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Periodical plastic flow pattern in friction stir processed Al–Mg alloy

G.R. Cui,[a] Z.Y. Ma[b,*] and S.X. Li[a]

[a]*Shenyang National Laboratory of Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China*

[b]*Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China*

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Onion rings are a prominent feature of the stir zone in many friction stir welded/processed samples. In this paper, a set of equations is proposed to describe the horizontal onion ring patterns that are believed to result from a geometric effect. The calculation indicates that the spacing of the adjacent rings is equal to the advance per revolution. The origin of the onion ring patterns in a longitudinal section consisting of wavy flow patterns is discussed.

Keywords: Friction stir processing; Friction stir welding; Aluminum; Microstructure

Friction stir processing (FSP), a development of friction stir welding (FSW) [1], is a solid-state processing technique. During FSP/FSW, the material undergoes intense plastic deformation at elevated temperature [2]. The semi-circular pattern on the surface of the processed workpiece is called an onion skin and the contrasting bands in the stir zone (SZ) are called onion rings (shown in Fig. 1a). The onion rings are the most prominent feature in most FSW/FSP stir zones, and also are direct evidence of characteristic material transport phenomena during FSW/FSP. However, a convincing explanation in the literature for the formation of the onion rings is still lacking.

In the past few years, several studies have been undertaken to explain the origin of the onion rings, which have been attributed to variations in the grain size [3], second-phase particle-rich bands [4] or texture variations [5]. Biallas et al. [6] suggested that the formation of onion rings was due to the reflection of the material flow from the cooler walls of the heat-affected zone. The induced circular motion led to circles that decrease in radii and formed the tube system. Threadgill [7] proposed that onion ring formation was associated with the forward motion of the tool in one revolution, and the formation process was unlikely to affect the properties of the weld. Based on the above studies, Krishnan [8] suggested that the FSW process could be thought to be simply extruding one layer of semicylinder in one rotation of the tool, and a cross-sectional slice through such a set of semicylinders resulted in the familiar onion ring structure. Recently, Chen and Cui [9] provided more direct evidence for material flow adjacent to the pin, and suggested that the spacing of the onion rings was equal to the tool advance per rotation due to geometrical restriction.

On the relationship between the metal flow and onion rings, Schneider and Nubues [5] suggested that the metal flow field around a FSW/FSP tool could be decomposed into three simple component fields and explained the relationship between plastic flow and the resulting microtextures in the SZ. Although onion ring patterns were reported to vary distinctly with the to-be-welded/processed materials and FSW/FSP parameters, regular and periodical patterns were observed, and the spacing of adjacent onion rings was observed to be the same as the distance traveled during a revolution of the tool. This implies that the onion ring structure observed in the SZ of FSW/FSP samples originates from a geometrical effect due to the rotation and translation of the tool. Chen and Cui [9] gave an explanation on the forming mechanism of the banded structure; however, they only considered the pin–workpiece interaction. For the FSW/FSP process, a tilt angle of the tool is necessary to generate a defect-free SZ, and correspondingly the effect of the shoulder on the SZ should not be omitted.

In this study, a set of equations was developed to describe the formation of the onion rings, and the effect of the shoulder on the formation of the onion rings was discussed.

* Corresponding author. Tel./fax: +86 24 83978908; e-mail: zyma@imr.ac.cn

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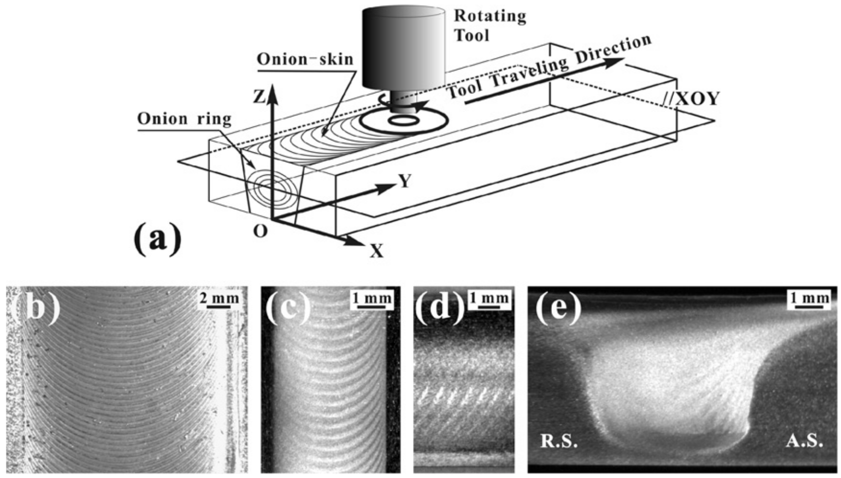

Figure 1. Schematic drawing of FSP and macroscopic images of the SZ in a FSP 5083Al sample: (a) schematic illustration of FSP; (b) onion skin on the surface of a FSP sample; (c) onion rings in the plane ||XOY; (d) onion rings in longitudinal section (YOZ); (e) onion rings in transverse section (XOZ).

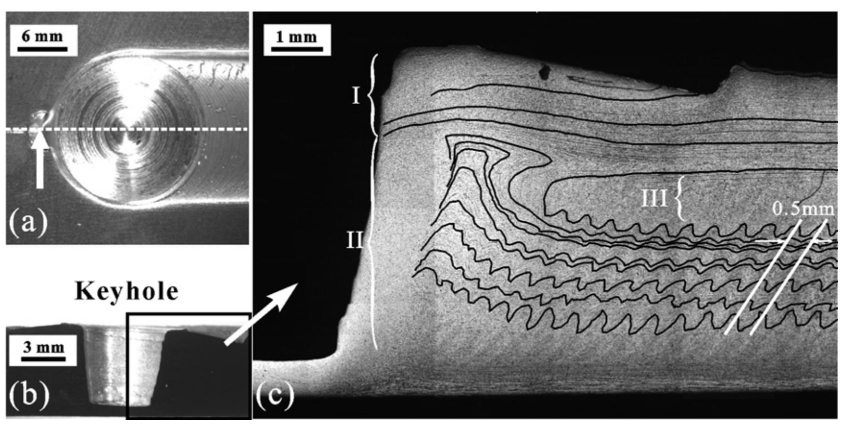

Figure 2. Optical images showing keyhole left after pull-out of pin: (a) top-view of keyhole; (b) longitudinal section of keyhole; (c) magnified view of the region as shown by rectangle in (b).

Commercial 5083 aluminum alloy (H112) with a nominal composition of 4.5Mg–0.8Mn–bal Al (in wt.%) was received in the form of 6.1 mm thick as-rolled plates. The plates were cut into pieces 70×400 mm^2 and were friction stir processed at a travel speed of 200 mm min^{-1} and a rotation rate of 400 rpm, with a tool tilt angle of 3°. The rotation sense was kept counterclockwise. When the tool reached the final point, it stopped moving but kept rotating for 2 s before being pulling out. A H13 steel tool with a shoulder 18 mm in diameter and a threaded (right-handed screw) cone-shaped pin 6 mm in root diameter, 5 mm in tip diameter, and 5.5 mm in length was used.

The SZ was cut along three orientations, i.e. transverse section (XOZ), longitudinal section (YOZ) and horizontal section (||XOY), as shown in Figure 1a. The specimens for optical microscopy and stereoscopy were ground using 2000 grit SiC paper, and electric etched in a 40 ml perchloric acid + 160 ml ethanol solution at room temperature.

Figure 1b–e shows macroscopic views of the SZ in a FSP 5083Al sample. While semi-circular patterns (onion skin) were observed on the surface of the FSP sample (Fig. 1b) and on the horizontal section (||XOY) (Fig. 1c, hereafter called a horizontal onion ring), slantwise lines were visible on the longitudinal section (Fig. 1d). The spacing of these semi-circular rings or slantwise lines was measured to be 0.5 mm. This value is simply the advance of the tool per revolution, i.e. the ratio of the travel speed to the rotation rate. A basin-shaped SZ which widened near the upper surface

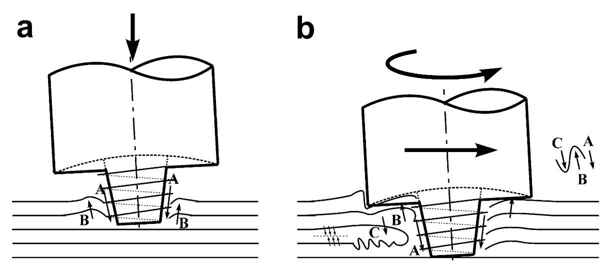

Figure 3. Schematic illustration of flow fields during FSP/FSW when (a) pin is being plunged into workpiece and (b) pin has been completely plunged into workpiece (arrows A, B, and C denote the material flow directions).

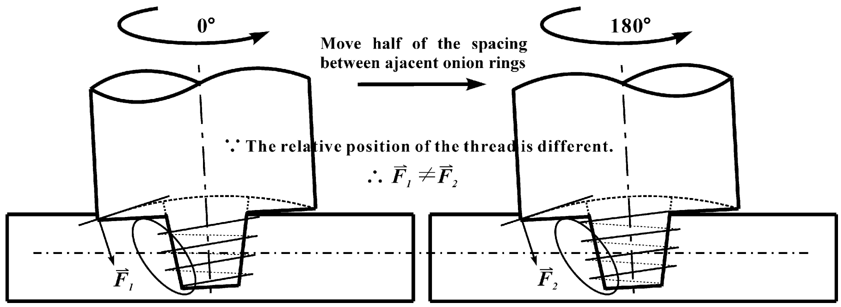

Figure 4. Schematic illustration of variation in stress state under a rotating pin after a half a revolution due to the change in relative position of the thread.

was observed on the transverse section with the onion rings (Fig. 1e). However, the onion rings were less pronounced on the retreating side of the SZ.

Figure 2 shows the top-view and longitudinal section macrostructures of the keyhole. Some flow lines are highlighted in black to better illustrate the morphology. The spacing between two adjacent wave crests corresponds to the advance of the tool in one full revolution (0.5 mm). The SZ adjacent to the keyhole could be divided into three zones by the morphologies of the flow lines: Zone I, affected only by the shoulder, where the flow lines were almost parallel to the bottom of the shoulder; Zone II, affected only by the pin, where the onion rings in the metallographs consisted of wavy flow lines; Zone III, affected by the shoulder and the pin, where the flow lines were caused by the combined effect of the shoulder and the pin, and the flow lines were not clear (Fig. 1d). The flow lines could not be seen in the metal around the keyhole, and this could be caused by the continuous rotation of the tool for 2 s before pulling out.

The flow fields around the keyhole shown in Figure 2 apparently could be divided into three characteristic zones according to the flow pattern, and they are easily connected with the origin of the deformation driving force. An explanation was made for the origin of the wavy flow lines and Zone III, and a schematic illustration is shown in Figure 3. The horizontal straight lines in Figure 3 indicate the unprocessed workpiece, and the curves around the tool indicate the deformation flows in the longitudinal section. When the pin was plunged into the workpiece as shown in Figure 3a, the metal adjacent to the pin flowed downward (indicated by arrow A) due to the effect of the thread, and meanwhile, the surrounding metal would be extruded upwards, as indicated by arrow B. When the pin was entirely plunged into the workpiece and the underside of the shoulder contacted the surface of the deformed metal, the metal flow upward was extruded downward by the shoulder, as indicated by arrow C (Fig. 3b). Under the combined effects of flows A, B and C, the wavy flow pattern was formed in the area away from the pin. The onion ring patterns visible in the longitudinal section consisted of such wavy flow patterns. Zone I was composed of horizontal flow lines caused by the shoulder, whereas the wavy flow line area caused by the combined action of the shoulder and the thread produced Zone II. In Zone III, the upward and downward flows were closely balanced, and the effects of the horizontal flow pushed by the shoulder could not touch this area, so there were no apparent horizontal or wavy flow lines.

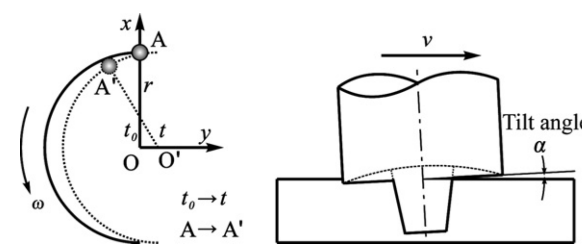

Figure 5. Schematic drawing for deriving Eq. (1), at time t_0, the trace is point A, after a while, at time t, the trace point will be A'.

The thread of the pin changed its relative position during the rotation, as shown in Figure 4, in which the space between the underside of the shoulder and the thread is definitely different, and correspondingly the stress state changed too. This periodical variation of the stress state resulted in the periodical variation of surface height (caused by the shoulder), thereby producing the fluctuating surface pattern, i.e. the onion skin pattern. In the same way, the onion rings in the SZ are also produced by the periodical variation of the stress state caused by the pin and the shoulder.

From the above analyses, these regular semi-circular patterns – onion skin and onion rings – can be easily described by mathematically. It is assumed that the onion skin was the travel trace of one point on the edge of the shoulder. The corresponding equations can then be written as

$$\begin{matrix} x = r\cos\omega t_{\mathrm{m}} \\ y = (vt_{\mathrm{m}} - r\sin\omega t_{\mathrm{m}})\cos\alpha \end{matrix} \quad (t_{\mathrm{m}} = t + 2(n-1)\pi/\omega,\ \ 0 \leqslant t \leqslant \pi/\omega,\ \ n = 1,2,3\ldots), \tag{1}$$

where x and y are the coordinates of the pattern, v is the travel speed (mm min^{-1}) of the tool, t_{m} is the time for

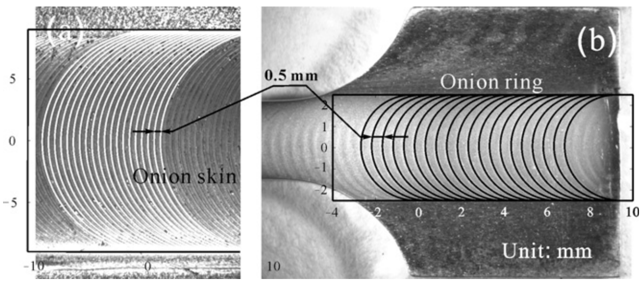

Figure 6. Good agreement between predicted curves and experimental observations: (a) onion skin on top surface of FSP sample; (b) onion ring on horizontal section in middle of sample (semi-circular lines represent the prediction by Eq. (1)).

formation of the nth onion skin/ring, r is the radius of the tool shoulder (for the onion skin) or the radius of the onion ring, ω is the rotation rate (rpm) of the tool, and α is the tilt angle. As shown schematically in Figure 5, at time t_0, the trace of point is A; after a while, at time t, the trace will be A'. The pattern in the SZ is actually a three-dimensional (3-D) configuration. The observed pattern is the projection of the 3-D configuration on the plane parallel to XOY. Since the tilt angle α is in the YOZ plane, the coordinate of the pattern along Y should be modified by $\cos\alpha$ as shown in Eq. (1).

For the onion skin on the processed workpiece surface in this study, substituting the parameters ($2r = 18$ mm, $v = 200\ \mathrm{mm\ min^{-1}}$, $\omega = 400\ \mathrm{rad\ min^{-1}}$, and $\alpha = 3°$) into Eq. (1), it is found that the predicted curves (white curves in Fig. 6a) fit the onion skin patterns very well. For the horizontal onion rings in the plane parallel to XOY, we assumed that the radius of the semi-circular material flow is equal to the radius of the horizontal semi-circular onion rings; then, substituting the radius of the onion ring (2.5 mm) and other parameters mentioned above into Eq. (1), the predicted curves (black curves in Fig. 6b) are in good agreement with the circular onion rings. These results indicate that the semi-circular feature in the interior of the FSP samples was formed due to the deformation flow as with the top surface of the SZ.

The time taken for the tool to rotate one revolution is

$$t = 2\pi/\omega. \qquad (2)$$

Substituting Eq. (2) into Eq. (1), we obtain the spacing between two adjacent semi-circular lines along the y direction as

$$D = v \cdot (2\pi/\omega) \cdot \cos\alpha. \qquad (3)$$

Considering that α is small, so that $\cos\alpha \approx 1$, then Eq. (3) simplifies to

$$D = v \cdot (2\pi/\omega). \qquad (4)$$

In Ref. [8], the experimental relationship between the spacing of semi-circular features and the processing parameters (rotation rate and travel speed) was discussed. The prediction according to Eq. (4) is consistent to the experimental data reported in Ref. [8].

In this study, the onion skin pattern on the surface of the FSP/FSW workpiece is attributed to the mechanical shaking effect caused by the variation in the stress state of the deformed metal due to the tool rotation. In addition, onion rings are not formed only by the pin, and shoulder effects should not be neglected. Flow fields around the keyhole can be divided into three characteristic zones by the flow patterns. A set of equations was established to provide a 2-D description of the horizontal onion ring pattern or onion skin, and these predicted that the spacing of the onion rings is equal to the advance of the tool per revolution.

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[1] W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Templesmith, C.J. Dawes, GB Patent Application No. 9125978.8, December 1991.
[2] R.S. Mishra, Z.Y. Ma, Mater. Sci. Eng. R 50 (2005) 1.
[3] H. Jin, S. Saimoto, M. Ball, P.L. Threadgill, Mater. Sci. Technol. 17 (2001) 1605.
[4] M.A. Sutton, B. Yang, A.P. Reynolds, R. Taylor, Mater. Sci. Eng. A 323 (2002) 160.
[5] J.A. Schneider, A.C. Nunes, Metall. Mater. Trans. B 35 (2004) 777.
[6] R.B.G. Biallas, C.D. Donne, G. Staniek, W.A. Kaysser, in: Proceedings of the 1st International Symposium on Friction Stir Welding, Thousand Oaks, CA, 1999.
[7] P.L. Threadgill, Friction Stir Welding—State of the Art, TWI Report 678/1999.
[8] K.N. Krishnan, Mater. Sci. Eng. A 327 (2002) 246.
[9] Z.W. Chen, S. Cui, Scripta Mater. 58 (2008) 417.