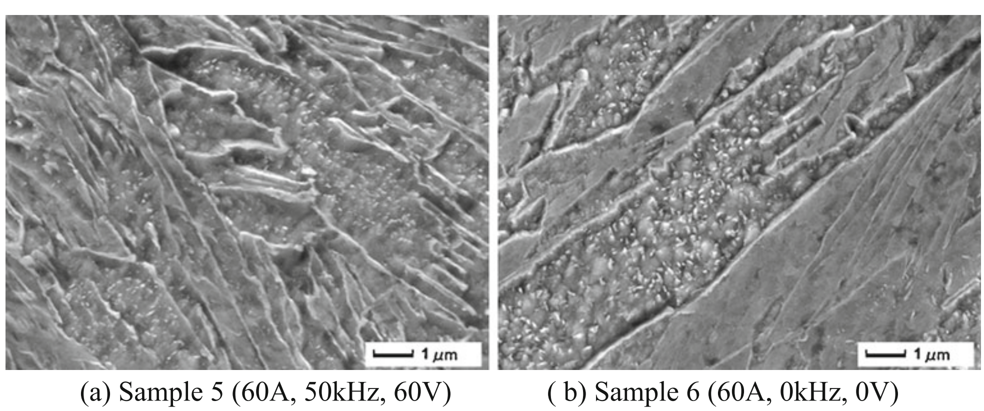


Fig. 2 SEM of TIG fusion zone without PWHT. **a** Sample 5 (60 A, 50 kHz, 60 V); **b** sample 6 (60 A, 0 kHz, 0 V)

and austenite grain is refined, moreover, the distribution of carbon and chromium in matrix becomes well-proportioned.

Generally speaking, martensitic transformation happens inside austenite, morphology of austenite can be expressed to a certain degree with martensite structure, and fine austenite grain is beneficial to forming tiny martensite lath. From the metallographic analysis of Figs. 2 and 3, it is clear that the arc-ultrasonic has a positive effect on refining of austenite grain at weld zone and the effect increases with the growing of incentive energy.

2.2 Metallographic characterization of HAZ

The microstructure of HAZ of the welded joint of CLAM steel without PWHT is shown in Fig. 3. It can be observed that the HAZ mainly consists of tempered martensite. The arc-ultrasonic action has an obvious effect on the refinement of crystal grains in the HAZ. When the excitation voltage is 20 V, the grain size of sample 1 is about 20 μm. When the voltage grows up to 60 V, the grain size of sample 4 decreases to about 10 μm. The increasing of excitation voltage has the same positive effect on grain refining at HAZ. Figure 3f shows the SEM picture of sample 6, the grain size is between 20 and 30 μm. Figure 3e shows the SEM picture of sample 5, the grain size is between 10 and 20 μm. The using of arc-ultrasonic refines the HAZ grain of CLAM steel weld joint effectively. Figure 4 shows the SEM picture of samples 5 and 6, we can conclude that arc-ultrasonic can also homogenize the composition of weld zone and make the distribution of carbide well-proportioned.

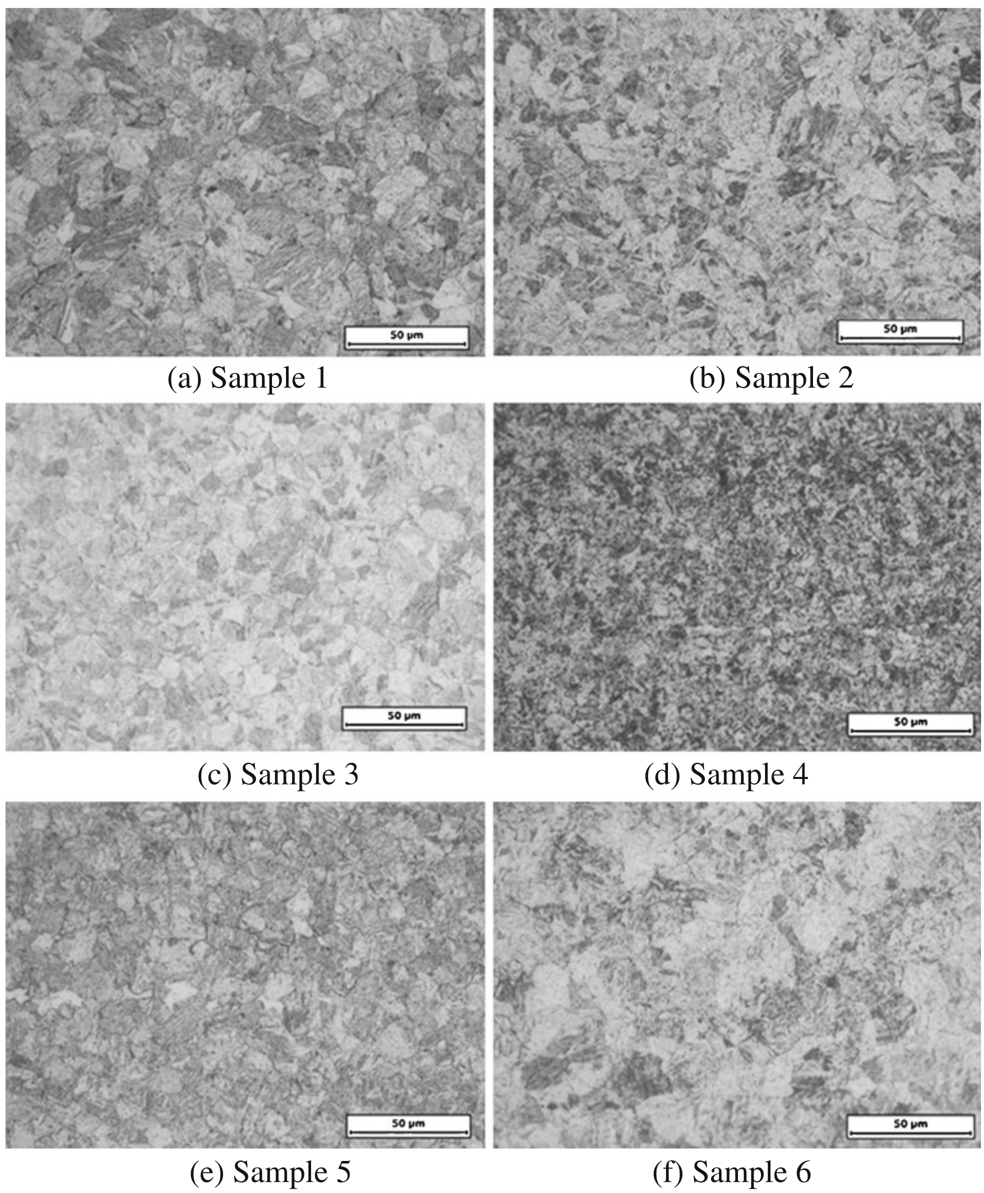


Fig. 3 OM microstructure of TIG joint HAZ without PWHT: **a** sample 1; **b** sample 2; **c** sample 3; **d** sample 4; **e** sample 5; **f** sample 6

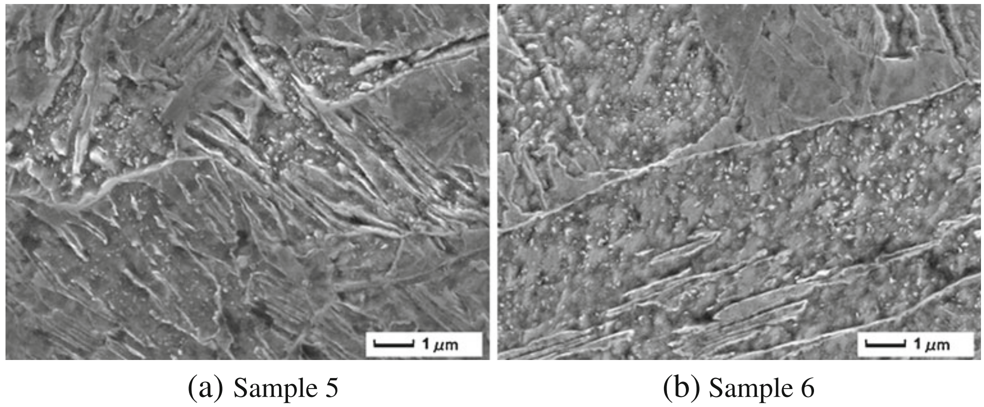


Fig. 4 SEM of TIG HAZ joint without PWHT: **a** sample 5; **b** sample 6

He et al. [15] use water as medium to study the propagation characteristics of ultrasound in liquid. As we know, ultrasound can be oscillated strongly on interfaces. The research demonstrates that stable acoustic field will be formed after the sound wave reflected repeatedly in liquid medium. During welding, ultrasonic energy propagates from the weld pool into the HAZ and base metal. As the arc-ultrasonic excitation voltage increase the alternating acoustic field forces strengthen. Under the stable acoustic field forces, the crystal boundary migration resistance at HAZ increases, which restrains the growing of austenite grain while heating and refine the grain [15]. Meanwhile, stress gradient makes the free energy of lattice distortion higher, which is beneficial to the nucleation of HAZ while cooling phase transformation.

2.3 Effects of arc-ultrasonic action on weld metal impact properties

Figure 5 shows the measured Charpy V-notch impact energies of the various samples.

According to the data, the Charpy V-notch impact energy varies significantly with the varying welding parameters. The result of impact experiment shows that impact property of weld metal is not in a linear relationship with the excited voltage.

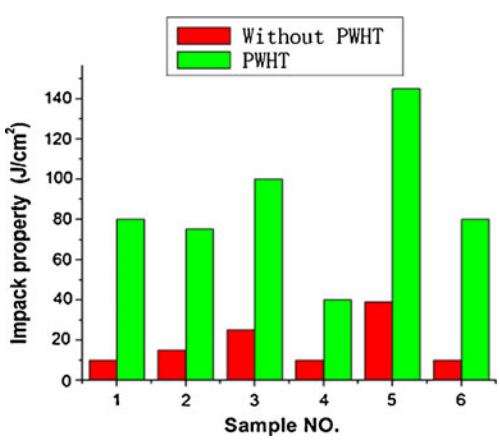


Fig. 5 Impact results

Under the same welding current, with the growing of excitation voltage, the impact property increases to a certain extent, then decreases. The impact property becomes best when the excitation voltage is about 40 V. Analysis suggests that the difference of impact properties under different processes results from the difference of heat input. In order to evaluate this perspective, two groups of supplemental experiments are conducted, experiment parameters are shown in Table 2. On that basis of sample 4, the impact property increases observably when the current is adjusted from 80 to 60 A; moreover, it is much better than that of TIG welding samples without ultrasound under the same current.

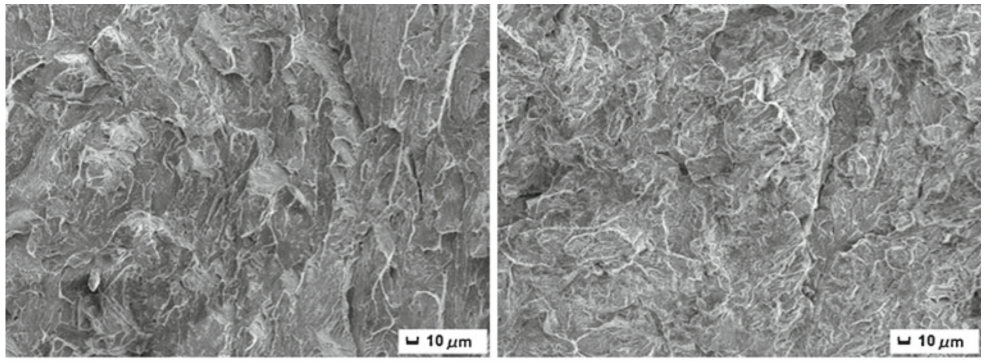
Figure 6 shows the fracture features of samples 5 and 6. Brittle behavior is observed in samples 5 and 6 without PWHT. Some evidence of plastic deformation as well as quasi-cleavage fracture features exist on both sample surfaces. Furthermore, sample 5 has a larger proportion of plastic deformation and therefore shows better plastic-like properties. Thus it is obvious that arc-ultrasonic excitation improves impact energy toughness.

In the former three groups, with the growing of excitation voltage, the impact property increases, the mass and heat transfer becomes stronger, and grain refining effect becomes more obvious. Welding parameters determine weld microstructure and microstructure determines. The mechanical properties of the material lie on its microstructure. The differences of in impact energy property can be explained from the microscopic perspective and related to yield strength. According to the Hall-Petch formula, the relation between grain size of the crystal and yield strength of the metallic material is as follows:

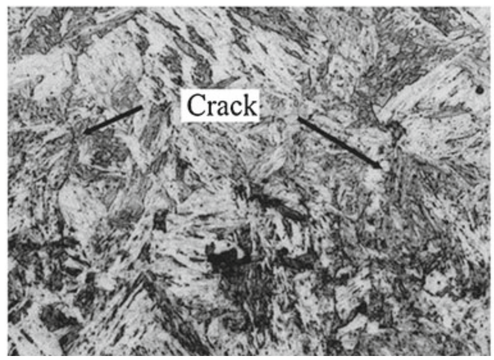
$$\sigma s = \sigma + K_y d^{-1/2} \tag{1}$$

where σ is a material constant associated with the friction stress for starting that the dislocation movements in the crystal, K_y is a material constant related to strengthening, and

Fig. 6 Microstructure and impact fractographs of weld fracture surfaces: **a** sample 5 without PWHT; **b** sample 6 without PWHT; **c** Fusion zone of sample 4 without PWHT



(a) Sample 5 without PWHT (b) Sample 6 without PWHT



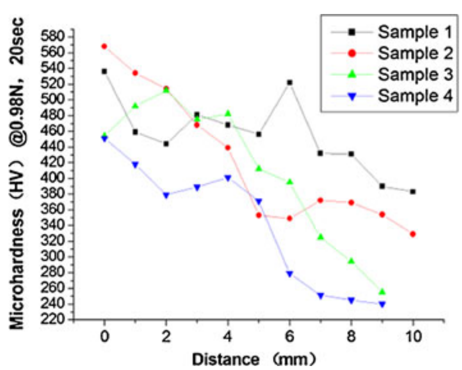
(c) Fusion zone of sample 4 without PWHT

d is the average grain diameter of the material. Both of them have nothing to do with the size of the crystal. Thus the finer the crystal is, the better is the impact property of the material.

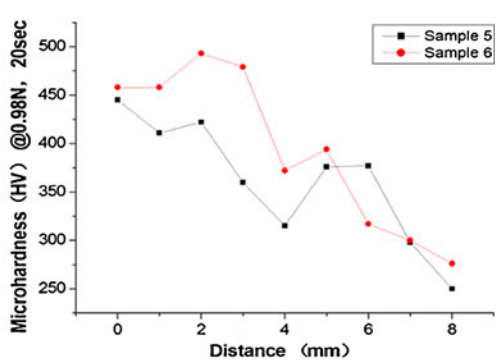
The ultrasonic excitation voltages of samples 1, 2, and 3 increase gradually from 20 to 40 V, and the pool stirring perturbation and heat transmission are gradually strengthened which promotes the formation of fine grains. Furthermore, the arc-ultrasonic action reduces the thermal gradients in the weld pool, which reduces the stress and increases the impact toughness of weld metal. However, beyond a certain combination of arc current and ultrasonic excitation, the impact energy does not increase with increasing excitation voltage as expected. When the excited voltage of sample 4 is 60 V at 80-A arc current, the impact energy decreases. Likely, the reason for this is that the higher excitation voltage puts too much extra heat into weld pool which leads to over-heating and higher temperatures in the weld pool, which in turn results during solidification and to stress concentrations or even hot cracking. Figure 6c is the enlarged metallographic partial structure of sample 4; some tiny cracks appear in the weld metal.

In order to reduce the welding heat input of sample 5, the ultrasonic excitation voltage and frequency remain 60 V and 50 kHz but the welding current was reduced to 60 A.

Fig. 7 Microhardness measurements across the weld joint. **a** Samples 1–4; **b** samples 5–6



(a) sample 1-4



(b) sample 5-6

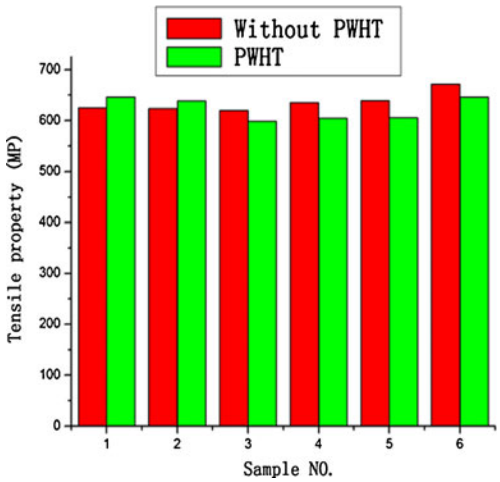


Fig. 8 The tensile property of welding joint

The reduction of welding input improves the impact properties of weld metal. After PWHT, impact property of sample 5 increases significantly compared to sample 4. Hence, the main reason why sample 4 also has a worse impact energy compared to sample 5 is that the heat input was too high which lead to overheating of the weld metal. Sample 6 is welded by standard TIG welding with a welding current at 60 A, its impact property after PWHT is 55% of that of sample 5. The proper arc-ultrasonic action can obviously and significantly improve the impact energy of the weld.

2.4 Effects of arc-ultrasonic action on weld metal hardness

Vickers micro-hardness measurements were performed on the cross-sections of the CLAM weld joints by using a Model HVS-1,000 digital micro-hardness tester.

Figure 7 presents the hardness scatter-plot of different samples of CLAM steel-welded joints. Figure 7 shows that the arc-ultrasonic action produces slightly higher hardness near the weld centerline and similar hardness in the HAZ and base metal compared to the weld made without arc-ultrasonic action. Likely, the grain refinement afforded by the arc-ultrasonic action reduced the microstructure stress of weld metal.

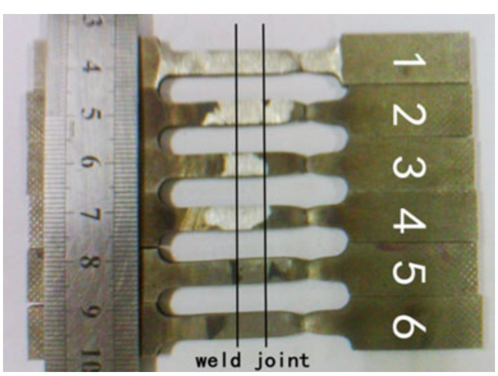


Fig. 9 The tensile specimen without PWHT

2.5 Effects of arc-ultrasonic action on weld metal tensile strength

The tensile strengths of all samples are shown in Fig. 8. All samples after tensile experiments fractured at base metal are shown in Fig. 9. Arc-ultrasonic energy mainly acts on weld area and fusion line region, the effect on base metal is very little because the distance to weld seam is relatively far. Tensile properties of weld joint change little and discretely distribute, which is clear in Fig. 8. Overall, the effect of arc-ultrasonic on tensile properties of CLAM steel weld joint is not obvious.

3 Conclusion

From this investigation following important conclusions are derived:

1. CLAM steel plates of 3 mm thickness are welded by arc-ultrasonic TIG welding with proper process in this paper, the impact property of weld joint increases by 80%; the increasing of excitation voltage results in the hardness decreasing of weld joint and uniform distribution of hardness; the introducing of ultrasonic makes relatively little effect on tensile property.
2. During the arc-ultrasonic TIG welding, under the frequency of 50 kHz, the refining effect of grain at weld zone and overheated zone increases with the growing of excitation voltage. Introducing of arc-ultrasonic has a positive influence on grain refining at weld zone and overheated zone.
3. Heat effect of arc-ultrasonic energy increases the heat input of weld joint, with the total heat input controlled, properly increasing excitation voltage and decreasing weld current are advisable ways to improve welding quality.

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