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Effects of tool geometry and process conditions on material flow and strength of friction stir spot welded joints[†]

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KEY WORDS: (FSSW) (Tool geometry) (Material Flow) (Strength) (Mg alloy)

1. Introduction

FSSW has been employed in various industries and has rapidly become one of the main processes for joining light materials. Strength of welded joints is a significant issue in FSSW researches. Though some reports are published the which the key issue is optimization of tool geometry to obtain the high strength [1-2], the theoretical concept for the tool design has not been established yet. In this study effects of tool geometry on strength of friction stir spot welded joints were investigated in terms of the view of material flow during FSSW.

2. Experimental Procedure

The material used in this study was AZ31 with 1.6mm thickness. **Figure 1** shows a schematic illustration of the tool geometries. No.1 is a conventional shape which has a flat shoulder with 10mm diameter and M4 threaded probe. No.2 has a concave shoulder with 7.5 degree to produce inward material flow efficiently beneath the rotating shoulder. No.3 has a bigger shoulder with 15mm diameter to increase heat input and be expected to make the stir zone bigger. No.4 tool has a combined shape of No.2 and No.3 tools to benefit from synergetic effects, and spiral slit is fabricated on the shoulder to produce another material flow beneath the tool shoulder. All tools are designed on the basis of material flow models proposed in previous researches to produce the large or optimized bonding area [3]. A constant plunging rate and dwell time were applied, which were 2.5mm/s and 4s, respectively. Tool rotational was varied from 1000rpm to 3000 rpm. The shoulder plunging depth below the upper sheet surface was varied from -0.2 mm to 0.65 mm. Cross tension tests and Tensile Shear tests were carried out according to the Japanese Industrial Standard (JIS) Z3137 and JIS Z3136 respectively.

3. Results and Discussion

Figure 2 shows the relation between cross tensile load and plunging depth in using No.1, No.2 and No.4 tools. In the case that No.1 tool is used, when the plunging depths under 0mm are applied the rupture load increases with the plunging depth and the rupture pass traverses the stir zone

since the stir zone is not grown up enough. However, when the plunging depths from 0 mm to 0.3mm are applied, when the tool shoulder completely contacts the surface of upper sheet the rupture load indicates peak values. At this time, the fracture mode is transited to the thickness direction. When further plunging is applied, which is over 0.3 mm the rupture load decreases linearly with the plunging despite the same fracture mode because of the thinning of the upper sheet. As shown in **Figure 2**, same relations are seen using No. 2 and No. 4 tools. However, the rupture load of welded joints produced by No. 4 tool is much higher than the other two tools.

Figure 3 shows the cross sectional macro images of the welded joints before and after cross tensile test. When No. 2 tool is used although width of stir zone is slightly bigger than that No.1 tool is used, the unbonded interface is longer than No. 1 tool. However, the angle formed by hooking and the interface between the upper sheet and the lower sheet is sweep. Thus, the interface would not open when cross tensile test is performed and rupture load is increased. When No. 3 tool is used pronounced hooking is formed and tip of the interface between upper and lower sheet toward the probe keyhole. Thus, the interface is easily opened when the cross tensile test is carried out and rupture load is very weak. In direct contrast, when No. 4 tool is used a much bigger stir zone is formed than other tools and rupture load is very high. Although the interface looks like a probe keyhole, propagation is in the through thickness direction. Spiral slit and concave taper on rotating shoulder produce a strong inward flow. It is presumed that this material flow facilitates stir zone growth and bonding the interface between upper and lower sheet.

Figure 4 shows the relation between tensile shear load and plunging depth when No. 2 and No. 4 tools, which were confirmed increasing of rupture load in cross tensile test and No. 1 tool are used. In the case that No. 1 and No. 4 tools are used, rupture load is increased with increasing plunging depth. Fracture mode transits from shear direction, which cut across the stir zone to mixed mode of thickness direction and zone direction at around 0.3mm plunging depth. As in the case of cross tensile test, rupture road is

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dramatically higher than other two tools in all plunging depths when No. 4 tool is used. As shown Fig. 4, width of stir zone is much larger than No. 1 and No. 2 tools. And fracture mode is a mixed mode cutting across stir zone with thickness direction. Thus fracture load is dramatically increased when No. 4 tool is used.

Figure 5 shows the relation between tensile shear load and tool rotational speed when No. 1, No. 3 and No. 4 tools are used. When No. 1 tool is used fracture load increases with the tool rotational speed. Fracture mode is in the shear direction at all rotation speeds. This means fracture load depends on the width of the stir zone. It is well known that the growth of stir zone facilitates with increasing tool rotational speed during FSSW using general tool shape. Thus fracture load increases with the tool rotational speed when No. 1 tool is used. In direct contrast, fracture load decreases with increasing tool rotational speed when No. 3 tool is used. When No. 3 tool is used under low rotation condition a hook is not formed and the interface between upper and lower sheets are bonded widely. Because material flow around probe periphery does not occur enough since heat generation is much lower than using higher rotational condition. However, big size shoulder produces efficient material flow beneath the rotating shoulder. Furthermore axial force during FSSW is higher when No. 3 tool is used. Thus the interface between upper

and lower sheets would be bonded like friction pressure welding. High strength joints are produced stably in every rotational speed by using No. 4 tool. By comparison with the higher rotational condition using No. 3 and No. 4 tool, it is presumed that tool slippage occurs at the contact interface between rotating shoulder and material. And efficient material flow just beneath the rotating shoulder would not occur when No. 3 tool is used under higher rotational speed. However, No. 4 tool has a concave taper inside of the tool shoulder and spiral slit outside, material beneath tool shoulder is forced to transport inwards. Thus strong inward material flow is produced despite high rotational condition using big size shoulder.

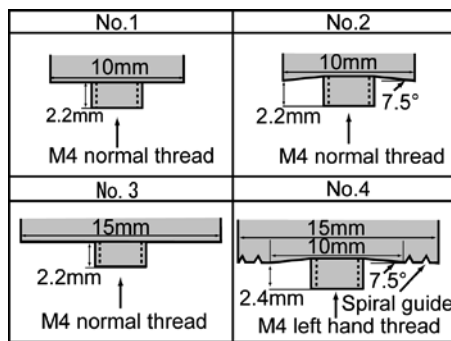


Fig. 1 Geometry of FSSW tool.

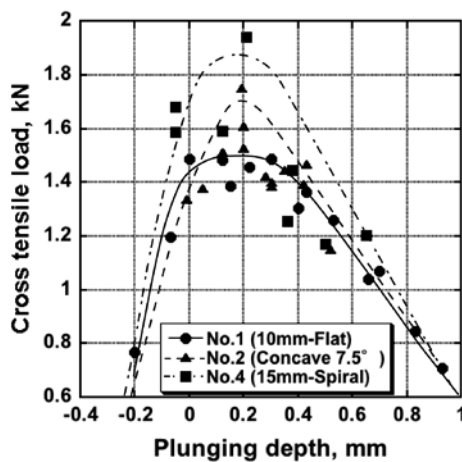


Fig. 2 Relationship between plunging depth and tensile shear load of friction stir spot welded joint made using different tool geometries.

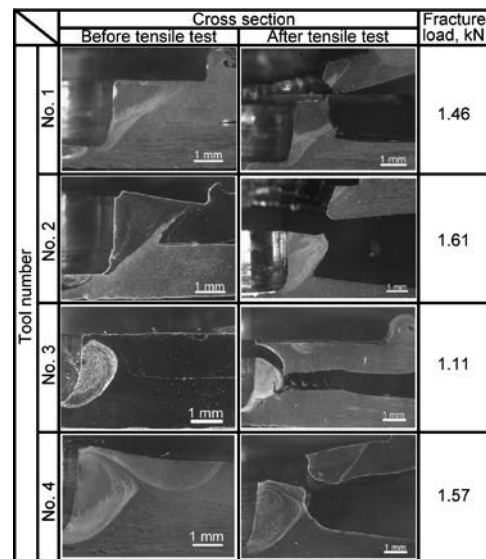


Fig. 3 Macro future of cross section and fracture pattern made using No. 1, No. 2, No. 3 and No. 4 tool. Rotational speed, plunging speed and dwell time are 2250rpm, 2.5mm/s and 4s respectively.

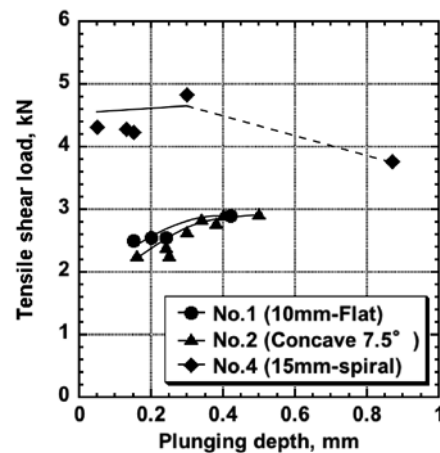


Fig. 4 Relationship between plunging depth and tensile shear load of friction stir spot welded joint made using different tool geometries.

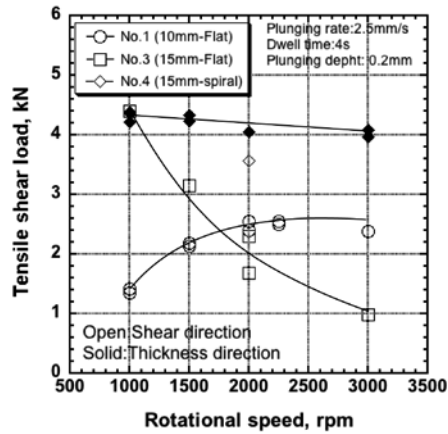


Fig. 5 Relationship between rotational speed and tensile shear load of friction stir spot welded joint made using different tool geometries.

4. Conclusions

Novel tool design which is based on material flow models during FSSW is proposed in this study. This tool is designed to facilitate the inward material flow beneath a rotating shoulder and succeeds in increasing both cross tensile load and tensile shear load drastically.

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