

# Excellent Formability of Light Metals Sheets by Friction Stir Incremental Forming

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# Excellent Formability of Light Metals Sheets by Friction Stir Incremental Forming

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**Abstract.** The results about friction stir incremental forming of light metals sheets from the beginning of development to the latest in the author's laboratory are introduced. Comparison of formability by the conventional single point incremental sheet metal forming and friction stir incremental forming for magnesium alloys, aluminum alloys and titanium sheets were introduced. Effect of tool rotation direction, multistage forming and double side forming are also introduced.

## Introduction

To reduce energy consumption and emission of CO<sub>2</sub> in automotive industry, light metals are increasingly used for body parts. Light metals such as aluminum alloys and magnesium alloys are difficult to deform at room temperature due to their poor ductility. Since those materials have low ductility at room temperature, it is necessary to deform plastically at elevated temperature. Because of their high thermal conductivity, heating method before or during forming is very important in forming of those materials. In forming of aluminum and magnesium alloys sheets, heating in a furnace before forming is not suitable because the sheet temperature is easy to cool down, and another heating method is required.

Cost and time for preparing dies and punches are serious problems for rapid prototyping, rapid manufacturing and small batch production of large size products. 3D printing is an innovative technology in the meaning of not only manufacturing complex shape including inner structure but also die free method. Incremental sheet metal forming process is a die-less forming process and it can be called one kind of 3D printing in sheet metal forming. Since incremental forming process necessitates very long time especially in manufacturing large size products, the sheet should be heated during forming. The authors developed friction stir incremental forming method by combining friction stir welding and incremental sheet metal forming to form magnesium alloys and aluminum alloys sheets without heating by external heat source [1]-[5]. In this process, as the tool rotation rate increases, formability jumps up when the tool rotation rate exceeds a threshold value by occurring dynamic recrystallization. So this process is not friction heating but friction stirring.

Since a number of reports about friction stir incremental forming are not so many and most of them are presented by the authors' group, results about friction stir incremental forming by the authors' group are introduced in this paper.

## Experimental method

A 3-axes NC milling machine (Roland DG, MDX-540) was employed for forming. A hemispherical tool which with a diameter of 6 mm made of high speed steel was used. Specimen sheet was put on a die and fixed by the blank holder with bolts. The size of the specimen sheet was 100 mm x 100 mm. The forming tool was moved in a pitch of 0.5 mm as shown in Fig. 1. The sheets were formed into frustum of pyramid shape having 40 mm x 40 mm right square bottom. Formability was evaluated by changing wall angle of pyramid,  $\theta$ , as shown in Fig. 2. 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. To measure the sheet temperature during forming, a thermocouple was attached by spot welding on the reverse surface to forming side in order to avoid detaching during forming.

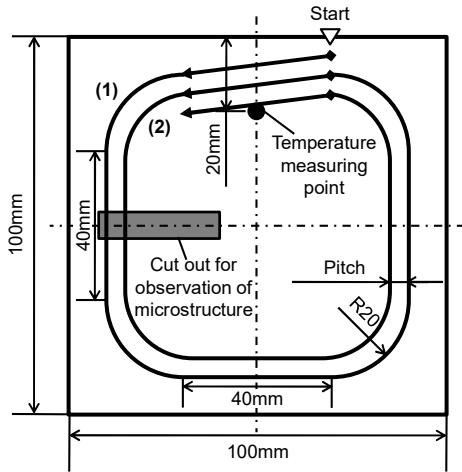


Fig. 1 Forming path and sequence [1]

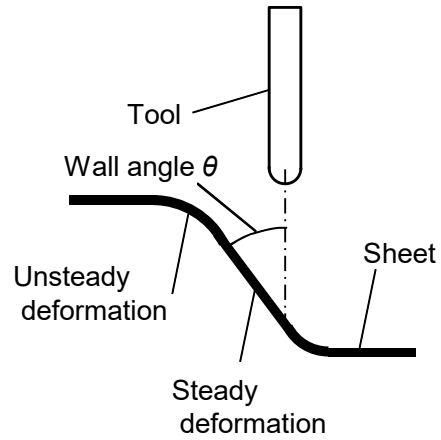


Fig. 2 Definition of wall angle [1]

**Magnesium Alloys**

**Effect of tool rotation rate.** Forming limit height of AZ31 sheet was studied by changing tool rotation rate at the tool feed rate of  $v = 3000$  mm/min and the wall angle of  $\theta = 45^\circ$ . Fig. 3 shows the relation between the forming limit height and the tool rotation rate. When the tool rotation rate was  $\omega = 0$  rpm, this coincides with the conventional single point incremental forming process, the forming limit height was only 3 mm (Fig. 4(a)). When the tool rotation rate was less than 7000 rpm, the forming limit height did not changed very much although the tool rotation rate increased (Fig. 4(b)). However, when the tool rotation rate was greater than 8000 rpm, the forming limit height improved dramatically, and the sheet was formed to 18 mm height that is the maximum height of this experimental equipment (Fig. 4(c)).

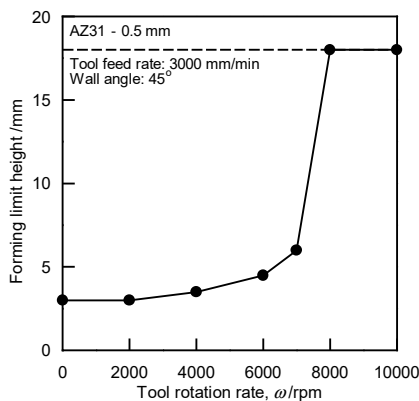
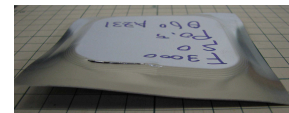


Fig. 3 Relation between forming limit height and tool rotation rate ( $v = 3000$  mm/min,  $\theta = 45^\circ$ ) [1]



(a)  $\omega = 0$  rpm



(b)  $\omega = 7000$  rpm



(c)  $\omega = 8000$  rpm

Fig. 4 Appearance of formed sheets ( $v = 3000$  mm/min,  $\theta = 45^\circ$ ) [1]

**Formable working conditions.** The tool rotation rate was fixed to 10000 rpm. The tool feed rate,  $v$ , was changed and the formable working conditions were studied. Fig. 5 shows the formable working condition for AZ31, AZ61 and AZ80 magnesium alloys sheets. In this figure, open circle marks indicate that the forming was succeeded and completed until 18 mm height. Cross marks means the sheet was broken during forming.

In a case of forming AZ31 sheets, the formable minimum wall angle became smaller, this means the formability became greater, as the tool feed rate decreased. The minimum wall angle was  $25^\circ$  at 1000 – 2000 mm/min in the tool feed rate. The fracture elongation in tension test of AZ31 sheet was 26%, however, the theoretical elongation formed by friction stir incremental forming was 137%. This result shows that the formability by friction stir incremental forming is remarkably improved.

In cases of forming AZ61 and AZ80 sheets, similar results were obtained. As the aluminum content increased, the formability decreased in general. The minimum half apex angles of AZ61 and AZ80 were  $30^\circ$  and  $40^\circ$ , respectively.

The thickness of AZ31 sheet was 0.5 mm and that of AZ80 was 0.8 mm. Area of occurring dynamic recrystallization and grain refinement by friction stir incremental forming is considerable to be limited to certain depth from the surface. AZ80 sheet was thicker and the effect of dynamic recrystallization and grain refinement on the improvement of formability was smaller than those of AZ31 ones. This should be the reason why the minimum half apex angle of AZ31 was smaller than that of AZ80 although the both fracture elongation by tension test was almost equal.

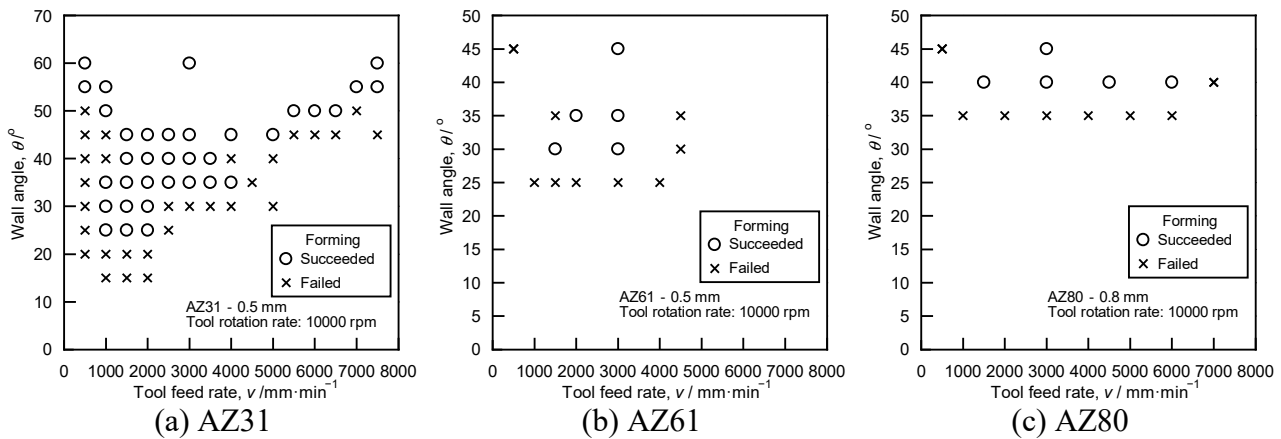


Fig. 5 Relation between formable wall angle and tool feed rate for magnesium alloys [1]

**Comparison with Conventional Hot Incremental Forming.** It is well known that the formability of magnesium alloys improves at elevated temperature. AZ31 sheets were heated during forming by a resistance heater put under the sheet, and conventional hot incremental forming was carried out. The tool rotation rate and the tool feed rate were fixed to  $\omega = 0$  rpm and  $v = 1500$  mm/min, respectively. Forming temperature and the wall angle were changed. The results were compared with those by friction stir incremental forming at  $\omega = 10000$  rpm and  $v = 1500$  mm/min.

The relation between formable wall angle and working temperature is shown in Fig. 6. An open double circle mark indicates the result by friction stir incremental forming. In cases of conventional hot incremental forming, the formability was improved at over  $180^\circ\text{C}$ , and the minimum wall angle

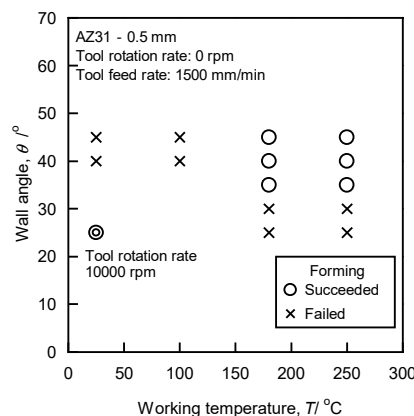


Fig. 6 Relation between formable wall angle and working temperature for AZ31 [1]

was  $35^\circ$ . Comparing with the result by friction stir incremental forming, the minimum wall angle by friction stir incremental forming was  $25^\circ$  and smaller than that by conventional hot incremental forming.

### Aluminum Alloys

Two types of aluminum alloy sheets were formed. One was A5052-H34 which is a work hardening type alloy, and the other was A2017 which is an age hardening type alloy. Formability of both aluminum alloys sheets by friction stir incremental forming was studied. The thickness of specimens was 0.5 mm. Forming limit height of A5052-H34 at a tool feed rate of  $v = 3000$  mm/min and a wall angle  $\theta = 30^\circ$  was shown in Figure 7. Where forming limit height is defined to maximum height without fracture and the maximum forming limit height is restricted to 20 mm because of specification of forming machine.

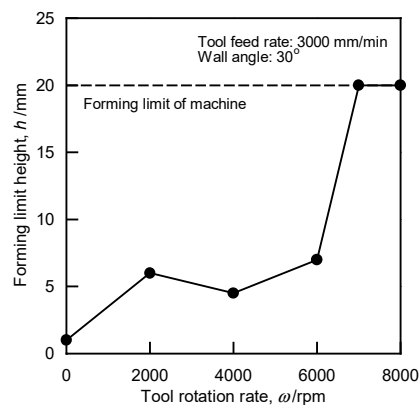


Fig. 7 Relation between forming limit height and tool rotation rate ( $v = 3000$  mm/min,  $\theta = 30^\circ$ ) [2]

When tool rotation rate was  $\omega = 0$  rpm, this coincides with the ordinary single point incremental forming, the forming machine stopped due to over loading and the sheet did not formed at all. In a range of  $\omega = 2000 - 6000$  rpm, the sheet broke during forming and the forming limit height was  $h = 6$  mm. When tool rotation rate was greater than 7000 rpm, formability was remarkably improved and forming limit height exceeded  $h = 20$  mm, the limit of forming machine.

The tool rotation rate was fixed to  $\omega = 10000$  rpm and tool feed rate was changed and formable wall angle was investigated. Fig. 8 shows the formable working condition by changing tool feed rate.

In case of A5052-H34 sheets, formable minimum wall angle by ordinary single point sheet metal forming was  $\theta = 45^\circ$ . As shown in Fig. 8(a), that was  $\theta = 20^\circ$  by friction stir incremental forming.

In case of A2017 sheets, sheet could not form at  $\theta = 45^\circ$ , however, the minimum wall angle was  $\theta = 25^\circ$  by friction stir incremental forming.

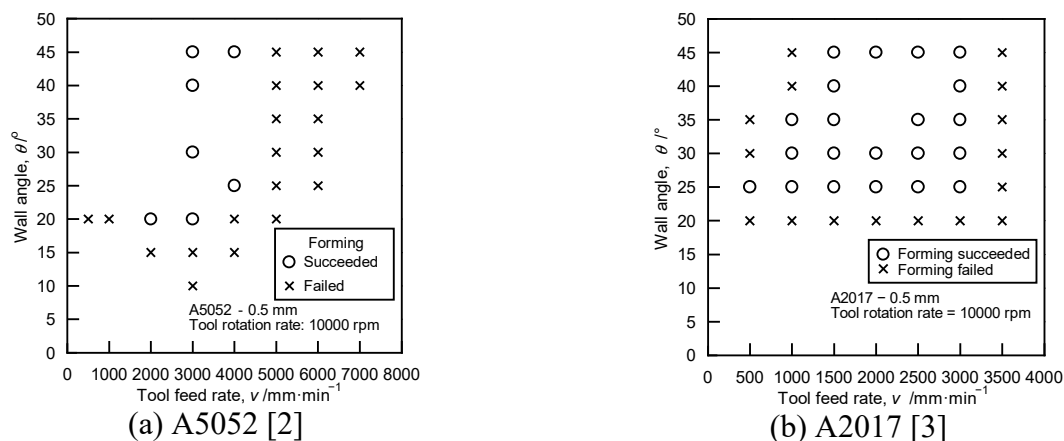


Fig. 8 Relation between formable wall angle and tool feed rate for aluminum alloys

**Titanium**

Commercial pure titanium sheets with a thickness of 0.4 mm was used for specimens. Since titanium is easy to occur galling and low thermal conductance, formable working conditions were quite different from those of magnesium alloys and aluminum alloys. The tool feed rate and wall angle were fixed to  $v = 5000$  mm/min and  $\theta = 35^\circ$ . Tool rotation rate,  $\omega$ , was changed and formable wall angle was investigated. Fig. 9 shows the relation between the forming limit height and the tool rotation rate. When the tool rotation rates were  $\omega = 500$  and  $1000$  rpm, the forming limit heights were same and only 3 mm. When the tool rotation rate was  $\omega = 1100$  rpm, the forming limit height was only 4 mm. Whereas the tool rotation rate became  $\omega = 1200$  rpm, the forming limit height was dramatically increased to more than 20 mm which is the maximum limit height of the used equipment. The forming limit height exceeded the equipment limit until the tool rotation rate was up to 1900 rpm. When the tool rotation rate became more than 1900 rpm, the forming limit height was lowered due to occurring the galling.

The tool feed rate was fixed to  $v = 5000$  mm/min and the tool rotation rate and wall angle was changed. Next, The tool rotation rate was fixed to  $\omega = 1500$  rpm, and the tool feed rate was changed and the formable working conditions were studied. Formable working conditions were shown in Fig. 10. Pure titanium sheets could not form at  $\theta = 45^\circ$  by conventional incremental sheet metal forming as shown in Fig. 10(a), however, the minimum wall angle was  $\theta = 35^\circ$  by friction stir incremental forming as shown in Fig. 10(a) and Fig. 10(b).

As the tool feed rate increased, the formable wall angle decreased and the minimum value was  $35^\circ$ . While formable wall angle increased as the tool feed rate increased in the cases of forming magnesium alloy and aluminum alloy sheets, formable wall angle decreased as the tool feed rate increased in the forming of pure titanium sheets and this is an opposite inclination.

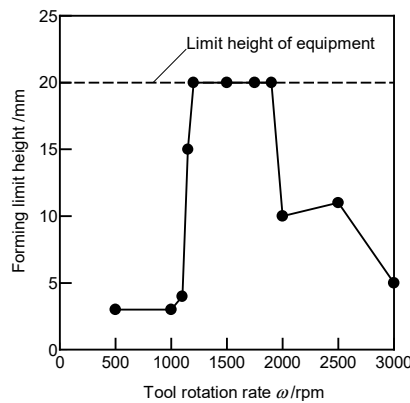


Fig. 9 Relation between forming limit height and tool rotation rate ( $v = 5000$  mm/min,  $\theta = 35^\circ$ ) [4]

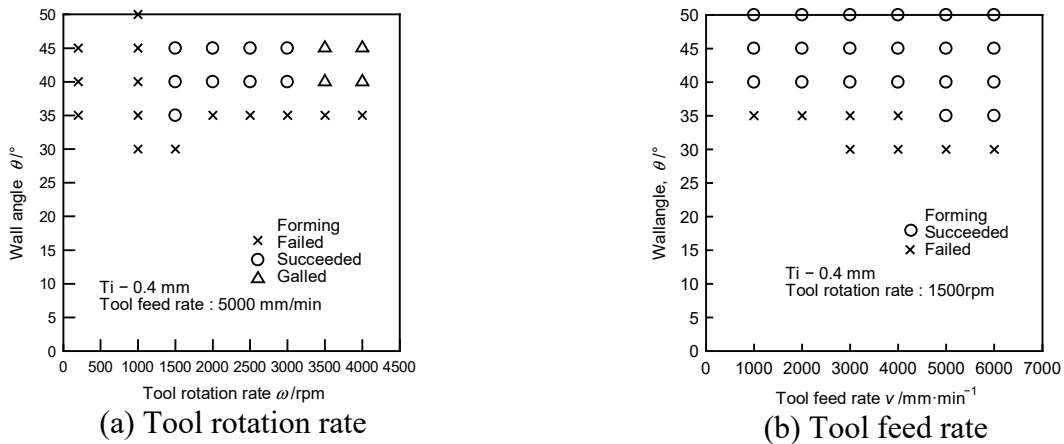


Fig. 10 Formable working conditions for pure titanium sheets [4]

## Rotational Direction

Effect of tool rotation direction or direction of the tool path, these coincide with advancing/retreating sides in friction stir incremental forming, on formability was studied. In advancing side, relative moving directions of rotating tool surface and sheet are opposite and the relative velocity between the tool surface and sheet is enhanced. In retreating side, relative moving directions of tool surface and sheet are same and the relative velocity is reduced.

A5052-H34 sheets with a thickness of 0.5 mm were used for specimen. When the tool rotation rate was fixed to 10000 rpm and the tool feed rate was changed, in both advancing and retreating direction cases, the sheets can be formed up to  $\theta = 20^\circ$  in wall angle at the tool feed rate of  $v = 1000$  mm/min. But the range of formable tool feed rate in advancing direction was wider than that in retreating direction. When the tool feed rate was fixed to 2000 mm/min and the tool rotation rate was changed, in both cases, the formable minimum wall angle was  $\theta = 25^\circ$ , however, the range of formable working condition for wall angle of  $\theta = 25^\circ$  in advancing direction is slightly wider than that in retreating direction.

From these results, forming limits in advancing direction and retreating direction were almost same but the formable ranges were different. So the relative velocity between the tool surface and sheets was focused on. The relative velocity between the tool surface and sheet is calculated by the tool radius  $r$ , the wall angle  $\theta$ , the tool feed rate  $v$  and the tool rotation rate  $\omega$ . The relative velocities in advancing direction,  $V_a$ , and retreating direction,  $V_r$ , are written as follows:

$$V_a = 2\pi r\omega \cos \theta + v \quad (1)$$

$$V_r = 2\pi r\omega \cos \theta - v \quad (2)$$

Relative velocities for advancing direction and retreating direction were calculated when the tool radius was  $r = 3$  mm. Fig. 11 shows the relation between formability and the calculated relative velocity. Although the combination of tool feed rate and tool rotation rate has a great variety, relative velocity between tool surface and sheet can estimate the forming is possible or not.

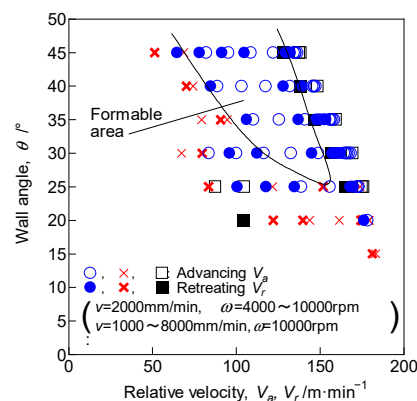


Fig. 11 Relationship between relative velocity and formable wall angle (A5052,  $t = 0.5$  mm) [5]

## Multistage Forming

To improve the forming limit, forming was divided into multistage and deformation per forming stage was reduced. A5052-H34 sheets with a thickness of 0.5 mm were used for specimen. In the first forming stage, the sheets were formed into a frustum of cone shape with a wall angle  $\theta_1$  and a height of  $h$  as shown in Fig. 12(a). After the first stage forming, the sheets were formed into a frustum of cone shape with a wall angle  $\theta_2$  and a height of 20 mm. In the first and second stages, forming pitch in  $z$  direction was fixed to 0.5 mm. The increment of wall angle,  $\Delta\theta = \theta_1 - \theta_2$ , was changed from  $0^\circ$  to  $8^\circ$ .

The effect of angle increment on formable wall angle was shown in Fig. 13. When single stage forming was employed, the minimum wall angle was  $\theta = 20^\circ$  (required elongation is 192%), however,

that by multistage forming was  $\theta = 18^\circ$  (required elongation is 223%) when the first wall angle was  $\theta_1 = 20^\circ$ , and the second wall angle was  $\theta_2 = 18^\circ$ .

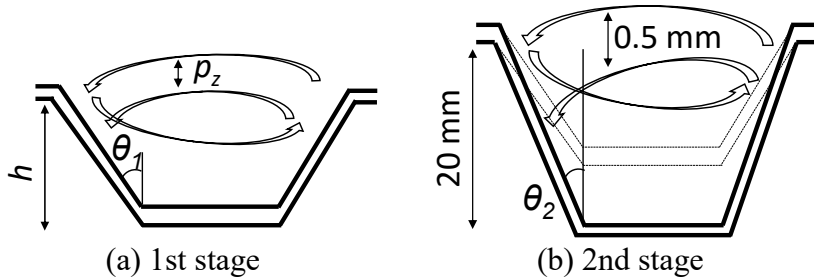


Fig. 12 Tool path of multistage friction stir incremental forming

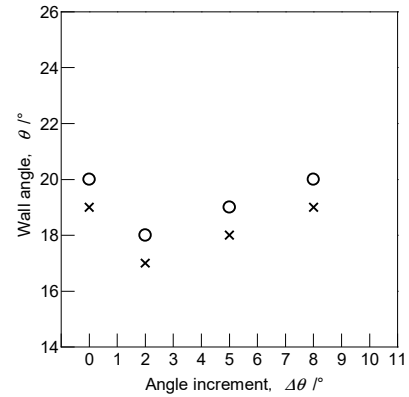


Fig. 13 Effect of angle increment on formable wall angle (A5052,  $t = 0.5$  mm)

### Double Side Forming

In friction stir incremental forming, unstable deformation as shown in Fig. 2 is occurred at the beginning of forming. The reason of occurrence of unstable deformation is the poor rigidity of sheet. To solve the problem, back support die is used in the conventional incremental sheet metal forming. Another solution is employing two forming tools from both upper and lower sides [6]. To realize double side forming by friction stir incremental forming, an original forming equipment was developed. A general view of developed double side forming machine is show in Fig. 14. Two sets of X, Y, Z sliders and spindle were mounted on the machine.

Tool rotation and tool feed rate were fixed to  $\omega = 10000$  rpm and A frustum of pyramid shape with a height of 5 mm and a wall angle of  $\theta = 40^\circ$  was formed. Cross-sectional shapes formed by single side forming and double side one was compared with in Fig. 15. When single side forming was employed, unsteady deformation was observed from the blank holder, however, when double side forming was used, unsteady deformation at flange was reduced and the forming accuracy was significantly improved.

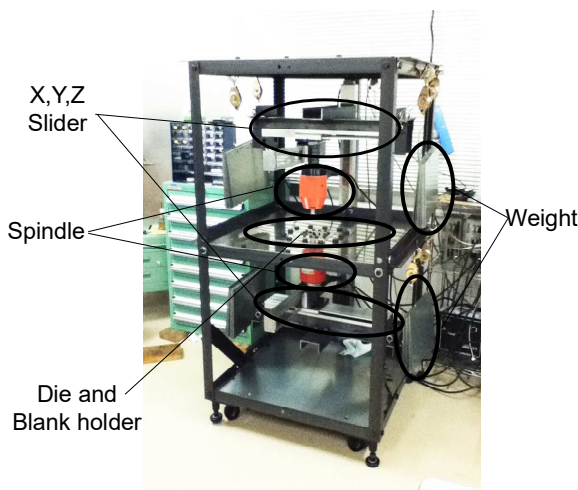


Fig. 14 General view of double side forming machine

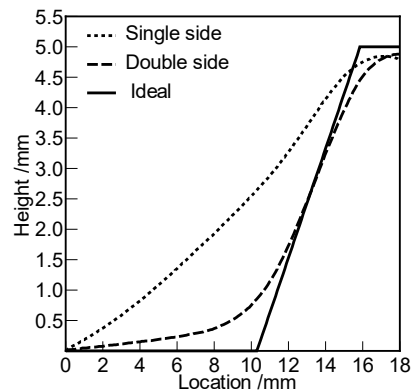


Fig. 15 Comparison of formed and ideal cross-sectional shapes (A5052,  $t = 0.5$  mm)



## Conclusions

This paper introduced the results studied in the author's research group. Sheet metals of magnesium alloys, aluminum alloys and pure titanium showed excellent formability by using friction stir incremental forming. To enhance the improvement of formability, multistage forming was introduced. Double side forming was also performed to improve the forming accuracy.

## Acknowledgement

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