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Friction stir incremental forming of A2017 aluminum sheets

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Abstract

Formability of A2017-T3 aluminum alloy sheets by friction stir incremental forming was studied. A2017-T3 aluminum alloy sheets with a size of 100 mm x 100 mm x 0.5 mm were formed into frustum of pyramid shape having 40 mm x 40 mm right square bottom by a hemispherical tool with a diameter of 6 mm. Formability was evaluated by formable wall angle. When the tool rotation rate was 8000 - 10000 rpm and the tool feed rate was 3000 mm / min, the formability became maximum and the minimum wall angle was 25 °. Formed sheets were artificially aged and Vickers hardness test was performed to confirm the effect of temperature elevation during forming. The hardness of the formed sheets was increased due to the work hardening. As aging time increased, however, the hardness was decreased by over aging. The tensile strength of formed sheet was the intermediate value between as received and over aged ones. The fracture elongations of formed sheet after giving 69% logarithmic strain was a little less than as received one but greater than aged one.

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Keywords: Friction stir incremental forming; A2017 aluminum sheets; Strength; Hardness; Microstructure

1. Introduction

In order to reduce weight of various industrial products, application of light metals such as titanium alloys, aluminum alloys and magnesium alloys is expanding. At the same time, development of technology for small lot production is required in industry. Die less forming is one of the candidates for the solutions. Incremental forming process (Jeswiet et al. (2005)) is a kind of die less forming methods for sheet metals. Incremental forming can form

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pure aluminum sheets into three-dimensional shape with large deformation, however, it is difficult to form high strength aluminum alloy and other light metals sheets. To improve formability of those hard-to-work metal sheets by incremental forming method, the authors developed friction stir incremental forming method. By the use of friction stir incremental forming method, A5052 aluminum alloy (Otsu et al. (2010)), magnesium alloys (Otsu et al. (2011)) and pure titanium (Otsu et al. (2012)) sheets can be formed. A2017 aluminum alloy, which is well used for aircrafts, business case and so on, is age-hardenable alloy. In friction stir incremental forming, the maximum temperature during forming becomes more than 250 ºC and the precipitate for strengthening of A2017 aluminum alloy may be change and mechanical properties may be lowered.

In the present study, A2017 aluminum alloy sheets were formed by friction stir incremental forming. Formable working conditions were studied. Observation of microstructure, hardness test, tension test for formed sheet were also carried out.

Nomenclature

t	thickness of specimen sheet
v	tool feed rate
θ	wall angle
ω	tool rotation rate

2. Experimental method

A2017-T3 aluminum allloy sheets were used for specimen. The chemical composition of used material is shown in Table 1. The size of the specimen sheet was 100 mm x 100 mm and the thickness of the sheet was 0.5 mm. Photo of forming equipment is shown in Fig. 1. A 3-axes NC milling machine (Roland DG, MDX-540) was employed for forming. A hemispherical tool with a diameter of 6 mm and made of high speed steel was used. Specimen sheet was put on a die and fixed by a blank holder with bolts.

Table 1. Chemical composition of used material.(wt.%)

Element	Cu	Mg	Si	Cr	Fe	Mn	Zn	Ti	Al
A2017	4.08	0.66	0.57	0.03	0.27	0.65	0.10	0.02	Bal.

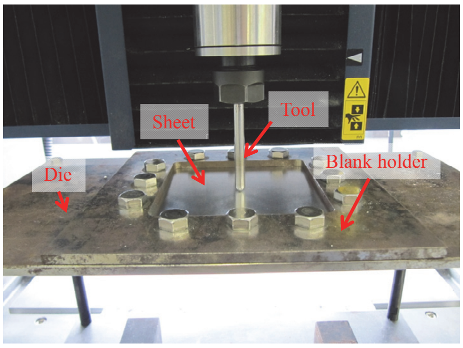


Fig. 1. Appearance of forming equipment.

The forming tool was moved in a pitch of 0.5 mm as shown in Fig. 2. The sheets were formed into frustum of pyramid shape having 40 mm x 40 mm right square bottom. Formability was evaluated by changing a wall angle of pyramid, θ, as shown in Fig. 3. In this case, formability is greater when the formable wall angle is smaller. The formability was investigated by changing a tool rotation rate and a tool feed rate. Microstructure of formed sheet was observed by scanning ion microscope. After forming, heat treatment for artificial aging was conducted and hardness change was measured. Tension test of formed sheet were also carried out.

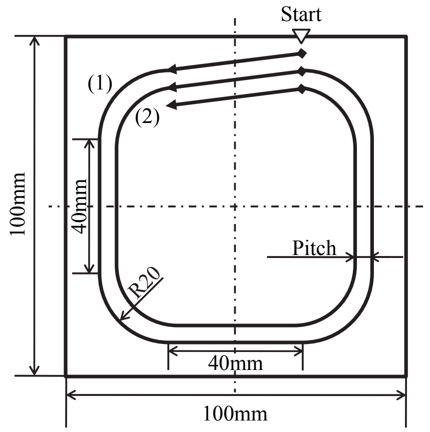


Fig. 2. Forming path and sequence.

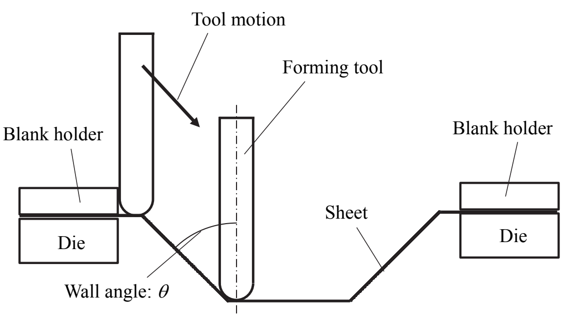


Fig. 3. Definition of wall angle.

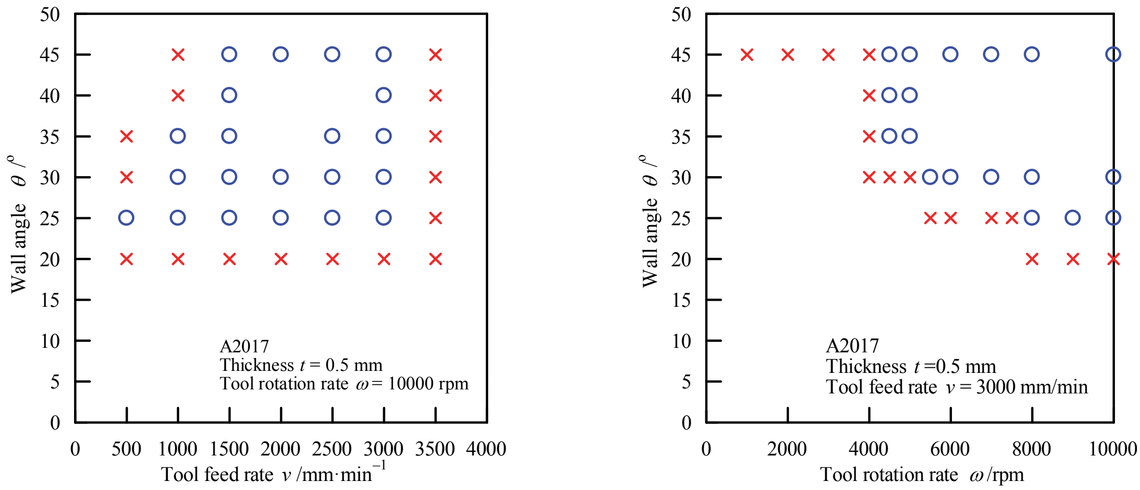
3. Results and discussions

3.1. Formable working conditions

Effect of the tool rotation rate and tool feed rate on formable wall angle were shown in Fig. 4. In Fig. 4(a), the tool rotation rate was fixed to ω = 10000 rpm and the tool feed rate were changed. In Fig. 4(b), the tool feed rate was fixed to v = 3000 mm/min and the tool rotation rate was changed. In both figures, open circle marks indicate that the forming was succeeded without fracture and cross marks mean that the sheet was broken during forming.

In the case of the maximum formability, the tool rotation was 8000 - 10000 rpm and the tool feed rate was 500 - 3000 mm/min, and the wall angle was θ = 25 º in accordance with 137% elongation in tension test. Since the fracture elongation by tension test of this sheet was only 5 %, the ductility of the sheet was improved significantly.

In Fig. 4(a), the forming was impossible when the tool feed rate was greater than 3500 mm/min. When the tool feed rate was from 1500 to 3000 mm/min, no difference of the formable wall angle was observed and sensitivity of the tool feed rate was small. In Fig. 4(b), the formable wall angle can be small until θ = 25 º when the tool rotation rate was greater than ω = 5500 rpm. In addition, the formable wall angle can be small until θ = 30 º when the tool rotation rate was greater than ω = 8000 rpm. It can be said that the tool rotation rate affects formability more than the tool feed rate.



(a) (b)

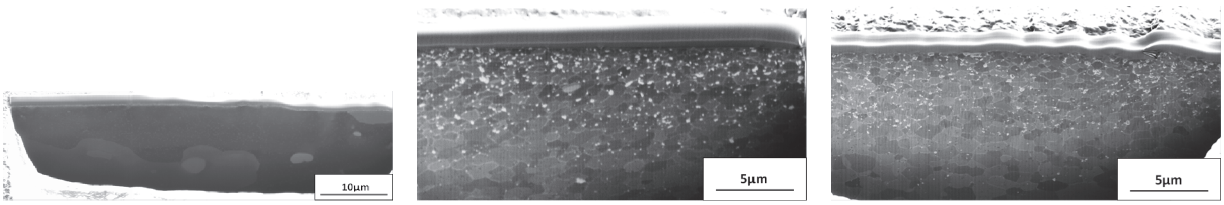
Fig. 4.(a) effect of tool rotation rate on formable wall angle. (ω = 10000 rpm), (b) Effect of tool feed rate on formable wall angle. (v = 3000 mm/min)

3.2. Observation of microstructure

Cross-sectional images of scanning ion microscope are shown in Fig. 5. As received material is shown in Fig. 6(a), and the cross sections parallel and perpendicular to the tool travel direction are Fig. 5(b) and Fig. 5 (c), respectively. The sheet was formed at the tool feed rate of v = 3000 mm/min, the tool rotation rate of ω = 10000 rpm and the wall angle of θ = 25 º.

In the case of as received material (Fig. 5(a)), contrast in the grains are almost uniform and dislocation is eliminated by T3 processing. It seems that the material has very large grains because each grain boundary cannot observed clearly.

In the case of formed sheet by friction stir incremental forming (Figs. 5(b) and (c)), equiaxed grains were observed in almost all area. The grain size at near the formed surface was about 500 nm, and became larger as the distance from the formed surface becomes longer and was about 1 μm at the area enough far from the formed surface. In addition, some voids and impurities between the grains were found near the formed surface. It is considerable that grain boundary separation may be occurred or oxide film generated during forming may be taken in by mechanical stirring.



(a) (b) (c)

Fig. 5. Cross-sectional images of scanning ion microscope (v = 3000 mm/min, ω = 10000 rpm, θ = 25 º) (a) before forming, (b) parallel to tool travel direction and (c) perpendicular to tool travel direction.

3.3. Hardness

Results of Vickers hardness test for as received and formed sheets are plotted in Fig. 6(a). The hardness of as received sheet is 120 HV, however, that formed at v = 3000 mm/min, ω = 6000 rpm and θ = 30 º was a little increase to 125 HV. This reason is considerable that although static or dynamic recrystallization, or recovery may be happened at almost formed part, work-hardened part remained and hardness was increased by grain refinement. But in another working conditions, the hardness of formed sheets became smaller. This is considerable that since the tool rotation rate was large (ω = 10000 rpm), heat generation was large and the grain size became larger due to temperature elevation. The hardness reduction at the formed area is also reported for friction stir welding. (Peel et al. (2003))

The sheet temperature during forming measured by thermo-couple at the reverse side surface became more than 250 ºC. Since A2017 aluminum alloy is age-hardenable alloy, strengthening mechanism may be eliminated by being high temperature during forming. If age-hardening mechanism was lost, artificial aging process is required after forming. To confirm remaining age-hardening mechanism, the formed sheets were processed for artificial aging at 275 ºC, and change of hardness was measured. The result of change of hardness is plotted in Fig. 6(b). As aging time became longer, the hardness decreased gradually. This means G.P. zone and intermediate phase remain and the material become state of over aging and the strengthening mechanism is not eliminated.

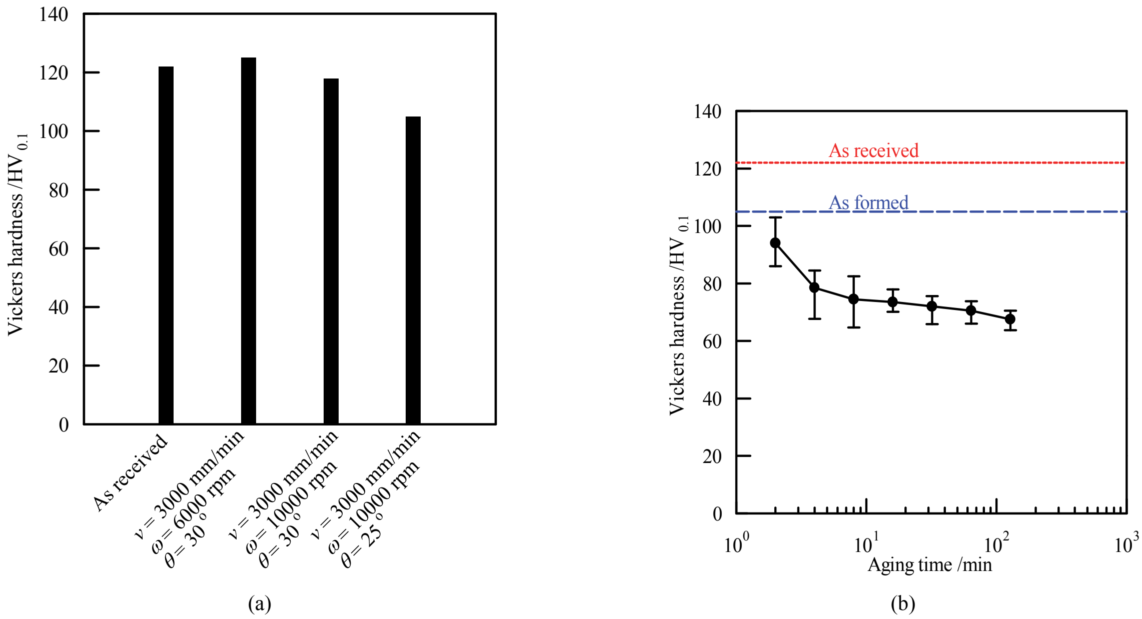


Fig. 6. (a) Vickers hardness, (b) hardness change by artificial aging.

3.4. Tensile strength and fracture elongation

Fig. 7 illustrates the stress-strain curves of as received, formed and completely aged sheets. The tensile strength and fracture elongation of as received sheet were 373 MPa and 5.3 %, respectively. Those of completely aged sheet were 200 MPa and 3.3 %. Those of sheet formed at v = 3000 mm/min, ω = 10000 rpm and θ = 30 º was 285 MPa and 4.8 %, and they are a little smaller than those of as received sheet. This reason is considerable that some voids and impurities between the grains exist. The strength and elongation of sheet formed at v = 3000 mm/min, ω = 6000 rpm and θ = 30 º were 320 MPa and 7.8 %, respectively. The elongation was greater than that of as received one. This is very surprising because superior elongation appeared after giving 69% logarithmic strain by forming. This is considerable that the grains were refined by mechanical stirring and dislocations were eliminated by occurring dynamic recrystallization, and then the elongation was improved.

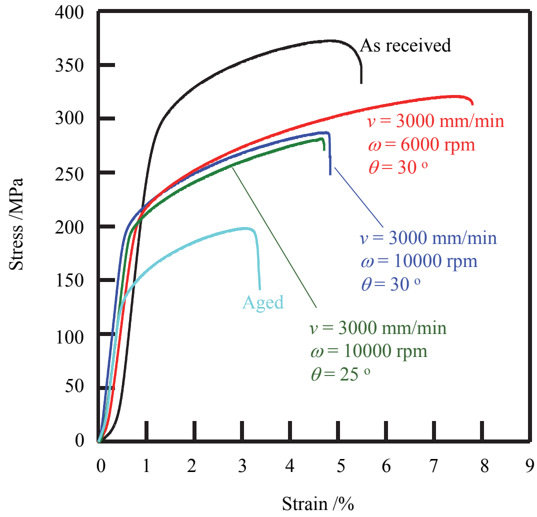


Fig. 7. Stress-strain curves of as received, formed and aged sheets.

4. Conclusions

Formability of A2017-T3 aluminum alloy sheets by friction stir incremental forming was investigated. When the tool rotation rate was 8000 - 10000 rpm and the tool feed rate was 3000 mm/min, the formability became maximum and the minimum wall angle was 25 º. Formed sheets were artificially aged and Vickers hardness test was performed to confirm the effect of temperature elevation during forming. It is confirmed that the pre-aging processing was not initialized or over aging was not completed by forming. The tensile strength of formed sheets were intermediate between as received and over aged ones. The fracture elongations of formed sheet after giving 69% logarithmic strain was a little less than as received one but greater than aged one. From the results of the microstructure observation, the grains were refined to less than 1 μm by forming. Some voids and impurities between the grains were found near the surface which contacted to the forming tool.

Acknowledgements

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References

[1] Jeswiet, J., Micari, F., Hirt, G., Bramley, A., Duflou, J., Allwood, J., 2005. Asymmetric single point incremental forming of sheet metal. CIRP Annals – Manufacturing Technology, 54(2), pp. 88–114.

[2] Otsu, M., Matsuo, H., Matsuda, M., Takashima, K., 2010. Friction Stir Incremental Forming of Aluminum Alloy Sheets. Steel Research International 81(9), pp. 942–945.

[3] Otsu, M., Ichikawa, T., Matsuda, M., Takashima, K., 2011. Improvement of Formability of Magnesium Alloy Sheets by Friction Stir Incremental Forming. Steel Research International Special Edition, pp. 537–541.

[4] Otsu, M., Arai, H., Matsuda, M., Takashima, K., 2012. Friction Stir Incremental Forming of Titanium Sheets. Steel Research International, Special Edition , pp. 419–422.

[5] Peel, M., Steuwer, A., Preuss, M., Withers, P.J., 2003. Microstructure, mechanical properties and residual stresses as a function of welding speed in aluminium AA5083 friction stir welds, Acta Materialia, 51, pp. 4791–4801.