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Study on failure mode and mechanism of tool in friction stir welded steel

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Abstract: The failure modes and mechanism of the tool in friction stir welding process are studied by welding of Q235 steel of 4mm thick, with the tool made of YG8 Cemented carbide. The results show that the main failure modes of the tool in FSW of Q235 steel are the mechanical wear, the oxidation, the brittle fracture of the pin, and the concave and convex ring area on the shoulder. The microstructure, fracture morphology and micro-hardness of the tool are analyzed, it can be shown that the main reason for the failure are the high temperature friction of the tool for a long time, resulting in uneven or partial diffusion of the Co phase, and the tungsten carbide particles are peeled off from the matrix under the action of force, which seriously destroys the matrix model of the cemented carbide. The free carbon and the hard-brittle phase Co6W6C in the crystal boundary greatly weakens the solid solution strengthening of the Co phase to tungsten carbide, which decreases the hardness, strength and wear resistance of the tool.

1. Introduction

Friction stir welding (FSW) is a novel solid-state joining process that is was invented at The Welding Institute (TWI), UK in 1991[1].Since no melting occurs during FSW, the process is performed at much lower temperatures than conventional welding techniques and circumvents many of the environmental and safety issues associated with these welding methods [2].It is primarily a three-stage process: a plunge, a dwell, and a welding stage. In the plunge stage, a hard-non-consumable rotating tool penetrates the plates to be welded. In the dwell stage, the tool penetrates the metal and rotates without moving forward, whereas the welding stage is the stage where the tool moves forward to form a weld bead. 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. As the steel, titanium and other materials had high melting point and hardness, which required the tool with good high temperature performance. In this paper, the tool was used to fabricate the joints of Q235 steel, and the main failure modes and mechanism of the tool during welding were discussed.

2. Experimental detail

The tool is made of YG8 cemented carbide cemented carbide, and dimensions of the tool are listed in Table 1. The Q235 steel of 4mm thickness was welded by butt welds. The welding parameters are presented in table 2. During the welding process, observed the changes of the tool. The metallographic samples were prepared from the cross section of the tool before and after the failure, and were analyzed by metallographic microscope after etching with 20% potassium ferricyanide + 20% sodium hydroxide (mass fraction).The micro-hardness of the original and the failure tool was tested on a HX-1000TM micro-hard meter.

Table 1 .Tool dimensions (mm)

Tool shoulder diameter(D)	Pin diameter (d)	Pin length(L)	Ratio of tool (D/d)	Tool pin profiles
20	5	3.7	4	Straight cylindrical

Table 2. Tool dimensions (mm)

Welding speed (mms^{-1})	Tool rotational speed (rpm)	Hold time（s）	Shoulder plunge depth（mm）	Axial force (kN)
10	1200	30	0.3	12

3. Results and discussion

3.1 Tool mechanical wear

The wear condition of the tool pin in the plunge stage and entire welding process are shown in Figure 1. It can be seen that the wear of tool pin are serious in the plunge stage, the wear of the pin increases in the welding process with increasing number of welding. There is little heat when the tool with high rotational speed and cold work-piece had just been contacted, and the wear of the tool are very serious. The wear of the tool is reduced when tool shoulder had an enough plunge depth.

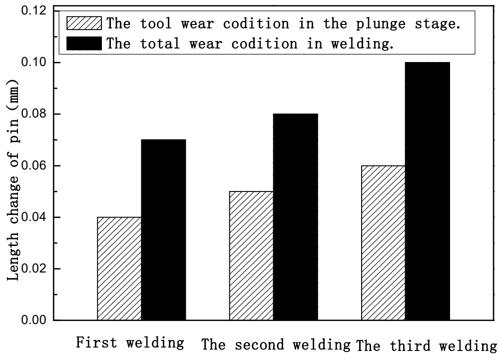

Figure 1. Wear of tool pin

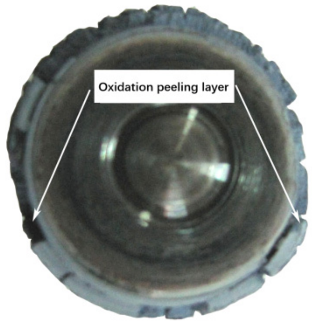

Figure 2. Oxidation peeling of tool

3.2 The surface of the tool is oxidized and peeled off

The macroscopic morphology of the oxidized tool is shown in Figure 2.It can be seen that the oxidation of the tool was very serious. The tungsten in the tool is stable at room temperature, oxidized at 400 ° C, oxidized accelerated at 500 ° C, and yellow tungsten trioxide is produced at high temperature [3-4].The surface temperature of the tool welding side was above 1000 ℃, and the yellow tungsten oxide was sublimated at about 850 ℃, and the surface of the material will generate new tungsten trioxide which continued to sublimate at 850 ℃ and took away the alloy of the tungsten element. At the end of the welding, the surface temperature of tool was high, and the tungsten oxide was formed when cooled in the air naturally, and the oxide layer which was brittle and low strength was easy to peel off from the matrix. Oxidation peeling exists throughout the welding process and is one of the main failure modes of the tool.

3.3 The brittle fracture of the pin

In FSW, the tool is acted upon by forces that are the work-piece opposite to the direction of welding shear stress and axial forging, and frictional heat production leads to low welding heat input, lower softening degree of welding material and worse flowability when the welding speed or tool rotated at a low speed. The shearing force of the tool pin increases and finally causes the pin to break along the root, and it is called brittle fracture that is shown in Figure 3. Brittle fracture generally exists at the lower heat input of the initial welding.

3.4 Shoulder failure
The tool shoulder is not only the welding heat source but also the welding pressure needs to soften the plastic metal during the welding process. The temperature of the shoulder in friction stir welding is over 1000 ° C. The long-time friction of the shoulder causes its high temperature performance to decline seriously, which leads to the softening phenomenon on the surface. Under the combined action of the lower pressure and the advancing force, the shoulder surface formed a rugged ring region that is shown in Figure 4. The failure of the shoulder occurs mainly at the end of the life cycle of the tool.

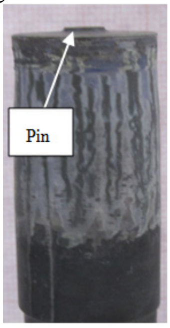

Figure 3. Brittle fracture of the pin

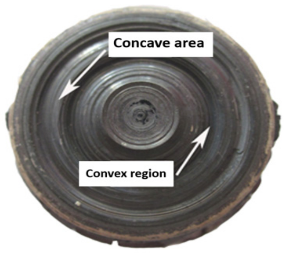

Figure 4. Shoulder failure

4. Failure mechanism of tool

4.1 Microstructure analysis
The hard phase WC bonded phase Co solid solution strengthening is the reason of higher hardness and strength of the cemented carbide tool in the early welding stage. Figure 5(a) shows that the small average size of tungsten carbide (WC) grains (gray particles) are connected to each other and the polymer is filled with an adhesive Co (bright white region), which basically conforms to the carbide skeleton theory proposed by German scholar Dawihl [5].

The microstructure of the shoulder and tool pin after failure is shown in Figure 5(b) and Figure 5(c). It can be seen that the WC grain organization scale is too large, the binder Co distribution is not uniform, loss of Co phase, more free carbon and decarburization intermediate phase Co_6W_6C (black spots in the constitution diagram) are gathered at the grain boundaries. The distribution is not uniform or loss of Co phase destruction of the skeleton model, and change the aggregation state of WC, then WC is flaking off the base and a concave area appears on the shoulder under the double action of high temperature and force. The effective size of the tool decreases with the increase of the spalling amount of tungsten carbide with the loss of cobalt phase and the exfoliation process of tungsten carbide continue [6]. The appearance of free carbon greatly reduces the strength and wear resistance of the tool. The intermediate phase Co_6W_6C is a hard and brittle metal compound, which causes stress concentration and brittle fracture.

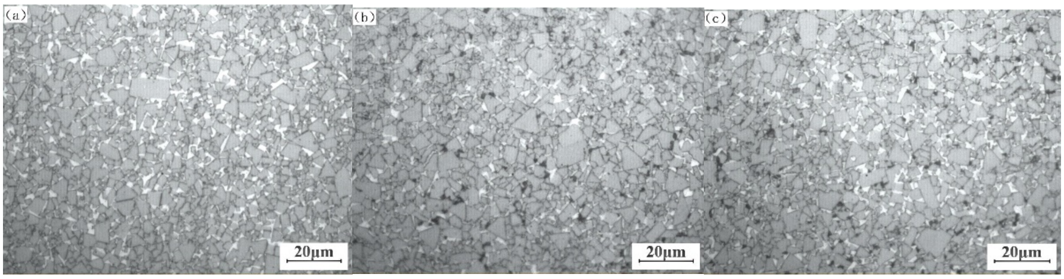

Figure 5. Microstructure of tool (a. before welding; b. microstructure of shoulder after failure; c.microstructure of pin after failure)

4.2 Fracture morphology and fracture mechanism analysis

The fracture micro-morphology of the root of the tool pin is shown in Figure 6. As shown by the Figure 6, the fracture of the tool pin is brittle high porcelain fracture, and the fracture surface is like the shape of white sugar. The toughness and plasticity of cobalt in bonding phase are higher than WC, under the action of tensile stress (or compressive stress), the cobalt phase is gradually plastically deformed, resulting in the formation and migration of micropores in the cobalt phase, which eventually joins and causes fracture of the bond phase. Therefore, the toughness of the tool is closely related to the cobalt content in the matrix. It can be seen in Figure 6 that a dimple existed in the local region of the fracture, which occurs in the thicker layer of the cobalt. The loss of Co phase diffusion in tool is serious, and the bonding phase in the matrix is very little, so the fracture form is mainly brittle fracture.

FSW is a load model which combined heat and force. The surface temperature of the tool changes alternately, and the temperature gradient appeared inside. The coefficient of thermal expansion of cobalt is greater than hard phase tungsten carbide, the cobalt bearing compressive stress when the temperature is high, and the tensile stress when the temperature is low, so it is easy to form the non-uniform stress field and temperature field in the welding end face of the tool. The cracks are caused by the migration of cobalt when the in-homogeneous stress reach a certain maximum, and the cobalt poor microspores are formed at the grain boundaries, form a source of longitudinal and transverse cracks. At the beginning of welding, the tool is subjected to a great impact force, and the crack is expanded, which result in the spalling of the hard phase WC and macroscopic fracture. In addition, the free carbon accumulation zone existed in the microstructure of the tool after welding, and the carbon elements migrate along the grain boundaries and form voids at the original position under the action of stress and heat. The migration of carbon leads to the interface of some WC/Co changes to the WC/C/Co interface, which reduces the wettability of cobalt to tungsten carbide and the strength at the joint surface decreases [7]. The WC and Co tend to dissociate and form cracks when subject to small stresses.

4.3 Microscopic hardness analysis

The micro-hardness before welding and after failure of tool are shown in Figure 7.It can be seen that the micro hardness distribution of the tool is more uniform before welding, and the hardness value fluctuated near 1500kg/mm^2, but the hardness value of the tool decreases remarkably after the failure, and the highest hardness after failure is 1200 kg/mm^2.After failure, the hardness of the tool decreases about 25% compare with before welding. The diffusion loss of the adhesive phase Co of the tool greatly reduces the strengthening of the matrix phase WC. Because the micro-hardness and strength of the tool are only the properties of the matrix WC and the precipitated phase (such as free carbon) in the welding process, so the hardness value of the tool fluctuates greatly, and the strength and wear resistance are greatly reduced which cause the tool to fail. The hardness value of the shoulder area fluctuates greatly than the tool pin area, which cause the shoulder to appear in a circular concave area.

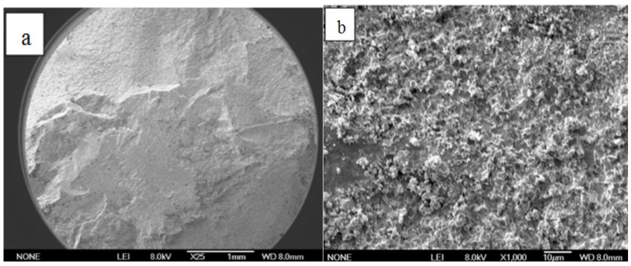

Figure 6. Fracture surface of tool pin (a. macroscopic appearance of fracture; b. fracture morphology)

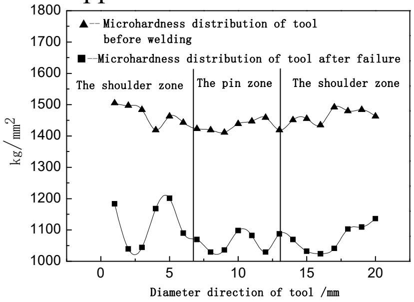

Figure 7. Micro-hardness distribution of tool

Thus, the failure form of the tool in the welding process is not independent, and is the result of several failure forms.

5. Conclusion

1. The main failure forms of YG8 carbide tool in friction stir welding process are mechanical wear of tool, the surface of the tool is oxidized and peeled off, the brittle fracture of the tool pin and convex ring area at the shoulder. Oxidation of the tool is a serious phenomenon, existed in the whole welding process and is one of the main failure modes of the tool; tool mechanical wear and tool pin fracture generally occur at the lower heat input of the initial welding; the failure of the shoulder occur mainly at the end of the life cycle of the tool.

2. The distribution is not uniform or loss of Co phase destruction of the skeleton model, and changes the aggregation state of WC, then WC is flaking off the base and a concave area appear on the shoulder under the double action of high temperature and force. The appearance of free carbon in the grain boundary leads to the solid solution strengthening effect of Co relative to tungsten carbide ,the strength, hardness and wear resistance of the tool, are greatly reduced; the existence of decarburization intermediate phase Co_6W_6C cause stress concentration and brittle fracture of alloy.

3. The fracture micro-morphology of the root of the tool pin is brittle high porcelain fracture, and the fracture surface is like the shape of white sugar; When the inhomogeneous stress reach a local maximum, the cobalt migration result in the formation of cobalt poor micropores, which are aggregated at the grain boundaries to form a source of longitudinal and transverse cracks. Free carbon along the grain boundary migration and holes form in the original position, resulting the interface of some WC/Co changes to the WC/C/Co interface, which reduce the wettability of cobalt to tungsten carbide and the strength at the joint surface decreased, when the strength of the bonding surface decreases, WC and Co tend to dissociate and form cracks.

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