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ORIGINAL ARTICLE

Evaluation on microstructure and mechanical properties of high-strength low-alloy steel joints with oscillating arc narrow gap GMA welding

W. H. Xu · S. B. Lin · C. L. Fan · C. L. Yang

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Abstract Abstract with the purpose of improving weld joint quality and productivity, the oscillating arc narrow gap gas metal arc (GMA) welding was employed in welding quenched and tempered high-strength low-alloy thick steel. The microstructure and mechanical properties of weld joints were evaluated, namely micro-hardness, tensile strength, and low-temperature impact toughness. The test results indicated that mechanical properties of weld joints with oscillating arc narrow gap GMA welding were excellent and found to meet stipulated requirements. Oscillating arc narrow gap GMA welding is a promising process for welding quenched and tempered HSLA thick steels due to the low energy input and narrow square-butt groove.

Keywords Oscillating arc · Narrow gap GMA welding · HSLA steel · Mechanical properties

1 Introduction

Quenched and tempered high-strength low-alloy (HSLA) steel are widely applied in the fabrication of various structures, such as shipbuilding, pressure vessel, offshore construction as well as submarine, owing to high strength, excellent toughness, and high strength-to-weight ratio [1–6]. In welding quenched and tempered HSLA steel, it imposes various problems, such as hydrogen-induced cracking, softening, and hardening of heat-affected zone (HAZ) because the steel is sensitive to thermal cycle [7, 8]. The softening region of HAZ exhibits low hardness and therefore low strength [9], while hardening region presents high hardness but inferior toughness, so HAZ is a weak link in any mechanical testing. It is well known that the mechanical of quenched and tempered HSLA steel joint is determined by the microstructure of the joint, which is affected by weld thermal cycle associated with welding energy input [1]. The high energy input could result in coarse grain in HAZ, and grain size significantly influences the microstructure and properties of HAZ in welding quenched and tempered HSLA steel. In the welding of HSLA-100, for example, with an energy input of 10 kJ/cm, the coarse grain size was about 80 μm, while at a higher energy input of 40 kJ/cm, the grain size was 130 μm [10]. Furthermore, a high energy input condition could cause HZA softening as limited austenite grain growth produces a faintly increase in hardenability [11] and the width of softening zone increases as the energy input increases. From the above discussions, it is necessary to control energy input in the welding of quenched and tempered HSLA steel for ensuring the mechanical properties of the joint, especially in military applications.

As mentioned before, quenched and tempered HSLA steel is primarily employed in welding large-scale metal structure, in which the heavy plate and extra heavy plate are widely used. High energy input welding process such as submerged arc welding (SAW) is applied in welding such metal structure with the higher productivity and economics, because high energy input could increase deposition rate and reduce welding time [8]. Therefore, there is a contradiction between productivity and quality. The increased demands for improving quality and cost efficiency in welding quenched and tempered HSLA steel required a high-efficiency welding process with low energy input, while the narrow gap gas metal arc (GMA) welding technique has the advantages of high efficiency and quality comparing with traditional welding process in welding heavy plates [12]. The narrow gap groove can be filled with less filler metal consumption with low current associated with low energy input due to the area of groove

W. H. Xu · S. B. Lin (✉) · C. L. Fan · C. L. Yang
State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, People's Republic of China
e-mail: sblin@hit.edu.cn

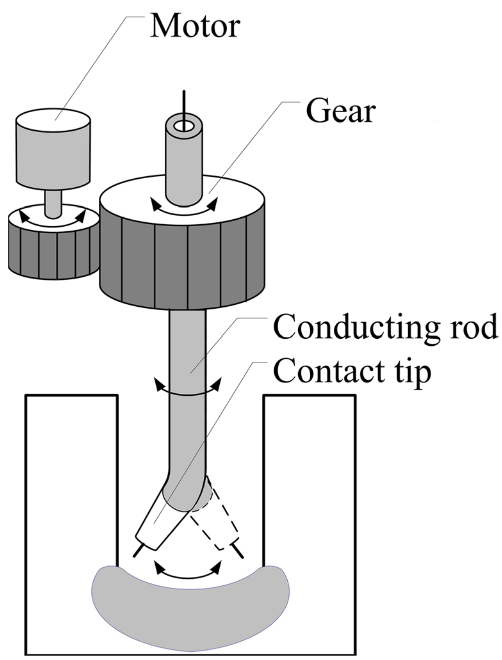


Fig. 1 Schematic diagram of narrow gap welding torch

cross section being diminished. In addition, the narrow gap groove can reduce weld volume and shorter welding time, which increases the productivity. It is clear from the above discussion that the narrow gap GMA welding could be a promising technique for welding quenched and tempered HSLA heavy steel.

In order to ensure the sufficient sidewall penetration, several methods were employed in narrow gap GMA welding, such as rotating arc [13, 14], oscillating or swing arc [15, 16], snake wire, and twin wires [16]. The oscillating arc narrow gap GMA welding was used in this experiment because of its suitability for position welding, low energy input, and convenience for controlling parameters. Hence, in this study, an investigation has been carried out to study the effect of oscillating arc narrow gap MAG process on microstructure and mechanical properties of vessel-grade quenched and tempered HSLA 10CrNi3MoV steel joints.

2 Experiment apparatus and process

The oscillating arc narrow gap GMA welding torch was developed to conduct this experiment. The schematic diagram

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

	C	Mn	Si	S	P	Mo	Ni	Cr	V
Base metal	0.10	0.13	0.18	0.001	0.011	0.22	2.68	0.97	0.07
Filler wire	0.02	1.31	0.32	0.002	0.011	0.24	2.50	0.13	-

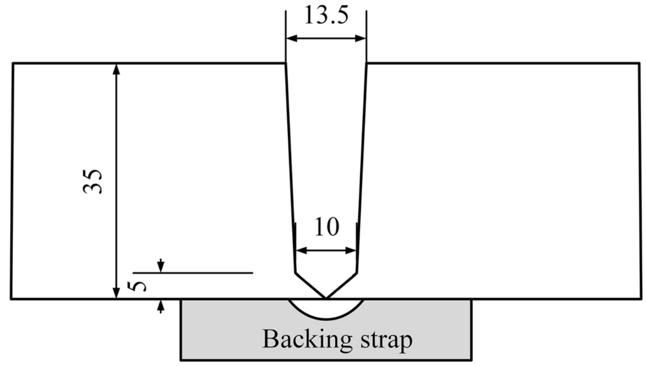


Fig. 2 Geometry of narrow gap groove

of the torch is shown in Fig. 1. The contact tip is screwed into the lower part of conducting rod which is bent to form an angle of 7°. The wire is fed through the inner hole of the conducting rod and stretches out from the contact tip so an angle of 7° is formed between the wire and the axis of the conducting rod. The arc and wire oscillate in the narrow gap groove as contact tip rotates forth and back with the conducting rod driven by a motor.

The base metal used in this experiment was quenched and tempered HSLA vessel-grade steel with a thickness of 35 mm, which are widely used in vessel industry and nuclear power plants. WM960S welding wire with a 1.2-mm diameter was used for depositing the weld beads. The chemical compositions of base metal and weld metal are shown in Table 1. In the present study, no heat treatment was taken for the base metal before welding, and the inter-pass temperature was controlled under 200 °C. Ar (92 %) + CO2 (8 %) mixture gas is selected as shielding gas, and the gas flow rate is 15 L min^{-1} during welding in this paper.

The geometry of the narrow gap groove prepared for multi-layer single-pass welding is shown in Fig. 2. The groove was designed as a square with a small groove angle for distortion compensation. The size of the groove gap is 13.5 mm wide at

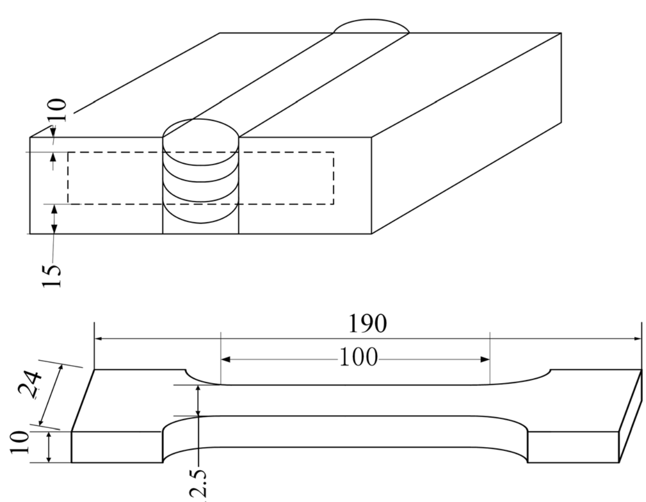


Fig. 3 Schematic diagram of transverse weld specimen for tensile testing

Table 2 welding parameters for narrow gap welding

Layer	Welding current (A)	Welding voltage (V)	Oscillating speed (rad/s)	Travel speed (mm/min)	Oscillating amplitude (°)	Dwell time (ms)
1	195	27		160		
2	195	27	1.4	160	40	300
3	195	27	1.4	160	37	300
4	195	27	1.4	160	37	300
5	195	27	1.4	160	37	300
6	227	28.5	1.4	160	43	300
7	227	28.5	1.4	160	43	300
8	227	28.5	1.4	160	43	300
9	227	28.5	1.4	160	43	300
10	227	28.5	1.4	160	48	300

the top and 10 mm at the bottom. In order to ensure the back formation, a ceramic backing strap was employed at the back of the groove.

Transverse sections were removed from the weld joints, and the microstructures of the welds and heat-affect zone were examined after conventional polishing and etching with 3 % nital solution, an OLYMPUS GX71 optical microscope is employed for the purpose.

Mechanical properties of the joints were examined after radiographic non-destructive testing. A hardness tester was employed to test the vikers micro-hardness of weld metal, heat-affected zone, and parent metal at a constant load of 1 kg. Charpy V notch impact test was carried out to evaluate the toughness of welded joints at −50 °C. According to GB2651-2008, tensile testing was used to evaluate the tensile strength and ductility of the joints. Figure 3 shows the schematic diagram of the transverse sample for tensile testing.

3 Results and discussion

3.1 Welding process

In oscillating arc narrow gap GMA welding, oscillating parameters such as dwell time and oscillating amplitude significantly influence the weld profile besides welding current, voltage, and travel speed. The criterion for selecting dwell time and oscillating amplitude was to ensure sufficient sidewall penetration but defect of undercut free. The optimal welding current, voltage, and travel speed were selected to avoid defect of interlayer and sidewall incomplete with remaining low energy input. The optimal welding parameter is listed in Table 2. The root welding was conducted without arc oscillating due to the narrow size of the groove bottom. Figure 4 shows the desired weld bead profile with the optimal welding parameters. After welding, the desired weld beads were examined by the X-ray test and the results showed that there was no defect in the weld beads.

3.2 Metallography

Optical micrographs of base metal, weld metal, and heat-affected zone are shown in Figs. 5 and 6. It can be seen from Fig. 5a, b that each layer of the bead is slightly concave shape and well formed with 9–11 mm in width and 3–4 mm in height, and the 1–2-mm sidewall penetration indicated completely sidewall fusion. The heat-affected zone in the narrow gap GMA welding is about 2 mm in width, which is smaller than in the conventional GMA welding due to the low energy input. The micrograph of base metal exhibits cementite

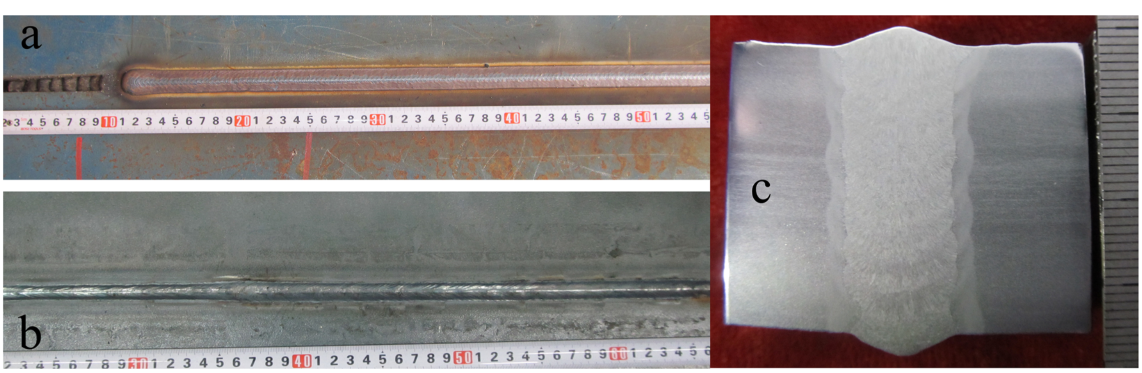


Fig. 4 Weld bead profile with optimal welding parameters (**a** weld bead surface, **b** back formation, **c** cross section)

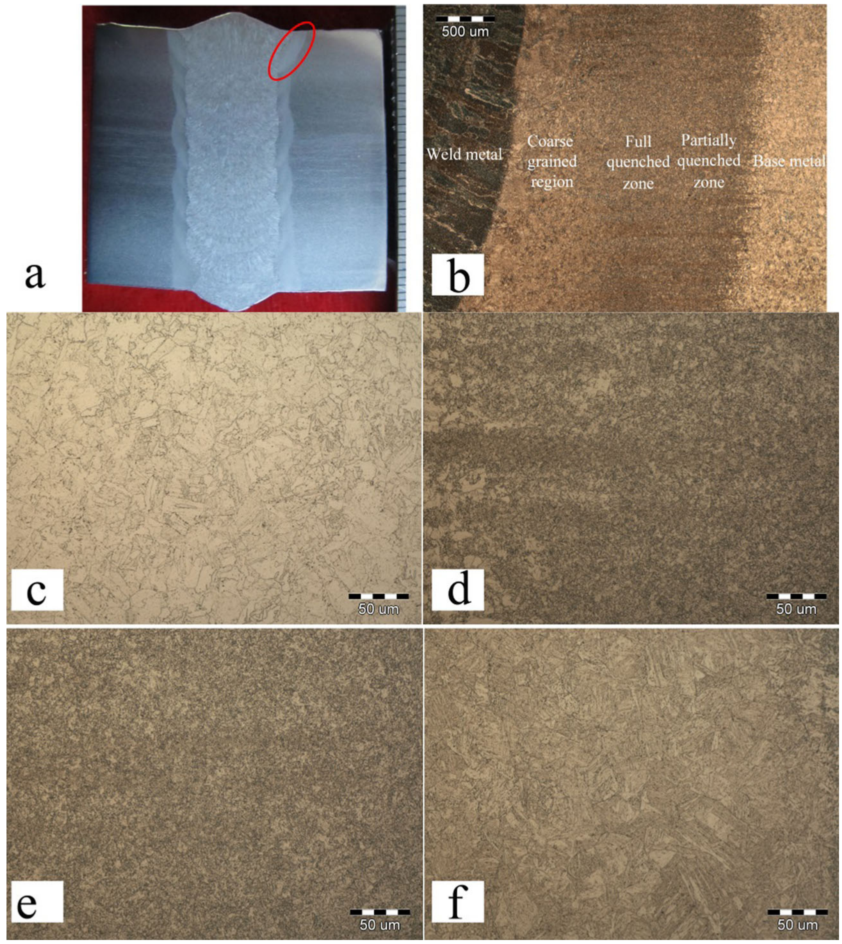


Fig. 5 Optical micrographs of base metal and HZA

particles (dark etched) in lath ferrite matrix (light etched), which means that the microstructure of the base metal is tempered sorbide, as shown in Fig. 5c. Careful observation of micrograph indicated that the HAZ contains three different zones, namely partially quenched zone, fully quenched zone, and grain-coarsened region very close to fusion boundary, as shown in Fig. 5b. Figure 5d shows the microstructure of partially quenched zone, and it is composed of acicular martensite and a little ferrite. The reduction in the size of ferrite phases can be seen in the partially refined quenched zone. The microstructure of quenched zone is fine martensite and limited number of granular bainite, as shown in Fig. 5e. Grain-coarsened zone (Fig. 5f) showed significant coarsening of phases which are lath martensite and bainite, while the width of this zone is very narrow, due to the oscillating arc narrow gap GMA welding with low energy input which can reduce the high-temperature residence time in the HAZ coarse-grained region and decrease the tendency of grains' growth. The reduction in the grain size of coarse martensitic structure is beneficial for the toughness of the weld joint. Figure 6a shows the microstructure of weld metal in surface layer; the figure indicates it is composed of a number of granular bainite and a small amount of lath ferrite. Comparing with surface layer weld metal, the filling metal contains fine grain (as

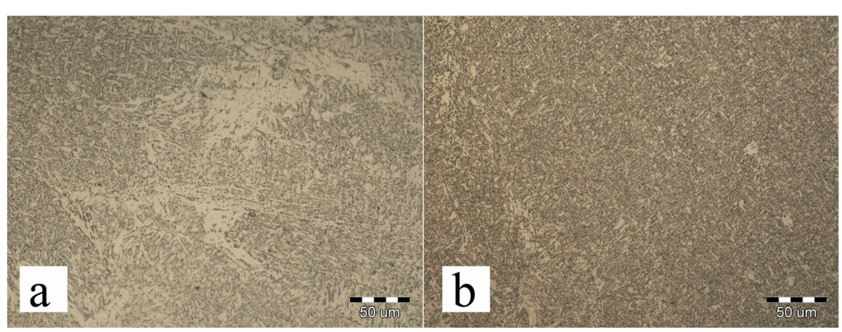


Fig. 6 Optical micrographs of weld metal in surface layer and filling layer

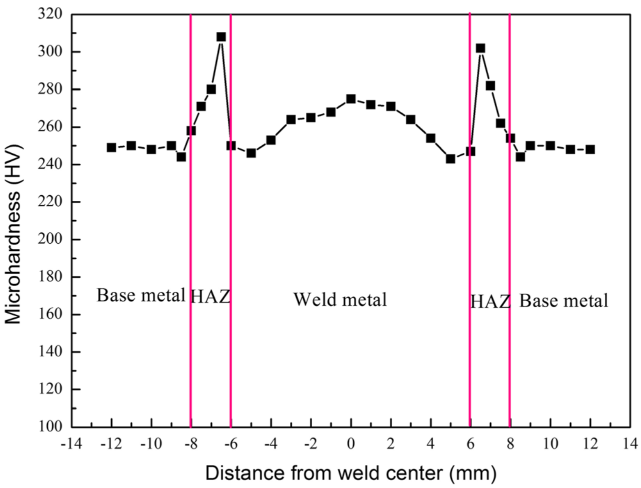


Fig. 7 The hardness characteristic of the narrow gap welding joint

Table 3 Welding parameters for non-oscillating GMA welding with V-type groove

Layer	Pass	Welding current (A)	Welding voltage (V)	Travel speed (mm/min)
1	1	195	27	160
2	2	195	27	160
3	3–4	195	27	160
4	5–6	227	28.5	160
5	7–9	227	28.5	160
6	10–12	227	28.5	160
7	13–16	227	28.5	160

shown in Fig. 6b), due to the heat effect of subsequent layer on prior layer in filling welding.

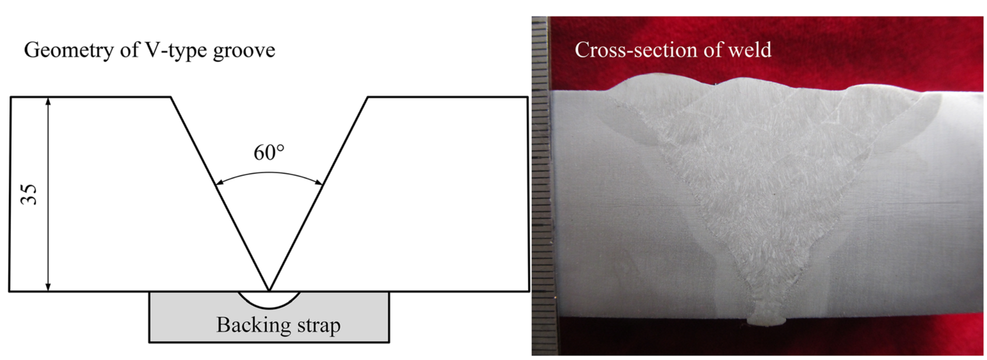
3.3 Mechanical properties

The variation in micro-hardness of narrow gap GMA welding joint related to the distance from the weld bead center is shown in Fig. 7. It is obvious that the average hardness of filling layer weld metal is 248 HV, the hardness in the weld center line is the highest, and a slight reduction in the hardness was noticed near the fusion boundary. It may be attributed to the fact the content of carbon and other alloying agents in weld bead center is higher than at the two sides due to the sequence of solidification. The hardness in HZA, in general, is higher than in weld metal and base metal, and the average hardness is about 277 HV. A hardening region with a peak hardness of 302 HV was found in the HAZ, and then the hardness decreases significantly from the peak hardness as the distance away from weld bead center line increases. It is obvious from the figure that the hardening region is related to the coarse-grained region which is composed with lath martensite and bainite, but the region is very narrow comparing with the high energy input welding process. Softening zone is apt to present in quenched and tempered HSLA steel joint using high energy input welding process, while it is not found in the oscillating arc narrow gap GMA welding joint with the optimal welding parameters.

In order to compare hardness of oscillating arc narrow gap GMA welding joint with traditional GMA welding joint, non-oscillating GMA welding was conducted on V-type groove with the welding parameters listed in Table 3. The geometry of V-type groove and cross section of weld is shown in Fig. 8.

The variation in micro-hardness of non-oscillating welding joint related to the distance from the weld bead center is shown in Fig. 9. It can be seen from the figure that the peak hardness is 322 HV, which is higher than the peak hardness in oscillating arc narrow gap welding, and the hardening region about 4 mm is wider than that in the narrow gap welding. The softening zone with the average hardness of 230 HV was found in non-oscillating welding joint with V-type groove, while it did not present in oscillating arc narrow gap welding joint. The above results illustrate that the oscillating arc narrow gap GMA welding can improve the HAZ softening and hardening problem. It is attributed to the fact that the low energy input in oscillating arc narrow gap welding reduces the high temperature-resistant time of HZA in oscillating arc narrow gap welding. With the increase in energy input, the grain-coarsened region which is composed of lath martensite

Fig. 8 Geometry of V-type groove and cross section of weld



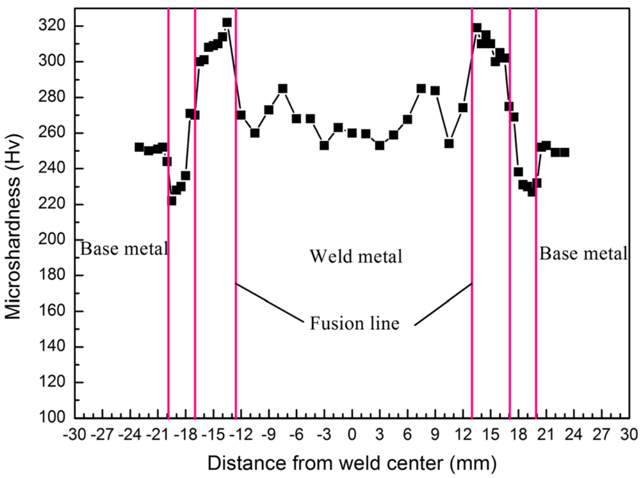


Fig. 9 The hardness characteristic of non-oscillating welding joint with V-type groove

and bainite increases due to the increase in the high temperature resistant-time of HZA, so the hardening region in oscillating arc narrow gap welding joint with low energy input is narrower than that in non-oscillating welding joint. As mentioned before, the softening zone presents non-oscillating welding due to the fact that the high energy input causes limited austenite grain growth.

The reduction in the energy input of arc oscillating narrow gap welding is explained below. The scheme of the wire moving trajectory is shown in Fig. 10. In an oscillating circle, the wire moving trajectory can be divided into four parts, namely AB, BC, CD, and DE. When the wire dwells at the side of groove, the wire moving trajectory is AB or CD. The wire moving velocity $V_{(AB)}$ and $V_{(CD)}$ in the two parts are equal to the welding velocity V_W. When wire oscillates between the sides of the groove, the wire moving trajectory is BC or DE, and it is a curve. In part BC and DE, the wire was driven for circular arc motion with an angular velocity of w and radius of r in the x–y coordinate plane and linear motion in the x direction with the velocity of V_W. The instantaneous velocity of the wire can be resolved into x and y directions, Vx and Vy, respectively. The instantaneous velocity V_{BC} or V_{DE}, Vx and Vy can be calculated as Eq. (1).

Table 4 Results of low temperature (−50 °C) impact test for oscillating arc narrow gap welding

Specimen	Impact toughness (−50 °C, J/cm^2)			Average (J/cm^2)	Notch position
A −1, −2, −3	261	271	265	266	Base metal
A −4, −5, −6	122	122	119	121	Weld bead
A −7, −8, −9	202	202	198	201	Fusion line
A −10, −11, −12	226	261	258	248	HAZ

$$V_{BC} = V_{DE} = \left\{ \begin{array}{l} V_x = wr\sin\left(\frac{\alpha}{2} - \frac{wt * 180}{\pi}\right) + V_W \\ V_y = wr\cos\left(\frac{\alpha}{2} - \frac{wt * 180}{\pi}\right) \end{array} \right\} = \sqrt{{V_x}^2 + {V_y}^2} = \sqrt{{V_W}^2 + (wr)^2 + 2wrV_W\sin\left(\frac{\alpha}{2} - \frac{wt * 180}{\pi}\right)} \quad , \quad t \in \left[0, \frac{\alpha}{w}\right] \tag{1}$$

In Eq. (1), α is the oscillating amplitude, and t means the oscillating time.

The average wire moving velocity in an oscillating circle can be calculated by the following equation.

$$V_a = \frac{S}{T} = \frac{V_W t_d + \int_0^{\frac{\alpha}{w}} V_{BC} dt}{\left(t_d + \frac{\alpha}{w}\right)} \tag{2}$$

Where S means the length of the wire moving distance in an oscillating circle, and T is the oscillating circle, and t_d means the dwell time.

The energy input E [17]:

$$E = UI/V \tag{3}$$

Where U, I, and V are welding voltage, welding current, and moving velocity of heat source, respectively. Therefore, the energy input in part AB and CD is

$$E_{AB} = E_{CD} = \frac{UI}{V_W} \tag{4}$$

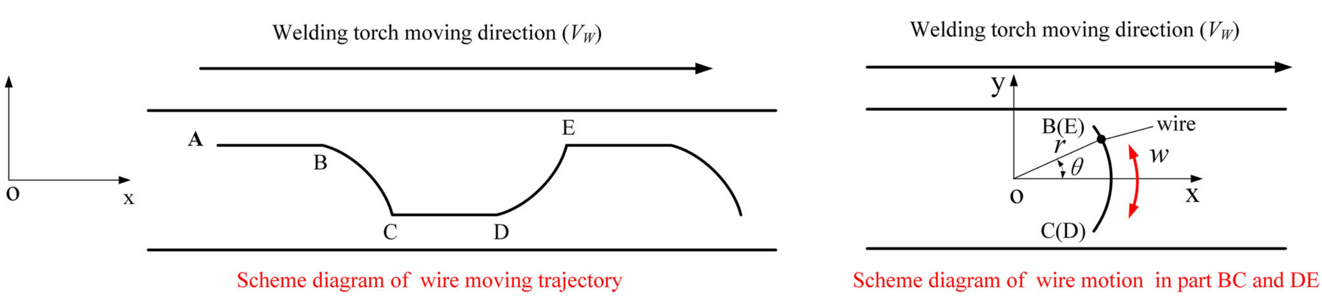


Fig. 10 Scheme diagram of wire motion

Table 5 Results of low temperature (−50 °C) impact test for non-oscillating welding

Specimen	Impact toughness (−50 °C, J/cm^2)			Average (J/cm^2)	Notch position
B −1, −2, −3	125	124	119	123	Weld bead
B −4, −5, −6	171	181	162	171	Fusion line
B −7, −8, −9	211	220	222	217	HAZ

while the energy input in part BC and DE is

$$E_{BC} = E_{DE} = UI/V_{BC} = UI\Big/\sqrt{V_W{}^2 + (wr)^2 + 2wrV_W \sin\left(\frac{\alpha}{2} - \frac{wt * 180}{\pi}\right)} \tag{5}$$

The average energy input in an oscillating circle E_a *is*

$$E_a = \frac{UI}{V_a} \tag{6}$$

The energy input of non-oscillating welding with V-type groove E_n is

$$E_n = \frac{UI}{V_W} \tag{7}$$

Take the welding parameter of layer 6 as example—U=28.5, I=227, V_W=2.67, w=1.4, r=8, $-21.5 \le \frac{\alpha}{2} - \frac{wt*180}{\pi} \le 21.5$. Then,

$$520\,\mathrm{J/mm} \le E_{BC} \le 616\,\mathrm{J/mm} \tag{8}$$

$$E_a = 734\,\mathrm{J/mm} \tag{9}$$

$$E_n = E_{AB} = 2423\,\mathrm{J/mm} \tag{10}$$

The above results illustrate that the effective energy input in oscillating arc narrow gap welding is reduced as compared to non-oscillating welding with V-type groove.

Table 6 Results of tensile strength test for oscillating arc narrow gap welding

Specimen	Tensile strength (MPa)	Maximum tension (N)	Fracture position
1	720	90,214.797	Base metal
2	720	90,146.102	Base metal
3	730	91,138.203	Base metal
4	715	89,364.898	Base metal
Average	721	90,215.000	

Charpy V notch impact test was conducted to examine the low temperature (−50 °C) impact toughness of weld metal, fusion zone, heat-affected zone, and base metal. Table 4 shows the results. The average toughness of weld metal, fusion zone, HAZ, and base metal was 121, 201, 248, and 266 J/cm^2, respectively. The base metal possesses the highest low temperature impact toughness in all the weld joints due to the excellent ductility of the HSLA steel, while the lowest toughness was found in weld metal. The hardness test results show that there is a small hardening region in HAZ which may damage the toughness of the joint. However, the impact test results show that the toughness of HAZ simply declines by 5.6 % comparing with base metal. Table 5 shows the impact toughness of non-oscillating welding joint with V-type groove. The impact toughness of fusion line and HAZ in non-oscillating welding is lower than that in oscillating arc narrow gap welding. It means that the oscillating arc narrow gap GMA welding process can improve the ductility of joint.

The transverse tensile properties of the narrow gap welding joint, such as tensile strength as well as fracture position are evaluated in this paper. Four test samples were prepared in each joint, and the results are listed in Table 6. The average tensile strength of the weld joints is 721 Mpa. During tensile test, all the specimens (joints) were found to fracture in the base metal as shown in Fig. 11. The results indicate that the tensile strength of the weld joint is roughly equal to the base metal, and there is no softening region in the oscillating arc narrow gap GMA welding joint.

Fig. 11 Fracture position of tensile test specimen

4 Inclusions

This study is to evaluate the feasibility in welding quenched and tempered HSLA thick steel using oscillating arc narrow gap GMA welding and the microstructure and mechanical properties of the weld joint. The following conclusions are from the present research.

1. The narrow gap oscillating GMA welding is a promising process for welding quenched and tempered HSLA thick steels. This welding process can improve the weld quality of quenched and tempered HSLA thick steels due to the low energy input and raise the productivity because of the narrow square-butt groove in narrow gap welding.
2. Microstructure study of all joints revealed that the side-wall penetration was about 1–2 mm deep, and the HAZ was about 2 mm in width. HAZ exhibited three regions, namely partially quenched zone with acicular martensite and a little ferrite, full-quenched zone with fine martensite and grain-coarsened region very close to fusion boundary.
3. The peak hardness was found in the grain-coarsened region of HZA, and then the hardness decreases significantly from the peak hardness as the distance away from weld bead center line increases. The softening zone is not noticed in the oscillating arc narrow gap GMA welding joint with the optimal welding parameters.
4. The low temperature (−50 °C) impact toughness of the HAZ was about 248 J/cm^2, and it found to be superior to that of the weld metal. The results of Charpy V notch impact test show that the oscillating arc narrow gap GMA welding process can improve the ductility of joint.
5. The average tensile strength of weld joints was 721 MPa, and the joints were found to fracture in the base metal. This means that the tensile strength of the weld joint is roughly equal to the base metal. The properties of the weld joint obtained by the narrow gap welding were found to meet stipulated requirements.

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