Development and Optimal Machining Path Determination of Incremental Forming Equipment for 120° Sidewall Machining Angles

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Abstract. In response to the limitations of incremental forming technology in the manufacture of thin-walled parts with large forming angles, this paper presents the independent development of an incremental forming equipment capable of multi-angle processing. The equipment achieves independent control over the two rotational degrees of freedom of the forming tool through the coordinated operation of the motor and the electromagnetic clutch, thereby enabling multi-angle plastic forming of metal sheets. By employing a strategically designed "pyramid" incremental forming path, the equipment has successfully processed thin-walled parts with forming angles exceeding 90 degrees.

Keywords: Incremental Forming, Multi-Angle Machining, Equipment Development, Large Angle Part Forming

1 Introduction

Incremental forming processes, which do not require mold, offer high flexibility and are well-suited for the production of small batches of parts, thus becoming a research focus both domestically and internationally. [1-3] However, the application of incremental forming equipment still encounters a technical bottleneck in machining thin-walled metal parts with side wall angles exceeding 90°, which restricts its further large-scale application. Researchers have conducted relevant studies: Zhang et al.[4] achieved the machining of conical parts with a 70° side wall through a spiral machining path; Zhu et al.[5], using a square punch and an alternating composite forming method, were only able to process box-shaped parts with 90° straight walls; Li et al.[6], based on the technology of three-axis and five-axis CNC progressive composite forming, although capable of processing parts with angles greater than 90°, only formed a small-sized conical protrusion in a specific area of the square pyramid, making it difficult to achieve all-around large-angle machining of parts. Therefore, addressing the challenge of ma-

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chining complex thin-walled parts with side walls greater than 90° remains a key research focus for progressive forming equipment.

The principle of incremental forming is essentially the superimposed combination of layer-by-layer manufacturing. It involves the discretization of complex three-dimensional shapes into orderly two-dimensional sections along a specific axis. The forming tool follows a predetermined planar motion trajectory, starting from point processing and gradually accumulating into line processing, to carry out layer-by-layer forming of the metal sheet. This continuous accumulation process achieves the forming of three-dimensional shape parts from the sheet metal. [7-11] For the processing of side walls with angles greater than 90°, the tool head is required to be tilted at a certain angle. However, the tool head is typically limited by its fixed installation, especially affected by the angle of reaction force from the sheet metal deformation, and its tilting angle must not exceed a critical value; otherwise, the tool head may exhibit vibration phenomena, and in severe cases, it can lead to lateral bending of the tool head and fixtures.

This paper presents the independent development of an incremental forming equipment capable of multi-angle machining, which improves the tool mounting method and eliminates machining vibrations. Moreover, by optimizing the machining path, it achieves the forming of parts with a 120° angle of deformation.

2 Experimental Equipment

This device is a compact five-axis incremental forming machine, utilizing a dual-head five-axis configuration. In addition to employing the most basic screw transmission method to achieve the XYZ three-axis motion of the tool, its forming tool can realize dual degrees of freedom, including rotation around the Z-axis and oscillation around the Y-axis (or X-axis). In the design of traditional CNC machines, it is often necessary to use two motors to control the single rotational degree of freedom of the tool to achieve rotation in the aforementioned two directions. However, for the small device designed in this paper, the use of multiple motors would not only occupy a large space but also lead to an excessively long cantilever structure at the tool, thereby reducing the stability of the processing. Therefore, this device achieves independent control of the tool's two rotational degrees of freedom through the engagement and disengagement mechanism of an electromagnetic clutch. This design not only enables the forming tool to perform multi-angle processing of metal sheets but also enhances the stability of the processing process. The design principle is detailed in Figure 1.

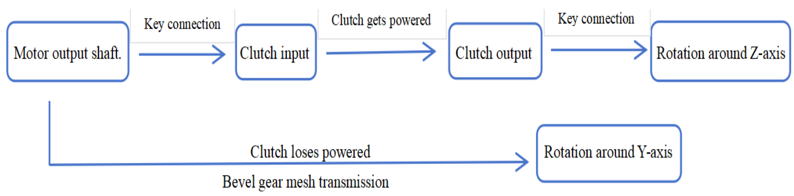

Fig. 1. Schematic diagram of the multi-angle machining tool structure.

The motor output shaft is connected to the input end of the electromagnetic clutch through a key connection at one end, and also achieves circumferential fixation with the horizontal bevel gear through a key connection at the other end, thereby enabling synchronous rotation of the three components. When the electromagnetic clutch is in the power-off state, its input and output ends are separated, and the motor output shaft drives the clutch input end and the horizontal bevel gear to rotate, achieving the tool head's oscillation around the Y (or X) axis through the bevel gear meshing transmission. When the electromagnetic clutch is energized and closed, the input and output ends of the clutch are tightly connected, and the entire clutch achieves synchronous rotation with the motor output shaft through a key connection, thereby driving the tool to rotate as a whole around the Z axis.

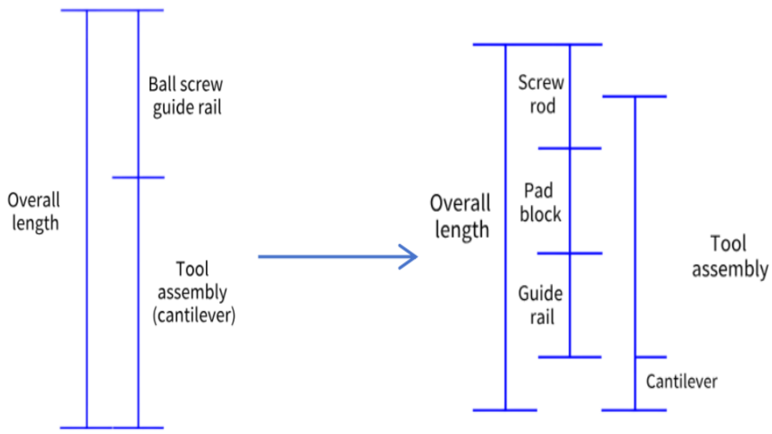

Fig. 2. Design Principle of the "Riding" Structure of the Forming Tool.

As shown in Figure 2, although the use of one motor is reduced, the total length H of the forming tool is still excessively long. If it is directly suspended vertically below the beam, a large cantilever structure will inevitably be formed, reducing the stability of the machining process. Therefore, a "riding" structural design is adopted: the main structure of the tool assembly stably "rides" between the screw rod and the guide rail, with the screw rod positioned above the guide rail and connected to the top of the tool assembly through the nut seat on it. Meanwhile, the slider on the guide rail is connected to the bottom of the tool assembly. This structural layout significantly reduces the cantilever length of the tool, thereby effectively enhancing the rigidity and stability of the entire equipment. The assembled equipment structure is shown in Figure 3. The equipment consists of five parts: the X-direction motion structure, the Y-direction motion structure, the Z-direction motion structure, the sheet clamping device, and the forming tool. In incremental forming, positive forming cannot be separated from mold support, making it difficult to achieve truly flexible forming. Therefore, this equipment adopts a negative forming method.

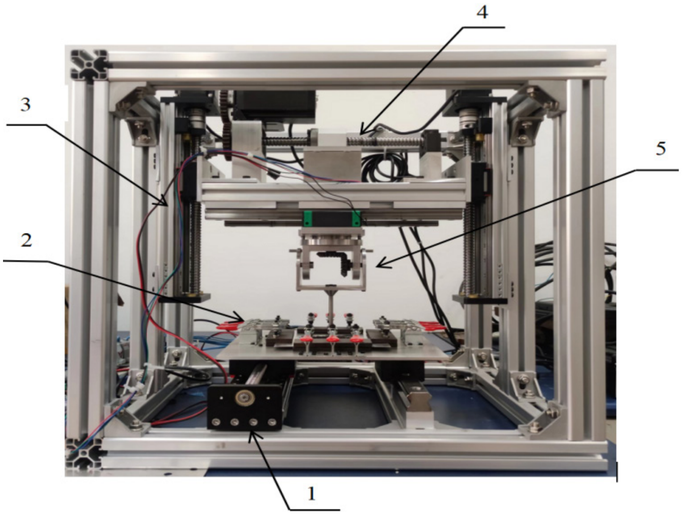

Fig. 3. Actual device photo: 1-X-axis; 2-fixture; 3-Z-axis; 4-Y-axis; 5-Forming tool.

After the assembly of the equipment structure and control system is completed, it is essential to conduct machining tests to ensure that the equipment functions properly. Figure 4 presents a variety of thin-walled parts of different shapes that were machined using this equipment. Upon measurement, the machining accuracy was found to meet the expected standards, thereby confirming the equipment's capability for normal operation.

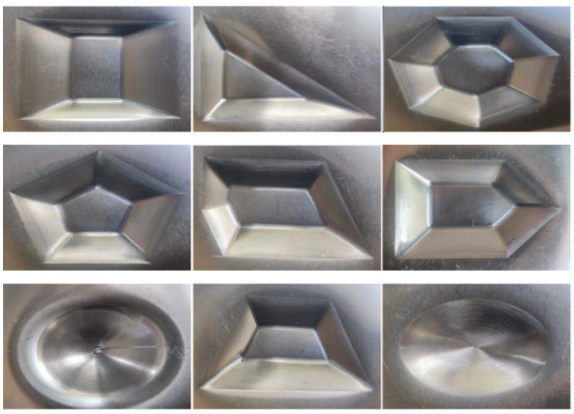

Fig. 4. Conventional thin-walled parts.

3 Experimental Material

The experimental material used in this paper is commercially available O-temper 1060 series aluminum alloy sheets, with dimensions of 150×150×0.5 mm.

4 Experimental Plan

4.1 90° Sidewall Machining Path

The 90° side wall forming path is shown in Figure 5: The tool starts from the preset starting point A1, following the inclined path from A1 to A2, and then from A3 to A4, to complete the first pass of the forming operation. After completing this pass, the tool returns to the starting point A1, and along the vertical path from A1 to B1, performs the second pass of vertical machining on the side wall of the part to form a vertically oriented side wall. Subsequently, the tool continues along the inclined path from B1 to B2, and then from B3 to B4, to execute the second pass of the forming operation, repeating the aforementioned forming process until the side wall of the part is completely transformed from the initial concave shape to the desired straight wall shape.

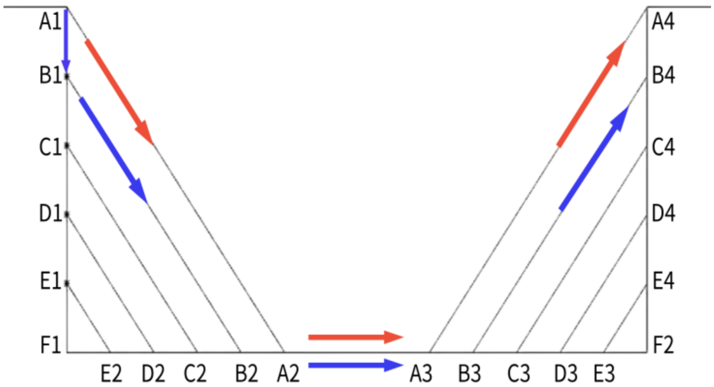

Fig. 5. Forming Path of Straight-Walled Parts.

4.2 Greater than 90° Sidewall Machining

The forming path is shown in Figure 6. Employing a "pyramid-like" layer-by-layer expansion path strategy for further large-angle forming of straight-walled parts. The processing tool completes the first large-angle expansion of the straight-walled part along the path from the starting point O to OA-AB-Bb. Afterward, the tool head returns to point A and performs the second expansion forming of the straight-walled part along the path AC-CD-DB. This process will be repeated until the expansion forming of the entire part is completed. Similar to the forming principle of straight-walled parts, this method achieves consistency in horizontal spacing between adjacent expansions through the "pyramid"-like layer-by-layer expansion forming. During a single layer expansion, the plastic deformation experienced by the metal at any position is relatively consistent in magnitude and direction, ensuring the uniformity of the deformation process. This deformation characteristic helps to achieve a uniform thickness distribution of the sheet metal side wall during the forming process, significantly reducing the risk of material rupture.

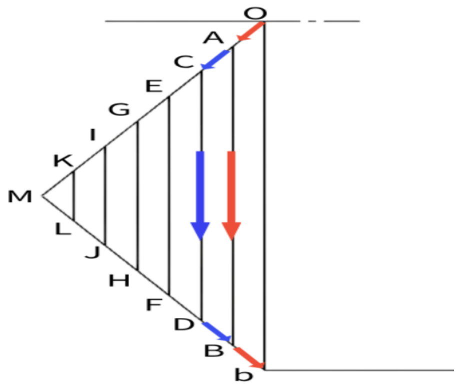

Fig. 6. "Pyramid"-style Expansion Forming Path.

Traditional incremental forming equipment is typically modified from three-axis CNC machines, and due to the fixed nature of their forming tools, they can only process thin-walled parts with forming angles less than 90°, resulting in concave pit shapes. However, the equipment independently developed in this study has overcome this limitation, enabling the forming tool to tilt at multiple angles. Based on the straight wall piece, this equipment can further achieve a large-angle expansion, thereby successfully processing thin-walled parts with forming angles greater than 90° in a concave style.

5 Experimental Results and Analysis

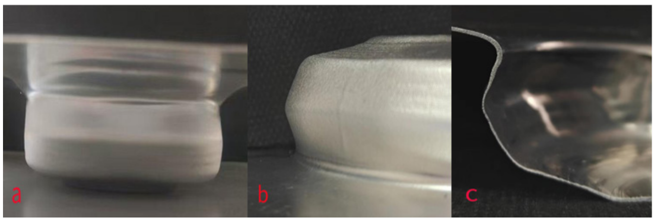

Fig. 7. Thin-walled part with a forming angle of 120°.

Figures 7(a) and 7(b) present the thin-walled parts with a 120° forming angle obtained from the experiment in this study. The surface of the parts is smooth and even, with no apparent machining vibration marks. Figure 7(c) is a cross-sectional view taken along the center line of the part, and it can be observed that the thickness of the part's side wall gradually decreases with the increase in forming depth. This variation in thickness is consistent with the thickness change observed in stamping formed sheet metal. To visually observe the trend of changes in the thickness of the part's side wall, Figure 8 displays the image of this cross-section under a microscope. In the initial unprocessed area, due to the entanglement effect of the metal in the processing area, a noticeable elastic deformation has occurred. As the forming depth increases, the thickness of the upper half of the processed area gradually decreases, especially at the corner, where the thinning is most pronounced. In contrast, the thickness of the lower half of the processed area is similar to that at the corner and exhibits a more uniform thickness distribution. Measurements revealed that the minimum wall thickness is located in the lower processed area, with a value of 0.1156 mm, and compared to the initial thickness of the sheet metal of 0.5 mm, the maximum thinning rate reached 76.88%.

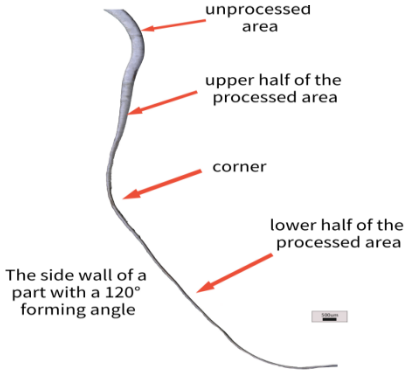

Fig. 8. Cross-sectional view of the side wall.

Incremental forming is a process that combines elastic and plastic deformation. During the forming process, the metal sheet first undergoes elastic deformation, which increases as the forming depth increases. When the forming depth reaches a certain value, the sheet reaches its yield limit, resulting in plastic deformation. After the processing is completed, when the forces applied by the forming tool head and the sheet clamping device are removed, the stored elastic deformation energy within the sheet is released, causing the part to spring back. Since spring back is inevitable in the incremental forming process, the measurement results show that the actual forming angle of the part's side wall is 118°, slightly lower than the expected 120°.

6 Conclusion

This paper successfully developed a compact five-axis incremental forming machine, which is primarily composed of five parts: the XYZ three-axis motion structure, the sheet clamping device, and the forming tool. By utilizing the engagement and disengagement of an electromagnetic clutch, it achieves independent control of the two rotational degrees of freedom of the forming tool with a single motor, enabling the tool to perform multi-angle processing and forming of metal sheets. Additionally, the "riding-style" structural design shortens the cantilever length of the tool, thereby improving the vibration issues caused by an excessively long cantilever during processing. After the development of the equipment, various shapes of thin-walled parts were processed and tested, verifying that the equipment meets the usage requirements. Finally, through a two-step process involving vertical machining paths and a "pyramid"-style layer-by-layer expansion forming path, the machine achieved the processing and forming of parts with a 120° side wall forming angle, significantly expanding the forming range of incremental forming.

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