Rare Metal Materials and Engineering
Volume 47, Issue 12, December 2018
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com

Cite this article as: Rare Metal Materials and Engineering, 2018, 47(12): 3659-3665.

ARTICLE

Friction Stir Incremental Forming of AA7075-O Sheets: Experimental Investigations on Performance Evaluation of Formed Parts

Zhang Qiaoxin[1], Li Guohao[1], Liu Zhaobing[1], Zhao Anguo[1], Xiong Xinhong[1], Lei Yongjie[2]

[1] Wuhan University of Technology, Wuhan 430070, China; [2] The 9th Designing of China Aerospace Science Industry Corporation, Wuhan 430040, China

Abstract: A comprehensive performance of formed parts by AA7075-O sheets was studied in friction stir incremental forming (FSIF). Various tool rotation speeds were set to form two typical parts (truncated funnel and pyramid frustum). The formability, surface quality, tensile strength, micro-hardness and thickness distribution of the formed parts were investigated. Results show that the formability generally increases as tool rotation speeds increase. On the contact surface, variation trends of the surface roughness are different in horizontal direction (parallel to tool path) and vertical direction (perpendicular to tool path). However, the surface roughness on the non-contact surface is almost not affected by tool rotation speed. Furthermore, mechanical properties including tensile strength and surface micro-hardness in formed parts are obviously enhanced compared to those of the initial sheet, of which the hardness values begin to fall down gradually after rotation speed reaches 3000 r/min. As for thickness measurement, more uniform thickness distribution of formed parts can be obtained at relative high tool rotation speeds. In general, parts formed at high rotation speed have a better comprehensive performance except the mechanical property.

Key words: friction stir incremental forming; formability; surface quality; mechanical property; thickness distribution

Light-weight alloy materials have a high potential for weight reduction in aerospace, automotive and some other applications, which helps to reduce fuel consumption and protect the environment. However, many of them are usually hard to deform due to their poor formability at room temperature. Hot incremental sheet forming (HISF), as an economical and efficient forming technology to improve formability of hard-to-form lightweight alloys, has attracted more and more attentions from both industry and academia. It is beneficial for the manufacture of small batch or customized three-dimensional sheet metal products compared to conventional forming processes.

There are several kinds of HISF introduced in previous papers. Duflou et al[1,2] used a laser-based heating system to create a heated spot in the moving contact zone between tool and sheet. They found that the process forces and springback were reduced, and the formability of sheet was significantly extended. Ji et al[3] and Ambrogio et al[4] formed the magnesium AZ31 sheet under hot air to get a higher formability. Electric heating was also used to improve the formability in single point incremental forming (SPIF)[5-8], but the surface quality was usually very poor. To solve this problem, novel form tools for electricity-assisted incremental sheet forming were developed by Liu et al[9]. They pointed out that both of rolling-ball and rolling-wheel tools with inner water cooling channel were conducive to reducing surface roughness of the formed part and the surface wear of the tool tip due to the change of friction mode (from sliding to rolling).

Received date: December 25, 2017
Foundation item: National Natural Science Foundation of China (51210008); Fundamental Research Funds for the Central Universities (WUT: 2017IVA017, WUT: 2017III047); Excellent Dissertation Cultivation Funds of Wuhan University of Technology (2016-YS-037)
Corresponding author: Liu Zhaobing, Ph. D., Associate Professor, School of Mechanical and Electronic Engineering, Wuhan University of Technology, Wuhan 430070, P. R. China, E-mail: zhaobingliu@whut.edu.cn

Although good performances have been found in HISF, there are also some disadvantages. Comparison of existing heat-assisted SPIF methods was made by Xu et al[10]. It showed that different heat-assisted SPIF methods have their pros and cons, and the frictional heating generated by tool rotation was considered to be the most flexibility and convenient way. Friction stir incremental forming (FSIF) was first presented by Otsu et al[11]. This technique was widely studied all over the world, and most researches focused on the formability. In general, the formability of sheets in SPIF increased with the increase of rotation speed[12-15]. Obikawa et al[16] formed the aluminum foils at 0, 2500, 5000, 10 000, 20 000, and 25 000 r/min. They revealed that the increase of tool rotation improved the formability but a sudden decrease occurred at 25 000 r/min. They believed that the decreasing of real contact areas and the increasing areas of elastohydrodynamic lubrication and boundary lubrication were the main reasons for the improvement of forming limit. Meanwhile, the sudden decrease was attributed to the producing of aluminum powders at 25 000 r/min. Previous researches also showed that the friction stir incremental forming helps not only the formability improvement but also the decrease of forming force[10,17,18].

Compared to formability, there were relatively few studies on other properties of formed parts in FSIF. Durante et al[19] and Obikawa et al[16] formed the aluminium alloy sheets and aluminum foils, respectively. Both of them pointed out that the surface roughness decreased as the tool rotational speed increased. In addition, Durante found that the surface quality was a little better for anticlockwise rotation compared to clockwise rotation at the same spindle speeds. On the contrary, Bagudanch et al[17,20] indicated that as spindle speed increased, the surface roughness also increased. In their work, polyvinylchloride sheets were processed. They thought that high temperature caused by friction changed the polymer molecular structure and induced the appearance of several blobs.

Although some works have been done to investigate the FSIF, lack of comprehensive evaluation on the performance of formed parts brings challenges to the wide application of FSIF. The aim of the present paper is to perform a comprehensive and systematic study about the influence of different tool rotation speeds on the performance of formed parts in FSIF. Various rotation speeds (0~7000 r/min) were set to form AA7075-O sheets, which has limited formability at room temperature. The influence of different rotation speeds on formability, surface roughness, tensile strength, micro-hardness, and thickness distribution was evaluated and discussed.

1 Experiment

The materials used in experiments were AA7075-O sheets with a size of 200 mm×200 mm×1.5 mm (length×width×thickness). Both of truncated funnel and pyramid frustum shapes were designed as forming benchmarks. The former was used to investigate the influence of rotation speeds on formability and the latter was used to investigate the surface roughness, mechanical property, and thickness distribution of parts formed at various spindle speeds. The geometrical details of truncated funnel and pyramid frustum are shown in Fig.1a and 1b, respectively.

Due to the frictional heat generated by high spindle speeds, lubricating performance of mineral oil may degrade. As a solid lubricant, graphite has excellent performances at high temperature. Therefore, in the present study, graphite powder (the average particle size is 1.6 μm) was mixed with mineral oil (the ratio of graphite and oil is 1:4) to guarantee the lubricating performance. The spherical head of forming tool with the diameter of 15 mm was made of tungsten carbide, and the material of the tool body was high speed steel. A vertical machining centre (MIKRON VCE 800W Pro) with a maximum spindle rotation speed of 10 000 r/min and a maximum feed rate of 16 000 mm/min, was employed to carry out the experiments. Table 1 shows the key process parameters in the experiment. A z-level tool path was generated by Siemens NX 8.5 software. Before forming the next part, the top of forming tool was dipped into dilute hydrochloric acid solution to keep the tool smooth and avoid the influence of adhesion.

The samples used for various tests were cut by wire electrical discharge machining (DK7732E), as shown in Fig.2a. The square samples were used for surface roughness measurements and micro-hardness tests, and the dog bone samples were used for tensile tests, as shown in Fig.2b. Tensile tests were carried out by a microcomputer control electronic universal testing machine (WDW-50E III) at a constant tension rate of 2 mm/min. Micro-hardness of contact surface and through-thickness section were measured by micro-hardness tester (HVS-1000) under 9.8 N with a dwell time of 10 s. The surface roughness was measured by TR210

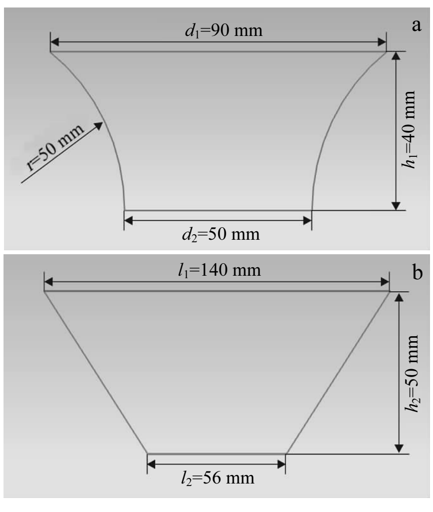

Fig.1 Geometrical details of designed parts: (a) truncated funnel and (b) pyramid frustum

Table 1 Process parameters in FSIF

Parameter	Value
Material thickness/mm	1.5
Tool diameter/mm	15
Step down/mm	0.2
Feed rate/mm·min^{-1}	3000
Spindle speed/r·min^{-1}	0, 500, 1000, 2000, 3000, 4000, 5000, 6000, 7000
Lubrication	Graphite powder+mineral oil (1:4)

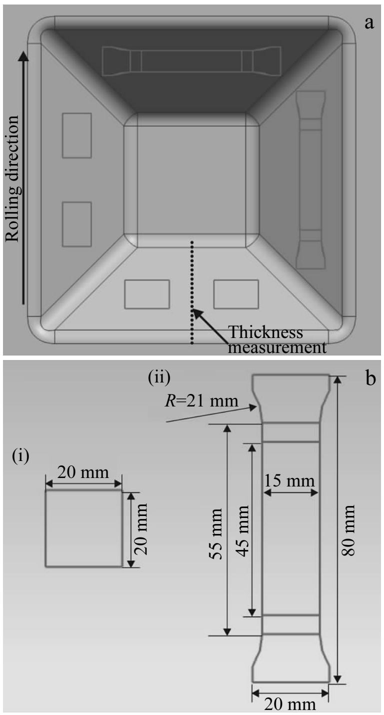

Fig.2 Sketch of test samples obtained by wire electrical discharge machining: (a) locations of the obtained samples and (b) geometrical dimensions of samples (i: surface quality and micro-hardness, ii: tensile test)

mobile surface roughness meter, and surface topography was also provided by a high-resolution camera. The temperature at the bottom of pyramid frustum parts was monitored by an infrared thermometer (AS852B) during forming process.

2 Results and Discussion

2.1 Formability

In conventional sheet metal forming, forming limit curves (FLCs) based on strain are widely used to assess the formability. Nevertheless, due to different deformation mechanisms existing in ISF, FLCs are not able to effectively estimate the formability. As a result, a maximum formable wall angle is proposed and widely accepted as the criterion to estimate the formability of metal sheets in ISF[10,21,22]. In this section, truncated funnel parts were formed at 0, 500, 1000, 2000, 3000, 4000, 5000, 6000, and 7000 r/min to evaluate the formability. It is worth noting that 0 r/min does not mean no rotation, but the tool is in a free rotation situation with about 100~200 r/min driven by frictional force. In addition, higher speeds under the maximum spindle rotation speed of machine tool are applied to form the parts. But strong unwanted milling effects occur since the prepared lubricant does not work at an extremely high rotation speed.

Fig.3 shows the maximum formable wall angles of AA7075-O sheets at various tool rotation speeds. From 0 r/min to 500 r/min, an improved formability is found. Formability falls slightly at 1000 r/min compared to that at 500 r/min, but it is still better than at 0 r/min. Subsequently, the maximum formable wall angle keeps increasing from 1000 r/min to 7000 r/min. The results are similar to the experimental findings by Xu et al[10] in the SPIF process of AA5052-H32 sheets. They divides the rotation speeds into four stages. A: the formability enhances as a result of a positive friction reduction. B: the formability slightly decreases due to a negative friction reduction. C: the formability improves on account of the pure thermal effect. D: the formability further increases because of the material softening and the material microstructure refinement. But the formability improves rapidly from 1000 r/min to 3000 r/min and slowly from 4000 r/min to 7000 r/min in their work. On the contrary, the formability of AA7075-O sheets used in the present work increases slowly from 1000 r/min to 3000 r/min and rapidly from 4000 r/min to 7000 r/min. The different mechanical and thermal properties of the selected materials lead to the difference of formability improvement between two materials.

2.2 Surface quality

Surface roughness is a critical product quality constraint in SPIF. Most of researchers focused on the influence of tool diameter, step down, and wall angle on surface roughness[23,24]. However, the effect of spindle speed was seldom mentioned. In order to find out the relationship between spindle speeds and surface quality, interior contact surface and exterior non-contact surface of each samples were measured. Moreover, the arithmetic mean roughness (R_a) of the contact

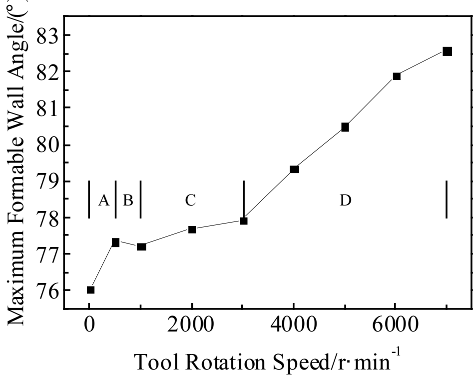

Fig.3 Formability at different tool rotation speeds

surface was measured in the horizontal direction (parallel to the tool path) and vertical direction (perpendicular to the tool path). As for exterior surface, the R_a was measured in a random direction due to the little difference between horizontal direction and vertical direction found in our previous work[25].

As shown in Fig.4a, the roughness formed at 0 r/min almost does not change compared to the initial sheet in the horizontal direction of interior surface. When the tool rotation speeds are ranging from 0 r/min to 2000 r/min, roughness increases as the speed increases. However, when the spindle speed exceeds 2000 r/min, R_a decreases as the tool rotation speed increases. Interestingly, different from the horizontal direction, the biggest surface roughness in the vertical direction is at 0 r/min. And then, R_a of the contact surface decreases as the tool rotation speed increases. It is noted that the roughness decreases sharply from 0 r/min to 2000 r/min and decreases slightly from 2000 r/min to 7000 r/min. On the whole, the discrepancy of roughness between horizontal direction and vertical direction decreases with the growing of rotation speeds. Apparently, the spindle speeds have a big influence on contact surface. On the contrary, no obvious effects are found in non-contact surface (Fig.4b).

In order to explain the results obtained, surface topographies are provided in Fig.5. Obvious forming marks in horizontal direction are found in Fig.5a. This explains why there is a big difference on surface roughness between horizontal and vertical direction. When the tool rotates, fish-scale pattern appears on the contact surface. With the increase of rotational speeds, the size of fish-scale decreases, and this is the reason why the value of roughness decreases and the discrepancy of roughness in two directions diminishes. The small vibration during rotation may be the origin of fish-scale pattern, and the interaction between feed rate and spindle speed influences the variation of fish-scale pattern. However, when a part is processed at high rotation speeds, it has a small problem that the graphite powder is more easily pressed into the surface layer of sheets by the rotating tool due to the thermo-softening. The details of hardness variations are discussed in the following section.

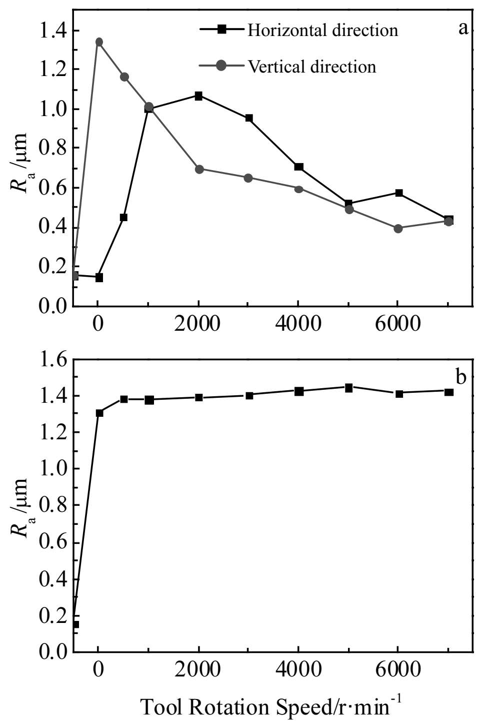

Fig.4 Relationship between surface roughness and tool rotation speed: (a) contact surface (values in horizontal and vertical directions) and (b) non-contact surface (average values of horizontal and vertical directions)

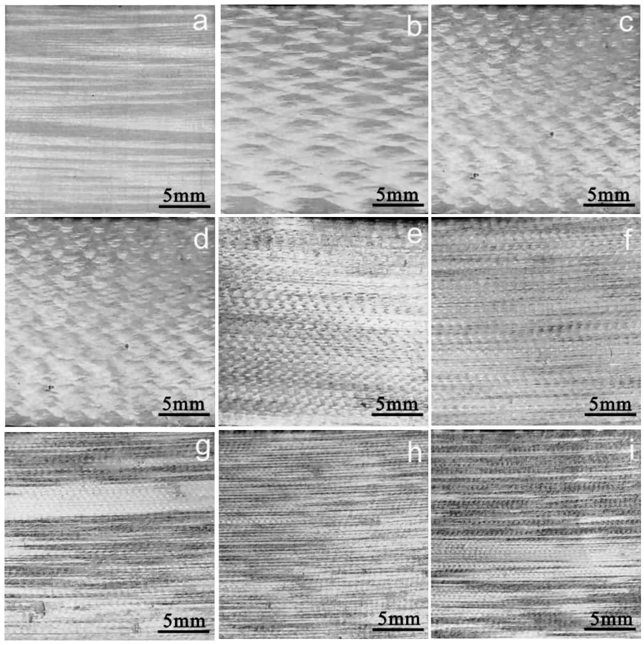

Fig.5 Surface topography of parts formed at different rotation speeds: (a) 0 r/min, (b) 500 r/min, (c) 1000 r/min, (d) 2000 r/min, (e) 3000 r/min, (f) 4000 r/min, (g) 5000 r/min, (h) 6000 r/min, and (i) 7000 r/min

2.3 Mechanical properties of formed parts

Mechanical properties are regarded as a significant and non-ignorable index for structural components manufactured by FSIF. However, they are seldom studied by researchers. Since mechanical properties are greatly affected by forming temperature, it is monitored during the forming process in the present study. In consideration of the changing of deformed area, it is very difficult to obtain the accurate temperature of deformed region. Giuseppina et al[26,27] investigated the temperature distribution in high speed incremental forming. The test result shows that the temperature of the equal height zone is similar. The temperature distributes around the bottom of cup. The further away from the center, the lower the temperature becomes. Therefore, the temperature at the bottom of pyramid frustum was measured as a reference instead of the deformed region. The temperature difference between contact zone and bottom of cup is ascribed to heat conduction and heat convection. Meanwhile, the temperature difference between actual value and measured value is farther extended because the lubricant gathers in the bottom of cup. When the measured value reaches up to 100 °C, the temperature of contact zone is about 15~20 °C higher than measured value. The variety of temperatures in forming process are shown in Fig.6. Meanwhile, to avoid the influence of locations, all samples are selected in analogous locations as shown in Fig.2a. The results of hardness tests and tensile tests are provided in Fig.7 and 8, respectively.

As shown in Fig.6, at 0 r/min, there is a little change in temperature during the forming process. From 500 r/min to 2000 r/min, the temperature before the end of forming is under 100 °C. From 3000 r/min to 7000 r/min, a rapid rising of temperature is found at the beginning of forming process, and then, after a short time of decreasing, the temperature increases steadily. The milling effects occur when the tool moves at the first contour line, which subsequently disappears at the second

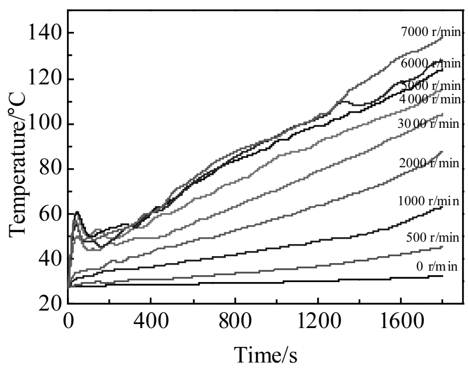

Fig.6 Temperature trends of AA7075-O sheets at different tool rotation speeds

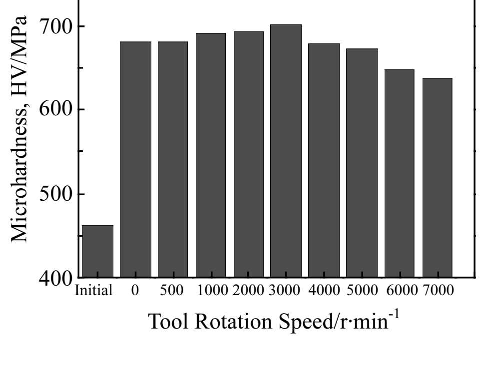

Fig.7 Micro-hardness values of AA7075-O formed parts at various rotation speeds

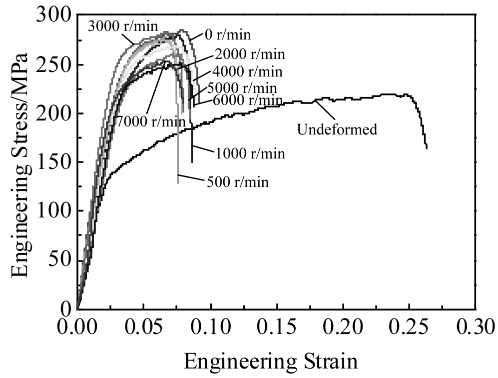

Fig.8 Engineering stress-strain curves of AA7075-O sheets at various rotation speeds

contour line. Interestingly, the same phenomenon is not found when the truncated funnel part is formed.

Fig.7 and 8 show apparent work hardening. When the rotation speed is below 4000 r/min, there is no big difference in mechanical properties for different spindle speeds. Compared to initial undeformed sheet, both of micro-hardness and tensile strength increases by nearly 50% and 28%, respectively. This is because the heat generated by friction is not able to activate the dynamic recrystallization. After the rotation speed reaches 3000 r/min, the friction heat between tool and sheet is enough to initiate the recrystallization. As a result, the mechanical properties decrease as the spindle speed increases. The experimental results are different from the conclusions in Buffa et al[28]. In their work, the microstructure and micro-hardness of AA6082-T6 formed at various rotation speeds were investigated. They pointed out that the average grain diameter and average micro-hardness of parts formed below 6000 r/min have no obvious difference with the parent material. When the rotation speed reaches up to 6000 r/min, both of grain size and micro-hardness decrease evidently. In fact, a microstructure analysis should be done to verify the macro-mechanical performances in the present work. The samples are disposed by different etching solutions at various erosion time, but metallographic figures which have clear crystal boundary are not found. So the grain sizes cannot be worked out to verify the mechanical property. We consider that the crystal boundary may be destroyed during the rolling procedure. The anisotropy of initial sheet is not distinct, so the tensile properties of rolling and transverse directions are similar. In future, a comparative study on tensile property of perpendicular and parallel to tool path will be done, because the part is principally deformed along the direction perpendicular to tool path.

2.4 Thickness distribution

The thickness distribution of parts formed at various rotation speeds is provided in Fig.9. It is noted that measure-ment points are selected from 15 nm to 63 mm since the

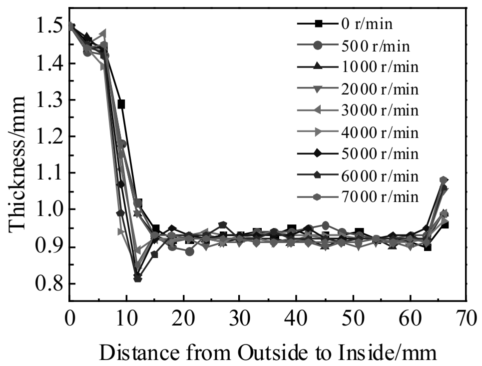

Fig.9 Thickness distribution of parts formed at different rotation speeds

thickness tends towards stability. It can be seen that the thickness distribution of parts formed at high rotation speeds is more uniform than that of parts formed at low rotation speeds, though it is not obvious enough. Generally, the inhomogeneity is due to the obvious thinning at the top of inclined wall. This is because the zones are always under tension in the whole forming process. At high rotation speeds, the deformed zone is at highest temperature compared to other areas, and the existence of temperature gradient leads to different mechanical properties at various locations. So the processing area is easier to deform as it is softer than other locations. The top of inclined wall is not always under a large tensile stress which leads to the uniform thickness distribution. In addition, an abnormality thinning is found at 12 mm due to the milling effects mentioned above.

3 Conclusions

1) The formability of AA7075-O sheets generally enhances as the increase of tool rotation speeds, of which only a little decrease has been witnessed at 1000 r/min.

2) As tool rotation speed increases, the surface roughness shows different trends in horizontal direction and vertical direction on contact surface. In horizontal direction, the roughness firstly increases with the increase of tool rotation speeds (0~2000 r/min), and then decreases with the increase of the rotation speeds (2000~7000 r/min). In vertical direction, the value of roughness always decreases as the rotation speed increases. However, no obvious variation is found in non-contact surface at various rotation speeds.

3) At low tool rotation speeds, the tensile strength and micro-hardness of formed parts are strengthened. However, there is no obvious distinction in parts formed from 0 r/min to 4000 r/min. At high tool rotation speeds, work hardening is also found, but the values of tensile strength and micro-hardness decrease as the rotation speed gradually increases (4000~7000 r/min) due to the influence of recrystallization caused by the friction heat.

4) The thickness distribution is a little more uniform at high rotation speeds than that at low rotation speeds.

References

1 Duflou J R, Callebaut B, Verbert J *et al. CIRP Annals-Manufacturing Technology*[J], 2007, 56(1): 273

2 Duflou J R, Callebaut B, Verbert J *et al. International Journal of Machine Tools and Manufacture*[J], 2008, 48(5): 543

3 Ji Y H, Park J J. *Journal of Materials Processing Technology*[J], 2008, 201(1-3): 354

4 Ambrogio G, Filice L, Manco G L. *CIRP Annals-Manufacturing Technology*[J], 2008, 57(1): 257

5 Fan G Q, Gao L, Hussain G *et al. International Journal of Machine Tools and Manufacture*[J], 2008, 48(15): 1688

6 Su Chunjian, Li Tiantian. *Rare Metal Materials and Engineering*[J], 2015, 44(3): 649 (in Chinese)

7 Ambrogio G, Filice L, Gagliardi F. *Materials and Design*[J], 2012, 34: 501

8 Zhang Q L, Xiao F G, Guo H L *et al. Journal of Materials Processing Technology*[J], 2010, 210(2): 323

9 Liu R Z, Lu B, Xu D K *et al. The International Journal of Advanced Manufacturing Technology*[J], 2016, 85(5-8): 1137

10 Xu D K, Wu W C, Malhotra R *et al. International Journal of Machine Tools and Manufacture*[J], 2013, 73: 37

11 Otsu M, Ichikawa T, Matsuda M *et al. J Jpn Soc Technol Plast*[J], 2011, 52(603): 490

12 McAnulty T, Jeswiet J, Doolan M. *CIRP Journal of Manufacturing Science and Technology*[J], 2017, 16: 43

13 Ham M, Jeswiet J. *CIRP Annals-Manufacturing Technology*[J], 2006, 55(1): 241

14 Le V S, Ghiotti A, Lucchetta G. *International Journal of Material Forming*[J], 2008, 1(S1): 1179

15 Khalatbari H, Iqbal A, Shi X F *et al. Materials and Manufacturing Processes*[J], 2015, 30(11): 1354

16 Obikawa T, Satou S, Hakutani T. *International Journal of Machine Tools and Manufacture*[J], 2009, 49(12-13): 906

17 Bagudanch I, Garcia-Romeu M L, Centeno G *et al. Journal of Materials Processing Technology*[J], 2015, 219: 221

18 Liu Z B, Li Y L, Meehan P A. *International Journal of Precision Engineering and Manufacturing*[J], 2013, 14(11): 1891

19 Durante M, Formisano A, Langella A *et al. Journal of Materials Processing Tech*[J], 2009, 209(9): 4621

20 Bagudanch I, Vivesmestres M, Sabater M *et al. Materials and Manufacturing Processes*[J], 2017, 32(1): 44

21 Al-Ghamdi K A, Hussain G. *International Journal of Precision Engineering and Manufacturing*[J], 2016, 17(12): 1633

22 Hussain G, Gao L, Zhang Z Y. *The International Journal of Advanced Manufacturing Technology*[J], 2008, 37(9-10): 920

23 Hagan E, Jeswiet J. *Proceeding of the Institute of Mechanical Engineers, Part B: Journal of Engineering Manufacture*[J], 2004, 218(10): 1307

24 Echrif S B M, Hrairi M. *Materials and Manufacturing Processes*[J], 2014, 29(6): 697

25 Liu Zhaobing, Liu Sheng, Li Yanle *et al. Materials and Manufacturing Processes*[J], 2014, 29(7): 808
26 Giuseppina A, Claudio C, Luigino F *et al. International Journal of Mechanical Sciences*[J], 2016, 108-109: 39
27 Ambrogio G, Gagliardi F. *The International Journal of Advanced Manufacturing Technology*[J], 2015, 76(9-12): 1819
28 Buffa G, Campanella D, Fratini L. *The International Journal of Advanced Manufacturing Technology*[J], 2013, 66(9-12): 1343

AA7075-O 铝合金板料的摩擦搅拌渐进成形：成形零件性能的实验研究

章桥新[1]，李国豪[1]，刘兆冰[1]，赵安国[1]，熊新红[1]，雷永杰[2]

(1. 武汉理工大学，湖北 武汉 430070)

(2. 中国航天科工集团第九总体设计部，湖北 武汉 430040)

摘 要：用不同的主轴转速来成形 2 种典型零件，研究了 AA7075-O 铝合金板料摩擦搅拌渐进成形零件的综合性能：成形性、表面质量、拉伸性能、显微硬度和壁厚分布。试验结果表明，板料的成形性随着转速增加而呈现增强趋势；接触面的表面粗糙度在水平和竖直方向表现出不同的变化趋势；非接触面的表面质量几乎不受转速影响；相比原板料，成形零件的拉伸性能和显微硬度明显增强，但转速超过 3000 r/min 后，硬度值开始逐步下降；在高转速下成形零件的壁厚分布略微优于低转速下的成形零件。总体上，除了力学性能，高转速下成形零件的综合性能比低转速下的成形零件好。

关键词：摩擦搅拌渐进成形；成形性；表面质量；力学性能；壁厚分布

作者简介：章桥新，男，1961 年生，硕士，教授，武汉理工大学机电工程学院，湖北 武汉 430070，E-mail: 995387947@qq.com