Multi-Stage Two Point Incremental Sheet Forming

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Abstract. In incremental sheet forming, the thickness of parts decreases with the sine law as the forming slope increases, resulting in serious thinning or even fracture of parts. For industrial products, extreme thinning of parts can not meet the design requirements, seriously affecting the application of incremental sheet forming in the industrial field. Multi-stage incremental sheet forming is found to effectively improve the thickness distribution of parts. For multi-stage two point incremental sheet forming, there are a great variety of multi-stage strategies, such as parallel linear tool-path strategy, parallel arcs tool-path strategy, variable angle straight lines tool-path strategy, and stretching assist multi-stage strategy. However, which multi-stage strategy is the best multi-stage strategy is not conclusive. Therefore, in this paper, a square cone is selected to analyse the influence of tool-path strategy on thickness distribution. Then, the best multi-stage strategy is obtained by comparing the thickness distribution with different strategies. Finally, by analysing the change of strain condition with an increase in stage, the causes of different strategies for increasing the thickness distribution are obtained.

1. Introduction

In incremental sheet forming (ISF), the thickness of parts decreases with the sine law as the forming slope increases, resulting in serious thinning or even fracture of parts. For industrial products, extreme thinning of parts can not meet the design requirements, seriously affecting the application of incremental sheet forming in the industrial field. Multi-stage incremental sheet forming (MISF) is found to effectively improve the thickness distribution of parts [1]. Incremental sheet forming includes single point incremental sheet forming (SPIF) and two point incremental sheet forming (TPIF). On the contrary to SPIF, TPIF shows better formability and geometric accuracy [2]. Therefore, this paper is focused on multi-stage two point incremental sheet forming (MTPIF).

Zhou Liuru [3] compared thickness distribution of different strategies, such as parallel linear tool-path strategy, parallel arcs tool-path strategy, variable angle straight lines tool-path strategy, in multi-stage incremental forming in experiment of vertical wall cylinder and found that the strategy of parallel lines can provide more uniform thickness distribution. An Chuanhai [4] proposed a new strategy called stretch-bend assist multi-stage strategy and found that this strategy increases thickness significantly in experiment of vertical wall cylinder. Cao Jiang [5] studied the forming of circular truncated cone with experiment and numerical simulation in MTPIF and found that the increase in stages increases the thickness. Therefore, for multi-stage two point incremental sheet forming, there are a great variety of multi-stage strategies. However, which multi-stage strategy is the best multi-stage strategy is not conclusive and there are few researches on multi-stage forming of square cone.

In this paper, forming experiment of a square cone is carried out to analyse the influence of tool-path strategies on thickness distribution. Four Strategies are parallel linear tool-path strategy, parallel arcs tool-path strategy, variable angle straight lines tool-path strategy and stretching assist multi-stage strategy. By comparing the thickness distribution with different strategies, the best multi-stage strategy
is obtained. Finally, by analysing the change of strain condition with an increase in stage, the causes of different strategies for increasing the thickness distribution are obtained.

2. Experiment

2.1. Experiment design
In this paper, a square cone specimen with 60 degree slope wall is selected to analyse the influence of tool-path strategy on thickness distribution as shown in Fig 1. The specimens are deformed with tool diameter of 20mm and step size of 1.00mm. The blank of specimen is made of aluminum AA5052, with 1.00 mm thickness and 300mm×300mm dimensions. As shown in Fig 2, all specimens are manufactured on an incremental forming machine with a maximum workspace of 1800mm×1350mm×500mm. In the experiment, the lubricant is smeared on the surface of the blank.

2.2. Tool-path strategy
In this paper, four multi-stage strategies are selected, such as parallel linear tool-path strategy (Strategy A), parallel arcs tool-path strategy (Strategy B), variable angle straight lines tool-path strategy (Strategy C) and stretch-bend assist multi-stage strategy (Strategy D) as shown in Fig 3. It is figured out that the slope of the specimen is formed from stage $s_0$ to stage $s_5$ with certain forming direction, in which stage $s_0$ is the first stage and stage $s_5$ is the final outline of the specimen. In order to analyse thickness distribution with increasing of stages, four transition stages, namely stage $s_1$ to $s_4$, are selected as listed in Table 1.

| Strategy   | Forming direction |
|------------|-------------------|
| Strategy A |                   |
| Strategy B |                   |
| Strategy C |                   |
| Strategy D |                   |

Figure 1. A square cone specimen

Figure 2. Incremental forming machine

Figure 3. Multi-stage strategies, namely parallel linear tool-path strategy (Strategy A), parallel arcs tool-path strategy (Strategy B), variable angle straight lines tool-path strategy (Strategy C) and stretch-bend assist multi-stage strategy (Strategy D).
3. Result

The thickness distribution with various multi-stage strategies is shown in Fig 4. The specimens are formed successfully with strategy A, B and C. However, the specimen formed with strategy D is fracture as a height of 15mm in the process of stage 24. In incremental sheet forming, the thickness of parts decreases with sine law as the forming slope increases. For 60 degree square cone, the thickness of slope wall is about 0.50 mm in single-stage incremental sheet forming. The thickness distribution of strategy C is more than 0.8 mm in the height from 20 mm to 50 mm. However, the thickness distributions of strategies A and B are less than 0.50 mm. Therefore, the thickness distribution of specimen formed with strategy C is higher than other strategies.

In order to observe the change of thickness with the increase of stage, thickness distributions with various multi-stage strategies are shown in Fig 5. For Strategy A, the minimum thickness of stage $s_2$ and $s_3$ appears at the height of 35 mm and 30 mm respectively, and the minimum thickness of stage $s_4$ and $s_5$ appears at the height of 25 mm and 20 mm respectively. With an increase of stages, the thickness of most areas decreases. In some areas, however, the thickness fluctuates due to the appearance and disappearance of wrinkles during the forming process. The minimum thickness of strategy A appears in the height from 20 mm to 30 mm.

For Strategy B, the thickness distribution is relatively uniform. The thickness distribution continues to decrease in the height from 35 mm to 50 mm while the thickness distribution changes little in the height from 0 mm to 35 mm. The minimum thickness of strategy B appears at the height of 5 mm.

For Strategy C, the thickness distribution in the height from 0 mm to 35 mm changes little and is more than 0.8 mm. However, thickness distribution continues to decrease in the height from 0 mm to 15 mm. The minimum thickness of strategy C appears in the height from 5 mm to 10 mm.

For Strategy D, the minimum thickness of strategy C appears in the height from 5 mm to 10 mm, where is the location of the corner of the path. The area above the corner of the path is deformed by the tension caused by deformation of the area below the corner of the path resulting in the largest forming force in the corner of the path. The greater the forming force causes the thinner the thickness, leading to the failure of the blank. However, the thickness distribution of strategy D is more than 0.50 mm in the height from 20 mm to 50 mm.

![Figure 4. Comparison of different strategies for thickness distribution](image_url)
4. Discussion

In order to analyse the cause that the thickness changes with the increase of the stage, the grid is printed on the blank and three specific positions, namely P1, P2 and P3, are selected to measure the strain conditions of three points with the increase in stage as shown in Fig 6. As shown in Fig 7, the strain conditions are almost plane condition for those strategies.

For Strategy A, P1, P2 and P3 are deformed in slope wall and the major strain of them increases since the blank is formed into a square cone with 30 degree slope wall in the first stage as shown in Fig 6. The major strain of P1 continues to increase from stage s2 to s3 although P1 is deformed into slope wall at stage s2. Meanwhile, the major strain of P1 changes little from stage s3 to s5. This indicates that the formed area will be affected by the tensile force caused by deformation zone within a certain range causing the major strain continues to increase. P2 is finally deformed into the corner of the specimen and the major strain of P2 changes little from stage s1 to s4 due to no change in slope. P3 is finally deformed into the flag of the specimen and the major strain of P3 changes little from stage s1 to s4. Therefore, for Strategy A, an increase in the thickness of the slope wall is achieved by thinning the flange area of final shape in the first stage, but the thickness of formed slope wall still decreases with increase in stage within a certain range due to the tension of the forming area.

For strategy B, P1 is located at the slope wall and P2 and P3 are located at the flange in the final shape. P1, P2 and P3 are deformed in slope wall of a variable slope square cone in the first stage and the major strain of them increases according to the slope of the generatrix. The major strain conditions of P1, P2 and P3 change little from stage s1 to s4 indicating that the slope of the initial generatrix determines the strain condition of the part. Therefore, for Strategy B, the slope of the curve determines the thickness distribution of the specimen.

For strategy C, P1 and P2 are located at the slope wall and P3 is located at the flange in the final shape. In the first stage, P1, P2 and P3 are deformed in slope wall and the major strain of them increases since the blank is formed into a square cone with 30 degree slope wall. Due to the slope of the wall slowly increases, P1 and P2 change little from stage s1 to s4. However, P3 located near the corner and the major strain condition of P3 increases obviously from stage s1 to s4. When P3 is away from the corner, the main strain changes little from stage s4 to s5. The thickness of the sloping wall is guaranteed through the thinning of the area around the corner of each stage and the area of corner is
located in flag in final part as stage increasing. Therefore, for strategy C, the shape of the specimen achieved through the thinning of the flag.

For strategy D, P1 and P2 are located at the slope wall and P3 is located at the flange in the final shape. In the first stage, P1, P2 and P3 are deformed in slope wall and the major strain of them increases since the blank is formed into a square cone with 30 degree slope wall. As shown in Fig 7, P1, P2 and P3 change little from stage $s_1$ to $s_2$. It is shown in Fig 5 that thinning of thickness occurs mainly around the corner. Therefore, for strategy D, the shape of the specimen deformed through the thinning around the corner.

**Figure 6.** Strain measurement positions.

**Figure 7.** Strain conditions with various multi-stage strategies.
5. Conclusion
This paper investigates the influence of multi-stage strategies on thickness distribution with thickness distribution. By analysing the change of strain condition with an increase in stage, the causes of different strategies for increasing the thickness distribution are obtained. The major conclusions are summarized as follows:
Four Strategies are parallel linear tool-path strategy, parallel arcs tool-path strategy, variable angle straight lines tool-path strategy and stretch-bend assist multi-stage strategy.

- The thickness distribution of specimen formed with variable angle straight lines tool-path strategy is higher than other strategies.
- For parallel linear tool-path strategy, an increase in the thickness of the slope wall of the specimen is achieved by thinning the flange area of final shape in the first stage, but the thickness of formed slope wall still decreases with increase in stage within a certain range due to the tension of the forming area.
- For parallel arcs tool-path strategy, the slope of the curve determines the thickness distribution of the specimen.
- For variable angle straight lines tool-path strategy, the shape of the specimen achieved through the thinning of the flag.
- For stretch-bend assist multi-stage strategy, the shape of the specimen deformed through the thinning around the corner.

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