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Experimental Analysis of Several Variables Influencing Formed Thickness in Two-Point Incremental Forming Process

Abstract- In the current paper, an experimental analysis on Al-sheet (AA 1050) with thickness 0.9 mm to reveal the effect of relevant forming factors on the formed thickness in two-point incremental forming (TPIF) process has been conducted. The formed thickness of pyramid-like shapes was analyzed by studying seven variables: die geometry, tool diameter, tool path, stepover, tool shape, lubricant and slope angle. The proposed analysis utilizes Box-Behnken design of experiment (BBD), main effects plot (MEP) and analysis of variance (ANOVA) for sake of studying the influences of the seven forming factors on the resulted thickness. The results of these analyses have indicated that the most significant factor affecting the formed thickness is the die geometry followed by tool shape, lubricant and stepover respectively for both slope angles of the pyramid. In addition, it has been found that the other variables have also significant effects on the formed thickness at both slopes of the pyramids produced.

Keywords- Analysis of Variance (ANOVA), Box-Behnken Design of experiment (BBD), formed thickness, Main Effects Plot (MEP), Two-Point Incremental Forming (TPIF).

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1. Introduction

Now, the production of complex shapes and small batches with reducing the production cost and shortening the lead-time is necessary. Thus, a new manufacturing technology that can form general sheet metal into any proposed geometry with a high flexibility is still demanded by many industrial institutions. Consequently, a novel non-traditional sheet metal forming process namely incremental sheet metal forming (ISMF) has been adopted [1]. ISMF is a flexible and novel sheet forming method that utilizes layer-based manufacturing. It converts the geometrical information of the part into a series of two-dimensional parameters, and then the locally plastic deformation is achieved layer by layer through the motions of the forming tool to make products with complex geometries in a CNC milling machine [2]. Two main types of ISMF have been the subjects of most engineering studies: two-point incremental forming (TPIF) and single-point incremental forming (SPIF), as depicted in Figure 1 [3].

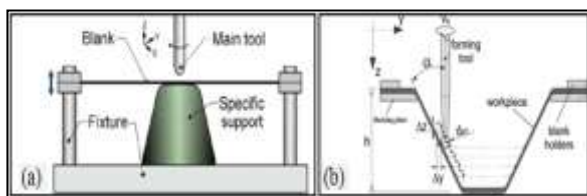


Figure 1: Types of ISMF; (a) TPIF, (b) SPIF

In TPIF, a rigid clamping around the sheet periphery is done by a blank holder that performs a vertical movement and the forming tool moves along a path on the exterior surface of the part, from the top to the bottom of the geometry as shown in Figure (1-a). Only specific zones of the blank can be supported by Partial dies. While the whole blank is supported by full dies, thus introducing improved accuracy and controlling deformation of the sheet [4]. Additionally, aviation, automobile parts and the other complex shapes can be produced via full dies as they present specific dies of the same product shapes in order to reach the desired accuracy. As a result of using full dies, TPIF does not diverge from its characteristic of flexibility because dies involved in such operation are manufactured from cheap materials and instead of performing as a deforming tool; they only represent as supporting tools [5].

2. Literature Survey

The formed thickness of the part plays a vital role in the analysis of ISMF process as it is considered as an indicator to explore the formability of the sheet.

Sarraji [6] showed that the most significant factor is the number of forming passes followed by the tool movement direction relative to the direction of rolling. It has been also proved that the typology of tool path has a significant effect on the formed thickness in ISMF. Hussain et al [7] demonstrated that as the blank stiffness

increases the magnitude of the maximum wall thinning decreases.

Jun-chao et al [8] showed that size of the tool has a great effect on the least thickness if a conventional tool path has been used, and the amount of the vertical step greatly defines the position of the minimum thickness. Tisza [9] concluded that the formability of ISMF becomes higher with an increase in sheet thickness. Hmida et al. [10] found that the formability of the incremental forming operation decreases as the rate of thickness to initial grain size decreases. Rattanachan [11] found that the thickness distribution is dependent on the slope angle of the part wall and by decreasing it, more uniform thickness is reached.

Consequently, in this paper, an experimental investigation has been conducted to determine the influence of seven relevant forming factors namely, (die geometry, tool diameter, tool path, stepover, tool shape, lubricant and slope angle) on the formed thickness of parts produced by TPIF process.

ISMF process is characterized by using very simple equipment in addition to utilize CNC milling machine compared with other sheet forming methods that have utilized punches and dies specific to one shape and size of the final product. These equipment are: CNC milling machine, forming frames and dies, forming tools and sheet material as shown in Figure 2.

In all experiments carried out, sheet metals of an Aluminum alloy (AA1050) have been used. The initial size of the sheet is 290×290×0.9 mm, while the working area for both positive and negative TPIF is 220×220 mm and 200×200 mm respectively as shown in Figure 3. Nine forming tools have been used in this study having spherical, hemispherical and toroidal heads of diameters (10, 12 & 14 mm) for each type as shown in Figure 3-c. The length of each forming tool is 110 mm. All the tools are manufactured from tool steel material having hardness of 60 HRC. In order to achieve the best possible smoothness (surface finishing) at the tool tip, all the tools have been polished using suitable finishing paper and grinding paste.

3. Experimental Setup and Equipment

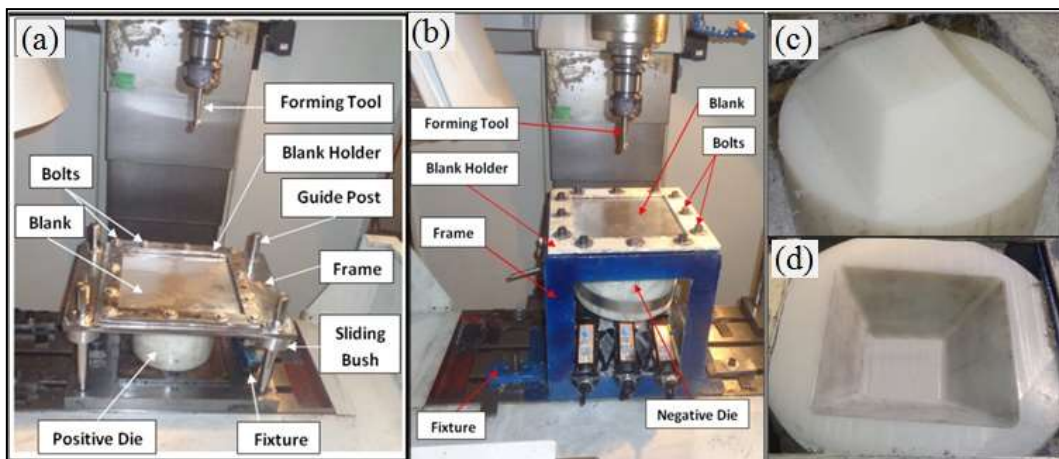


Figure 2: The forming structure used for experiments, (a) positive TPIF setup, (b) negative TPIF setup, (c) positive die, (d) negative die

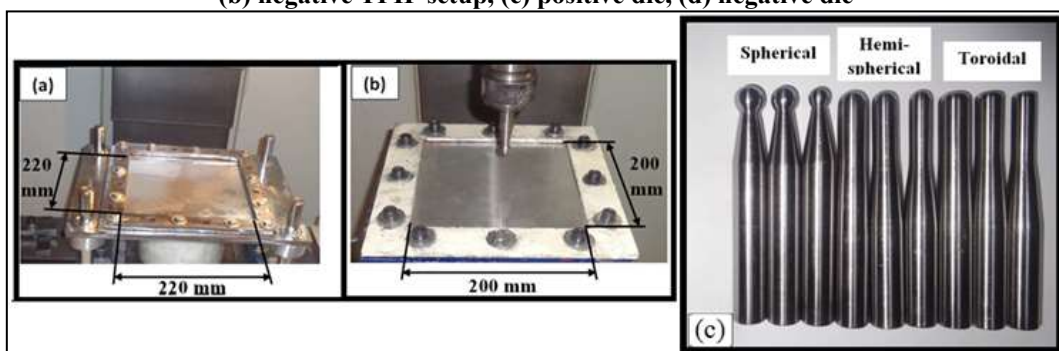


Figure 3: (a) Al-sheet for positive TPIF, (b) Al-sheet for negative TPIF, (c) forming tools

4. Experimental Campaign

I. Geometry of the parts

The geometry of the formed parts is asymmetric positive and negative truncated pyramids with total depth of (45mm) for all products as shown in Figure 4. This geometry is kept constant during all the twenty-six runs in order to investigate the influence of the control factors that have been used in this study.

II. Forming parameters

In this work, the forming parameters are (die geometry "G", tool diameter "D", tool path "P", stepover " ΔZ ", tool shape "S", lubricant "L" and slope angle " α "). Figure 5 illustrates the terminology of forming factors utilized in TPIF. Two geometries of supporting die have been used in this work: positive and negative. While three values of tool diameter and stepover have been utilized, those are (10, 12 & 14) mm for tool diameter and (0.2, 0.4 & 0.6) mm for stepover [12]. In addition, three types of tool path have been adopted; those are helical (P_1), iso-planar (P_2) and bidirectional iso-planar (P_3) tool path as illustrated in Figure 6. All tool paths for the positive and negative pyramids have been generated using Siemens PLM (UGS-NX) CAD/CAM software package.

Regarding lubrication, three types of lubricating materials have been used; machine oil (SAE 30), MoS_2 (with spray form) and graphite powder with slight layer of grease as shown in Figure 7.

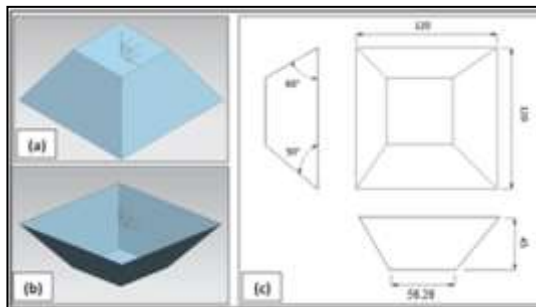


Figure 4: CAD model for the product that used: (a) positive pyramid, (b) negative pyramid, (c) different views for dimensional details

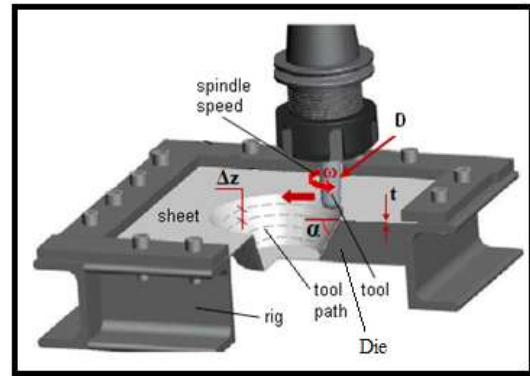


Figure 5: TPIF process factors

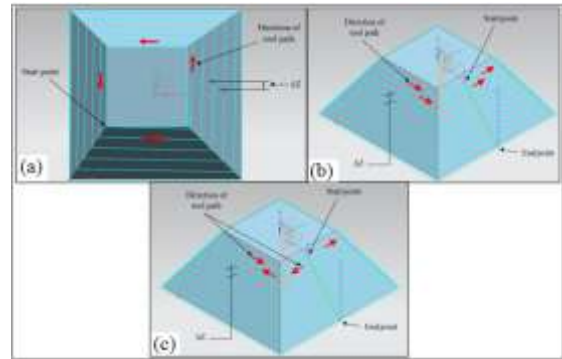


Figure 6: categories of tool paths used; (a) helical path " P_1 ", (b) iso-planar path " P_2 ", (c) bi-directional iso-planar path " P_3 "



Figure 7: Application of lubricant to TPIF with (a) MoS_2 , (b) machine oil, (c) graphite

With regard to tool shape, three geometries of tool head have been used; toroidal (S_T), hemispherical (S_H) and spherical (S_P) head tools have been used in this study. Toroidal tool has two radii at the tip: major radius (R) and minor radius (r), while the hemispherical and spherical head tools have one radius (R).

The values of radii for toroidal, hemispherical and spherical end tools utilized in this study are identified as given in Table 1.

Since die geometry, tool shape, tool path and lubricant are of discrete (non-measurable) factors, therefore the level of these factors have been conducted in terms of coded values (1, 2, 3). Eventually, the sides of the positive and negative pyramids that have been created are inclined to two slope angles (α); 50° and 60° .

The identified factors and their levels have been listed in Table 2.

Figure 8 shows the pyramids like shape that have been produced using TPIF process.

Table 1: Forming tool shapes that used

Tool type	R (mm)	r (mm)
Toroidal (S _T)	5	1
	6	2.1
	7	3.5
Hemispherical (S _H)	5	----
	6	----

Spherical (S _P)	7	----
	5	----
	6	----
	7	----

Table 2: The proposed forming factors and their levels

Parameter	Unit	Levels	Parameter	Unit	Levels
Die Geometry (G)	----	(negative) 1	Tool Path (P)	----	(P ₁) 1
		(positive) 2			(P ₂) 2
Tool Diameter (D)	mm	10	Stepover (ΔZ)	mm	(P ₃) 3
		12			0.2
		14			0.4
Tool Shape (S)	----	(S _T) 2	Lubricant (L)	----	(MoS ₂) 1
		3			(Oil) 2
		(S _H) 4			(Graphite) 3
		(S _P) 5	Slope Angle (α)	Degree	50/60

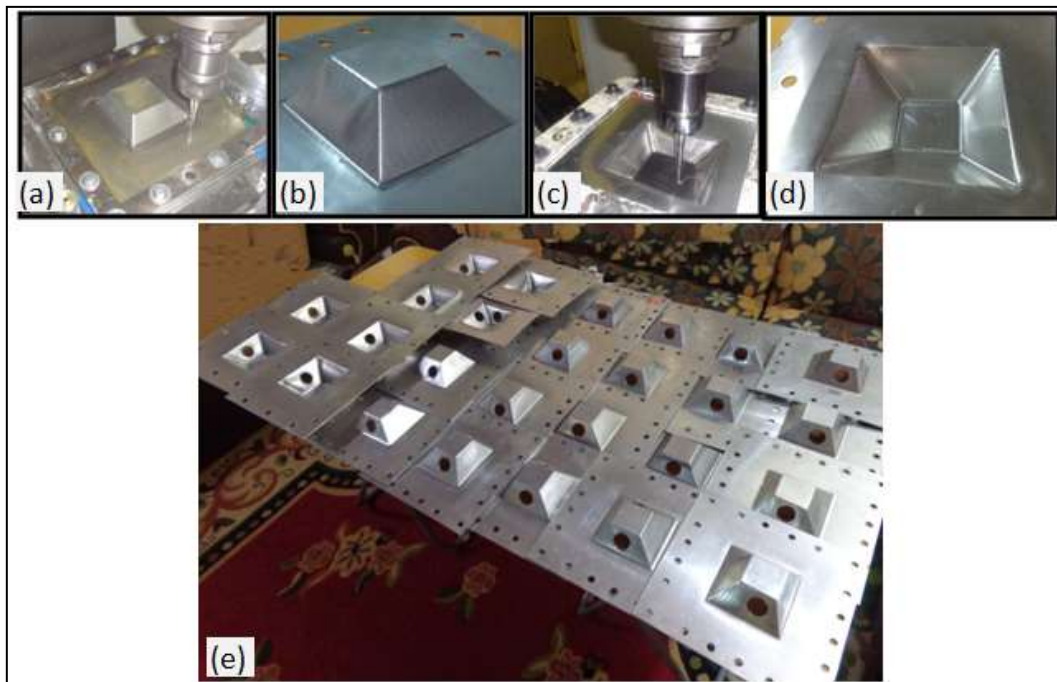


Figure 8: Different views of the pyramid like shape that produced using; (a) & (b) positive TPIF, (c) & (d) negative TPIF, (e) the whole products

III. Thickness Measurement

In order to measure the thickness of the part, five points have been selected along each face of the pyramidal part and the mean value of these points has been taken. The wall thickness has been measured by thickness measuring device with range 0 to 10 mm and resolution of 0.1 mm as shown in Figure 9-a. Thickness of the pyramids

has been recorded at all the five points aforementioned. All the pyramids produced have been cut from their non-deformed region along both angles for sake of thickness measurement as shown in figure below.

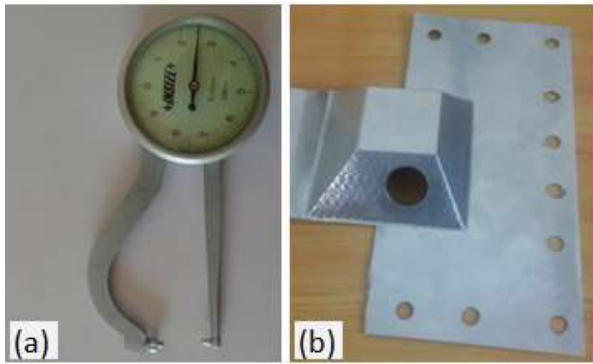


Figure 9: thickness measurement scope; (a) measuring device, (b) prepared pyramid for measurement

the experimental matrix that involves 26 runs by using statistical software package (Minitab 17). The final design layout of the experimental matrix with corresponding results of the formed thickness can be seen in Table 3. In order to analyze the data extracted from the experimental results for determining the influence of the dominant factors on formed thickness of parts produced by TPIF process, the main effects plot (MEP) and analysis of variance (ANOVA) techniques have been utilized. The analysis of sheet thickness has been considered for the two slope angles (50° and 60°) of the pyramids produced.

5. Results and Discussion

In this experimental work, Box-Behnken design (BBD) of experiment with D-optimality criterion has been adopted to develop the design layout of

Table 3: The matrix layout according to BBD design of experiments

No.	Forming Factors						Mean Thickness t (mm)	
	G	D	P	ΔZ	S	L	($\alpha=50^\circ$)	($\alpha=60^\circ$)
1	2	10	2	0.6	4	2	0.576	0.44
2	1	14	2	0.4	5	1	0.568	0.432
3	2	12	3	0.2	4	1	0.582	0.446
4	2	10	1	0.4	5	2	0.592	0.456
5	1	12	2	0.6	2	2	0.562	0.428
6	2	12	1	0.2	4	3	0.568	0.432
7	2	12	2	0.2	2	2	0.594	0.458
8	1	10	2	0.2	4	2	0.562	0.426
9	1	10	2	0.4	1	1	0.578	0.444
10	1	12	1	0.4	4	1	0.56	0.426
11	2	12	3	0.4	4	3	0.56	0.424
12	2	12	1	0.6	4	3	0.56	0.42
13	1	14	2	0.6	4	2	0.55	0.414
14	2	12	2	0.6	5	2	0.584	0.448
15	2	14	2	0.2	4	2	0.58	0.444
16	1	12	2	0.2	5	2	0.57	0.434
17	2	12	3	0.4	4	1	0.578	0.442
18	2	12	1	0.6	4	1	0.578	0.442
19	2	14	2	0.4	3	1	0.558	0.422
20	1	12	3	0.4	4	1	0.556	0.422
21	2	12	3	0.6	4	3	0.556	0.42
22	2	14	3	0.4	5	2	0.584	0.448
23	2	10	3	0.4	1	2	0.596	0.46
24	2	10	3	0.4	5	2	0.588	0.452
25	2	12	2	0.4	4	2	0.578	0.442
26	2	12	1	0.4	4	1	0.584	0.446

I. Main Effects Plot (MEP)

In order to specify the relationship between the forming factors studied and the sheet thickness measured, main effects plot (MEP) method has been adopted. Figures 10-11 show the MEPs of 50° and 60° slope angles respectively. From these MEPs, the die geometry is directly proportional

to the thickness but tool diameter and stepover have an inverse relationship. While tool path, tool shape and lubricant factors incorporate both relationships within various levels as shown in Figures 10-11. These MEPs also show that for both slopes, similar relationships of the forming factors with the thickness have been observed.

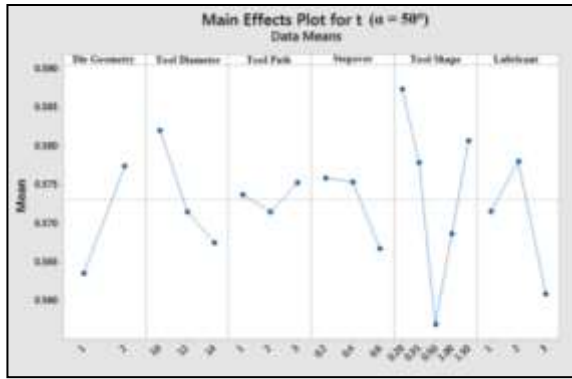


Figure 10: MEP in TPIF for thickness at $\alpha=50^\circ$

factors on the formed thickness as given in Tables 4 and 5.

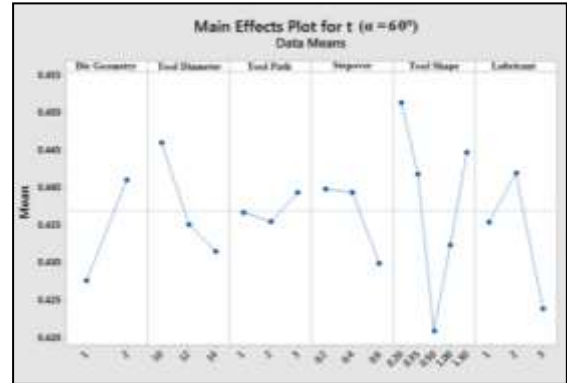


Figure 11: MEP in TPIF for thickness at $\alpha=60^\circ$

II. Analysis of Variance (ANOVA)

In order to determine the statistical significance of the six process factors for a specified slope angle, ANOVA table has been created for both angles in order to measure the effects of those

Table 4: ANOVA test for thickness at $\alpha=50^\circ$

Source	Sum Sq.	d.f.	Mean Sq.	F	P	Percentage Contribution (%)
G	0.00167	1	1.67×10^{-3}	∞	0	45.504%
D	0.00003	2	1.5×10^{-5}	∞	0	0.817%
P	0.00005	2	2.5×10^{-5}	∞	0	1.362%
ΔZ	0.0002	2	0.0001	∞	0	5.45%
S	0.00099	4	2.475×10^{-4}	∞	0	26.975%
L	0.00073	2	3.65×10^{-4}	∞	0	19.891%
Residual Error	0	12	0			0%
Total	0.00367	25				100%

Table 5: ANOVA test for thickness at $\alpha=60^\circ$

Source	Sum Sq.	d.f.	Mean Sq.	F	P	Percentage Contribution (%)
G	1.618×10^{-3}	1	1.618×10^{-3}	$\frac{2008.6}{8}$	0	44.304%
D	3.2×10^{-5}	2	1.6×10^{-5}	19.66	2×10^{-4}	0.876%
P	2.9×10^{-5}	2	1.45×10^{-5}	17.99	2×10^{-4}	0.794%
ΔZ	2.41×10^{-4}	2	1.205×10^{-4}	149.54	0	6.6%
S	9.63×10^{-4}	4	2.407×10^{-4}	298.72	0	26.369%
L	7.59×10^{-4}	2	3.795×10^{-4}	471.27	0	20.783%
Residual Error	1×10^{-5}	12	8.333×10^{-7}			0.273%
Total	3.652×10^{-3}	25				100%

The source of variation (factor) is considered significant if it satisfies the condition in Eq. (1):

$$F \geq F_T(\beta_2, v_n, v_e)$$

(1)

Where:

F: the calculated F-ratio of a given source of variation as illustrated in the tables above

F_T : the tabulated F-ratio,

β_2 : the level of significance used in the test ($\beta_2=0.05$),

v_n : the degree of freedom of given sources ($v_n = 1, 2 \& 4$) and

v_e : the degrees of freedom error ($v_e = 12$).

The tabulated F_T ratios for all factors that based on 5% level of significance and degree of freedom are [$F_T(0.05, 1, 12) = 4.7472$] for (G) source, [$F_T(0.05, 2, 12) = 3.8853$] for (D, P, ΔZ and L) sources and [$F_T(0.05, 4, 12) = 3.2592$] for (S) source.

For this reason, the results of ANOVA tests demonstrate that all the forming factors have a significant effect on the formed thickness of the sheet metal for both inclinations of the pyramid walls as their P & F values are statistically confident. ANOVA results of thickness at $\alpha=50^\circ$ show that the die geometry (45.504% contribution) is the most significant factor followed by tool shape (26.975%), lubricant (19.891%), stepover (5.45%), tool path (1.362%) and tool diameter (0.817%) respectively. Additionally, for $\alpha=60^\circ$, ANOVA results indicate that the die geometry (44.304% contribution) is the most influential parameter of thickness followed by tool shape (26.369%), lubricant (20.783%), stepover (6.6%), tool diameter (0.876%) and tool path (0.794%) respectively.

6. Conclusion

In the modern manufacturing processes, the demands for higher flexibility of production is increasingly important. ISMF is adoptable for performing productions of small or medium-sized batches. Utilizing TPIF process, the period of time required for manufacturing a prototype with its supporting die is much shorter than that for the traditional forming operations. Depending upon the experimental results obtained throughout this paper, the following remarks can be summarized:

1. The Box-Behnken design (BBD) of experiment with D-optimality criterion adopted in this work is a powerful approach for designing experiments to cover all the TPIF parameters with minimum time and cost.
2. The MEP is an efficient method for specifying the relationship between the forming parameters and the formed thickness as well as ANOVA test has been proved to be an effective technique for determining the statistical significance of forming factors.
3. The die geometry is directly proportional to the thickness but tool diameter and stepover have an inverse relationship. While the other parameters incorporate both relationships within various levels.
4. The geometry of the supporting die is the most significant forming factor affecting the formed sheet thickness with percentage contribution of (45.504% at $\alpha=50^\circ$ & 44.304% at $\alpha=60^\circ$).

5. For both slopes of the pyramids produced, similar relationships of the forming factors with the sheet thickness have been observed.

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