Study on the Forming Properties of Round-hole Flanging of 1060 Aluminum Alloy Plate by Two-pass Path Incremental Forming with Variable Angle

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Keywords: round-hole flanging, two-pass path, variable angle, incremental forming.

Abstract: Based on the DYNAFORM finite element platform, this paper studies the forming properties of round-hole flanging by two-pass incremental forming. By comparing the differences between two-pass incremental forming and single-pass incremental forming, this paper summarizes the characteristics of wall thickness distribution and flanging height of the two-pass incrementally formed round-hole flanging. Finally, the experimental results are verified through physical experiments.

1. Introduction

The incremental forming technology of sheet metal originates from the idea of "layered manufacturing" in rapid prototyping manufacturing technology, which decomposes the whole part into a series of two-dimensional layers for layered point-by-point machining, and finally produces parts of the product. [1-2]

Round-hole flanging is a kind of sheet metal forming technology widely used in automobile, aerospace and aviation industries. Incremental process of forming round-hole flanging is different from the traditional stamping process. In incremental forming process, simple fixtures, rather than special moulds, are designed for different sizes of flanging parts, which greatly reduce the costs and shorten the manufacturing cycles of small scale flanging part production. The technique is suitable for the small scale production of various products. [3-4]

The principle of incremental forming round-hole flanging process is shown in Figure 1. When forming, a round hole is pre-opened on the sheet metal and clamped by a splint; the NC device drives the forming tool head to plastic process the sheet metal according to pre-set forming trajectory and finally gets the target shape. [5] Finally, the material around the round hole is turned vertically into a straight edge.

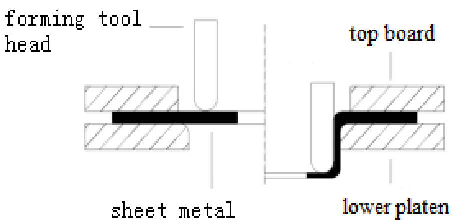

Figure 1. Incremental forming of round-hole flanging.

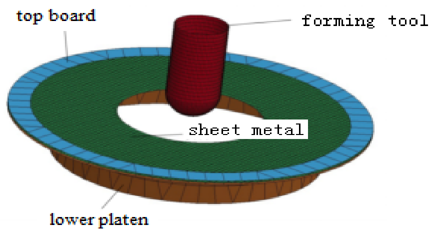

Figure 2. The finite element model.

In the process of incremental forming round hole flanging, single-pass pattern can be used to achieve once-forming; multi-pass pattern can also be used to realize multi-forming. At the same time, a hot topic for a long time is whether multi-pass can improve the flexibility and process ability of materials.

There are many forming paths in the two-pass pattern. The first pass is in an intermediate state; how to select it greatly affects the forming performance and forming limit of the sheet metal. This paper studies the forming properties of round-hole flanging in 1060 aluminum alloy plates by two-pass path incremental forming with variable angle.

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2. The Finite Element Model

The finite element model of incremental forming round-hole flanging in DYNAFORM software is shown in Figure 2. In the pre-processing step, shell element is used to define parts; Belystchko-Wong-Chiang unit algorithm is adopted for sheet metal. In order to maintain the accuracy and efficiency of simulation, the mesh size of sheet metal is set as 1mm; the minimum of forming tool is set as 0.1mm (maximum 1mm); the minimum sizes of top board and lower platen are set as 0.5mm (maximum 30mm). All above meshes are adaptive meshes.

In pre-processing, the displacement and rotation of top board and lower platen are all restrained; the top board is loaded with blank holder force. Rotation constraint is imposed on the forming tool. The forming tool head does not rotate during the simulation process; it only has displacement in X, Y and Z directions. [6]

The 1060Al sheet with thickness of 1.06mm and in H14 state is studied in this paper. The forming process is supported by outer contour; the spiral with rise angle of 0.8 degree is used as the forming trajectory.

In the forming process of round-hole flanging, the diameter of the hole should be prefabricated before forming as d0; the diameter of blank hole before flanging is d0, which will be continuously enlarged during processing. Finally the holes will be erected with final pore diameter of dm.

3. The Plan for Round-hole Flanging by Two-pass Path Incremental Forming

When the prefabricated hole diameter is small, the thickness reduction zone will appear in the middle of round-hole flanging by single-pass incremental forming under the influence of radial and circumferential tension, [5-6] resulting in uneven wall thickness. In order to eliminate the thickness reduction strip in the middle of flanging when the prefabricated diameter of the hole is small, and obtain straight flanging wall of uniform thickness, a two-pass forming path is designed. Differences between the results of two-pass forming path and single-pass forming are compared through experimental data.

Figure 3 shows a two-pass incremental forming path with variable angle, in which the conical hole with the angle of θ is formed in the first pass; the straight wall of 90º is formed in the second pass. Obviously, this path needs to define the forming angle θ. The path is shown in the diagram below.

Figure 3. Two-pass incremental forming path with variable angle

In order to study the influence of forming path on the formability of round-hole flanging parts, the flanging of round hole with sheet thickness t_0=1.06mm and flanging hole diameter d_m=56mm is studied.

In the experiment of single pass incremental forming round-hole flanging, mesh instability will occur when the flanging hole diameter d_m = 56mm and the prefabricated hole diameter d_0 = 32mm. Therefore, it is necessary to ensure that this key area is covered in the process of two-pass incremental round-hole flanging forming. The arrangement of the simulation experiment is shown in Table 1.

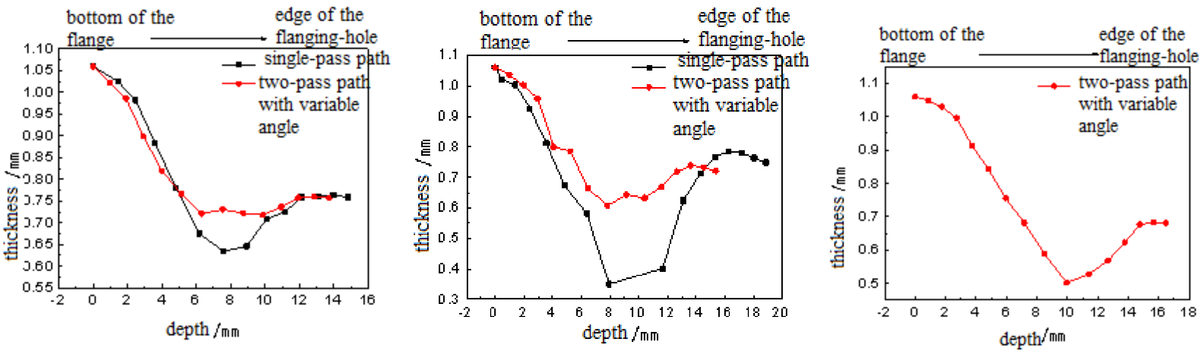
Table 1. Schedule of simulation experiments

Path Parameters	d_0/mm
θ=60°	34
θ=60°	32
θ=60°	30
θ=60°	28
θ=60°	26

For the process parameters, the diameter of forming tool head d_t = 12mm; the first pass has a complex shape, so we use the load ΔZ = 0.5mm contour path to take shape. The second pass forms the straight wall. Based on the study of single-pass forming, a spiral path with an elevation of 0.8° is used.

4. Experiment Results

Wall thickness distribution. In the post-processing experiment, the researcher obtains the curves of wall thickness of round-hole flanging with prefabricated hole diameters of d0=28mm, 30mm and 32mm and formed through the two-pass incremental forming path with variable angle. The curves are compared with the curves of single-pass thickness distribution.



(a) d_m=56mm, d_0=32mm (b) d_m=56mm, d_0=30mm (c) d_m=56mm, d_0=28mm

Figure 4. Curves of wall thickness distribution under different paths

It can be seen that multi-pass forming has great influences on the wall thickness distribution of round-hole flanging parts. Figure 4-a about round-hole flanging by single-pass forming with d_0=32mm shows a thinning band in the middle of the work piece at the flanging height of 6mm to 10mm, while the thickness distribution of the work piece formed by two-pass forming is uniform from the area with flanging height greater than 6mm to the edge of the hole.

When the round-hole flanging d_0=30mm is formed by single-pass, the middle of flanging becomes obviously thinner. The minimum thickness is 0.35mm, almost breaking. The minimum wall thickness of the work piece formed by two-pass forming is 0.607mm.

In the process of single-pass forming experiment, when the prefabricated hole diameter d_0 = 28mm, the middle part of the work piece ruptures; the phenomenon of instability also occurs in the simulation. The work piece can be formed by the two-pass path, which shows that the two-pass path can improve the forming limit of round-hole flanging in incremental forming.

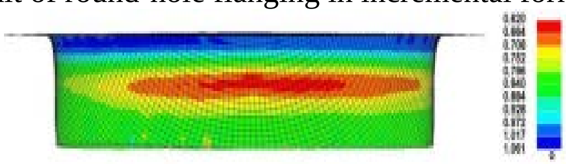


Figure 5. dm=56mm, d0=32mm. Distribution of work piece thickness formed by single-pass forming path

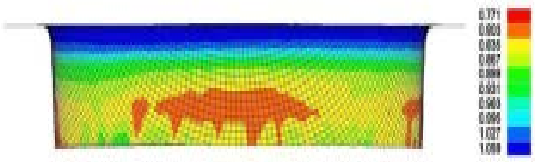


Figure 6. dm=56mm, d0=32mm. Distribution of work piece thickness formed by two-pass forming path

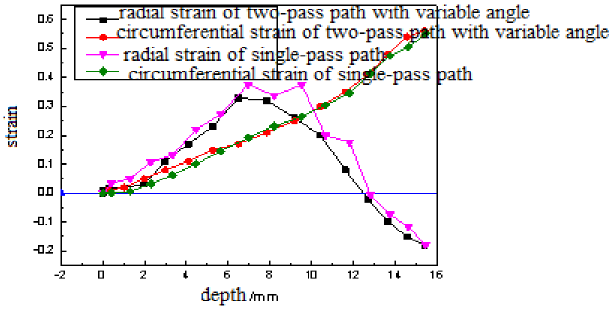


Figure 7. dm=56mm, d0=30mm. The distribution of circumferential strain and radial strain of different round-hole flanging paths

It can be seen that, compared with single-pass path, two-pass path with variable angle can obviously prevent the thinning of wall thickness in the middle of round-hole flanging.

Strain distribution. The curves of circumferential strain and radial strain of round-hole flanging with d_m=56mm, d_0=30mm are shown in Figure 7. The distribution of circumferential strain on metal sheet in two-pass flanging is similar to that in single-pass flanging; both of them show a linear increasing trend with the increase of depth. Meanwhile, compared with single-pass flanging, the maximum radial strain in the middle of two-pass flanging decreases.

Minimum wall thickness and flanging height. The minimum wall thickness and flanging height of round-hole flanging with d_m=56mm, d_0=34-26mm are shown in Table 2. With the decrease of d_0, the prefabricated diameter of the hole, the minimum wall thickness t_{min} decreases correspondingly. At the same time, the central thinning phenomenon becomes increasingly obvious. Therefore, the two-pass incremental forming of round-hole flanging can alleviate and reduce the occurrence of central thinning phenomenon to a certain extent, and improve the forming limit of round-hole flanging. But the two-pass forming also has to follow the law of one-pass forming: the central thinning phenomenon is becoming more obvious with the reduction of prefabricated diameter of the hole, and there is also a forming limit.

Table 2. Minimum wall thickness and flanging height of round-hole flanging by two-pass incremental forming with variable angle

d_0/mm	t_{min}/mm	H/mm
34	0.734	13.01
32	0.718	14.23
30	0.625	15.85
28	0.484	18.38
26	0.286	22.75

For the flanging height, the plate is assumed to have no elongation in the radial direction. The deformation area is approximately calculated according to the principle that the length of the neutral layer of the bending parts remains unchanged (see figure 8).

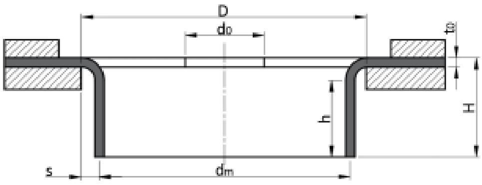


Figure 8. Height of flanging

The flanging deformation area is composed of rounded corner area and straight wall area. The radius of rounded corners in rounded corner area is related to the gap between parts and the lower platen. In Figure 8, s is a reserved unilateral gap. According to the geometric relation, the radius of the bottom corner can be regarded as approximately equal to s. Based on above assumptions, the following equation can be obtained:

$$\frac{D-d_0}{2}=\frac{\pi}{2}s+h$$

Among which

$$D=d_m+2s$$

The flanging height is:

$$H=\frac{d_m-d_0}{2}+0.43s+0.5t_0 \tag{1}$$

In the formula:

t_0 is the initial sheet thickness;

H is the flanging height;

h is the height of vertical wall area;

dm is the final diameter of the hole;

d_0 is the prefabricated diameter of the hole.

In the two-pass incremental forming process, the thickness of sheet metal becomes smaller and the flanging height becomes higher. The radial elongation of the work piece is larger than that of the single-pass process. Thus, the theoretical flanging formula is properly enlarged in the calculation of flanging height. According to experiment results, the proportion of H^2=1.05H is adopted.

Taking d_m-d_0 as the abscissa and flanging height H as the ordinate, the flanging height distribution map of circular holes with t_0 = 1.06mm and d_m = 56mm is drawn and compared with the drawing of H^2 formula. It is found that the calculated value of the formula is in good agreement with the actual value when the value of d_m-d_0 is small, that is, when the prefabricated diameter of the hole d_0 is large; when the value of d_m-d_0 is large, that is, when the prefabricated diameter of the hole d_0 is small, the deviation is large.

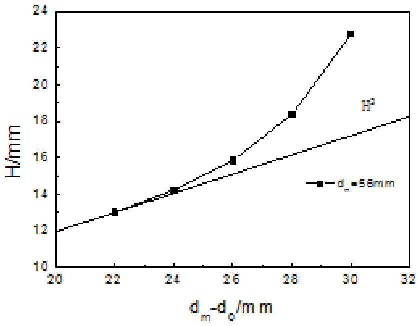


Figure 9. Height distribution of round-hole flanging by two-pass incremental forming

When the value of d_m-d_0 is relatively large, the actual flanging height is larger than the calculated value. With the decrease of the prefabricated diameter of the hole, the actual flanging height is greatly larger than calculation, while the minimum wall thickness reduces greatly. The calculation formula cannot predict the flanging height of flanging parts. The formula for flanging height is obtained though fitting method, with error less than 5%. This formula can be used to calculate the flanging height of two-pass incremental forming flanging parts.

$$H=-9.0798+0.1284d_m+0.6037(d_m-d_0)-0.0047d_m(d_m-d_0)+0.0101(d_m-d_0)^2+0.43\mathrm{s}+0.5t_0$$

5. Experimental Verification

In the numerical simulation experiment of round-hole flanging path by two-pass incremental forming, the phenomenon of central thinning in the single-pass incremental forming sample is effectively alleviated. The round-hole flanging is formed with sheet metal with thickness t_0 =

1.06mm, diameter of flanging hole d_m= 56mm and prefabricated diameter of the hole d_0 = 30mm by the special equipment for incremental forming.

(a) The complete work piece (b) Cross-section of the work piece

Figure 10. Experimental Results

As shown in Figure 10, (a) is the complete work piece; (b) is the cross-section of the work piece after wire-electrode cutting. The formed parts have good surface quality and no obvious defects. The thickness distribution of the round-hole flanging part is relatively uniform; the wall thickness is uniform from the area with flanging height more than 6 mm to the hole. The experiment has proved that two-pass incremental forming path can improve the forming limit of round-hole flanging.

6. Conclusions

Compare with single-pass forming, round-hole flanging by two-pass incremental forming has a greater forming limit, and less possibility of becoming thin in the middle of metal sheet.

Similar to single-pass forming, the round-hole flanging by two-pass incremental forming also has to follow the law of forming: the central thinning phenomenon is becoming more obvious with the reduction of prefabricated diameter of the hole, and there is also a forming limit.

When the prefabricated diameter of the hole is large, the flanging height of round holes by two-pass incremental forming can be calculated through theoretical formula (1). When the prefabricated diameter of the hole is large, the radial elongation of flanging parts is obvious; the height can be predicted by fitting formula.

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