Effect of Difference of Tool Rotation Direction on Forming Limit in Friction Stir Incremental Forming

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Keywords: A5052 aluminum alloy sheet, friction stir incremental forming, tool rotation direction, forming limit

Abstract. An effect of tool rotation direction on forming limit in friction stir incremental forming was studied. A 3-axes NC milling machine and a hemispherical tool which with a diameter of 6 mm made of high speed steel was used for forming. The thickness of commercial A5052-H34 aluminum sheet was 0.5 mm. The forming tool was moved from the outside to inside in a pitch of 0.5 mm spirally, and the sheets were formed into frustum of pyramid shape. Formability evaluated by minimum wall angle of the pyramid was investigated by changing a tool rotation rate, tool feed rate and tool path direction. When the tool paths were clockwise and counter clockwise, they were defined to "advancing direction" and "retreating direction" as well as in friction stir welding, respectively. From the experimental results, forming limits by both rotation directions of advancing and retreating were almost the same, however, the range of formable working conditions in advancing direction was slightly wider than that in retreating direction. Evaluating the forming limits in relative velocity between the tool surface and the sheet, no difference of forming limit was obtained between forming in advancing direction and retreating directions.

Introduction

In recent years, in order to reduce environmental impact, high-strength and light materials have been desirable for various industrial products, including transportation equipment. Therefore, for products made of steel have been replaced to aluminum alloy ones. So in recent years, aluminum alloy sheets have been employed to practical use for many products in many fields such as automobile, aircraft, train, etc. because of their high specific strength and high corrosion resistance [1]. In addition, the market requirement has shifted from ready made products to order made ones, and manufacturing process has to correspond the needs change from mass production to small lot production. Therefore, cost reduction in small lot production is the important problem in press working for sheet metals.

The authors have developed friction stir incremental forming [2-4] in order to solve those problem. Friction stir incremental forming is a forming method that is combined the conventional incremental forming and friction stir welding, which is a solid phase bonding method. 5000 series aluminum alloy, AZ series magnesium alloys and pure titanium sheets, they are difficult to form by press working and conventional incremental forming at room temperature, can be formed by this forming method. In addition, the remarkable improvement of formability has been reported in the forming process. In those papers, effects of the tool rotation rate, tool feed rate on formability were investigated, however, 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 not 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. The microstructures of bonded parts by friction stir welding are different at advancing and retreating sides [5]. Therefore, there is a possibility that the formability in advancing side and retreating side would be different in friction stir incremental forming.

In this study, forming limit in advancing side and retreating side in friction stir incremental forming was studied. The results were summarized by relative velocity between the tool surface and sheet.

Experimental method

Commercial A5052-H34 aluminum alloy sheets were used for specimen. The size of the specimen sheet was 100 mm x 100 mm. The thickness of the sheet was 0.5 mm. Photo of experimental equipment is shown in Fig. 1. A 3-axes NC milling machine (Roland DG, MDX-540) was employed for forming. A stick tool which top shape is hemispherical was used. A diameter of the tool is 6 mm and the tool is made of high speed steel. Specimen sheet was put on a die and fixed by a blank holder with bolts.

The forming tool was moved along the contour line of objective shape. After forming one round, the tool was moved to height direction for 0.5 mm. The sheets were formed into frustum of pyramid shape having 40 mm x 40 mm right square bottom as shown in Fig. 2.

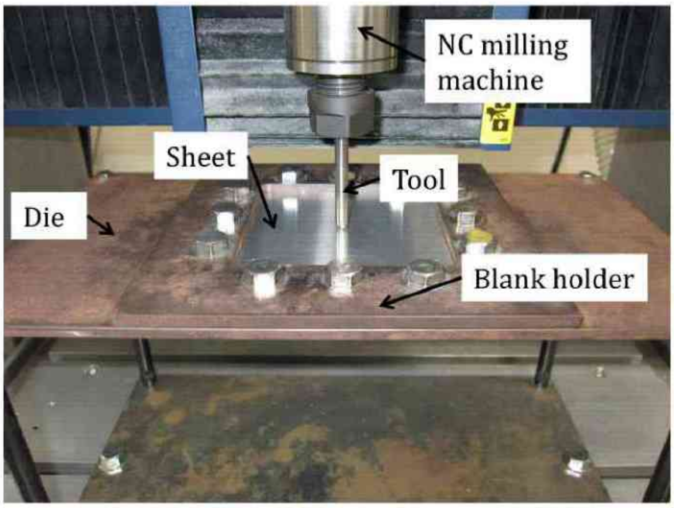


Fig. 1 Appearance of tool, blank holder and die

Fig. 2 Appearance of formed sheet

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.

The tool paths, advancing and retreating directions, are shown in Fig. 4. In this study, the tool rotation direction was clockwise due to the restriction of the forming machine. In order to change tool rotation direction relatively, the direction of tool path was changed. When the tool path is clockwise as shown in Fig. 4(a), the relative velocity between the tool and sheet surfaces is added and larger. When the tool path is, however, counter clockwise as shown in Fig. 4(b), the relative velocity is subtracted and smaller. The former case is defined to "advancing direction" and the latter case is defined to "retreating direction" as well as friction stir welding.

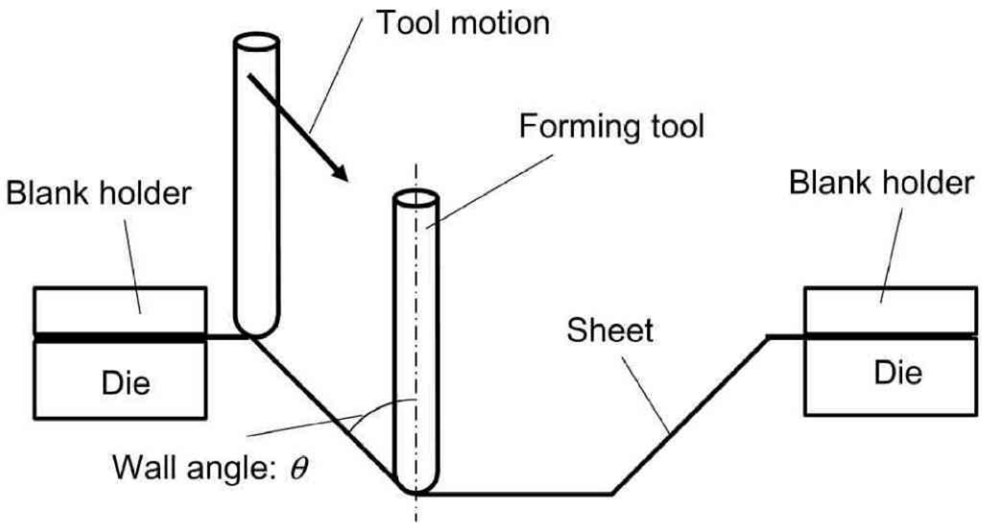
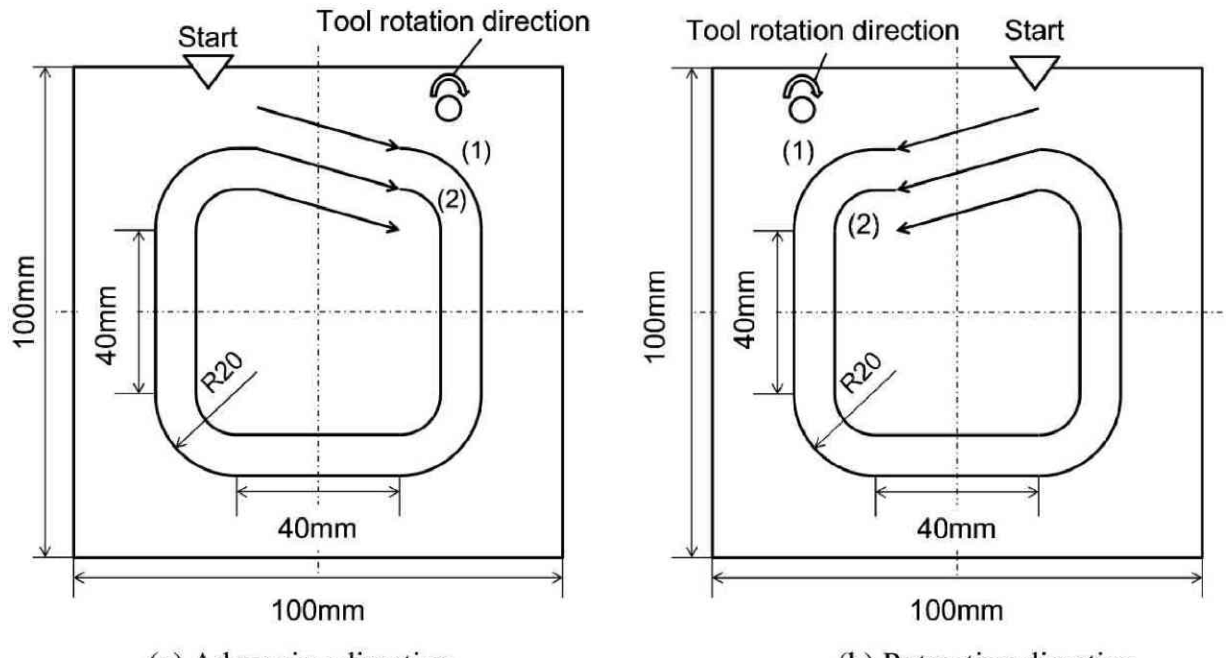


Fig. 3 Definition of wall angle



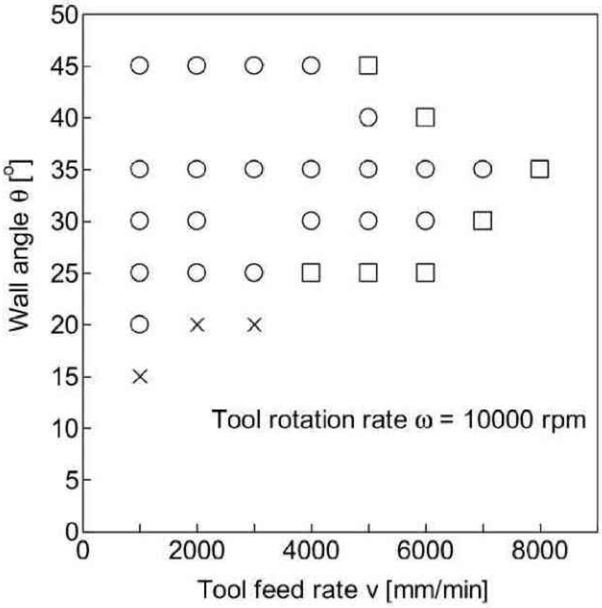
(a) Advancing direction (b) Retreating direction

Fig. 4 Forming path and definition of tool rotation direction

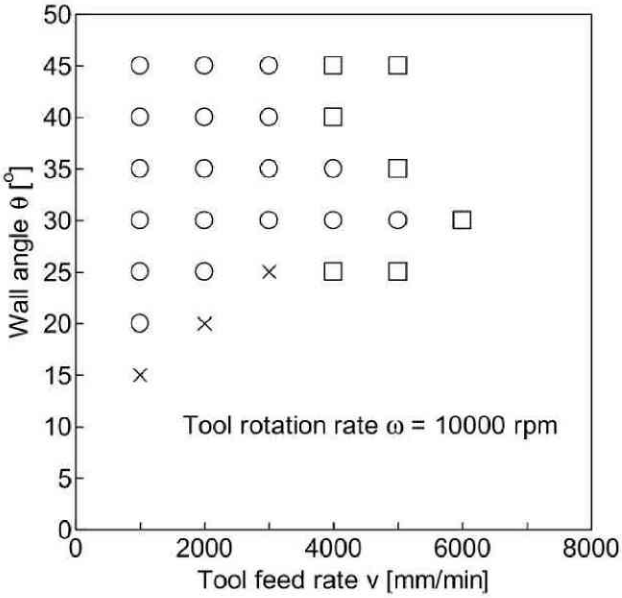
Results and discussions

Effect of tool feed rate. The tool rotation rate was fixed to 10000 rpm and the tool feed rate was changed. Formable working conditions are shown in Fig. 5. In the figure, open circle marks indicate that forming until 20 mm height was succeeded. Cross marks indicate that the sheet was broken before achieving 20 mm height. Square marks indicate that the forming machine was stopped due to over loading.

In both advancing and retreating direction cases, the sheets can be formed up to $\theta = 20°$ 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. Since sheet can be formed at higher tool feed rate, forming time can be shorten by forming in advancing direction.



(a) Advancing direction

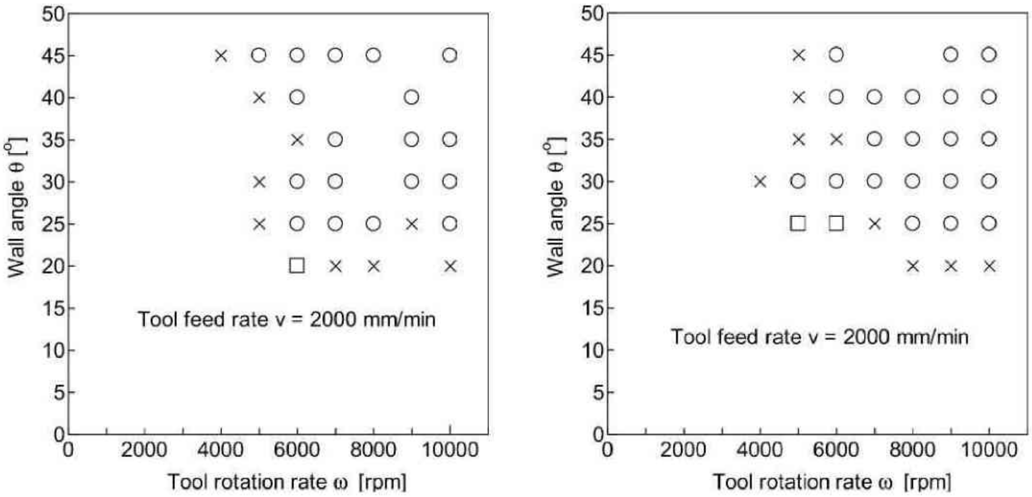


(b) Retreating direction

Fig. 5 Formable working conditions ($\omega = 10000$ rpm)

Effect of tool rotation rate. The tool feed rate was fixed to 2000 mm/min and the tool rotation rate was changed. Formable working conditions are plotted in Fig. 6. In the figure, open circle marks indicate that forming until 20 mm height was succeeded and cross marks indicate that the sheet was broken before achieving 20 mm height. Square marks indicate that the machine was stopped due to over loading.

In both cases, the formable minimum wall angle was $\theta = 25°$, however, the range of formable working condition for wall angle of $\theta = 25°$ in advancing direction is slightly wider than that in retreating direction.



(a) Advancing direction (b) Retreating direction

Fig. 6 Formable working conditions (v = 2000 mm/min)

Effect of relative velocity between tool surface and sheet. From above results, forming limits in advancing direction and retreating direction were almost same but the formable ranges were different. This reason is considerable that the formability depends on certain physical quantities, essentially. In this study, the relative velocity between the tool surface and sheet was focused on. The relative velocity between the tool surface and sheet is calculated by the tool radius r, the wall angle θ, the tool feed rate v and the tool rotation rate ω. The relative velocities in advancing direction, V_a, and retreating direction, V_r, are written as follows:

$$V_a = 2\pi r\omega \cos\theta + v \tag{1}$$

$$V_r = 2\pi r\omega \cos\theta - v \tag{2}$$

Relative velocities for advancing direction and retreating direction were calculated in the case of Fig. 5, the tool radius of r = 3 mm, the tool rotation rate of ω = 10000 rpm and wall angle of θ = 45°. Relationship between relative velocity and tool feed rate was shown in Fig. 7. Effect of the tool rotation rate on relative velocity is great comparing with the tool feed rate. When the tool feed rate is v = 8000 mm/min, the difference of relative velocities in advancing direction and retreating direction is 16 m/min, about 13% in advancing direction.

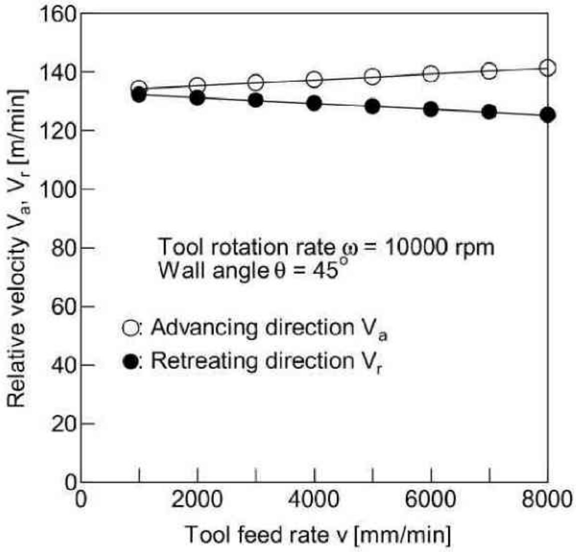


Fig. 7 Relationship between relative velocity and tool feed rate

Relative velocities for advancing direction and retreating direction were calculated in the case of Fig. 6, the tool radius of r = 3 mm, the tool feed rate of v = 2000 mm/min and wall angle of $\theta = 45°$. Relationship between relative velocity and tool rotation rate was shown in Fig. 8. Since the difference of relative velocities in advancing direction and retreating direction is constant to 2v = 4000 mm/min, effect of the tool feed rate on relative velocity becomes smaller when the tool rotation rate is larger.

The relative velocity about all experimental result in Figs 5 and 6 were calculated. Fig. 9 shows the relation between formability and the calculated relative velocity. In this figure, red, blue and black marks are the recalculated data in Figs 5 and 6. Formable wall angle θ became smaller, that is higher formability, as relative velocity became larger regardless of the tool rotation direction.

From Fig. 9, it is estimated that when the relative velocity is in the formable area, forming with other sets of working conditions may success. So, forming with other sets of working conditions were tried. In working conditions of v = 1100 mm/min, ω =7000 rpm, θ =40° and V_r = 100 m/min, forming is predicted to success. In working conditions of v = 2800 mm/min, ω = 6000 rpm, θ = 40°, V_a = 75 m/min, and v = 2200 mm/min, ω = 5000 rpm, θ = 40°, V_r = 75 m/min, forming is estimated to fail. The results with additional forming are plotted to Fig. 9 in green marks. The estimated results that forming would success or fail were obtained. Thus, fail or success of forming can be predicted without testing the combination of various forming conditions by calculating the relative velocity between the tool surface and sheet.

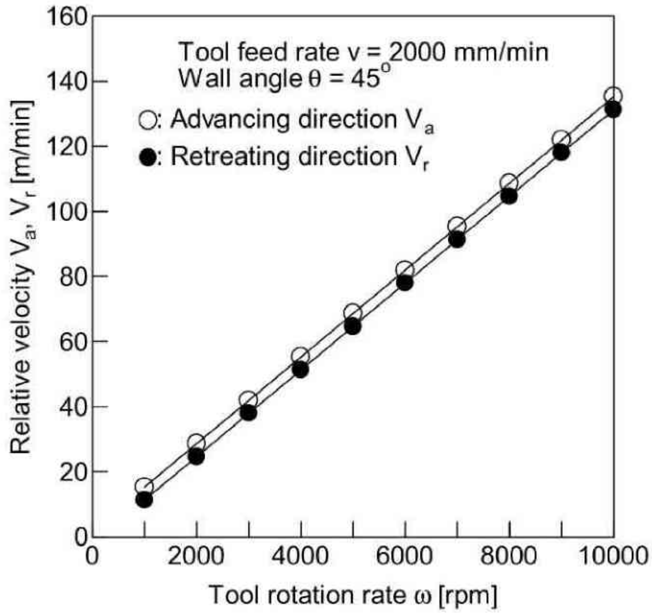


Fig. 8 Relationship between relative velocity and tool rotation rate

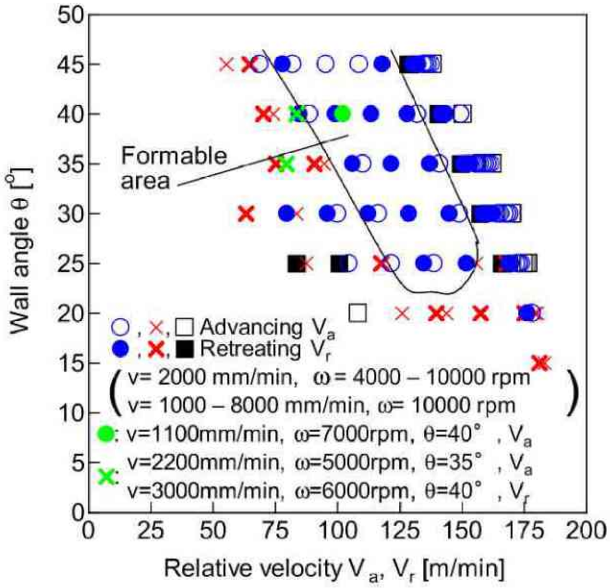
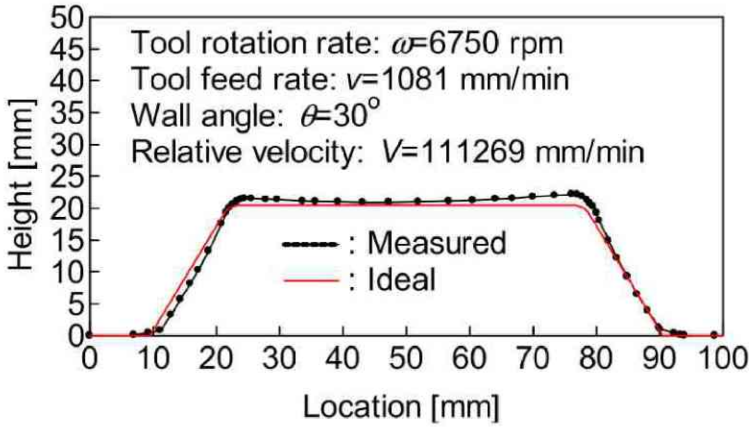
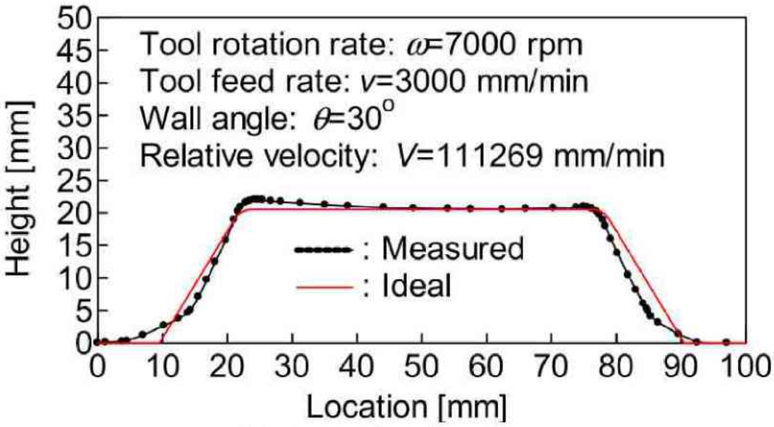


Fig. 9 Relationship between relative velocity and formable wall angle

Shape of formed sheets. Fig. 10 shows the cross-sectional shape of sheets formed in advancing and retreating direction with the same relative velocity. Comparing with the ideal shape, shape at the corner of flange portion in advancing direction was near than that in retreating direction. The shapes at other portion in advancing and retreating directions were almost similar. The top and cone surfaces of frustum of pyramid are concave due to residual stress.



(a) Advancing direction



(b) Retreating direction

Fig. 10 Cross-sectional shape of formed parts

Conclusions

In this study, effects of tool rotation direction and relative velocity between the tool surface and sheet on formability and formed shape were investigated. From the experimental results, the followings were obtained.

1. Formabilities in different tool path direction were almost same, however, the range of formable working condition in advancing direction was slightly wider than that in retreating direction.
2. Regardless of tool rotation rate and tool feed rate, either forming will success or fail can be predicted by relative velocity between the tool surface and sheet.
3. Formed shapes in advancing direction and retreating direction were almost similar, but the shape at the corner of flange in advancing direction was closer to the ideal shape than that in retreating direction.

Acknowledgement

The authors would like to acknowledge Japanese government for financially supporting a part of this work by Grant-in-Aid for Scientific Research (B) 22360309.

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