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Effect of tool geometry on tool wear characterization and weld formation in friction stir welding of 316L stainless steel*

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316L stainless steel plate was friction stir welded using PCBN tools. The effect of tool shoulder profile and tool probe profile on tool wear characterization and weld formation was investigated. Two different shoulder profiles (screw with different pitches) with four different tool probe profiles (two different probe end shapes and two different probe lengths) have been used to fabricate FSW zone. Experimental results show that the tools with narrow pitch screw shoulder profile produce deeper FSW zone compared to the tools with wide pitch. The tools with spiral probe profile produce deeper FSW zone compared to the tools with chamfer probe profile. The tools with wide pitch screw shoulder profile is apt to produce lower working loads. The wear resistant of tools with chamfer probe profile is significantly higher than that of tools with spiral probe profile. The relation between tool geometries and tool wear and weld formation is discussed.

Key Words: Stainless steel, Friction stir welding, Tool profile, Tool wear, Weld formation

1. Introduction

Austenitic stainless steel, AISI type 316 and its modified grades like 316L have applications as structural material in nuclear power plants for the construction of water storage tanks [1]. The choice of this alloy is based on its excellent high temperature tensile and creep-fatigue strengths in combination with good fracture toughness. As nuclear plants around the world grow older there are increasing incidences of stress corrosion cracking (SCC) problems [2]. The repair of SCC is becoming an urgent task to extend the service life of stainless steel water storage tanks which have experienced SCC cracks at the external surface. Friction stir processing [3] is a technique which has grown out of friction stir welding (FSW) technology and essentially provides a high integrity smooth repair of shallow surface defects. Compared with conventional weld repair methods, this technology can offer advantages for on-line application particularly in terms of its lower risk of through-wall penetration. It is well known that the formation of FSW zone is affected by the material flow behavior under the action of FSW tool. That is to say, the material plastic flow behavior and the heat generation are predominantly influenced by the FSW tool profiles and FSW tool dimensions when FSW process parameters are fixed. Up to date, a few studies about the effect of tool geometry on the microstructure evolution and mechanical properties have been reported on FSW of aluminum alloys. The available literature focusing on the effect of tool geometries on tool wear characterization and weld formation during FSW of steel is very minimal. Hence, in this investigation an attempt has been made to understand the effect of tool geometries on tool wear characterization and weld formation on FSW of steel. In this study, 316L stainless steel is friction stir welded using a polycrystalline cubic boron nitride (PCBN) tool to investigate the weldability of this material. The effect of tool shoulder profile and tool probe profile on tool wear characterization and weld formation are investigated.

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2. Experimental procedure

The base material is a 15-mm-thick 316L stainless steel plate. Rectangular welding samples, 250 mm long by 200 mm wide, are welded using a FSW machine. FSW experiments are carried out by stir-in-plate method. The welding parameters are rotation speeds of 5 r s^{-1} and welding speeds of 0.333 mm s^{-1}. The welding tilt angle is 0 °. To avoid surface oxidation, argon shielding is employed around the tool during welding. The tool is fabricated from PCBN and consists of a convex shoulder having a diameter of 24 mm and a tapered probe. The probe tapers from 8.9 mm at the shoulder to the probe tip. The angle between probe side and the central axis of the tool is 30 °. Two kinds of probe length (5 and 6 mm) and two kinds of probe end shape (spiral probe profile and chamfer probe profile) are selected for FSW. The typical PCBN tool appearance is shown in Fig.1. The shoulder surface has a screw pattern to enhance the stirring effect. Two different shoulder profiles (with screw pitches of 1.25 mm and 1.9 mm) have been used to fabricate FSW zone. Characterization of tool wear and formation of FSW zone have been analyzed macroscopically. The depth and width of FSW zone is measured to evaluate the service ability of tool.

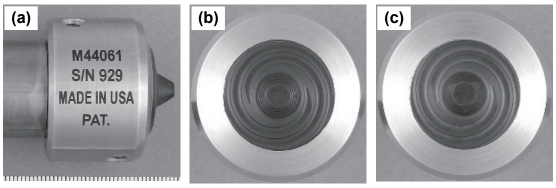

Fig. 1 Appearance of PCBN tool; (a) side view, (b) spiral probe and (c) 3 sides chamfer probe.

After welding, the joint is cross-sectioned perpendicular to the welding direction for the metallographic analyses and tensile tests using an electrical-discharge cutting machine. The mechanical properties of the joints are measured using tensile tests. The tensile tests are carried out at room temperature at a cross-head speed of 0.0167 mm s^{-1} using a tensile testing machine, and the mechanical properties of the joints are evaluated using three tensile specimens cutting from the same joint. The shape of the test specimen is shown in Fig.2. Vickers hardness profiles are measured under a load of 0.98 N for 15 s along the centerlines of the cross-sections of the samples with the distance between neighboring measured points being 1 mm. Microstructural observations are performed by optical microscopy (OM) and scanning electron microscopy (SEM). The specimens for OM and SEM are mechanically ground with water abrasive paper and polished with 3 and 1 μm diamond, and etched electrolytically in a solution of 10% oxalic acid + 90% water with a power supply set to 15 V for 90 s.

3. Result and discussion

In order to decide the basic geometry of the FSW tool, preliminary experiments are carried out and the effects of tool geometries on working load and weld formation are shown in Table.1. Out of the 2 joints fabricated using flat shoulder profiled tool, the joints fabricated by the tools with screw shoulder are found to be defect free. Moreover, the results show that the probe shape has a significant effect on the working loads during FSW. The experiments performed by 3 sides chamfer probe profiled tool or spiral probe profiled tool show lower working loads. The object of our work is aimed at relatively thin-walled 316L stainless steel water storage tanks which have experienced SCC cracks at the external surface. For this particular purpose, lower working load mode can offer advantages in terms of its lower processing temperature and lower risk of through-wall penetration when compared with higher working load mode. Therefore, 3 sides chamfer probe profiled tool and spiral probe profiled tool are selected in current experiments. Meanwhile, two different screw shoulder profiles (screw pitches of 1.25 mm and 1.9 mm) have been used to enhance the stirring effect and get defect free joints.

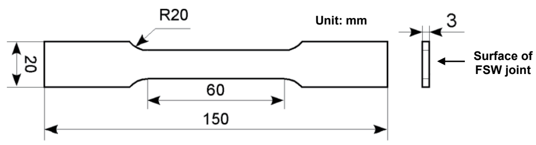

Fig. 2 **A** schematic of a tensile test specimen.

Fig.3 shows the typical cross-sections of joints welded using a series of PCBN tools. The configurations of the PCBN tools used in current experiments as well as the effect of tool geometries on weld formation and tool wear are summarized in Table 2. It can be seen from these figures that defect free joints can be obtained when appropriate welding parameters are carried out. The typical stir zone (SZ), thermo-mechanically affected zone (TMAZ) and base metal (BM) are observed. Characterization of the formation of FSW zone has been analyzed macroscopically. The weld depth (WD) of FSW zone is measured to evaluate the service ability of tool. In consideration of the potential width of SCC crack, the weld width (WW) at 5 mm depth of SZ is measured to evaluate the possible processing width of the tools at near-surface. The details are marked on Fig.3a and the results are summarized in Table.2.

Table 1 Effects of tool geometries on working load and weld formation

Shoulder	Probe	Load	X-ray inspection
Screw	2 sides chamfer	40.5 kN	Defect free
Screw	3 sides chamfer	23.2 kN	Defect free
Screw	Spiral	24.8 kN	Defect free
Flat	3 sides chamfer	24.0 kN	Tunnel defect
Flat	Flat	27.7 kN	Tunnel defect

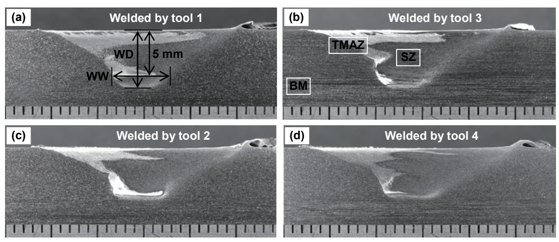

Fig. 3 Cross-sections of typical welds.

From Table 2 we can find that the tools with narrow pitch screw shoulder profile produce slightly deep FSW zone compared with the tools with wide pitch screw profile. The depth of the former is about 0.2-0.3 mm deeper than that of the latter. It means that the tools with narrow pitch screw shoulder profile can force more materials to flow in the SZ compared with the tools with narrow pitch screw shoulder profile are used. Meanwhile, the counteracting force from the flow material in FSW zone will also be increased, which results in higher working loads. The present study suggests that the tools with wide pitch screw shoulder profile are strongly recommended when lower working loads are required.

Table 2 Effects of tool geometries on tool wear and weld formation

Shoulder shape	Probe shape	Tool No.	Probe length	WD	WW	Tool wear
Narrow pitch screw shoulder profile	spiral probe profile	1	6 mm	6.4 mm	5.9 mm	Heavy
		2	5 mm	5.8 mm	6.1 mm	Heavy
	chamfer probe profile	3	6 mm	6.2 mm	6.0 mm	No wear
		4	5 mm	5.5 mm	5.6 mm	No wear
Wide pitch screw shoulder profile	spiral probe profile	5	6 mm	6.1 mm	5.7 mm	Heavy
		6	5 mm	5.6 mm	5.7 mm	Heavy
	chamfer probe profile	7	6 mm	6.0 mm	5.3 mm	No wear
		8	5 mm	5.4 mm	5.4 mm	No wear

wide pitch screw profile. In addition, the tools with spiral probe profile produce deep and wide FSW zone compared to the tools with chamfer probe profile. But the wear resistant of tools with spiral probe profile is significantly lower than that of tools with chamfer probe profile. After FSW, the probe tip with spiral probe profile shows significant wear but the ones with chamfer profile does not show wear. The typical tool appearances before and after FSW are presented in Fig.4. Although the tools with spiral probe profile causes deeper FSW zone, this design weakens the wear resistant of the tools. The large reduction of the wear resistant of the tools with spiral probe profile would be due to the insufficient strength of the thin spiral. The thin spiral just likes many thin blades on the surface of probe, which is easily abraded by stiff stainless steel compared with tools with chamfer probe profile. From the view point of tool life, the tool design with chamfer probe profile is reasonable.

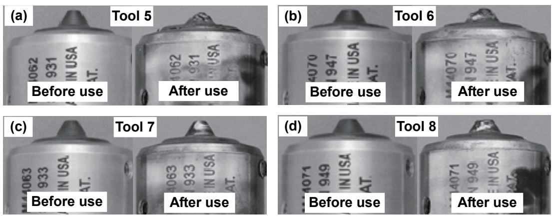

Fig. 4 Appearance of PCBN tool before and after FSW.

Fig.5 shows the effects of tool geometries on working loads in FSW of 316L stainless steel. The tools with narrow pitch screw shoulder profile produce higher working loads when compared with the tools with wide pitch screw profile. The amplitude contraction is about 10 kN when others parameters are fixed. These results may be attributed to the screw number of unit area on the surface of shoulder. As we known, narrow pitch screw means more screw are in the unit area. Such screw will force more material to flow in FSW zone. Therefore, the weld depth and weld width of the FSW zone increase when the tools with

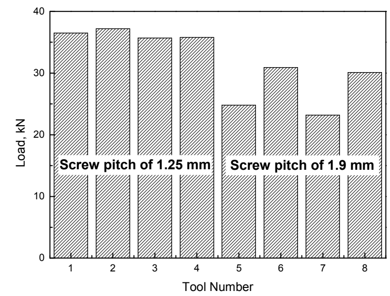

Fig. 5 The effect of tool geometries on working loads during FSW.

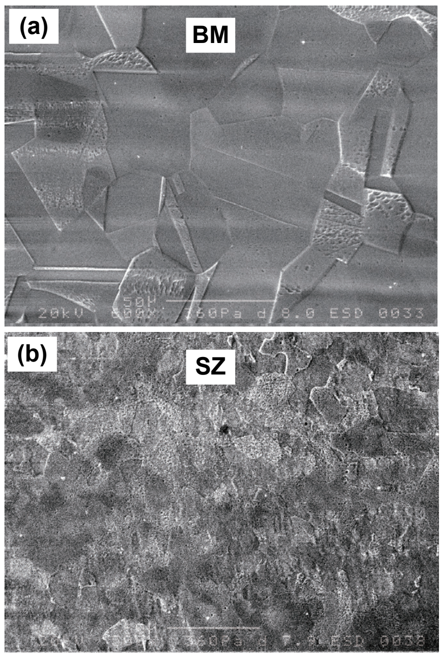

Fig. 6 SEM micrographs of BM and SZ.

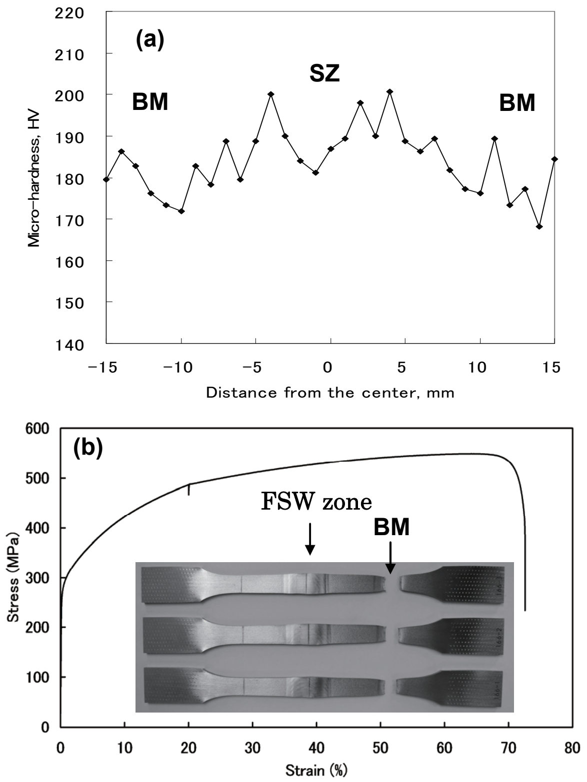

Fig. 7 Micro-hardness profiles and tensile properties of FSW joint.

Fig.6 and Fig.7 show the typical microstructures and the mechanical properties of joints. It can be seen from Fig.6a that the BM has an annealed coarse grain structure ranging in size from 30- 80 μm. Fig.6b shows the SEM micrograph in the center of SZ. The grains in SZ are refined by the tool. The SZ shows a roughly equiaxed grain structure and the grain size is in range of 10-30 μm. Fig.7 shows the typical micro-hardness distribution, tensile properties and fracture locations of the joints. Tensile test results show that the tensile strength of joints is equal to that of BM. All the joints fracture at the BM side. The stress-strain curve shows a typical ductile fracture feature because the joints fracture at BM side. It can be seen from Fig.7a that the micro-hardness in SZ is slightly higher than that of BM. In general, the tensile properties and fracture locations of the joints are dependent on the micro-hardness distributions for defect free FSW joint [4,5]. As shown in Fig. 7a, the minimum-hardness zone is in the BM of each joint, therefore the joints fracture in the BM during tensile test.

4. Conclusions

The tool geometries have a significant effect on tool wear and weld formation. The tools with narrow pitch screw shoulder profile can produce deeper FSW zone compared the tools with wide pitch screw shoulder profile, but the tools with wide pitch screw shoulder profile is apt to produce lower working loads; the tools with spiral probe profile can produce deeper FSW zone compared to the tools with chamfer probe profile, but chamfer probe profile are beneficial to the improvement of wear resistance of the tools. Therefore, from the view point of weld formation and the service life of tools, the design of the tool with narrow pitch screw shoulder profile and chamfer probe profile is reasonable; from the view point of lower working loads, the design of the tool with wide pitch screw shoulder profile is recommended.

Acknowledgements

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