Effect of longitudinal magnetic field on grain growth of hollow stud welded joint

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Research Article

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Abstract

Aiming at the defects of large diameter hollow stud welding such as arc blow and incomplete fusion, drawn arc stud welding with the longitudinal magnetic field was used to 30CrNi3MoV steel and Q235 stud. The grain growth process of joint was studied. With the assistance of longitudinal magnetic field, the arc action area on the end face of the hollow stud was increased, and the end face of stud was melted evenly. The solidification and crystallization process of molten pool was changed due to magnetic field stirring. Within a certain range, the microstructure of the joint is gradually refined and the size is homogeneous with the increase of magnetic field. But too large current can be attributed to the very coarse grain structure. Besides, the proportion of small angle grain boundary was decreased during appropriate magnetic field current, while the proportion of large angle grain boundary was increased. Meanwhile, preferred orientation of grains of the joints was changed due to the magnetic stirring.

Introduction

As a lightweight and excellent material, high-strength steel is widely used in armored vehicle manufacturing and other fields [1,2]. The 30CrNi3MoV steel is composed of martensite and bainite, which has attracted much attention because of its excellent mechanical strength, high hardness, high temperature resistance and formability [3-6]. Drawn arc stud welding as an efficient and energy-saving welding method, was widely used in shipbuilding, armored vehicle manufacturing, construction and other fields [7]. Since hollow stud has a large burning area and striking arc junction can not be set, the arc igniting position of end face is random. In addition, the carbon equivalent of 30CrNi3MoV steel is over 0.60 which has high hardenability tendency. Therefore, welding defects such as arc deflection, non-melting, crack are easy to occur for large diameter hollow studs.

Magnetic field was introduced into welding process by many researchers, because it can make the arc rotated and the grain refined by electromagnetic stirring. Wu [8] found that the arc would not rotate under the external alternating pointed magnetic field, but with the change of excitation current and frequency, meanwhile the shape and microstructure of the weld were changed. Abralov [9] found that the process of electromagnetic stirring was affected on grain refinement and improving of mechanical properties by external magnetic field during the welding. Chen [10] found that Lorentz force and thermoelectric force in the molten pool had a great influence on the weld microstructure. The diffusion of aluminum atoms could be inhibited, the reaction area between steel and aluminum and the microhardness was reduced and tensile strength was significantly increased by the magnetic field. Khartz-Behrend [11] found that the square mean of the arc motion average velocity in the drawn arc stud welding increased approximately linearly with the coil current. Although magnetic field is widely used in welding field, there are few reports on the effect of magnetic field on grain size change and grain orientation in hollow stud welding.

From our previous studies, the arc rotated along the end face of the hollow stud and the action area was broaden by the action of Lorentz force under longitudinal magnetic field [12]. Therefore, aiming to study the growth trend of weld structure and the change of grain orientation, longitudinal magnetic field is
introduced into the welding process of Q235 hollow stud and 22SiMn2TiB steel. The effect of magnetic field on the mechanical properties of welded joints will be reported in the follow-up research.

**Experimental Methods**

30CrNi3MoV steel was used as the substrate, the hollow stud was made of Q235 with length of 30mm, outer diameter of 16mm and inner diameter of M8. The chemical composition of 22SiMn2TiB steel is listed in Table 1.

Table 1. the chemical composition of 30CrNi3MoV steel wt%

| chemical element | C        | Si      | Mn      | Ni      | Mo      | Ti  | V      | Cr |
|-----------------|----------|---------|---------|---------|---------|-----|--------|----|
| content         | 0.26-0.32| 0.15-0.35| 0.3-0.5| 2.8-3.2| 1-1.5   | trace | 0.06-0.13| 0.6|

Sawyer BMH-22SV3000A drawn-arc stud welding machine is used, the self-developed welding torch is mounted on the Yakawa robot Motoman-ES165N, the welding machine and welding torch were connected by robot to realize automatic welding. The magnetic field generating device is made of enameled wire of IEC-P180. The welding process is shown in Fig 1. The robot movement and the welding power supply on and off were controlled by the control cabinet. The welding torch was moving above the stud which is grabbed to lift and start arc by the air claw. The magnetic field intensity is changed by adjusting the constant current source.

The microstructures of welded joints were studied by Zeiss metallograph microscope and field emission environment scanning electron microscope (FEI-QUANTA 250F). The grain size and orientation of the joint were analyzed by FIB/SEM double-beam system (Zeissauriga).

**Results And Discussion**

3.1 Effect of external magnetic field on microstructures of the joints

Fig. 2 shows the microstructures of stud welding joints under different magnetic field currents. Welding current of 800A and time of 1300ms were employed. The cooling rate of molten pool was fast due to the difference of chemical composition between the two materials and the element diffusion was not uniform, which was easy to cause segregation. Therefore, large proeutectoid ferrite precipitated along the austenite grain boundary without magnetic field (Fig. 2(a)), which spread along the grain boundary in elongated or polygon shape. Supersaturated carbides diffused into austenite and precipitated carbides between or inside the ferrite bars during the growth of ferrite nucleus. Therefore, bainite appeared on both sides of eutectoid ferrite firstly [13]. From previous studies, an appropriate amount of Ti elements could form a large number of diffused nonmetallic inclusions in the weld metal. Nucleation and growth of elongated acicular ferrite could be induced by these inclusions during the $\gamma \rightarrow \alpha$ phase transition, which
could improve the mechanical properties of weld metal [14]. The strength and low temperature toughness of the weld and heat affected zone could be improved due to the existence of acicular ferrite in high strength and low alloy steel [15]. With a little martensite between acicular ferrite, the hardness of the weld is high but the plasticity and toughness is poor, cracks are easy to initiate in this part. According to the theory of Bhadeshia [16, 17], proeutectoid ferrite grew forward in a plane manner after nucleation at the original austenite grain boundary, and its growth rate was determined by the diffusion rate of carbon in the austenite at the front of grain boundary. The dendrites in the molten pool are affected by multiple forces and the resultant of forces can be expressed as:

\[
\sigma_{\text{max}} = \frac{1}{D_r} 48 A^2 f n B \sqrt{1 + \frac{\rho f B}{\eta}} + 16 A^2 f^2 D_r \rho B \sqrt{1 + \frac{\rho f^2 B}{\eta^2}} \geq [\delta] \tag{3.1}
\]

In the formula, [\delta] is the critical shear allowable stress of dendrite, f is the vibration frequency, B is the amplitude, A is dendrite length-diameter ratio, D_r is dendrite radius, \eta is melt viscosity, \rho is dendrite density. It shows that with the increase of magnetic field current, the frequency and amplitude of molten pool movement and the resultant of the forces on dendrite will increase. When the stress was greater than the shear allowable stress, the dendrite would fracture and form equiaxed grains, which inhibited the growth of columnar grains. With the increase of the magnetic field current, the heat loss and cooling rate of the molten pool would be further accelerated by the enhancement of the electromagnetic stirring. Because carbon has no time to diffuse outside the austenite grain boundary, the growth of proeutectoid ferrite was inhibited and the proportion of acicular ferrite gradually increased, as shown in Figs. 2 (b)-(c). The proeutectoid ferrite became longer and narrower than that with no magnetic field and the number of it decreased gradually, as the acicular ferrite in grain boundary would increase gradually. The electromagnetic damping phenomenon would occur when the magnetic field current was further increased [18]. The molten pool convection would be inhibited as the electromagnetic damping played a dominant role in the magnetic field [19, 20]. At the same time, heat conduction was inhibited, which reduced the undercooling degree of molten pool metal and increased the growth tendency of proeutectoid ferrite and grain coarsening, as shown in Fig. 2 (d). Meanwhile, nucleation rate of acicular ferrite would be reduced due to the loss of Ti.

3.2 SEM photographs of stud welded joint

The proportion of proeutectoid ferrite was relatively high without magnetic field (Fig. 3 (a)), acicular ferrite and a small amount of martensite appeared in some intracrystalline areas and a large amount of bainite precipitated along the austenitic grain boundary. At 0.25A (Fig. 3 (b)), the proportion of proeutectoid ferrite and corresponding amount of bainite decreased as the acicular ferrite increased obviously. Increasing magnetic field current to 0.45A (Fig. 3 (c)), the proportion of proeutectoid ferrite and bainite decreased accompanying the acicular ferrite appeared in most of intracrystalline region. Further
increasing magnetic field current to 0.55A (Fig. 3 (d)), the proportion of proeutectoid ferrite and the amount of bainite increased while the acicular ferrite decreased. The results prove that the proeutectoid ferrite showed a trend of refining firstly and then coarsening, while acicular ferrite increased first and then decreased with the increase of magnetic field current. Meanwhile, there were many gas pores with no magnetic field current while there were only individual pore defects when increased to 0.45A. As the current further increased to 0.55A, the number of pores increased again due to the electromagnetic damping effect and poor flowability of the molten pool. The number of pore defects decreased firstly and then increased with the increase of the magnetic field current.

3.3 Effect of longitudinal magnetic field on grain growth

There was slender acicular ferrite in austenite grains and some black martensite phase without magnetic field due to the metal oxides of Ti elements formed in the weld (Fig. 4 (a)). The grain orientation was $<001>$, $<101>$, $<111>$. At magnetic field current of 0.45A, as shown in Fig. 4 (b), the grain was refined and the generation of oxides of Ti and B element were accelerated by the stirring effect compared with no magnetic field, thus the nucleation rate of acicular ferrite was improved. At this time, the amount of acicular ferrite increased. The temperature gradient of the molten pool was changed and the Martensitic transformation point was reduced due to the magnetic stirring. As a result, the number of martensite decreased because its transformation time was shortened. The grain orientation would not be changed by the magnetic field in general. The average grain size of the joint with no magnetic field was 4.3031 $\mu$m, while at 0.45A was 3.138 $\mu$m. The frequency distribution of grain size at 0A and 0.45A are shown in Fig. 4 (c) and Fig.4 (d). The grain size of the studwelded joint after electromagnetic stirring is obviously refined. For example, when the grain size ranges from 1 to 2 $\mu$m, it can be seen from the figure that the frequency of applying a 0.45A magnetic field (Fig. d) is 0.14 higher than the frequency of no magnetic field (Fig.c). when the grain size ranges from 2 to 3 $\mu$m, it can be seen that the frequency of applying a 0.45A magnetic field (Fig.d) is 0.025 higher than that of no magnetic field (Fig.c). In general, the grain size of the part without magnetic field is greater than 20 $\mu$m, while the grain size of 0.45A magnetic field is almost below 10 $\mu$m.

There were acicular ferrite and martensite in the austenite crystal, as shown in Fig. 5(a), the adjacent acicular ferrite grain boundary was blue large-angle grain boundary, and the martensite is mainly green and red. In contrast, after applying magnetic field current of 0.45A, the number of blue large-angle grain boundaries were obviously more than that with no magnetic field, and the number of red and green small-angle grain boundaries with no magnetic field was more than that with magnetic field, as shown in Fig. 5(b). According to Fig. 5 (c), the grain boundary orientation angle was mainly distributed in 0 °~ 20 ° and 45 °~ 65 °, in which the proportion of small angle grain boundary ($<15^\circ$) with magnetic field and no one was 75.73% and 65.8% respectively, and this difference was mainly caused by microstructure. According to 3.2, the joint with no magnetic field was composed of martensite, bainite and proeutectoid ferrite. The content of bainite, martensite and proeutectoid ferrite decreased after magnetic field stirring and a large amount of acicular ferrite appeared at the same time. The higher the content of martensite and proeutectoid ferrite, the more the percentage of small angle grain boundary, while the acicular ferrite in
the grain was distributed at large angle grain boundary. As a result, the proportion of large angle grain boundary at 0.45A was larger than that with no magnetic field. The crack propagation direction could be effectively changed, the propagation path could be extended, and the energy needed for crack propagation was increased due to the existence of large angle grain boundary, namely the impact absorption work increased. Meanwhile, the crack propagation could not be hindered obviously by the small angle grain boundary. This explains that the impact toughness of the welded joint increased with the increase of magnetic field current in a certain range. However, the large proeutectoid ferrite would appear and the proportion of small angle grain boundary would be increased with the further increase of magnetic field current, so the impact toughness would be reduced.

Fig. 6 is microtexture change of weld zone. From Fig. 6 (a), there were three hot spots on the {100} plane and the grains presented a growth trend along <100> direction. The strength of its extreme point was 9.33. For the magnetic field current of 0.45A (Fig. 6 (b)), there were still three hot spots on the {100} plane and one on the {110} plane, but the strength of the extreme point was low and the highest was 4.5. A threshold value of 2° for grain orientation spread (GOS) were chosen to identify the grains[21]. Compared with Figs. 6 (c)-(d), the orientation of the texture of the joint stirred by magnetic field was more dispersed. The results show that the texture strength of the joint decreased and the texture orientation became more random after the stirring.

**Conclusion**

(1) The solidification process of molten pool was accelerated and accompanied by electromagnetic stirring caused by magnetic field current, the growth of proeutectoid ferrite was gradually inhibited. Because Ti fully contact with O element to produce nonmetal inclusions, the nucleation rate of acicular ferrite increased, namely the proportion of acicular ferrite increased gradually. The metal flow of molten pool was impaired as the magnetic field current was too large. The growth trend of eutectoid ferrite increased again when the undercooling decreased, the nucleation rate of acicular ferrite was reduced due to the increase of Ti loss. The gas pore defects decreased firstly and then increased with the increase of magnetic field current.

(2) The average grain size was 4.3031μm with no magnetic field and 3.138μm with magnetic field. The proportion of large-angle grain boundaries was changed from 24.27% to 34.2%, which was mainly due to the change of microstructure. Acicular ferrite was arranged at large-angle grain boundaries (>15°). The crack propagation direction could be effectively changed, the propagation path could be extended, the energy needed for crack propagation and the impact toughness were increased due to the existence of large angle grain boundary.

(3) The texture aggregation strength of the weld was changed with the magnetic stirring of magnetic field which was decreased from 9.23 to 4.5. The joint texture strength was decreased and orientation was more random with the stirring.
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