Crystallographic Dependence on Deformation Characteristics of Friction Stir Processed Pure Aluminum

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Anisotropic deformation behaviors of the friction stir processed dynamic recrystallized commercial pure aluminum alloys were studied in this study. Recrystallized and refined grain size can be acquired after friction stir process is conducted. However, this is not guaranteed of isotropic deformation characteristics. Microhardness profile within the friction stir processed region is crystallographic orientation dependence. This dependence is manifested properly by the corresponding average Taylor factors.[doi:10.2320/matertrans.M2012356]

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1. Introduction

It is well known that recrystallized and refined structures are essential to improve performance.1,2) Friction stir process (FSP) combines both thermal and mechanical treatments which facilitates dynamic recrystallization,1,3) FSP is favorable to modify structures for its efficiency. Refined structures can be obtained by FSP with single pass instead of multiple procedures by other process (such as equal channel angular extrusion (ECAE), accumulated rolled bonding (ARB)). Microstructural features correlate tightly with corresponding properties. Consequently, it is meaningful to investigate structural features produced by FSP. Many studies4-21) devote to exploring microstructures of friction stir processed (FSPed) aluminum alloys, such as grain size,8,9,16,18) dislocation structures,6-8,13) precipitates,14,17,19) grain boundary characteristics,4,10,21) crystallographic orientation.4,5,8,11,12,15,20) Variations in mechanical properties of FSPed aluminum alloys can usually be explained in terms of certain of abovementioned microstructural evolutions.

According to our previous research,22) orientation gradients were observed in stir zone (SZ). However, tensile flow curves of specimens which were tested perpendicular to processing direction exhibited similar behaviors in spite of different orientation distributions. It is instructive to wonder whether orientation plays a role in deformation. Besides, references23-25) reported that FSP would improve formability of aluminum alloys by modified structures. The region where had been modified by FSP often experiences strain both along or across processing direction as manufacturing or stretching.23-25) Consequently, the effect of crystallographic orientation on deformation behaviors should be clarified. Nevertheless, the influence of orientation features on deformation characteristics is rare reported for FSPed aluminum alloys. To diminish other microstructural factors but crystallographic orientation in deformation behaviors, we selected AA1050 commercial pure aluminum alloy as experimental material in this study.

2. Experimental Procedures

A thickness of 7 mm as received cold rolled AA1050 aluminum alloy sheets were in H14 strain-hardened condition and chemical composition (in mass%) is 0.16 Cu–0.03 Mn–0.03 Fe–0.02 Zn–0.01 Si. These sheets were subsequent given a heat treatment at 450°C for 10 h to be fully annealed samples. FSP was operated with a constant rotation speed of 841 rpm and downward pressure of 50 MPa but with two different feeding speeds of 1.1 and 3.4 mm/s, respectively. The diameter of shoulder of rotation tool is 20 mm while that of the stirring probe is 12 mm. In addition, the length of the stirring probe is 5 mm. These parameters are determined to produce defect-free FSPed materials in present study. To understand whether the orientation dependence is a common phenomenon or not; therefore, we adopted two different but adequate feeding speeds. Samples conducted with the slower speed were abbreviated as O-FSP1.1 while the faster ones were termed as O-FSP3.4. Present authors define five consecutive regions (C-5.0AS, C-2.5AS, C-0, C-2.5RS and C-5.0RS) were defined and dimensions of each region were given in a unit of mm.

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dimensions and locations of each region; in addition, relations between PD, ND and TD is also shown there. These regions were labeled as C-5.0AS, C-2.5AS, C-0, C-2.5RS and C-5.0RS from advancing side (AS, in which the rotation direction is consistent with processing direction) to retreating side (RS, where the rotation direction is contrary to processing direction). Here, the capital C represents the center of SZ and the subsequent number is the distance (mm) of the section away from the center of SZ towards AS or RS. For example, C-5.0RS means the section is 5 mm away from center SZ toward RS, and so on. Dimensions of these samples were about 2.5 mm in width, 10 mm in length and 3.5 mm in thickness, as indicated in Fig. 1. These samples were prepared consistent with each other as can as possible. Vickers hardness (HV) was tested on TD planes of abovementioned five sections (here, the plane normal of TD plane is transverse to the processing direction of FSP, and ND is identical to the plane normal of original rolling plane). The microhardness was tested with a ten-second dwell time at 25 g with a 0.5 mm separation. To acquire a convinced and statistical meaningful representative, hardness of each TD plane is shown by the average of 40 experimental results. The orientation data of each region was detected by X-ray diffraction and samples are large enough (three specimens were extracted from the same region then combined with each other) to ensure sufficient signal to be collected. Moreover, the orientation data had been corrected by pure aluminum powder for further analyzing. Taylor factor (M) is an appropriate connection between orientation and hardness. For multiple orientation aggregation in SZ of FSPed aluminum samples,4,12,15,22) it is proper to adopt average Taylor factor (\( M \)) to quantify crystallographic influence on hardness of each region in present study. The calculation procedure of \( M \) is demonstrated in appendix.

3. Results and Discussions

Microhardness profile of TD planes of each region within SZ are indicated in Figs. 2(a) and 2(b). There are some similar phenomena can be obtained even though a three-fold difference in feeding speed is conducted. Both O-FSP\(_{1.1}\) and O-FSP\(_{3.4}\) exhibit discernible variations in microhardness across SZ. C-0 regions exhibit the maximum average microhardness while the minimum value occurs in C-5.0RS (for O-FSP\(_{1.1}\)) or C-5.0AS (for O-FSP\(_{3.4}\)). Regarding a distinct hardness distribution in SZ, we may infer that some microstructural issues contribute this phenomenon.

Hall–Petch equation\(^{26,27}\) describes how a change in grain size affects tensile yield stress and is presented as:

\[
\sigma_y = \sigma_0 + k \gamma d^{-1/2}
\]

A relationship of \( H_V \propto 3 \sigma_y \) when appreciable strain hardening is absence, in which \( H_V \) and \( \sigma_y \) are Vickers hardness and tensile yield stress, respectively. As Hall–Petch equation is adopted to delineate hardness and eq. (1) can be converted into the following one:\(^{18}\)

\[
H_V = H_0 + k_1 d^{-1/2}
\]

Equations (1) and (2) are descriptions of deformation resistance and microstructural features. Constants \( \sigma_0 \) and \( H_0 \) are significant to depict variations in deformation resistance when grain size rarely changes. \( \sigma_0 \) is tensile friction stress as dislocations are moving within polycrystal grains and it depends on several factors, such as deformation temperature,\(^{2,29}\) dislocation density,\(^{30}\) concentration of solute atoms\(^{30}\) and crystallographic orientation\(^{29,30}\) etc. As orientation is the only concern among materials (other factors remain identically), \( \sigma_0 \) can be presented as \( \sigma_0 = M \tau r \) where \( M \) is Taylor factor and \( r \) is shear stress applied on effective slip system. In this study, hardness profile can be seen as a function of \( H_0 \) because of little difference in grain size which was produced at constant feeding speed. By the similarity of eqs. (1) and (2) as well as the dependence of \( \sigma_0 \) on orientation, \( \sigma_0 = M \tau r \) is a constant. It is reasonable to introduce \( H_0 \) to elucidate variations in hardness with average Taylor factor (\( M \)). Considering the ratio of hardness to tensile yield strength is not always consistent with a factor of \( 3^{21} \) and the existence of orientation dependence on hardness,\(^{33,34}\) We proposed that \( H_0 \) can be presented as \( H_0 = c M \tau r \) where \( c \) is a constant.

The corresponding TD \( M \) of each section is plotted in Fig. 3(a) for O-FSP\(_{1.1}\) and Fig. 3(b) for O-FSP\(_{3.4}\). The minimum value of O-FSP\(_{1.1}\) and O-FSP\(_{3.4}\) occurs in regions away from central SZ (C-5.0RS or C-5.0AS) and an ascending trend is performed as toward C-0 regions. Only an exception is found in O-FSP\(_{1.1}\) in which C-2.5AS possesses a lower \( M \) of 3.02 than the value of 3.30 in the adjacent region of C-5.0AS. The minimum \( M \) of O-FSP\(_{1.1}\) takes place in C-5.0RS and the corresponding value is 2.70 while O-FSP\(_{3.4}\) exhibits a minimum \( M \) of 2.89 in C-5.0AS.
The maximum $\bar{M}$ of O-FSP$_{1.1}$ and O-FSP$_{3.4}$ are both in C-0 sections and the correlate $\bar{M}$ is 3.50 and 3.61, respectively. According to the relation of $H_0 = c\bar{M}$, we can expect that average hardness relates with $\bar{M}$ to a certain extent. In order to clarify orientation dependence on hardness profile, Fig. 4 is constructed by a coordinate of $\bar{M}$ and average hardness of each region. In addition, the results of linear regression of these two properties are also given in Fig. 4. Relation coefficients ($r$) are 0.659 for O-FSP$_{1.1}$ and 0.822 for O-FSP$_{3.4}$. Comparison between Figs. 4(a) and 4(b), the somewhat poor linearity of O-FSP$_{1.1}$ can be explained in a view of disturbance from other microstructural characteristics. Chen et al. reported that a slower feeding speed promotes the formation of more apparent interchanged fringes result from different degrees of deformation and retained dislocations. A slower speed accompanies a higher heat input which diminishes density of retained dislocations and leads to a distinct hardness drop in FSPed materials. These structural issues interfere with the dependence of orientation on microhardness. Contrary to O-FSP$_{1.1}$, O-FSP$_{3.4}$ encounters less significant structural influence and this contributes to an excellent relation coefficient of 0.822. Considering the qualified relation coefficient ($r$) for both O-FSP$_{1.1}$ and O-FSP$_{3.4}$, this provides that orientation is an essential factor which involves in deformation resistance of the FSPed aluminum alloys.

4. Conclusions

Friction stir processed commercial pure aluminum exhibits orientation aggregation and the concomitant influence is examined in present study. The correlation of orientation and deformation resistance was investigated quantitatively. The meaningful relation coefficient ($r$) of average Taylor factor ($\bar{M}$) and average microhardness provides that the orientation plays a considerable role in deformation.

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Appendix

$\bar{M}$ is resultant of individual orientations and can be calculated as following:

$$\bar{M} = \frac{\sum M_i I_i}{\sum I_i}$$

where $M_i$ and $I_i$ are corresponding Taylor factor and intensity of orientation $i$. For simplification, the orientation $i$ is counted for calculation as long as its intensity is stronger than a quarter of the maximum intensity ($I_i > I_{\text{max}} \times 25\%$) or it is neglected. The $\bar{M}$ processed by this principle is almost identical to that one calculated including all orientations, i.e., this criterion is verified. Calculation of $\bar{M}$ of each region (C-5.0AS, C-2.5AS, C-0, C-2.5RS and C-5.0RS) is made up of two steps. First, we calculate $M_{\varphi_2}$ for a specify $\varphi_2$ sectioned Euler space. As completing all 19 $M_{\varphi_2}$ ($0^\circ \leq \varphi_2 \leq 90^\circ$, $\Delta \varphi_2 = 5^\circ$) in one of five consecutive regions, the $\bar{M}$ is calculated by the weight of intensity of each $\varphi_2$ section. The calculation procedure is shown as following.
\[ M_{\varphi_2} = \sum \frac{M_i l_j}{\sum l_j}, \quad \sum l_j = I_{\varphi_2}, \quad \varphi_2 = \text{const.} \]
\[ \bar{M} = \sum \frac{M_{\varphi_2} I_{\varphi_2}}{\sum I_{\varphi_2}}, \quad 0^\circ \leq \varphi_2 \leq 90^\circ, \quad \Delta \varphi_2 = 5^\circ \]

At a constant \(\varphi_2\) sectioned Euler space, above mentioned \(M_i\) and \(l_j\) are the corresponding Taylor factor and intensity of orientation \(j\).

REFERENCES