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Study on microstructure and properties of friction stir welding in mild steel

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Abstract: The microstructure and properties in friction stir welds of Q235 steel are studied. The weld surface is well formed, without grooves, pits and other defects. The microstructure of joint is made up of the stir zone, the heat-affected zone, the thermo-mechanically affected zone and basic material zone. The microstructures of the stir zone are fine grain pearlite and ferrite, which with good mechanical properties. However, the average grain size in the whole region of the heat-affected zone is larger than that of basic material zone, and also the macroscopic mechanical property is reduced,which is the weakness area of the joint performance. The basic material zone is composed of a long strip of pearlite and a fine ferrite which is evenly distributed on the matrix. Tensile fracture surface is located near the heat-affected zone. Fracture mode is mainly brittle fracture, local toughness fracture exists, and the tensile strength of joint can reach about 68% of basic metal; the microhardness of the joint is unevenly distributed in all regions, and the overall distribution is approximately "W" shape.

1. Introduction

In recent years, a novel solid-state joining process called friction stir welding (FSW) has been developed [1]. It has the advantages of low distortion, excellent mechanical properties, high performance and energy, cost saving of machines and structures and little waste or pollution [2]. At present, it has been successfully applied to the joining of lightweight materials like aluminum alloys and magnesium alloys, and the research has been focused on the welding of high strength alloys such as steel, titanium alloy and stainless steel [3]. Compared to the many fusion welding processes that are routinely used for joining structural steel， friction stir welding (FSW) process can realize industrial automation and cannot produce smoke and dust， welding operator body harm is small and little environmental pollution; friction stir welding (FSW) is an emerging solid state joining process in which the material that is being welded does not melt and recast，the phenomenon of hydrogen embrittlement and hot crack in steel has been effectively eliminated that can improve the performance of the joint.

2. Experimental method

The Q235 steel of 4mm thickness was cut into the required size (250mm×100mm). Cleaning the oil stain rust of the welding surface and washed by acetone before welding. The steel was welded by butt welds and the special friction stir welding machine was used for the present study. The tool made of cemented carbide was used to fabricate the joints, and the tool dimensions are shown in Table 1.

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All welds are made under the following process condition: 1000～1200rpm tool rotational speed; 5～10mm/s welding speed; 30s hold time; and 0.3mm shoulder plunge depth. The angle between the direction of the pin and the surface of workpiece is 2° . When welded Q235 steel that has high hardness, the pin plunged into the workpiece at a slow speed, so as to reduce the vibration of the worktable and the wear of the mixing head during welding. The tensile test is carried out on universal testing machine, observation of fracture morphology by scanning electron microscope. The metallographic specimens are cut along the direction perpendicular to the weld line and chemical etching with 4% nitric acid alcohol solution. Finally, the micro-hardness of the welded joints is tested.

Table 1. Design parameters of FSW tool (mm)

Shoulder diameter /D	Pin diameter /d	Pin length/L	FSW tool pin profiles
20±0.1	5±0.1	3.7±0.01	Straight cylindrical

2.1 Macroscopic characterization of welds

The macro-morphology of joint in FSW is Figure1.It can be seen the weld surface is well formed and less burr on the edge of joint, no groove, dent and other defects. Thus it can be seen that the welding under the experimental process condition, the shaft shoulder have enough depth pressure and the heat produced by friction between stirring pin and workpiece are enough to make weld metal softening and plastic flows. As a result, the surface of weld joint is smooth and uniform.

2.2 Microstructure Characterization of weld joint

The microstructure of joints show that the cross sectional structure of Q235 friction stir welded joints can be divided into four areas. There are stir zone (SZ), heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and base material (BM). It can be seen that there is a distinct boundary between the weld and base material, the microstructure of each zone as shown in Figure 2.

Figure 1. Macro-morphology of weld

With reference to Figure 2a, it is easy can see that the microstructure of Q235 is composed of long striped pearlite (black) and basically uniform distribution of very fine ferrite (white)[4] . HAZ is made up of grain coarsening (compare with other areas of joint) pearlite (black) and ferrite (white). HAZ which is close to TMAZ, on the other hand HAZ is far away from SZ (centre of weld), and there is no dynamic recrystallization of the microstructure. The microstructure of the HAZ is treated by aging process, in addition, under the effect of welding thermal cycle, grain growth, static recrystallization and recovery occurred in all parts of the microstructure, and some of the microstructure is softened due to overaging. The partial morphology of the long strip rolling structure of the base material is retained. The average grain size in the whole HAZ region is larger than that in the BM, and the comprehensive mechanical properties are decreased. It is the weak area of the joint, as shown in Figure 2b. TMAZ (Figure 2c) consist of irregularly shaped pearlite (black) and ferrite (white). TMAZ is near SA, the metal in this zone is simultaneously subjected to friction heat, press load of shaft shoulder, and stirring effect by the stirring pin. However, the mechanical stirring is not as strong as the stirring zone. The pearlite and ferrite grains are elongated along the interface direction and are heated in homogeneously, which shows in irregular shape. Some of grain growth abnormally, so as there are different size of grains are appeared. In addition, there are a large number of stir residues in TMAZ, and the uneven friction heat production exacerbates the phenomenon of different grain size. Due to grains in the interfacial transition zone are broken by the pin during stirring and the plastic flow of the base material, the grain has obvious deformation. SZ (Figure 2d) is located in the centre of weld, the temperature of that material can reach above 1100℃ with friction heat and strongly stirring by stirring pin and shaft shoulder, plastic metals flow fluidity, the velocity of crystallization nucleation is much faster than grain growth. At the same time, the mechanical stirring of the friction head makes the original grain in BM break up in a large quantity, and in order to form a plastic flow layer along the rotating direction of the stirring pin [5]. Therefore, the long strip rolling microstructure of BM is transformed into uniform and fine equiaxed crystal. The matrix structure is completely recrystallized, the microstructure of pearlite (black) and ferrite (white) are obtained, and the mechanical properties are better.

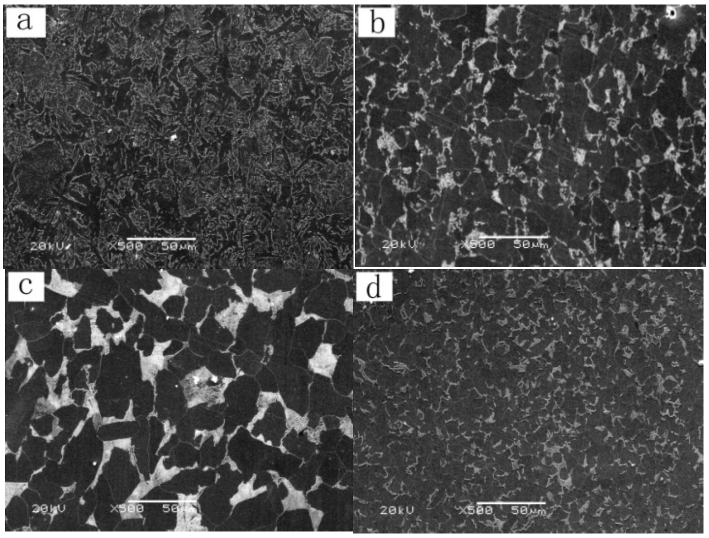

Figure 2.Microstructure of joint (a. Base Metal; b. Heat Affected Zone; c. Thermo-Mechanically Affected Zone; d. Stir Zone)

2.3 Tensile strength and fracture morphology of welds

From the tensile test results, it is found that the tensile strength of joint should reach 329.50MPa, which is about 68% of the Strength of base material (tensile strength of the base metal is measured to be about 490MPa). Fracture occurs near the HAZ, which is related to the coarse grain size and poor comprehensive mechanical properties in HAZ. The fracture surface is smooth and bright, no obvious plastic deformation, no necking produced, the whole joint belongs to brittle fracture, local dimples exist.

The fracture surface of the joint is shown in Figure 3.It can be seen that the weld seam has obvious lamination in the vertical direction of the cross section of the joint. This is related to the plastic flow of the weld metal along with the vertical direction during welding process. The width of the plastic deformation zone of the weld decreases gradually from the surface down along the thickness direction. At the horizontal direction of the weld, the plastic material in the upper part of the weld move to the center of the weld, otherwise, and the plastic metal in the middle and lower part migrated to the center of the weld [6-7]. The upper part of the weld is subjected to the joint in action of the high speed rotating shaft shoulder and the stirring pin, the friction heat is more, the temperature rises rapidly, as a result the metal reached the plastic state. The weld metal softens under the action of the high tool rotating speed, and the plastic metal slips under stirring of stirring pin and press load of shaft shoulder. These holes aggregate and grow up under the action of friction heat and shaft shoulder extrusion force, finally separate, in order to form dimples, which shows a ductile fracture. The metal in the middle of the weld is affected by the joint action of the shaft shoulder, the pin, BM and the pad, in addition, the plastic material comes from multiple directions, both the metal flowing from the upper part by the action of the shaft shoulder, and the original metal which is in the middle of the weld. There is also the metal flowing from the lower part by the action of the pad and the pin. The combinations of these plastic metals are not as good as the upper, some of them achieved interatomic combination, and some of the metals are not affected by the pin, and shafts. The grains size is large, and the metal toughness is poor. There is no obvious slip phenomenon and brittle fracture occurs under the action of force, and the fracture surface is even bright.

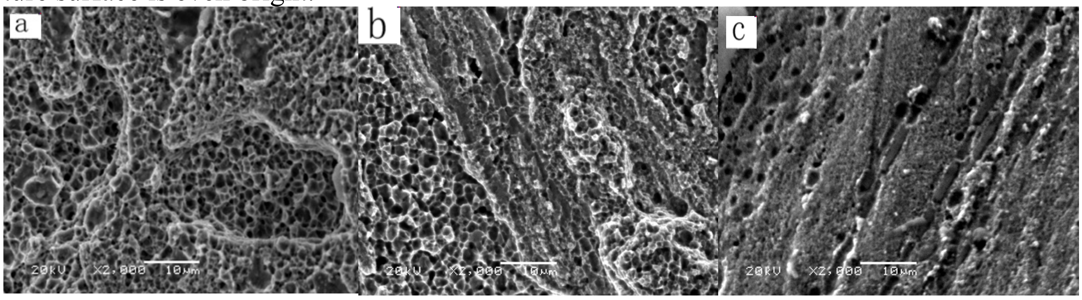

Figure 3. Joint fracture morphology（a.upper parts of weld; b.middle of weld; c.lower parts of weld）

Therefore, the fracture morphology of the middle part of the weld is both ductile and brittle, and the metal in the lower part of the weld is affected by the joint action of the stirring pin and the pad, its plastic material comes from the central migration and the original metal. Because of the temperature of the pin is high, the pad temperature is relatively lower, from the end of the tool pin to the vertical direction of the pad, the temperature decreases successively, and the temperature difference is very large. The metal near the end of the pin has a high temperature and long cooling time, by the contrast, the metal near the pad has a low temperature and a fast cooling time. As the result, the weld metal formed lamellar structure in the thickness direction.

3. Micro-hardness of joint

Figure 4 presents the micro-hardness distribution of joints in the Q235 FSW. It can be shown that the micro-hardness of joint is unevenly distributed in all regions, and the overall distribution approximately in “W” shape. Among of them, the microstructure of HAZ is treated by aging process. Under the effect of welding thermal cycle, grain growth, static recrystallization and recovery occurred in all parts of the microstructure, and some of the microstructure is softened due to overaging.

Some morphologies of the long strip rolling structure of the substrate are retained. But the average grain size in the whole HAZ region is larger than the BM, and the hardness decreased obviously. In SZ, under the shaft shoulder and the pin are stirred strongly, it can be seen that there are producing more heat by friction and dynamic recrystallization of matrix structure, and the original grain in BM are broken in large quantities, the nucleation speed is much faster than that of grain growth rate. At the same time, form a plastic flow layer along the rotating direction of the tool pin. The long strip rolling microstructure of BM is transformed into uniform and fine equiaxed crystal. So as a result, the microstructure grain is fine, the micro-hardness distribution is uniform, and the highest hardness is about 160 HV. The effect of friction heat, press load of shaft shoulder, and the pin in TMAZ during stirring, the structure of grain of pearlite and ferrite is elongated along in the direction of interface, so as the grain grows abnormally and the size of grain are uneven. At the mean time, there are a large number of stirring residues, which leads to the uneven distribution of micro-hardness in this area, the average value which is between HAZ and SZ. The rolling microstructure in BM is not subjected to the mechanical stirring of the friction head, and the matrix structure has no dynamic recrystallization, so the micro-hardness is lower than that in the stirring zone, which is about 140 HV.

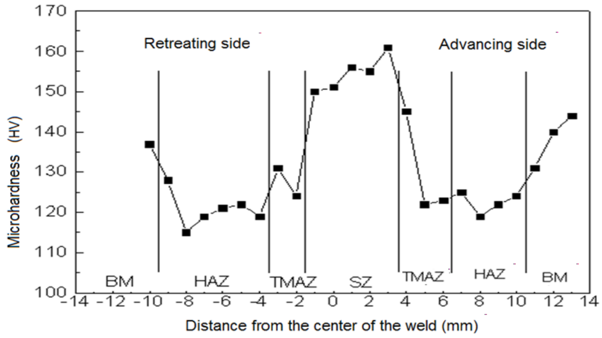

Figure 4. Micro-hardness distribution of joint

4. Conclusion

1. Under the following process condition：1000~1200rpm rotational speed, 5~10mm/min welding speed, 30s hold time, shoulder plunge depth of 0.3mm，the weld surface is well formed. There are a small number of edges exist on the edge of the weld joint, and no groove, dent and other defects.

2. The microstructure of Q235 is composed of long stripe pearlite and ferrite uniformly distributed on the matrix. The microstructure of weld in SZ is pearlite and ferrite with good comprehensive mechanical properties. The all parts microstructure in HAZ are grain growth, static recrystallization and recovery, the whole grain is coarse. Therefore, the region is composed of coarse pearlite and ferrite; On the other hand, TMAZ are consisted of the irregular pearlite and ferrite, the grain has obvious deformation and its mechanical property is superior to HAZ.

3. The tensile strength would reach 329.50Mpa, the tensile fracture surface appears near HAZ, and the fracture is flat and bright, no necking occurs. Fracture modes of joints include brittle fracture and ductile fracture with local dimple morphology. The distribution of micro-hardness in each region is very uneven; however, the overall distribution is about "W" shape. The microstructure of HAZ is softened due to failure treatment, and the micro-hardness is the lowest; Dynamic recrystallization occurs in the matrix in SZ with fine grains and uniform distribution of micro-hardness with the highest hardness about 160 HV. The micro-hardness of TMAZ is uniform distribution which is between HAZ and SZ; The micro hardness of BM is lower than SZ which is around 140HV.

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