

Effect of tool eccentricity on surface periodic banded structures in friction stir welding

N Guo^{1,4}, M R Wang², Q Meng³, L Zhou¹ and D Y Tang²

¹ Shandong Provincial Key Laboratory of Special Welding Technology, Harbin Institute of Technology at Weihai, Weihai 264209, China

² Department of Chemistry, School of Science, Harbin Institute of Technology, Harbin 150001, China

³ Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China

E-mail: gn21c@126.com

Abstract. This paper describes the relationship between tool eccentricity and surface formation of periodic banded structures in friction stir welding. Motion characteristics of welding tool are calculated to explore the forming mechanism of banded structures. The results reveal that the welding tool motion differences on advancing side and retreating side caused by eccentricity are crucial for the formation of banded structures. The crests and troughs of banded structures form during tool motion on retreating side and advancing side, respectively.

1. Introduction

As known, the surface structures and internal microstructures of friction stir welding (FSW) joints show a spatial periodic distribution characteristic, and the space of periodic structures always equals to the distance traveled by the welding tool in one revolution [1, 2]. The surface periodic structures display as semi-circle strips packed closely along welding line, and there is a very obvious sense of crests and troughs. The internal periodic microstructure presents as dark and light strips, which commonly calls “onion ring”. Yang, et al. [3] and Reynolds [4] reported that the grain size of light strips was larger than that of dark strips. Furthermore, texture characteristic and second phase particles distribution are also different in those areas [3, 5], and all of these can affect the fracture behavior of FSW joints [6-8].

Although the periodic phenomena in FSW are widespread and easy to observe, the causes and mechanism are not known very clearly yet. At present, studies suggest some completely different views about the formation mechanism of periodic phenomena in FSW: banded structures are formed by (1) the effect of pin thread on metal flow [9, 10]; (2) a repeating occurrence of the tool stop traveling for a very short time to make material plastify [2]; (3) a sucking-extruding mechanism [11]; (4) a cooler walls mechanism [12]. However, theories above cannot clearly explain the common phenomenon that the periods of banded structures always correspond with tool rotation and same shapes of banded structures are formed on the surface of joints whatever the tool has pin or not [13, 14]. Moreover, for common FSW structures, welding tools have an axisymmetric geometrical shape,

⁴ Address for correspondence: N Guo, Shandong Provincial Key Laboratory of Special Welding Technology, Harbin Institute of Technology at Weihai, Weihai 264209, China. E-mail: gn21c@126.com.



and welding tracks are straight lines. Theoretically, banded structures are not able to be formed in the welding process.

In recent years, some researchers pointed out that the tool eccentricity may play a key role in periodic metal flow of FSW. Gratecap, et al. [15] proposed that the welding tool could present a periodic up-and-down motion in the vertical direction under the combination effect of tilt angle and eccentricity. Recent results contributed to understanding FSW, but some conclusions lacked enough evidence, and theoretical defects also existed. Therefore, in this study, microstructures observation and mathematical calculation have been carried out, and the forming process of banded structures on the surface of joints has been discussed systematically.

2. Experimental procedure

The base material used in present work is 7 mm thick commercially pure lead rolled plate with lead amount more than 99.9% (wt.%). The rotational speed of 60 revolutions per minute (rpm), traveling speed of 60 mm s^{-1} , the tilt angle of 2.5° and counterclockwise of the sense of rotation are used during the welding process. An H13 steel pinless welding tool with double ring concave and shoulder with the diameter of 11.5 mm is used. Two eccentricity values are designed: (1) eccentricity of $60 \mu\text{m}$ made by the welding system spontaneously when the welding tool is installed directly; (2) eccentricity of $400 \mu\text{m}$, by using a welding tool which has been grinded the handle appropriately.

FSW equipment applied in this study is modified from an XK5032 computer numerical control milling machine. $15 \text{ mm} \times 15 \text{ mm}$ samples crossing the joints are cut by electro-discharge cutting machine (EDCM), and well cleaned by using anhydrous alcohol. The glue is applied evenly over the banded structures for several times in order to prevent further deformation. The stir zone is cut along the longitudinal section and carefully polished using 2000-grit SiC paper, the micro appearance of banded structures is observed by Axio Imager A1m optical microscope.

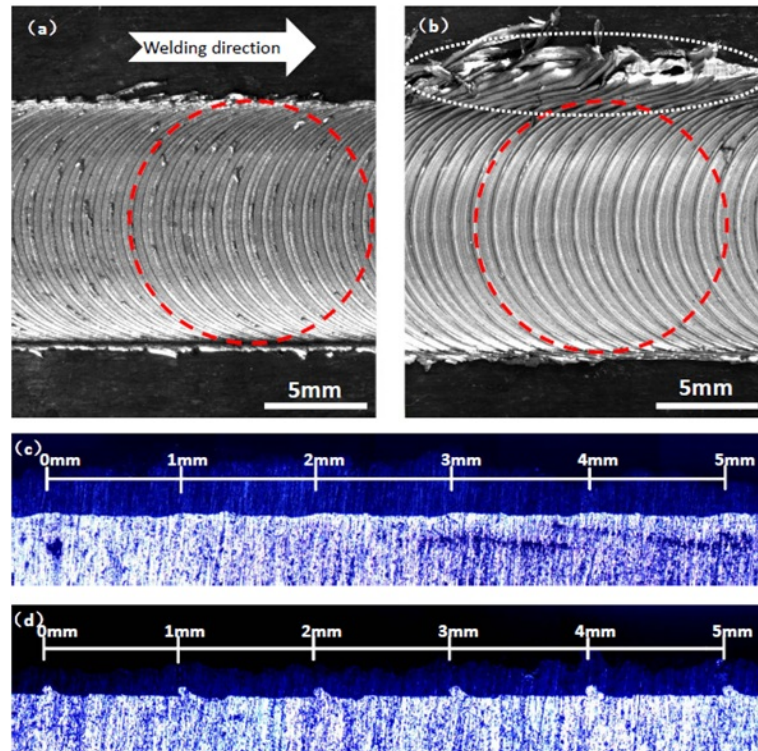


Figure 1. Surface banded structures on welds made with eccentricity of (a) $60 \mu\text{m}$ and (b) $400 \mu\text{m}$; longitudinal cross-section with eccentricity of (c) $60 \mu\text{m}$ and (d) $400 \mu\text{m}$.

3. Results and discussion

Figures 1(a) and 1(b) present the images of banded structures on joints surface with tool eccentricity of 60 μm and 400 μm , respectively. By comparing the banded structures with dash circles in figures 1(a) and 1(b), it can be observed that the banded structures are more obvious with the eccentricity of 400 μm . Moreover, in the dotted oval area shown in figure 1(b), a string of close packing bands appear on the surface of the flash on retreating side (RS), which connect with the surface bands one by one. It indicates that the forming mechanisms of the two kinds of bands are same.

Longitudinal section images of banded structures are shown in figures 1(c) and 1(d). When the eccentricity is 60 μm , the longitudinal cross-section profile of banded structures appears as a gradual periodic curve, with the average height of 34 μm between crests and troughs. But when the eccentricity is 400 μm , the average height is increased to 82 μm . Furthermore, spaces of each wave in figures 1(c) and 1(d) are both equal to 1 mm accurately. The remarkable different morphologies of banded structures only can be caused by variation of tool eccentricity.

The eccentric rotating and traveling process of the tool in FSW is illustrated in figure 2. The outer circle and inner circle with dash line are the motion trail of tool's edge and center, respectively. The velocity of tool movement along welding direction is defined as v that is the sum of v_1 and v_2 , where v_1 is the feeding speed, v_2 is velocity component along welding direction only caused by eccentric rotation. One revolution of the tool can be divided into two stages: tool center O near advancing side (AS) and near RS. In the former case, the directions of v_1 and v_2 are same, but in the latter case, directions of v_1 and v_2 are opposite.

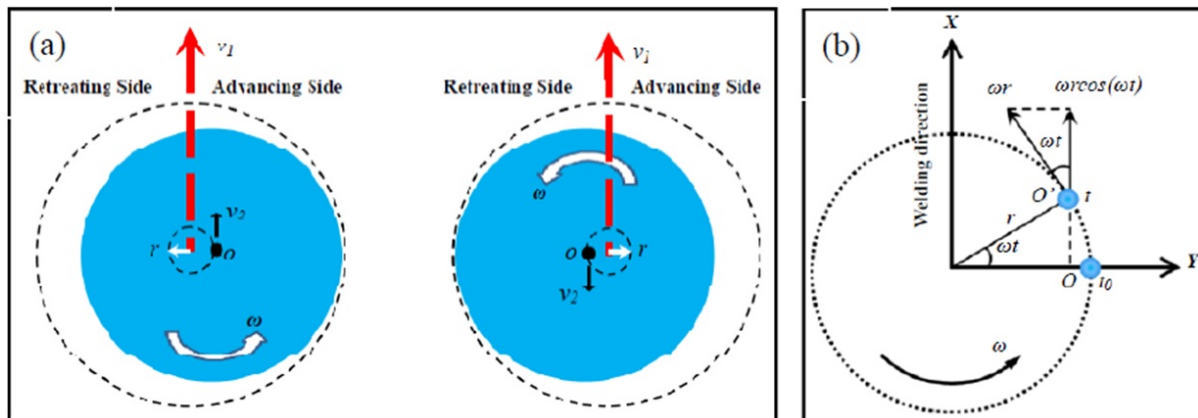


Figure 2. Eccentric rotating and traveling process of tool in FSW: (a) schematic of traveling process; (b) relationship between the angular velocity, eccentricity and tool velocity components in welding direction.

According to figure 2(b), v_2 can be expressed as equation (1), where ω is the angular velocity of tool, r is eccentricity, and α is tilt angle of the tool.

$$v_2 = \omega r \cos \alpha \cos(\omega t) \quad (1)$$

Considering that α is small, and then v can be defined as

$$v = v_1 + \omega r \cos(\omega t) \quad (2)$$

According to equation (2), the curves of tool velocity along welding direction changing with time under different eccentricities are plotted in figure 3. It can be clearly seen that tool velocity shows significant cyclical variation. However, the frequency of fluctuation is 1 s, which well coincides with the period of banded structures in figure 1. In figure 3(a), the maximum speed reaches 1.38 mm s^{-1} , and the minimum speed is 0.62 mm s^{-1} . The changing amplitude is 0.76 mm s^{-1} , which is a relatively high value compared with preset velocity. The eccentricity of 60 μm is fairly small for current FSW equipment, but it has already made a significant effect on tool motion. With the eccentricity of 400 μm ,

the maximum speed is 3.51 mm s^{-1} , and the minimum speed is -1.51 mm s^{-1} . The changing amplitude reaches 5.02 mm s^{-1} , which is almost five times of preset velocity. Meanwhile, it indicates that if the eccentricity and angular velocity of tool reach an enough high value, the velocity will be negative. It means tool moves towards the reverse direction of welding for a period.

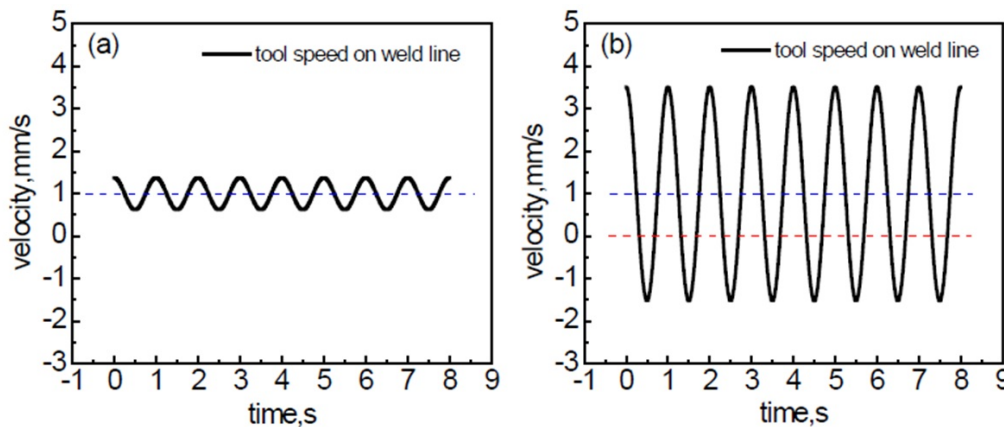


Figure 3. Velocity varied with time under different eccentricities (a) 60 μm and (b) 400 μm .

Under the condition of FSW tool rotating with eccentricity, feeding length of tool center on AS is longer than that on RS. In another word, on unit welding length, the friction time of AS is shorter than that of RS. In addition, during the welding process, FSW equipment provides down force continuously to avoid the upwards motion of welding tool. Therefore, under the effect of down force and rotating motion, the tool will be plunged into parent metal deeper on RS than that on AS. So the forming process of banded structure can be described as follows. When tool center travels on RS, rotating with eccentricity and tilt angle can make the welding tool moving downwards and plunging into parent metal much deeper. It causes more metal extruded out and accumulated at the rear edge of shoulder. Sequentially, the crest of the banded structure is formed. Conversely, the tool tends to move upward on AS, which induces less metal extruded. Thus the trough is formed. Under the condition of tool eccentricity 400 μm , L_R is negative, which indicates that shoulder will push the surface metal backward and form horns.

It is impossible to make FSW equipment without eccentricity. Therefore, it can't be authenticated that banded structures cannot be formed without eccentricity. However, it had been proved in many numerical simulation papers of FSW [16, 17]. Even though the eccentricity is very small, it is bound to affect the metal flow, macrostructure and microstructures of FSW joints.

4. Conclusions

From the present study, it can be concluded that the formation of surface periodic banded structures in friction stir weld is caused by the different motion characteristic of welding tool on AS and RS induced by tool eccentricity. The trough and crest is formed on AS and RS, respectively, due to the different flow behavior and extruded metal volume. So tool eccentricity considered or not has great effect on the accuracy of the flow models, because the flow laws of metal is totally different, which is one of the core issues of FSW.

Acknowledgments

We are grateful to the Weihai Science and Technology Development Planning (grant no.2013DXGJ07) for the financial support for this study.

References

- [1] Xu S W and Deng X M 2008 A study of texture patterns in friction stir welds *Acta Mater* **56** 1326-41

- [2] Krishnan K N 2002 On the formation of onion rings in friction stir welds *Mater. Sci. Eng. A* **327** 246-51
- [3] Yang B C, Yan J H, Sutton M A and Reynolds A P 2004 Banded microstructure in AA2024-T351 and AA2524-T351 aluminum friction stir welds Part I. Metallurgical studies *Mater. Sci. Eng. A* **364** 55-65
- [4] Reynolds A P 2008 Flow visualization and simulation in FSW *Scr. Mater.* **58** 338-42
- [5] Schneider J A and Nunes A C 2004 Characterization of plastic flow and resulting microtextures in a friction stir weld *Metall. Mater. Trans. B* **35** 777-83
- [6] Sutton M A, Yang B C, Reynolds A P and Yan J H 2004 Banded microstructure in 2024-T351 and 2524-T351 aluminum friction stir welds Part II. Mechanical characterization *Mater. Sci. Eng. A* **364** 66-74
- [7] Sutton M A, Reynolds A P, Yang B C and Taylor R 2003 Mode I fracture and microstructure for 2024-T3 friction stir welds *Mater. Sci. Eng. A* **354** 6-16
- [8] Sutton M A, Reynolds A P, Yang B C and Taylor R 2003 Mixed mode I/II fracture of 2024-T3 friction stir welds *Eng. Fract. Mech.* **70**, 2215-34
- [9] Mahoney M W, Rhodes C G, Flintoff J, Spurling R A and Bingel W H 1998 Properties of friction-stir-welded 7075 T651 aluminum *Metall. Mater. Trans. A* **29** 1955-64
- [10] Colligan K 1999 Material flow behaviour during friction stir welding of aluminium *Weld. J.* **75** 229s-37s
- [11] Ke L M, Pan J L, Xing L and Wang S L 2009 Sucking-extruding theory for the material flow in friction stir welds *Chin. J. Mech. Eng* **45** 89-94
- [12] Biallas G, Braun R and Donne C D 1999 Mechanical properties and corrosion behavior of friction stir welded 2024-T6 *First International Conference on Friction Stir Welds* (Thousand Oaks, CA) paper no. S2-P3
- [13] Simoncini M and Forcellese A 2012 Effect of the welding parameters and tool configuration on micro- and macro-mechanical properties of similar and dissimilar FSWed joints in AA5754 and AZ31 thin sheets *Mater. and Des* **41** 50-60
- [14] Zhang G F, Su W, Zhang J, Wei Z X and Zhang J X 2010 Effects of shoulder on interfacial bonding during friction stir lap welding of aluminum thin sheets using tool without pin *T. Nonferr. Metal. Soc.* **20** 2223-8
- [15] Gratecap F, Girard M, Marya S and Racineux G 2012 Exploring material flow in friction stir welding: Tool eccentricity and formation of banded structures *Int. J. Mater. Form.* **5** 99-107
- [16] Hamilton R, MacKenzie D, Li H J 2010 Multi-physics simulation of friction stir welding process *Eng. Computation* **27** 967-85
- [17] Kim D, Badarinarayan H and Kim J 2010 Numerical simulation of friction stir butt welding process for AA5083-H18 sheets *Eur. J. Mech. A-Solid* **29** 204-15