IJMF, Iranian Journal of Materials Forming, Vol. 4, No. 2, pp 51-61
Printed in The Islamic Republic of Iran, 2017

Two Point Incremental Forming of a Complicated Shape with Negative and Positive Dies

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Abstract: In this study, incremental sheet forming of a complicated shape is investigated experimentally. Two point incremental forming with negative and positive dies are employed for manufacturing of a complicated shape with positive and negative truncated cones. The material is aluminum alloy 3105 with a thickness of 1 mm. The effects of process parameters such as sequence of positive and negative forming processes, step depth (incremental depth) and rotational speed of the tool on the maximum achievable outer and inner heights for the proposed specimen are investigated. The selected ranges for the step depth and rotational speed are 0.2 mm - 0.6 mm and 0-1000 rpm, respectively. The results indicate that both maximum achievable outer and inner heights of the specimen are increased with a change in Positive/Negative variant to Negative/Positive variant. Moreover, the results prove that both maximum achievable outer and inner heights are increased by decreasing the step depth and increasing the rotational speed of the tool. An optimum parameter combination (Negative/Positive, step depth = 0.2 mm and rotational speed = 1000 rpm) is obtained to get both maximum achievable outer and inner heights using signal to noise ratio analysis.

Keywords: Two point incremental forming (TPIF), Aluminum alloy 3105, Design of experiments (DOE)

1. Introduction

Incremental Sheet Forming (ISF) is an extremely flexible process using a single generic tool for an infinite variety of shapes with great potential for production of short runs of new or replacements parts. By using this process, useable parts can be formed directly from CAD data with a minimum of specialized tooling. Therefore, the incremental sheet forming process is particularly useful in rapid prototyping applications of small and medium sized batches due to the following advantages: lower cost, the use of a conventional CNC machine, quick design changes, direct production of parts from a CAD file, the reduction of stresses acting in the material, the possibility of forming parts having any dimension, a good surface finish of the formed parts, the ability of avoiding molds and dies and a high material formability. A three axis milling machine is a commonly used machine tool for incremental forming.

Depending on the existence or absence of a die or support post, the two main variants of the process are identified as Single Point Incremental Forming (SPIF) or Two Point Incremental Forming (TPIF). The SPIF consists of the blank or raw material in sheet form fixed by a clamping device. The blank is progressively deformed using a hemi-spherical end forming tool. The movement of the tool is driven by a CNC machine or robot (not shown). This simplicity results in the accessibility of any manufacturing facility having CNC machinery and CAD/CAM software to the incremental sheet forming (ISF) technology. While, the usage of machining hardware and software is the key of the ISF's versatility promise, it also brings important limitations to the process: (a) the force required to form a candidate part shall comply with the working limits of the ISF adapted machine and (b) in most of the cases, the machining tool-path generated from the part's geometry will result in a component outside the tolerances

Received by the editors August 25, 2017; Revised October 10, 2017 and Accepted October 15, 2017.
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required in the industry. TPIF is based on the presence of a partial or full die, which supports the sheet during the deformation. When using TPIF, the sheet is contemporarily deformed in two points: the contact points between tool and sheet and between sheet and die. This method of sheet deformation can cause a decrease of sheet formability in comparison with SPIF, but it allows increasing the geometric accuracy reachable in a single pass. The TPIF can be classified as negative (Fig. 1-a) or positive (Fig. 1-b) depending on the type of part to be formed. Note that a movable clamping device is needed for the latter.

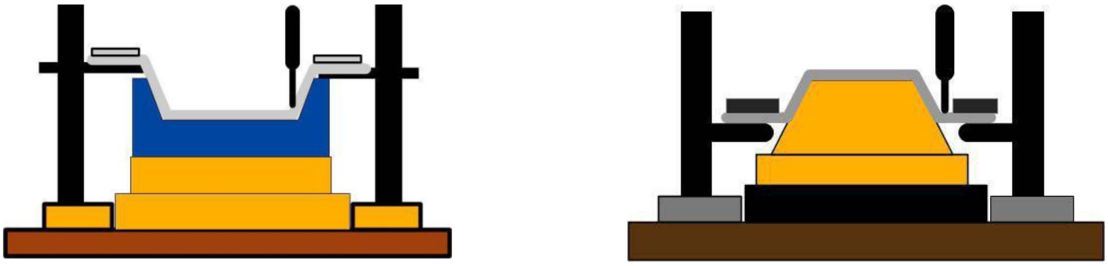


Fig. 1. Schematics of different types of two Point Incremental Forming, a- Negative, b-Positive.

In the last decades, research in SPIF has become a focus of interest in the area of sheet forming. Lozano-Sánchez et al. [1] studied the mechanical and structural properties of single point incremental formed polypropylene-MWCNTs composite sheets. Their results showed that the presence of small quantities (<1 wt%) of f-MWCNTs lead to a mechanical reinforcement of the polymer matrix, without affecting its formability. Li et al. [2] studied the deformation mechanics and also predicted the efficient force in the single point incremental forming. For this purpose, they established a comprehensive finite element (FE) model for the cone-forming process with fine solid elements which allowed the quantitative study of the deformation behavior of stretching, bending and shearing during the process. Based on such analysis, they considered an efficient model for tangential force prediction analytically. The proposed efficient model was comprehensively validated with both truncated cone and pyramid shapes by varying forming parameters. Their results showed that the trend of tangential force could be properly represented by the change of the curvature of the formed part. Also, they concluded that considering the proposed model could be solved within only several minutes, it will guide the forming process and shorten the lead time. Raju and Narayanan [3] with a hybrid optimization technique determined an optimal combination of input process parameters to obtain favorable responses in the single point incremental forming of multiple sheets. Based on the ANOVA results, they concluded that the feed rate was the most dominant parameter in the SPIF of multiple sheets. Also, Raju and Narayanan [4] investigated the forming limit diagram and fractography of multiple sheet that is formed with single point incremental forming. Their results showed that the major true strain values decreased from the top sheet to the bottom sheet in all of the cases when two, three or four sheets were formed together, but the minor true strain values were found to be independent with respect to the position of the sheet in the stack. Mirnia et al. [5] proposed a strategy for implementing multistage SPIF that improved the thickness distribution in SPIF of a truncated cone. For this purpose, they developed a simple model based on sequential limit analysis. Their results showed that by the improved strategy, the bulging of the bottom of the cone can be controlled and also the process time is shorter than in the case for the conventional multistage strategy due to forming smaller cones in the intermediate stages. Bahloul et al. [6] focused on the development of single point incremental sheet forming process and its optimization in order to accurately analyze the impacts of some forming factors. A set of numerical simulations were conducted on SPIF, based on Box–Behnken DOE in order to determine the influence of process parameters. The main objective of their work was to examine and minimize the sheet thinning rate and the punch loads generated in the single point incremental forming. Bagudanch et al. [7] compared single point versus two point incremental forming of thermoplastic materials. The results showed that with two point incremental forming, it was possible to enhance the geometrical accuracy of the final parts and reduce the effect of the springback. Silva and Martins [8] developed an analytical model to illustrate the differences in formability between single point incremental forming (SPIF) and two-point incremental forming (TPIF). Matsubara [9] investigated different tool paths for producing cones and pyramids with an arbitrary number of sides and concluded that TPIF with partial die allows producing a wide range of complex three-dimensional shapes. Matsubara also claimed that the wall thickness of TPIF parts follow the sine law of shear spinning. Attanasio et al. [10] investigated tool path optimization strategies with the objective of improving the overall surface quality and geometric accuracy of an automotive component produced by TPIF. Hirt et al. [11] compared the forces and the geometrical accuracy in pyramidal benchmark parts produced by TPIF with partial and full dies. They also reported the utilization of metallic foams to produce self-configuring full dies as an alternative to rigid dies. Vahdati et al. [12] investigated the ultrasonic vibration assisted single point incremental forming method. In their work, a statistical analysis and optimization of the effective factors on surface roughness of formed specimen were performed.

It should be noted that to the best of the author's knowledge, all of the reported studies in the TPIF are focused on negative TPIF or positive TPIF and there is no reports on the TPIF with both negative and positive variants. However, in this work, TPIF with both negative and positive variants is investigated and a specimen with both negative and positive TPIFs is formed. Furthermore, the effects of some process parameters such as sequence of negative and positive forming processes, step depth and rotational speed on the maximum achievable inner and outer heights of the specimen without necking are investigated based on the design of experiments.

2. Material and Method

In this study, sheet metals made of aluminum alloy 3105, with 1mm thickness and 200mm × 200mm dimensions are used. Aluminum alloy 3105 is a medium strength and general purpose alloy which has a wide application in building and packaging industry such as vehicle bodies, refrigerated trucks, ambulances, cold rooms, anti skid flooring, ship platforms and stair treads. It also has high corrosion resistance, and good weldability and formability [13]. The chemical composition of the employed aluminum alloys are presented in Table 1.

Table 1. Chemical composition of employed aluminum alloy 3105.

Element	Al	Ga	V	Cr	Ti	Zn	Mg	Mn	Cu	Fe	Si
Composition (%)	96.95	0.01	0.01	0.02	0.01	0.33	0.61	0.67	0.23	0.81	0.27

The die is made from CK45 steel and both negative and positive TIPF processes can be performed with this die. Figure 2 depicts a schematic view of experimental setup of negative and positive TIPF processes.

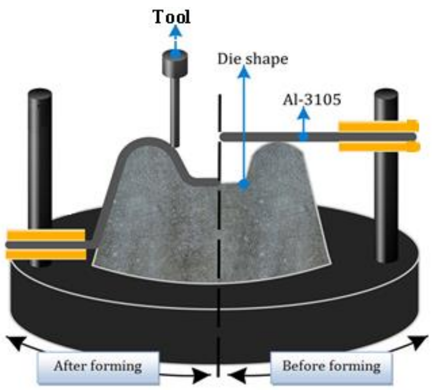


Fig. 2. Schematic view of experimental setup of negative and positive TIPF processes.

In Fig. 2, aluminum blank before and after forming processes is shown. Also, in this figure the die, guide pins, fixture and the tool have been presented. As it is seen in Fig. 2, at once clamping of aluminum sheets in the fixture, both negative and positive TIPF processes can be performed. Figure 3 illustrates the used die, fixture and forming tool in the experimental work. In addition, Fig. 4 shows the deformations of the aluminum sheet in various conditions of TPIF and also the final manufactured specimen.

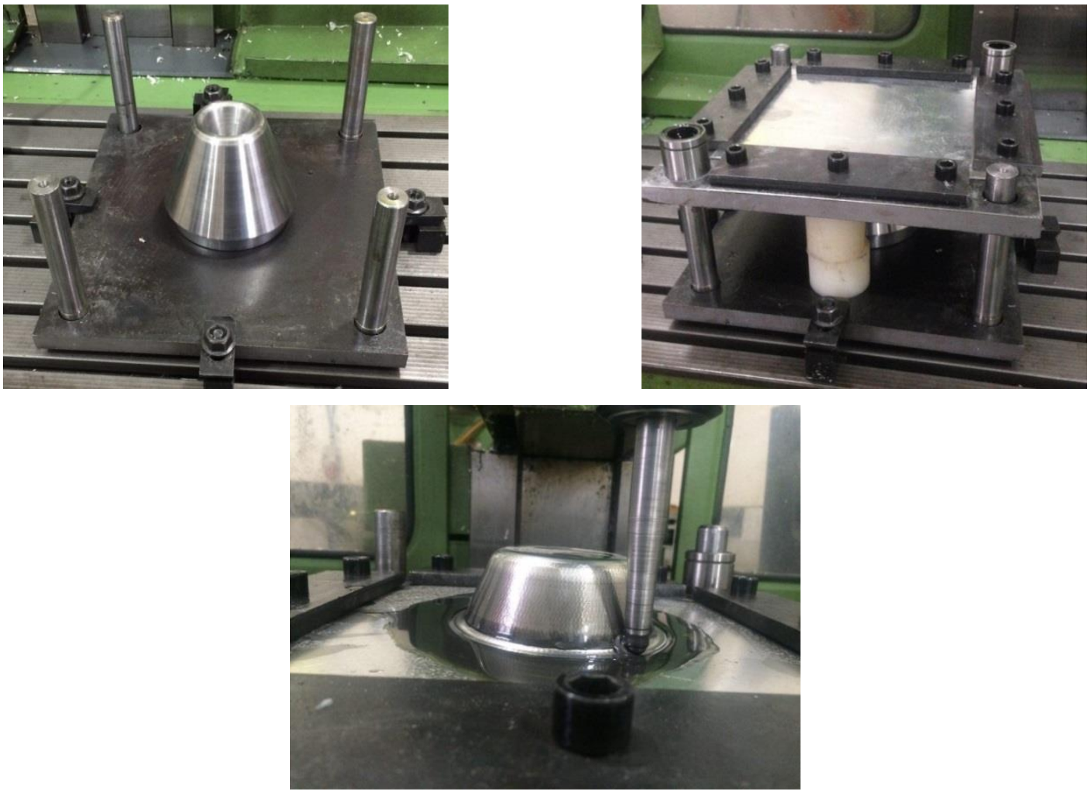
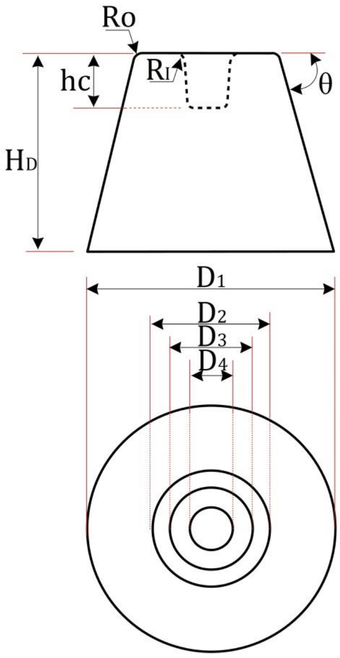


Fig. 3. The die, fixture and forming tool in the experimental work.

Fig. 4. Different stages of negative and positive TPIF of aluminum 3105 and the final manufactured specimen.

Figure 5 depicts the schematic view and dimensions of the final desired shape of the specimen in this paper with TPIF. The tool path is made up of a series of contours generated transverse to the long axis of the cone. The forming tool follows the predetermined tool path and gradually forms the sheet metal in a series of incremental steps until the final depth is reached. The steps of two point incremental sheet metal forming are usually defined as Δx, Δz and h, representing increments in the X and Z directions and a finite forming depth h, respectively. The experimental tests were performed on a 3-Axis milling centre, modified to be used for sheet incremental forming applications. The tool used for all the tests had a hemispherical head with 10 mm diameter. In this paper, the effects of process parameters such as sequence of positive and negative incremental sheet processes, incremental depth (step size) and rotational speed of the tool on the maximum achievable forming height of the specimen without necking are investigated. For this purpose, two combinations of sequence of positive and negative incremental processes such as Negative/Positive (first, negative process is performed and then positive process is done) and Positive/Negative (first, positive process is performed and then negative process is done) are performed. In addition, TPIF processes are performed in three incremental depths such as 0.2, 0.4 and 0.6 mm and also three rotational speeds such as 0, 400 and 1000 RPM.



Parameter	Ro	RI	HD	hc	θ	D1	D2	D3	D4
Dimension (mm)	5	5	95	40	70	142.16	75.40	46.60	**19.88**

Fig. 5. Schematic view and dimensions of the final desired shape of the specimen.

3. Design of Experiments

Design of experiment (DOE) is a method that is employed to investigate the effect of various factors on the output of a process. The output of the process is determined by performing a test at a certain level of all affecting factors. The factors and their levels that are used in this investigation are shown in Table 2. An orthogonal $L_{18}(3^2 \times 2^1)$ array is selected. According to Taguchi procedure, experiments were repeated three times. Therefore, the total number of experiments is 3×18=54. The objective of these experiments is to predict the maximum achievable outer and inner heights without necking for the proposed specimen in Fig. 5, which are functions of the process parameters mentioned in Table 2.

Table 2. Factors and their corresponding levels

Factors	Levels		
	1	2	3
Sequence of positive and negative forming	Positive/Negative	Negative/Positive	----
Rotational speed of tool (rpm)	0	400	1000
Step depth (mm)	0.2	0.4	0.6

In Table 2, Positive/Negative refers to a forming process that firstly positive incremental sheet forming is performed and then negative incremental sheet forming is done. Moreover, Negative/Positive refers to a forming process that firstly negative incremental sheet forming is performed and then positive incremental sheet forming is done.

4. Data Analysis

4.1. Effects of factors on maximum achievable outer and inner heights

Main effects plots of factors can be used to draw an initial conclusion about effects of factors. The plots of main effects of factors for outer and inner heights are shown in Figs. 6 and 7 respectively. It has to be mention that the mean value data is used to determine each factor's effect. Moreover, for one of the experiments, the initial blank is fully formed and a specimen with dimensions similar to die dimensions (Fig. 5) is achieved. The parameters values for complete forming of the blank are sequence of positive and negative forming (Negative/Positive), rotational speed (1000 rpm) and step depth (0.2 mm).

As it is seen from Figs. 6 and 7, change in sequence of positive and negative forming from Positive/Negative to Negative/Positive leads to an increase in the outer and inner heights of the produced specimen with ISF. The reason is that in the Positive/Negative as firstly the outer shape of the specimen is formed therefore forming stiffness for incremental sheet forming of inner cavity is increased and therefore the maximum achievable inner height of the specimen is decreased. Furthermore, it is concluded from Figs. 6 and 7 that the maximum achievable outer and inner heights in the proposed specimen in this paper are decreased with an increase in the step depth. The reason is that a negative stress distribution occurs under the tool contact zone and tensile stresses are created on the walls of the formed part.

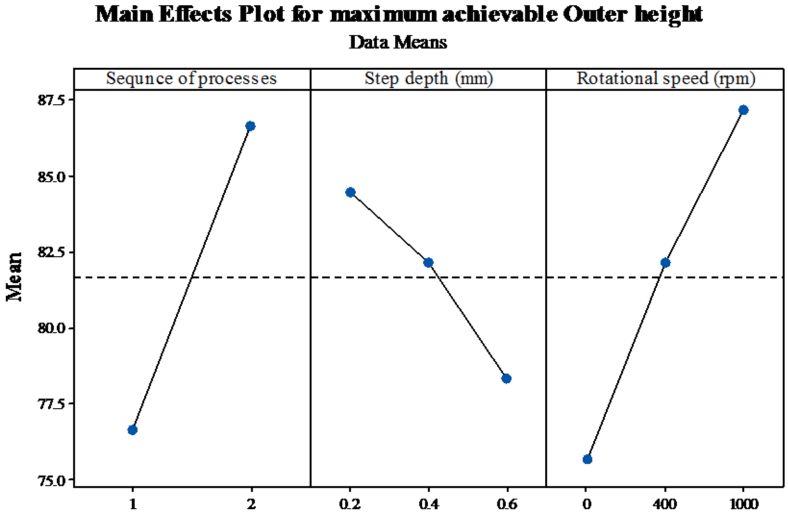


Fig. 6. Plots of main effects on maximum achievable outer height of the proposed specimen.

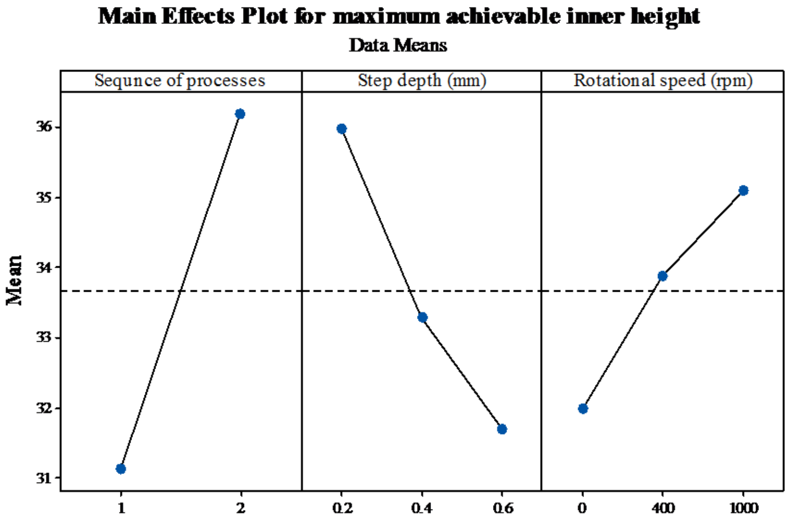


Fig. 7. Plots of main effects on maximum achievable inner height of the proposed specimen.

These stresses decrease with decreased incremental depth. It is seen in Figs. 6 and 7 that the increase in the rotational speed of the forming tool leads to an increase in the maximum achievable outer and inner heights of the proposed specimen.. The reason is that the relative motion between the tool and blank is directly proportional to the heat generated by friction. However, it is generally believed that the formability increases along with the rotational speed due to its heating effects. In this paper, analysis of variance (ANOVA) has been often employed by experimenters, since it covers the shortcomings of graphical assessment. Two of these shortcomings are inaccuracy in the inferences made and that the inferences are only comparatively valid. Before conducting ANOVA, the following assumptions should be verified:

1. Residuals are distributed normally
2. Error is independent
3. Variance is constant

It is necessary to check the above-mentioned three assumptions before performing ANOVA. The normal probability plot of residuals of maximum outer height, residuals versus fitted values, residuals versus observation order and histogram graph for outer and inner heights are displayed in Figs. 8 and 9 respectively. A normal probability plot is just a graph of the cumulative distribution of the residuals on normal probability paper, that is, graph paper with the ordinate scaled so that the cumulative normal distribution is plotted as a straight line. The other two assumptions are shown to be valid by means of plot of residuals versus fitted values. This plot is illustrated in Figs. 8 and 9. It is evident that data points are structurelessly distributed. This indicates that variance constancy and error independency are valid. Since the assumptions are proved not to be violated through this experimentation, therefore ANOVA results can be trusted and are listed in Tables 3 and 4 for maximum achievable outer and inner heights.

The P-value is the probability of obtaining a test statistic that is at least as extreme as the actual calculated value, if the null hypothesis is true. A commonly used cut-off value for the P-value is 0.05. If the calculated P-value of a test statistic is less than 0.05, the null hypothesis is rejected [14].

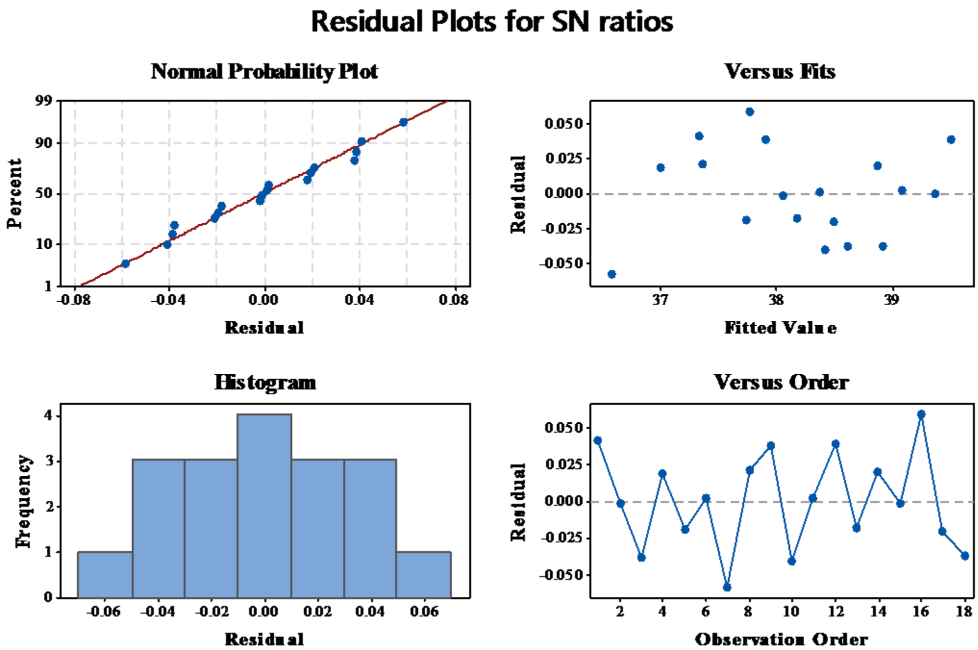


Fig. 8. Normal probability plots for maximum achievable outer height

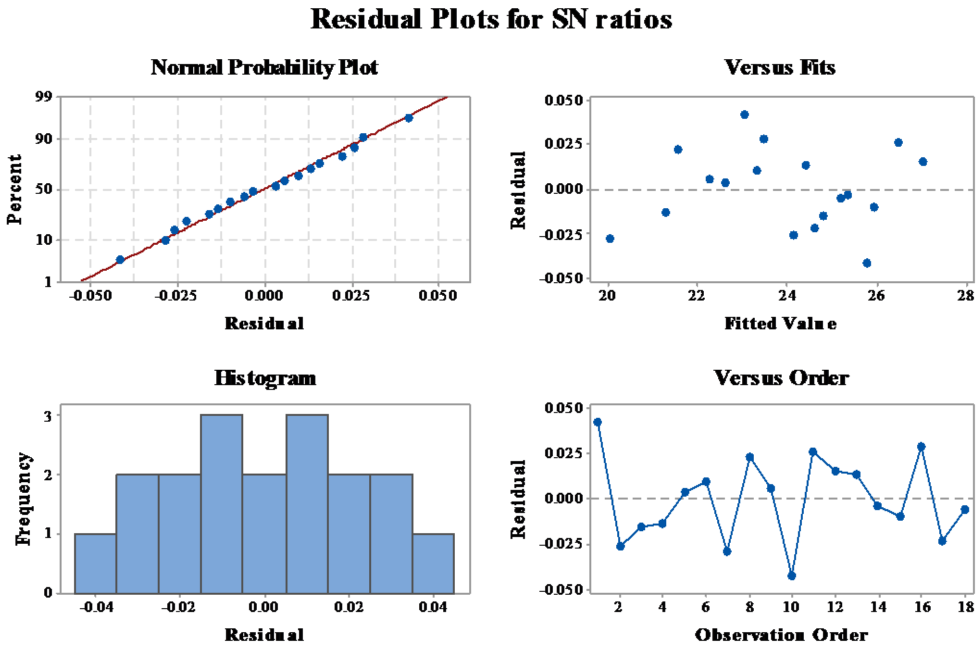


Fig. 9. Normal probability plots for maximum achievable inner height.

Table 3. ANOVA for maximum achievable outer height without necking.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Sequence of positive and negative processes	1	5.1595	5.1594	5.1594	1120.13	0.000
Step depth (mm)	2	1.3477	1.34772	0.67386	146.29	0.000
Rotational speed of tool (rpm)	2	4.6187	4.61872	2.30936	501.36	0.000
Residual Error	4	0.0184	0.01842	0.00461		
Total	17	11.1925				

R-Square = 99.8 %

Table 4. ANOVA for maximum achievable inner height without necking.

Source	DF		Seq SS	Adj SS	Adj MS	F	P
Sequence of positive and negative processes	1		7.8157	7.81570	7.81570	63410.49	0.000
Step depth (mm)	2		3.7473	3.74734	1.87367	15201.48	0.000
Rotational speed of tool (rpm)	2		2.0038	2.00383	1.00192	8128.76	0.000
Residual Error	4		0.0005	0.00049	0.00012		
Total	17		13.6043				

R-Square = 99.0 %

In this table, DF is the degrees of freedom, Seq SS is the sequential sum of squares, Adj SS is the adjusted sum of squares, Adj MS is the adjusted mean squares, F is the F-value, and P is the P-value. Confidence level is chosen to be 95% in this study. Therefore, the P-values, which are less than 0.05 indicate that the effect of the respective factor is significant. As it is indicated in table 4, sequence of positive and negative processes, step depth and rotational speed of tool have significant effects on the maximum outer height at the 0.05 α level.

5. Determination of the Optimum Conditions

Optimum condition is obtained by means of S/N ratio method. The rationale behind this method is to find a condition under which the effect of signals (controllable factors) is the greatest of all compared with the effects of noises (uncontrollable factors). The type of problem for both maximum achievable outer and inner heights is "the-larger-the-better" [15]. For such type of problems, statistic S/N ratio (η) can be obtained by the following equation:

$$\eta = -10 \times \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (1)$$

where y_i is the ith observation of a treatment combination and n is the number of replications. The η values for maximum achievable outer and inner heights are presented in Tables 5 and 6 respectively. The largest value of η indicates the optimum condition. It is concluded from Table 5 that rotational speed, sequence of positive and negative processes and step depth have the most important effects on maximum achievable outer height for the proposed specimen respectively.

Table 5. η values for maximum achievable outer height for the proposed specimen.

Level	Sequence of positive and negative processes	Step depth (mm)	Rotational speed (rpm)
1	37.67	38.51	37.55
2	38.74	38.26	38.27
3	----	37.85	38.79
η	1.07	0.66	1.24

Table 6. η values for maximum achievable inner height for the proposed specimen

Level	Sequence of positive and negative processes	Step depth (mm)	Rotational speed (rpm)
1	29.84	31.09	30.06
2	31.16	30.42	30.56
3	----	29.99	30.87
η	1.32	1.11	0.81

As it is concluded from Table 6, sequence of positive and negative processes has the largest value of Eta (η=1.32). Therefore, sequence of positive and negative processes has the most important effect on the maximum achievable inner height of the proposed specimen. After sequence of positive and negative processes, step depth (η=1.11) and rotational speed of the tool (η=0.81) have the most important effects on maximum achievable inner height of the proposed specimen. Most effective level of each factor or in other words the optimum setting for both maximum achievable outer and inner heights have been represented in Table 7.

Table 7. Optimal setting for maximum achievable outer and inner heights

Level	Sequence of positive and negative processes	Step depth (mm)	Rotational speed (rpm)
Level number	2	1	3
Factor magnitude	Negative/Positive	0.2	1000

It should be mentioned that in Table 7, the values for step depth and rotational speed are the optimal values in the range studied in the present work. For instance, increasing the rotational speed beyond the range of the present work may lead to another trend. The same may be true for the step depth.

6. Conclusion

In this paper, incremental sheet forming process was used for production of a complicated shape specimen with large deformations. The effects of process parameters such as sequence of positive and negative forming processes, step depth and rotational speed of the tool were investigated on the maximum achievable outer and inner heights. The results showed that both maximum achievable outer and inner heights were increased with change of Positive/Negative variant to Negative/Positive variant. Moreover, both maximum achievable outer and inner heights are increased by decreasing the step depth and increasing the rotational speed of the tool. It was demonstrated from S/N ratio statistic (η) that the rotational speed of the tool had the most important effect on maximum achievable outer height of the specimen. Moreover, Negative/Positive variant of the sequence of positive and negative forming processes had the most important effect on maximum achievable inner height of the specimen. An optimum parameter combination was obtained to get the both maximum achievable outer and inner heights using the S/N ratio analysis.

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شکل دهی تدریجی دو نقطه ای یک شکل پیچیده به وسیله قالب های مثبت و منفی

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چکیده: در این پژوهش، شکل‌دهی تدریجی یک شکل پیچیده به صورت تجربی مورد بررسی قرار می‌گیرد. بدین منظور شکل‌دهی تدریجی دونقطه‌ای با قالب‌های مثبت و منفی جهت تولید یک شکل پیچیده با مخروط های ناقص مثبت و منفی مورد استفاده قرار می گیرد. ماده مورد استفاده، آلیاژ آلومینیم 3105 با ضخامت 1 میلیمتر می باشد. اثر پارامترهای فرآیند از جمله ترتیب فرآیندهای شکل دهی مثبت و منفی، عمق تدریجی و سرعت دورانی ابزار بر روی ماکزیمم ارتفاع های داخلی و خارجی قابل دستیابی برای قطعه بررسی می شود. محدوده های انتخاب شده برای عمق تدریجی و سرعت دورانی به ترتیب 0/2 تا 0/6 میلیمتر و 0 تا 1000 دور بر دقیقه می باشند. نتایج نشان می دهند که ماکزیمم ارتفاع های داخلی و خارجی قابل دستیابی قطعه، با تغییر ترتیب فرآیند مثبت/منفی به منفی/مثبت افزایش می یابند. همچنین نتایج ثابت می کنند که ماکزیمم ارتفاع های داخلی و خارجی قابل دستیابی با کاهش عمق تدریجی و افزایش سرعت دورانی افزایش می یابند. ترکیب بهینه‌ای از پارامترها (ترتیب فرآیند منفی/مثبت، عمق تدریجی 0/2 میلیمتر و سرعت دورانی 1000 دور بر دقیقه) به منظور دستیابی به ماکزیمم ارتفاع های داخلی و خارجی قابل دستیابی با استفاده از آنالیز سیگنال به نویز به دست می آید.

واژگان کلیدی: شکل دهی تدریجی دو نقطه ای، آلیاژ آلومینیم 3105، طراحی آزمایش ها