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Improving profile accuracy in SPIF process through statistical optimization of forming parameters †

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Abstract

In single-point incremental forming (SPIF) process, a number of parameters are involved and need to be adjusted before the commencement of the forming operation. The inappropriate selection of these parameters could be detrimental to process accuracy. In this paper, the effect of five parameters, namely, sheet thickness, tool radius, step size, wall angle, and pre-straining level of sheet, on the profile accuracy of the produced part of AA1060 with SPIF is experimentally investigated. A response surface method is employed for the experimental design and regression analysis. The experimental results are presented in the form of graphical three-dimensional response surfaces. The results of ANOVA show that the sheet thickness, wall angle, step size, and the interaction between the sheet thickness and wall angle are extremely significant in terms of their effect on profile accuracy. Furthermore, an empirical model is proposed to achieve improved profile accuracy in terms of the optimized parameters.

Keywords: Empirical model; Forming parameters; Optimization; Profile accuracy; Response surface; SPIF

1. Introduction

Single-point incremental forming (SPIF) is a novel sheet-forming process. In this process, a sheet blank is tightly held at the periphery and a single-point tool deforms it in an incremental fashion during successive downward steps (Fig. 1) [1]. The tool moves according to a pre-defined trajectory. As a result, three-dimensional (3D) shaping can be obtained without dedicated dies. Due to the absence of these dies, the process is well suited for customized and small batch sizes of sheet metal products. Several applications of SPIF process have been demonstrated in literature. A variety of asymmetric complex shapes, automotive service panels, and customized medical products (e.g., ankle support) are some relevant examples [2].

On one hand, SPIF offers higher flexibility and lower per unit cost by eliminating the fixed cost of dedicated dies. On the other hand, however, it suffers a serious drawback of poor profile accuracy [3-8]. If this shortcoming can be overcome, the SPIF process could be successfully employed for industrial applications.

To address the aforementioned shortcoming of SPIF process, various strategies have been attempted. Hirt et al. [4] employed counter dies to reduce the spring-back. Ambrogio et al. [5] introduced an online profile measurement and correction system. Duflou et al. [6] used different tool path strategies to improve profile accuracy. The use of counter dies does not only reduce the process flexibility, but also increases the product cost. Similarly, online profile measurement complicates the process. This last strategy provides a simple solution; however, the method involves material waste and extensive trial-and-error. Optimization of forming parameters can be another simple solution. Ham and Jeswiet [7], as well as Ambrogio et al. [8], have performed work in this direction.

The results of the study by Ham and Jeswiet [7] were not conclusive. Meanwhile, Ambrogio et al. [8] performed a statistical analysis on the effects of five parameters, namely sheet thickness, tool radius, step size, wall angle, and part depth, on the geometrical error of pyramids. The results provided guidelines, to some extent, for process optimization. However, this work was also subject to several shortcomings:

They [8] confined the analysis by measuring the profile error at the bottom of part at two points (K_1 and K_2) only (see Fig. 2). The bottom cannot be the representative of the whole part profile. Ongoing work by the authors showed that the profile error near the clamped edge of part increases with the increasing tool radius, whereas the same has reverse effect at the bottom. Therefore, the geometrical error in the zone adja-

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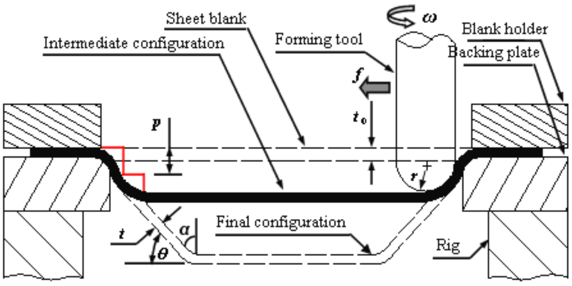

Fig. 1. Schematic of SPIF process [1].

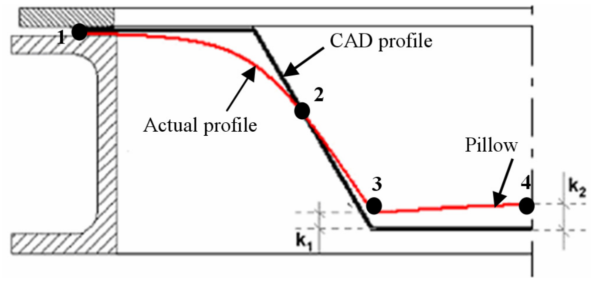

Fig. 2. Actual (under- and over-deformed) and CAD profiles of a test specimen formed by SPIF process [8].

cent to the clamped edge cannot be ignored if conclusive results are to be achieved.

The range over which three (i.e., sheet thickness, tool radius and wall angle) parameters had been investigated was too narrow (Table 1). Moreover, pre-straining level of the sheet with a potential effect on the profile error was not considered.

Because the profile in [8] was measured only at two bottom points (K1 and K2) and separate empirical models were proposed for each point, these models cannot be reliably employed to monitor and control the profile error of an entire part. A single empirical model representing the average error of entire part profile should be developed. This model should predict a set of optimal parameters able to manufacture the complete profile with fairly acceptable accuracy.

The objective of this study is to investigate the effects of forming parameters on the profile error produced by SPIF process by extending the work along the above-mentioned lines and rectifying the shortcomings of previous work. Moreover, this study aims to develop a single empirical model for predicting and optimizing profile error in SPIF parts through parametric optimization. Five parameters, namely sheet thickness, tool radius, step size, wall angle, and pre-straining level, are varied over wide ranges. In addition, their effect on the profile error are measured and analyzed. The error between the produced and designed profiles is measured along the full section of the part at 18 equidistant points, and is quantified through a response surface experiment design called the central composite rotational design (CCRD) [9]. In addition, the interaction among parameters and their corresponding effects on the profile error is shown as 3D response surfaces.

Table 1. Forming parameters and their respective settings in Ambrogio et al. [8] and in the current study.

Forming parameter	Ambrogio et al. [8]		Current study	
	Low	High	Low	High
Sheet thickness [mm]	0.5	1.5	0.7	2.6
Tool radius [mm]	6	9	3.5	10
Wall angle [degree]	50	60	20	55
Part depth [mm]	10	30	-	-
Step size [mm]	0.1	0.5	0.1	0.8
Hardening exponent	-	-	0.04	0.2

2. Design of experiments (DoE)

Preliminary experiments with eight forming parameters (i.e., sheet thickness, tool radius, step size, wall angle, sheet prestraining level, forming speed, part diameter, and part depth) were carried out. The results of these experiments revealed that the forming speed and part diameter do not significantly influence the profile error. One factor, part depth, was discarded from the test plan, due to shortage of material. However, sufficiently large values of this dropped parameter was set so that their interactive effect, if any, could appear in the results. Table 1 presents the low and high settings of the investigated parameters. These settings were decided by considering the [1]process and [2]resource constraints.

Design of experiments (DoE) was performed using software known as Design Expert dx-7. This software makes use of statistical designs proposed in [9] to formulate a test plan, and employs the Derringer-Suich [10] multi-criterion algorithm for numerical optimization. The settings shown in Table 1 were given as an input to dx-7 software. A comprehensive plan of 47 tests with 5 replicates of the central point (Table 2) was suggested. Each point was equidistant from the central point, and each predictor was varied over three levels.

3. Experimental procedure

A fully annealed AA-1060 aluminum sheet was used as the experimental material. The hardening exponent of this annealed sheet was 0.2. It was cold-rolled in such a way to induce two more levels of hardening exponent, 0.12 and 0.2. For the sake of simplicity, frustum of cone with constant major diameter of 111 and 25 mm depth, contrary to pyramids [8], was used as the test geometry. The minor diameter of frustum, however, differed with variation in the wall angle (i.e., Θ), as shown in Table 2. During forming, mineral oil was used as lubricant. After forming the profile test along the transverse

[1] During the current investigations, when the sheet with 2.5 mm thickness was observed to be deformed with a tool smaller than 3.5 mm radius (e.g., 3 mm), the material squeezed out from the tool/sheet interface and the process became unstable. This is an example of process constraint.

[2] Material unavailability and machine capacity are some examples of resource constraints.

Table 2. Design of 47 experiments following CCRD response surface method.

Run	t_o	Θ	n	r	p
1	0.7	55	0.2	10	0.8
2	0.7	20	0.2	10	0.8
3	0.7	20	0.04	3.5	0.8
4	2.6	20	0.2	10	0.1
5	2.6	55	0.04	10	0.8
6	1.65	37.5	0.12	6.75	0.45
7	0.7	55	0.2	3.5	0.8
8	0.7	55	0.04	10	0.8
9	2.6	20	0.2	3.5	0.1
10	0.7	20	0.2	3.5	0.8
11	2.6	20	0.2	3.5	0.8
12	0.7	37.5	0.12	6.75	0.45
13	0.7	55	0.2	10	0.1
14	1.65	37.5	0.12	6.75	0.45
15	0.7	20	0.04	10	0.8
16	2.6	20	0.04	3.5	0.1
17	0.7	55	0.2	3.5	0.1
18	2.6	55	0.04	3.5	0.8
19	0.7	55	0.04	3.5	0.1
20	2.6	55	0.2	3.5	0.8
21	1.65	55	0.12	6.75	0.45
22	2.6	55	0.2	10	0.1
23	2.6	20	0.04	10	0.8
24	0.7	20	0.2	10	0.1
25	1.65	37.5	0.12	6.75	0.45
26	1.65	37.5	0.2	6.75	0.45
27	1.65	20	0.12	6.75	0.45
28	2.6	55	0.04	10	0.1
29	1.65	37.5	0.12	6.75	0.45
30	2.6	20	0.04	10	0.1
31	2.6	20	0.2	10	0.8
32	2.6	55	0.04	3.5	0.1
33	1.65	37.5	0.12	3.5	0.45
34	0.7	55	0.04	10	0.1
35	2.6	20	0.04	3.5	0.8
36	2.6	55	0.2	3.5	0.1
37	1.65	37.5	0.12	10	0.45
38	1.65	37.5	0.12	6.75	0.8
39	0.7	20	0.04	10	0.1
40	1.65	37.5	0.12	6.75	0.45
41	0.7	20	0.2	3.5	0.1
42	2.6	37.5	0.12	6.75	0.45
43	0.7	55	0.04	3.5	0.8
44	1.65	37.5	0.12	6.75	0.1
45	1.65	37.5	0.04	6.75	0.45
46	2.6	55	0.2	10	0.8
47	0.7	20	0.04	3.5	0.1

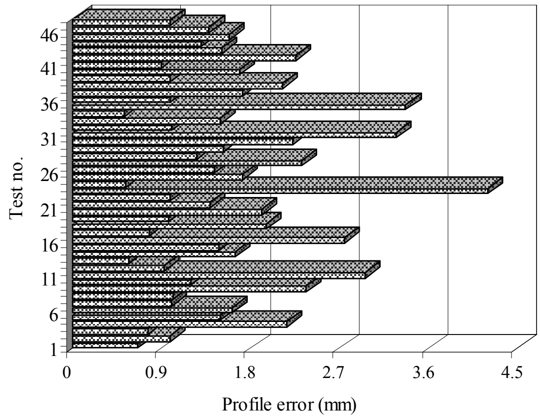

Fig. 3. Profile errors exhibited during DoE tests.

sections, cut along the vertical plane (as shown in Fig. 2) of each frustum was made with the help of a co-ordinate measuring machine (Make: Zett Mess). The measurement was carried out over the entire profile, contrary to bottom [8], at 18 equidistant points. The experimental profile was compared with the designed profile, and the discrepancy between the two was expressed as root mean squared error (RMSE).

4. Results and discussion

Fig. 2 shows the arbitrary experimental and CAD profiles for each test specimen. The experimental profile can be divided into 3 regions (i.e., 1–2, 2–3, and 3–4) with respect to discrepancies from the designed CAD profile. Distinct error patterns were observed in these regions for different samples. The observations made regarding these regions are summarized below:

1. In Region 1, the profiles of 75% of the parts were found below (i.e., over-deformed) the CAD profiles, whereas those of the remaining 25% parts were found above (i.e., under-deformed) the CAD profiles.
2. In Region 2, the profiles of 75% of the parts were found above the reference CAD profiles. This less-than-intended deformation can be attributed to elastic spring-back.
3. In Region 3, a pillow can be seen on the bottom of the part. This unwanted deformation could be due to SPIF stresses in the adjoining deformation zone. The pillow height was observed to increase with increase in the sheet thickness and hardening exponent, and to reduce with increase in the wall angle.

Fig. 3 shows the quantified profile errors obtained during 47 tests, as listed in Table 2. The profile error varied from 0.4 to 4.4 mm. Due to higher ratio of maximum to minimum value (i.e.,>10) of response, logarithmic transformation was applied. Table 3 shows the ANOVA results carried out after transformation. These results show the most significant individual parameters (i.e., sheet thickness, wall angle and step size), two-factor interactions (i.e., sheet thickness and wall angle; sheet thickness and step size; wall angle and tool radius) and

Table 3. Analysis of variance for response surface reduced cubic model.

Source	Sum of squares	Degree of freedom	Mean squares	F-value	P- value Prob > F	Significance
Model	28.249	16	1.765562	54.21083	< 0.0001	yes
t_o	12.76264	1	12.76264	391.8712	< 0.0001	yes
Θ	5.838453	1	5.838453	179.2672	< 0.0001	yes
n	0.47089	1	0.47089	14.45847	0.0007	yes
r	0.059619	1	0.059619	1.830576	0.1862	no
p	2.93235	1	2.93235	90.03654	< 0.0001	yes
$t_o.\Theta$	4.191774	1	4.191774	128.7066	< 0.0001	yes
$t_o.n$	0.01182	1	0.01182	0.362925	0.5514	no
$t_o.p$	0.629105	1	0.629105	19.31641	0.0001	yes
Θn	0.026644	1	0.026644	0.818083	0.3729	no
$\Theta.r$	0.241451	1	0.241451	7.413638	0.0107	yes
$\Theta.p$	0.065133	1	0.065133	1.99987	0.1676	no
$r.p$	0.055943	1	0.055943	1.717716	0.1999	no
n^2	0.173146	1	0.173146	5.316366	0.0282	yes
$t_o.\Theta.n$	0.099038	1	0.099038	3.040904	0.0914	no
$t_o.\Theta.p$	0.136897	1	0.136897	4.203359	0.0492	yes
$\Theta.r.p$	0.554099	1	0.554099	17.01338	0.0003	yes
Residual	0.977053	30	0.032568			
Lack of fit	0.952863	26	0.036649	6.060021		
Pure error	0.02419	4	0.006048			
Cor total	29.22605	46				

three-factor interactions (i.e., sheet thickness, wall angle, and step size; wall angle, tool radius, and step size). Furthermore, most significant parameters (i.e., sheet thickness, wall angle, and step size) are individually involved in strong interactions with the less significant parameters. However, the sheet thickness does not constitute any significant interaction with the hardening exponent.

The significant effects plots, under the middle levels of considered factors, are shown in Figs. 4(a-d). Fig. 4(a) reveals that the hardening exponent, whose effect was not examined previously [8], is an influential parameter. Its higher value poses positive effect on reducing profile discrepancy, thereby suggesting the use of annealed blanks. Fig. 4(b) shows that the profile discrepancy increases with an increase in the sheet thickness. Furthermore, the discrepancy increases with a decrease in the wall angle for sheets with greater thickness. Fig. 4(c) demonstrates that an increase in the step size, regardless of sheet thickness, adversely affects the profile accuracy. However, the severity of increased step size is higher for thick sheets than for the thin sheets. Fig. 4(d) depicts that a decrease in the tool radius helps improve profile accuracy for large wall angles. However, the same, contrary to [2], poses an adverse effect when the wall angle is small.

There are two significant interactions at the three-factor level (i.e., sheet thickness, wall angle, and step size; wall angle, tool radius, and step size). Their effects can be understood by combining Figs. 4(b–d). The small tool radii, in combination with small step sizes, lead towards minimum profile error at large wall angles. In addition, large tool radii, in combination with small step sizes, lead towards least profile discrepancy at

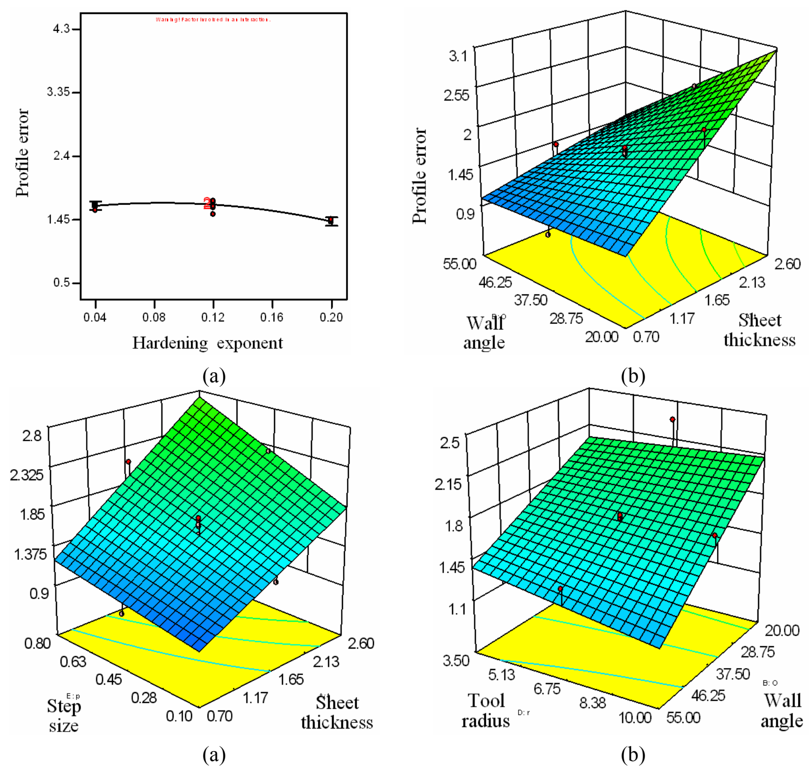

Fig. 4. Plots of significant effects.

small wall angles. To facilitate the selection of rational combination of parameters settings, a hyper surface is proposed below:

$$\begin{aligned} Ln(PE) &= 3.19 - 0.355t_o - 0.122\theta + 2.71n \\ &-0.196r - 3.7p - 0.013t_o\theta - 4.5t_o n + 0.23t_o r \\ &+0.84t_o p + 0.077\theta n - 0.001\theta r + 0.026\theta p + 8.45np \\ &-0.122rp + 0.26t_o^2 + 0.0014\theta^2 + 2.25p^2 - 0.256\theta np \\ &+0.003\theta rp + 1.198t_o^2 n - 0.058t_o^2 r - 0.215t_o^2 p \end{aligned}$$

where *PE* stands for profile error.

The R^2 (multiple correlation factor) value for the above empirical model is 94%. The adjusted and predicted R^2 values of the model are 89% and 76%, respectively. The adequate precision, which measures the signal-to-noise ratio, desired for the above model is 4. Meanwhile, the model possesses a ratio of 31, indicating an adequate signal. These high-correlation values indicate that the data is well fitted to the model.

The suitability of the proposed model was tested to optimize forming parameters for the manufacturing of a conical frustum. The constraints were placed on its wall angle (i.e., 30^o), sheet thickness (i.e., 1.5 mm) and depth (i.e., 25 mm). These optimization criteria were set in the dx-7 software. The software uses Derringer-Suich [9] multi-criterion algorithm for simultaneous optimization. After several iterations, the said software recommended the following solution: tool radius = 10 mm; step size = 0.1 mm; and hardening exponent = 0.2. This combination of parameters was suggested to manufacture frustum with average profile error not more than 0.8 mm. To verify this optimized solution, a frustum with these suggested parameters was experimentally formed and tested for profile accuracy. The difference between the predicted and actual profile errors was found to be merely 0.06 mm, which is very small. This confirms the validity of the proposed model.

The above-proposed empirical model can be used in the following ways for real-product manufacturing:

To predict profile error in the investigated range of parameters, and, hence, to optimize parameters for manufacturing parts, at least for the considered geometry, with the best possible profile accuracy.

To predict whether the desired profile accuracy can be achieved through optimizing parameters and to determine whether alternative strategies (e.g., tool path optimization) can be adopted if the desired results are not obtained.

5. Conclusions

The SPIF process is ready to be employed in commercial applications. As a result of the present work, accuracy, productivity, and surface quality can be integrated in SPIF. In this study, the effects of five forming parameters (i.e., sheet thickness, tool radius, wall angle, step size, and hardening exponent) on the profile accuracy in SPIF of cones were investigated using statistical design called CCRD response surface design. The following conclusions were drawn:

1. Pre-straining level of sheet, which has not been considered previously, appears to be a significant parameter. Out of the five main parameters, sheet thickness, wall angle, and step size are equally extremely significant in terms of their influence on profile accuracy of cones.

2. The interaction between the two extremely significant parameters (i.e., sheet thickness and wall angle), is also extremely significant. Moreover, these two extremely significant parameters are involved in increasingly significant interactions with relatively less significant parameters in the order of $t_o.\Theta$, $t_o.p$, and $\Theta.r$. No significant two-factors interaction between the hardening exponent and other significant/non-significant parameter exists. At the three-factor level, there exist two significant interactions (i.e., $t_o.\Theta.p$ and $\Theta.r.p$).

3. Increases in pre-straining level, sheet thickness, and step size pose adverse effect on profile accuracy. In contrast, an increase in wall angle has a positive effect on profile accuracy. The nature of effect of tool radius depends on the angle of forming: large tool radius proves beneficial when the angle is small and the same is detrimental when the angle is large.

4. The proposed empirical model can be helpful in optimizing forming parameters in order to form components, especially the considered geometry, with the acceptable profile accuracy.

Nomenclature

t_o : Sheet thickness
r : Tool radius
θ : Wall angle
p : Step size
n : Hardening exponent

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