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Factors Affecting the Pillow Effect in Single-Point Incremental Forming

Guoping Jiang, Xiaojun Liu, and Jin Shi

School of Mechanical Engineering, Southeast University, Nanjing, Jiangsu 211189, China

ABSTRACT

Single-point incremental forming (SPIF) is a machining process that uses a tool to perform extrusion motion on a metal sheet blank, causing plastic deformation of the metal sheet blank to achieve the target model size accuracy requirement. The pillow effect, which occurs in the unformed region at the bottom of the part, significantly impacts the accuracy of the final product. Optimizing process parameters is necessary to minimize the impact of the pillow effect on accuracy. Conducting experiments to optimize the process parameters will inevitably increase research and development costs and extend the research and development cycle. However, using simulation models to simulate and optimize process parameters can effectively reduce research and development costs and shorten the research and development cycle. This work aims to study the effects of seven factors that affect the formation of the pillow effect in SPIF machining parts, including wall angle, diameter, height, wall thickness, downward step size, tool path interlayer connection method, and side wall shape. First, based on the ANSYS Workbench/LS-DYNA platform, a simulation model is constructed, and machining experiments and simulations are conducted to compare the results of the experiments and simulations by comparing the key points of the pillow effect profile curve to verify the feasibility of the model. Due to the layered machining characteristics of the single-point system, the pillow effect feature is easily formed in the unformed area at the bottom, and the pillow effect can be clearly seen to experience an increase zone, an upward zone, and a steady zone from the cross-sectional profile chart through the center axis. The simulation results show that the minimum pillow effect amount can be obtained when the process parameters are wall angle of 30°, bottom diameter of Φ50mm, forming depth of 30mm, plate thickness of 1mm, downward step size of 1mm, straight-line interlayer connection method, and hyperbolic side wall shape. Then, using the Taguchi method to set up an orthogonal experiment of L18(3^7), conduct simulation experiments, and obtain the measurement data of the pillow effect. The software used for the analysis of experimental signal-to-noise ratio data is Minitab-19, and the signal-to-noise ratio refers to the ratio of useful data read in the experiment to interference noise data. Variance analysis is performed on the obtained results to determine the optimal process parameter configuration of the seven factors. A prediction model is generated, and a confirmation experiment is conducted to validate the model. The confirmation experiment was conducted three times, and the average value of the measurement peak results was taken. The measurement results of the confirmation experiment were within the confidence interval of 95% confidence level. The results showed that the pillow effect decreases with an increase in wall angle and downward step size, and increases with an increase in bottom diameter, forming depth, and plate thickness. When the tool path is selected to be a straight-line interlayer connection method and the part side wall shape is a hyperbolic shape, a smaller pillow effect can be obtained.

Keywords: Single point incremental forming, Pillow effect, Taguchi, LS-DYNA

INTRODUCTION

In recent years, single-point incremental forming (SPIF) of metal sheets has gained considerable attention as an emerging advanced manufacturing technology. Based on the layer-by-layer manufacturing concept, SPIF is particularly suitable for producing custom-made parts in small quantities (Li and Wang, 2022; Li et al., 2014). The SPIF process involves using a ball or flat-headed tool to shape a part along a pre-defined path (Kumar and Gulati, 2019; Ambrogio et al., 2006). Due to its high flexibility, low cost, and ability to process complex shapes, SPIF has shown great potential for applications in aerospace, automotive, and medical fields (Pandre et al., 2021; Sen et al., 2020; Sbayti et al., 2022). Currently, research on SPIF has extended to various types of materials, such as perforated sheets, high-density polyethylene sheets, and titanium alloy sheets (Bouzidi et al., 2022; Rosca et al., 2023; Frikha et al., 2022). Studies on SPIF have also focused on optimizing process parameters and planning machining paths (Mezher and Kovacs, 2022; Formisano et al., 2023). For instance, Manisn Oraon et al. investigated the effects of downward step size, tool end face area, and wall angle on machining quality (Oraon and Sharma, 2022). Miao Shang et al. studied the application of hydraulic systems in SPIF and determined the critical angle of uniform wall thickness corresponding to different support pressures (Shang et al., 2023). Some studies have also examined the impact of process parameters on machining forces in SPIF (Duflou et al., 2007; Jeswiet et al., 2005). Ambrogio et al. proposed an industry-oriented method for detecting failure modes in incremental forming based on an analysis of forming force trends (Ambrogio et al., 2006). Research on stress-strain magnitude and wall thickness reduction in single-point forming also demonstrated significant effects on improving machining accuracy and reducing metal sheet springback (Qadeer et al., 2023; Hassan et al., 2022; Singh et al., 2023a; Singh et al., 2023b). Xiaofan Shi et al. proposed a new non-interference spiral toolpath optimization method for expanding electrically assisted incremental forming to low-carbon steel DC04 metal sheets (Shi et al., 2013).

In practical applications of SPIF, the theoretical model's bottom surface is often flat, and the flat surface is formed naturally after the theoretical model's sidewalls are layered. However, the bottom surface may experience bulging due to plastic deformation during the machining process, which can affect the machinability of the part and the quality of the finished product (Pepelnjak et al., 2022). Therefore, it is essential to give sufficient attention to this issue and conduct further research on its forming mechanism and countermeasures. Prior studies on bottom surface bulging have been conducted by Najm et al., who used machine learning to investigate the effects of process parameters on sidewall and bottom surface bulging in single-point forming (Najm and Paniti, 2023).

This paper will construct a simulation model to study the bottom surface bulging phenomenon in SPIF and conduct experiments to validate the model.

DESIGN OF EXPERIMENT FOR OPTIMIZATION OF PROCESS PARAMETERS

As a method of machining metal sheets by using a tool to squeeze and deform them to achieve the required dimensions, single point incremental forming (SPIF) belongs to the category of non-linear metal deformation due to the plastic deformation of the metal sheet during the machining process. Therefore, analyzing the deformation mechanism of SPIF using various finite element analysis software has become an important and cost-effective means. The finite element analysis software used in this article is ANSYS WorkBench/LS-DYNA, and the target model is a truncated cone (see Figure 1). Firstly, the three-dimensional model is constructed in the three-dimensional modeling software. Secondly, the three-dimensional model is imported into the finite element analysis software for boundary condition settings. Thirdly, simulation calculation is performed. Finally, the simulation results are analyzed.

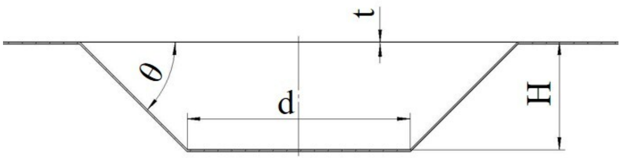

Figure 1: Truncated cone and dimensions.

The pillow effect curve of the cross-section of the central axis of the finished product is shown (see Figure 2), where only half of the curve is displayed due to the symmetrical nature of the bottom curve along the central axis of the frustum. From the graph, it can be observed that the pillow effect can be divided into three regions: surge zone, upward zone, and stable zone.

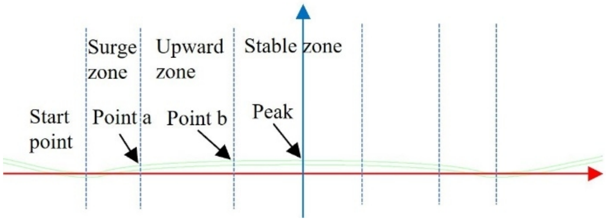

Figure 2: Pillow effect curve.

The pillow effect is influenced by many factors during the processing. This paper selects seven representative factors among them for research, including model wall angle θ (°), bottom diameter d (mm), forming depth H (mm), wall thickness t (mm), downward step Δz (mm), interlayer connection method, and model side wall shape (see Table 1). Among them, the model side wall shape refers to three cases where the model side wall generatrix is a straight line, a parabola, and a hyperbola.

Table 1. Forming parameters for SPIF process.

Symbol	Input parameters	Levels of input factors		
		Level 1	Level 2	Level 3
A	Forming angle θ(°)	30	45	60
B	Diameter d(mm)	50	60	70
C	Forming depth H(mm)	30	40	50
D	Thickness t(mm)	1	1.2	1.5
E	Step size Δz(mm)	0.6	0.8	1
F	Connection method	Linear	Stepladder	Jump
G	Sidewall shape	Parabola	Cone	Hyperbola

Analysis of Mean Value and Signal-to-Noise Ratio

The layout diagram of L27 orthogonal experiment and the response data, signal-to-noise ratio, and mean value obtained in each experiment are shown (see Table 2). The mean range value table in Table 3 and the signal-to-noise ratio range value table in Table 4 can be calculated based on Table 2.

Table 2. Layout of L27 OA with response data.

Run	Input parameters and their levels							SN ratio	Mean
	Forming angle	Diameter	Forming depth	Thickness	Step size	Connection method	Sidewall shape		
1	30	50	30	1	0.6	Linear	Parabola	-2.829	1.385
2	30	50	30	1	0.8	Stepladder	Cone	-0.427	1.050
3	30	50	30	1	1	Jump	Hyperbola	0.925	0.899
4	30	60	40	1.2	0.6	Linear	Parabola	-2.330	1.308
5	30	60	40	1.2	0.8	Stepladder	Cone	-2.617	1.352
6	30	60	40	1.2	1	Jump	Hyperbola	-2.194	1.287
7	30	70	50	1.5	0.6	Linear	Parabola	-3.378	1.475
8	30	70	50	1.5	0.8	Stepladder	Cone	-5.734	1.935
9	30	70	50	1.5	1	Jump	Hyperbola	-5.513	1.886
10	45	50	40	1.5	0.6	Stepladder	Hyperbola	-0.024	1.002
11	45	50	40	1.5	0.8	Jump	Parabola	-1.376	1.172
12	45	50	40	1.5	1	Linear	Cone	-3.684	1.528
13	45	60	50	1	0.6	Stepladder	Hyperbola	-0.055	1.006
14	45	60	50	1	0.8	Jump	Parabola	-3.909	1.568
15	45	60	50	1	1	Linear	Cone	-0.730	1.088
16	45	70	30	1.2	0.6	Stepladder	Hyperbola	-3.572	1.509
17	45	70	30	1.2	0.8	Jump	Parabola	-6.064	2.010
18	45	70	30	1.2	1	Linear	Cone	0.822	0.910
19	60	50	50	1.2	0.6	Jump	Cone	-0.693	1.083
20	60	50	50	1.2	0.8	Linear	Hyperbola	1.848	0.808
21	60	50	50	1.2	1	Stepladder	Parabola	-0.372	1.044
22	60	60	30	1.5	0.6	Jump	Cone	-1.687	1.214
23	60	60	30	1.5	0.8	Linear	Hyperbola	0.899	0.901
24	60	60	30	1.5	1	Stepladder	Parabola	0.797	0.912
25	60	70	40	1	0.6	Jump	Cone	-5.695	1.926
26	60	70	40	1	0.8	Linear	Hyperbola	2.445	0.755
27	60	70	40	1	1	Stepladder	Parabola	-2.279	1.300

Table 3. Response table for means.

Level	Forming angle	Diameter	Forming depth	Thickness	Step size	Connection method	Sidewall shape
1	1.397	1.108	1.199	1.22	1.323	1.128	1.353
2	1.31	1.182	1.292	1.257	1.283	1.234	1.343
3	1.105	1.523	1.321	1.336	1.206	1.449	1.117
Delta	0.293	0.415	0.123	0.116	0.117	0.321	0.236
Rank	3	1	5	7	6	2	4

Table 4. Response table for S/N ratios.

Level	Forming angle	Diameter	Forming depth	Thickness	Step size	Connection method	Sidewall shape
1	-2.6775	-0.737	-1.2374	-1.3949	-2.2514	-0.7709	-2.4156
2	-2.0658	-1.3141	-1.9728	-1.6859	-1.6595	-1.587	-2.2717
3	-0.5264	-3.2187	-2.0595	-2.1889	-1.3587	-2.9118	-0.5824
Delta	2.1511	2.4817	0.8221	0.794	0.8927	2.1409	1.8333
Rank	2	1	6	7	5	3	4

Analysis of Variance

The mean of pillow effect obtained from Table 2 can be used as an input to perform variance analysis on various influencing factors to distinguish the significant factors affecting the pillow effect. The variance analysis table of the pillow effect (see Table 5) indicates that the significance factor P-value of the bottom diameter of the truncated cone is less than 0.05 at a 95% confidence level, which suggests that the bottom diameter of the truncated cone is a significant factor affecting the pillow effect.

Table 5. Analysis of variance for bottom pillowing.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Forming angle	2	0.40643	0.20321	2.18	0.156
Diameter	2	0.88167	0.44083	4.73	0.031
Forming depth	2	0.07374	0.03687	0.4	0.682
Thickness	2	0.06375	0.03187	0.34	0.717
Step size	2	0.06399	0.03199	0.34	0.716
Connection method	2	0.48151	0.24075	2.58	0.117
Sidewall shape	2	0.32028	0.16014	1.72	0.221
Error	12	1.11852	0.09321		
Total	26	3.40988			

Effects of Process Variables

The simulation results show that the surface pillow effect decreases with the increase of the wall angle and the step size of the downward pressure. Moreover, the pillow effect increases with the increase of the bottom diameter of the truncated cone. This is because the larger the bottom diameter, the greater the curve span of the pillow effect formed by the plastic deformation of the tool during the processing of the bottom plate, and the higher the pillow effect height. The pillow effect increases with the increase of the forming depth and the thickness of the plate. Among the interlayer connection methods, the pillow effect generated by the straight-line connection method of the tool path layer is the smallest. Among the side wall shapes, the pillow effect generated by the hyperbolic corresponding to the model side wall is the smallest.

The Predictive Model

According to the range table and range chart, in order to minimize the pillow effect, the level of each influencing factor must be specified. Based on the analysis presented earlier, the optimal process parameters are as follows: wall angle of 30°, bottom diameter of Φ50mm, forming depth of 30mm, plate thickness of 1mm, step size of 1mm for downward pressure, linear interlayer connection mode, and hyperbolic side wall shape.

The optimal parameters were used as input parameters to perform the confirmation experiment for the minimum pillow effect of 304 stainless steel plate on a single point incremental forming system. The confirmation experiment was conducted three times, and the average value of the measured peak points was taken. The measured results of the confirmation experiment were within the confidence interval of 95% at the confidence level.

CONCLUSION

Firstly, in this study, a simulation model of the pillow effect in single-point incremental forming (SPIF) was constructed and the effectiveness of the model was verified through experiments. Secondly, the Taguchi method was used to investigate the influence factors of the pillow effect in seven SPIF processes. Finally, three conclusions were drawn. Due to the layer-by-layer processing characteristic of SPIF, the pillow effect is likely to form in the unformed area at the bottom, and the profile of the pillow effect from the center axis clearly shows an increasing region, a rising region, and a stable region from the edge to the center. The simulation results showed that the minimum pillow effect could be obtained with a wall angle of 30°, a bottom diameter of Φ50mm, a forming depth of 30mm, a sheet thickness of 1mm, a downward step of 1mm, and a linear interlayer connection and hyperbolic sidewall shape. The pillow effect decreased with an increase in wall angle and downward step, but increased with an increase in bottom diameter, forming depth, and sheet thickness. A smaller pillow effect could be obtained by selecting a straight interlayer connection and a hyperbolic sidewall shape for the tool path.

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