Influence of Tool-Sheet Contact Conditions on Fracture Behavior in Single Point Incremental Forming

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Abstract. The tool-sheet contact condition has significant effect on the crack occurring of forming parts in the single point incremental forming process. Experimental tests were carried out on sheets of 1060 aluminum and 2024 aluminum to form parts with varying wall angles under different contact conditions to explore the influence rule. Through the observation of the macro fracture depth and the microstructure of the micro fracture morphology, it is found that fracture depth of forming part is highest and the corresponding formability is best with hard alloy forming tool processed by the Cr/C coating with Molybdenum disulfide lithium base grease. The fracture occurring of the 1060 aluminum sheet is due to the instability of the sheet material, and the fracture of the 2024 aluminum sheet is due to its forming limit. In addition, it is also found that the fracture of single point incremental forming part occurs from the outer surface to the inner surface.

1. Introduction

Single point incremental forming (SPIF) is a highly flexible process for rapid manufacturing of complex sheet metal parts. This process is particularly suitable to small batch production and prototypes in various fields and has wide application prospects [1-2]. During the forming process, the forming tool is always in contact with the sheet and continuously rolls the sheet metal to cause plastic deformation locally, which is accompanied by the friction phenomenon. Friction not only affects the energy consumption and the forming force, but also directly affects the forming limit, the amount of springback and the surface quality of the formed parts. Therefore, it is important to study the influence of contact condition between the forming tool and the metal sheet on the forming process to improve the formability and to suppress the premature fracture of the sheet metal.

The formability of single point incremental sheet metal is no fracture occurred when the sheet was extruded by the forming tool with predetermined trajectory under the certain processing condition. The contact conditions affect the flow of metal materials, change the distribution of stress and strain, and further affect the formability of sheet metal. Hussain and Gao [3] propose that the single point incremental formability can be simply characterized by the forming limit angle corresponding to the fracture point and the relationship between the forming parameters and the maximum forming angle is studied through a lot of experiments. Some scholars have studied the reasons for the improvement of the formability of certain material in the single point incremental forming. Allwood [4] found that the
strain in the direction of thickness is an important factor for improving the formability. Xu [5] studied the influence of the rotational speed of the forming tool on the deformation mechanism and forming limit of the AA5052-H32 aluminum alloy sheet. The results show that when the rotational speed of the forming tool is less than 1000r/min, the friction force is the main reason for reducing the forming limit, when the speed is higher, the heat effect produced by the friction will increase the formability of the sheet material, while the speed reaches 3000r/min or more, the heat generated by the friction is larger, which makes the material softer and recrystallized, so the formability of sheet material is improved significantly. Durante [6] studied the influence of different contact conditions on the surface quality and formability of the formed parts with forming tools of different types and sizes to form AA7075TO sheet. The experimental results show that rolling friction contact and larger forming tool radius can improve the maximum forming angle of sheet metal.

In this paper, our work intends to give a more profound understanding about the crack occurring of forming parts under different contact conditions while the location and morphology of cracks on 1060 aluminum sheet and 2024 aluminum sheet were compared and analyzed.

2. Single point incremental forming principle

SPIF technology has attracted the interest of scholars both at home and abroad because of its high flexibility and other advantages [7-8]. The basic principle is based on the hierarchical manufacturing idea of rapid prototyping technology. The complex three-dimensional model is dispersed along the height direction into a series of two-dimensional contour lines. The forming principle is shown in Fig.1, where $t$ is the initial thickness of the sheet, $\alpha$ is the forming angle, $D$ is the diameter of the forming tool, and $Z$ is the step size. Besides, spindle speed and feed speed are also common forming parameters.

![Figure 1. Diagram of single point incremental forming principle.](image)

3. Experimental design

The forming angle corresponding to point of the first fracture occurring is called the maximum forming limit angle. In this paper, the formability of the single point incremental forming is evaluated with the maximum forming limit angle.

The experimental setup is shown in Fig.2. Qin Chuan MVC510, a three axis CNC milling machine was employed, the forming tools is shown in Fig.3. To obtain forming tool with certain coatings, the Teer-UDP closed field unbalanced magnetron sputtering ion plating equipment is used and the sputtering graphite target is used as the main source of the C element on the hard alloy forming tool, the Cr/C coating was prepared to make the hardness of forming tool surface reach about 1500HV. In the research, truncated funnels with continuously varying wall angle $\alpha$ from 30° to 86° were formed to evaluate material formability, and the geometric dimension of the forming part is shown in Fig.4. The corresponding forming angles at any point $P(x_0, y_0)$ on the forming part can be recorded as:

$$\alpha = \cos^{-1}(y_0/R).$$

In order to research the effect of friction and lubrication on fracture in single incremental forming, three lubrication methods are adopted. The specific lubrication conditions and forming parameters are shown in Tab.1.
Figure 2. Experimental device.  
Figure 3. Forming tool.  
Figure 4. Geometry size.

Table 1. Lubrication condition and forming parameters.

| Run | Lubrication condition                                      | Other parameters                  |
|-----|------------------------------------------------------------|-----------------------------------|
| 1   | L-HM 46 anti-wear hydraulic oil                           | Thickness $t=1$                   |
| 2   | Molybdenum disulfide lithium base grease and tool head treatment | Step size $Z=0.2$                |
| 3   | Colloidal graphite powder                                 | Feed speed $F=300\text{mm/min}$  |
|     |                                                            | Spindle speed $S=600\text{r/min}$|
|     |                                                            | Forming tool diameter $D=10\text{mm}$|

4. Experimental results and analysis
The forming parts of 1060 aluminum and 2024 aluminum sheet parts formed with the same forming parameters under the above three lubrication conditions are shown in Fig.5 and Fig.6 respectively.

Figure 5. Forming parts of 1060AL in different lubrication condition.

Figure 6. Forming parts of 2024AL in different lubrication condition.

After the test is completed, the height of the fracture is measured by the height measuring instrument, as shown in Fig.7, the measurement results are shown in Tab. 2.
Table 2. Fracture depth of forming parts under different working conditions.

| Type of material | Fracture depth(mm) |
|------------------|-------------------|
|                  | Condition 1 | Condition 2 | Condition 3 |
| 1060AL           | 29.6        | 32.7        | 21.2        |
| 2024AL           | 24.7        | 26.3        | 19.5        |

The single point incremental forming of metal sheet is a local plastic deformation. When the strength of the material is low, the ability to resist constant deformation is low. During the forming process, when the forming tool is moved down by layer, the thickness of the sheet become thinner and thinner, eventually causing greater stress concentration, resulting in severe necking and cracking. Generally, this process is called the instability of the forming process, or the sheet has reached its plastic forming limit and failure. The greater the friction, the greater the stress and strain of the sheet under the same deformation. Therefore, friction is an important factor affecting the forming fracture of the sheet metal.

The columnar analysis of the influence of the contact conditions on the maximum forming angle of the two kinds of sheet material is shown in Fig.8. The surface of the forming tool of the Cr/C coating has a multi-functional film, which can adsorb lubricants and realize self-lubrication, greatly reduce the friction between the forming tool and the sheet material and raise the formability of metal materials. It can be seen that better contact lubrication conditions can lead to smaller contact friction, larger forming limit angle, and higher sheet forming ability. The friction between the sheet material and the forming tool leads to the abrasion of the contact surface. When the lubrication condition is poor, the material flowing is not uniform, larger stress concentration causes the sheet to break first. When the friction is large, the material of the forming area is pushed forward by the forming tool and the resistance is larger. The stress of the material is larger than that of the material. The material easily loses its stability or reaches its forming limit and breaks up. In addition, the worse the friction condition, the greater the three axis stress of the sheet metal, thus the sheet material is more prone to fracture.

Figure 7. Height measuring instrument. Figure 8. Influence on the maximum forming angle.

Due to the good plasticity of 1060 aluminum, the depth of fracture is relatively deeper, and the material properties also have great influence on the formability of sheet metal. The cross section outline of the fracture position of the forming part under 2# lubrication conditions is shown in Fig.9, the position of breakage is always along the direction of the tool head movement, and the fracture occurs where the metal sheet is the weakest. This is mainly due to the extrusion of sheet metal by the forming tool, which makes the circumferential stress greater.
From Fig. 9, it can be seen that the fracture shape of the 1060 aluminum forming parts is serrated, while the fracture shape of the 2024 aluminum forming parts is flat. In addition, the forming parts of 1060 aluminum have become very thin and have obvious necking phenomenon, while the forming parts of 2024 aluminum is relatively thick, the broken cracks occur suddenly, and there is no obvious necking phenomenon. Therefore, the fracture of 1060 aluminum sheet is due to the instability of deformation, and the fracture of the 2024 aluminum sheet is due to its plastic forming limit.

![Figure 9. Fracture shape.](image)

The fracture morphology of the forming parts can be obtained by scanning electron microscope (SEM). The formation of dimples on the fracture cross section is the main feature of ductile fracture. Fig. 10 shows the fracture morphology of forming parts of 2024 aluminum. The Fig. 10 (a) shows the forming part under the condition of lubricating oil. The Fig. 10 (b) shows the formed part under the grease condition with the tool head treated with PVD. Because the material near the inner surface is subjected to a significant shear effect, the formation of dimple is inhibited. While dimples on the outer surface is relatively undisturbed, the dimple is expanding and breaking, therefore, the stress on the outer surface of the sheet is greater than that on the inner surface, the crack extends from the outer surface to the inner surface.

Comparing the dimples on the fracture surfaces under two lubrication conditions, it is easy to see that the dimple size in Fig. 10 (b) is larger than that in Fig. 10 (a), it shows that the better contact conditions can improve the formability of sheet metal. This is mainly due to the larger friction causes the material insufficiently deformed and fractured, which indicates that the friction reduces the plasticity of the material.

![Figure 10. Fracture morphology of 2024 aluminum forming parts (a. Condition 1#; b. Condition 2#).](image)

The fracture morphology of the 1060 aluminum sheet under the condition of lubricating oil is shown in Fig. 11. We can obvious see from Fig. 11 that the plasticity of the 1060 aluminum sheet is...
better and the size of the dimple is relatively large. As the forming process, the thickness of the sheet gradually became very thin, resulting in the phenomenon of inner surface and outer surface adhesion, the dimple size of the sheet is not easy to be compared and analyzed under different lubrication conditions, but its dimple is larger than the dimple of the 2024 aluminum sheet, Therefore, under the same lubrication condition, the forming parts of 2024 aluminum sheet are priority formed crack and fracture. Meanwhile, the adhesion between the inner surfaces and outer surfaces of the crack also proves that the fracture of the 1060 aluminum plate is due to the instability.

![Fracture morphology of 1060 aluminum forming parts.](image)

**Figure 11.** Fracture morphology of 1060 aluminum forming parts.

5. Conclusion
(1) Take Molybdenum disulfide lithium base grease and the forming tool with Cr/C coating treated surfaces is able to delay the fracture of the sheet to a great extent, and improve the formability of the sheet material. This is mainly because the lubrication condition greatly reduces the friction of the contact surface between forming tool and sheet material.

(2) By analyzing the shape of crack and the morphology of fracture, the breakage of the 1060 aluminum sheet is caused by the instability of the sheet metal, while the 2024 aluminum sheet failure is due to the forming limit.

(3) Due to the forming tool has the greatest extrusion force on the sheet along the circumference, therefore, the fracture of forming parts is always along the circumferential direction of forming tool movement, and the crack is extended from the outer surface to the inner surface.

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