Influence of some Relevant Process Parameters on the Surface Roughness of Surfaces Produced by ISMF Process

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ABSTRACT

Incremental Sheet Metal Forming (ISMF) is a novel sheet metal forming technology where the deformation of the thin sheet metal blank occurs locally and progressively by using the CNC milling machine which control the movement of a simple forming tool. The surface quality is of vital importance in any manufacturing process. Therefore, the present study is focused on the surface quality of parts formed by single point incremental forming (SPIF) process. Consequently, the objective of this study is to investigate the effect of five forming parameters (number of forming stages, feed rate type, tool overlapping, rotational speed, and state of initial blank) on the dimensional accuracy and surface roughness of parts. Each control factor is studied based on two levels (low level and high level). To study the effects of these control factors, a D-optimal Design of Experiment is used to develop the experimental plan and analyze data. The ANOVA results show that the tool overlapping and the number of forming stages are the most important factors affecting the surface roughness. These two factors are proportional to the surface roughness. The maximum and minimum surface roughness, which is achieved from all the 16 experiments is (R_a = 4.06 & R_a = 2.04 µm) respectively. The qualitative assessment reveals that the surface roughness decreases radialy as the tool moves towards the center of the blank.

Keywords: Incremental sheet metal forming, D-optimal Design, ANOVA.

دراسة بعض العوامل المؤثرة على الخشونة السطحية للأسطح المنتجة بطريقة تشكيل الصفائح التزايدية

ألخلاصة

تعد عملية التشكيل الصفائح التزايديـة تقنية حديثة وواعدة لتشكيل الصفائح المعدنية التي تستخدم مكائن التفريز المبرمجة (CNC- milling machines) حيث تتشوه صفيحة المعدن الرقيقة بشكل موقعي وتدريجي من

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حركة اداة تشكيل بسيطة تسيطر عليها مكائن التفريز المبرمجة. أن جودة الأسطح تعد أهمية حيوية وفاصلة فى أي عملية تصنيعية. لذلك فأن هذه الدراسة ركزت على جودة الأسطح للمنتجات المشكلة بواسطة عملية التشكيل التزايدية المنفردة (SPIF). عمليا أن الدقة الهندسية للمنتجات المصنعة بواسطة عملية التشكيل التزايدية تكون اقل من المنتجات المصنعة بواسطة عمليات التشكيل التقليدية. وبناءا على ذلك فأن هدف البحث هو دراسة تأثير خمس عوامل (عدد مراحل التشكيل, نوع معدل التغذية, تداخل العدة, السرعة الدورانية وحالة الصفيحة المعدنية الاولية) على الخشونة السطحية والدقة الهندسية للمنتجات المشكلة بواسطة عملية التشكيل التزايدية المنفردة. أن كل عامل من هذه العوامل المسيطرة قد درس بالاعتماد على مستويين (مستوى عالي ومستوى واطئ). أشارت النتائج الى ان تداخل العدة وعدد مراحل التشكيل من اهم العوامل المؤثرة على الخشونة السطحية ويتناسبان طرديا معها. الحد الاقصى والادنى للخشونة السطحية لكل التجارب (16) هو(R_a = 4.06 & R_a = 2.04 μm) على التعاقب. التقييم النوعي للخشونة السطحية يكشف انها في حالة تناقص بالاتجاه القطري كلما اتجهنا الى داخل السطح او مركز السطح.

INTRODUCTION

Nowadays, the production of small batch series, complex shapes with shorting the lead-time and reducing the production cost is required. A great deal of research works have been concerned in order to adapt to the changing requirements of the market. Thus, a new trail manufacturing process that can deform general sheet metal into an arbitrary shape with flexible is still required by many industrial sectors [1]. Consequently, in the last few decades, scientists have to find answers to these urgent requests and new non- conventional sheet metal forming process namely Incremental Sheet Metal Forming (ISMF) technology. ISMF process seems to be a sustainable approach to reach the aim of high flexibility because specialized tooling is not required, reducing the manufacturing costs and the time-to-market when small series, pre-series or rapid prototypes need to be realized [2].

Incremental sheet metal is a flexible and a novel technology that is based on the forming of a metal sheet by means of a CNC milling machine, including a CAD/CAM system to plan the tool path, where the cutting tool (cutter) is replaced by a cylindrical tool of hemispherical or spherical head allowing it to follow any required contour on the blank sheet without using any dictated die [3].

In particular, surface roughness is one of the important quality aspects in incremental forming and regarded as a weak point when compared to the traditional processes, consequently, the possibility to predict the surface roughness values in incremental forming can be useful, in order to control this important target [4]. **Hagan and Jeswiet (2004)** [5], highlight the importance of the roughness, especially for automotive parts. In their studies, they describe the surface finishing in incremental forming as a combination of large-scale waviness results from the tool path and small-scale roughness resulting from large surface strains; it is shown that, as the vertical tool step decreases, the surfaces are seen to transform from wavy to strictly roughness without waviness. Furthermore, the tool rotation speed does not influence the roughness. The dynamic local heating has been proposal and implementation by **J.R. Duflou et al. (2008)** [6]. The authors have opted for an alternative approach in which the material properties are differentiated by localized temperature variations. In this way, different zones can be created in the sheet metal part being processed. By means of a dynamic heat, input in the direct vicinity of the stylus, a ductile area with low-yield strength is generated. Effects of such strategy were reduced forces on the stylus and, in consequence, a better localized deformation and thus a higher precision. The significant reduction of the orthogonal error along the slope of the cone demonstrates the effectiveness of the dynamic, local heating concept. The author believes that R_a and R_t roughness is effected by dynamic heating, but after experimental tests it is found that the roughness does not change significantly due to heating. **M. Durante et al. (2010)** [7], compare between the analytical and the experimental values of the surface roughness of components created by incremental forming. A model for evaluating the roughness, both in terms of amplitude and spacing, has been described depending on three parameters: the slope angle, the vertical step and the tool radius. As for amplitude parameters, the average roughness [R_a] and a parameter of max roughness [R_z] are analyzed. In this study, it is concluded that the initial model for the spacing parameter and the modified ones for the amplitude parameters allow to reach a very good prediction of the roughness, in absolute values 10%, so it is necessary to modify the models for the amplitude parameters. In the light of what was above-mentioned, it is clear that the current state-of-the-art does not cover all the aspects of this innovative technological process. Consequently, in the present study, increased the number of factors that believed affecting the quality of surfaces produced by SPIF process in terms of surface roughness to find out their combined influence of these five factors (number of forming passes, feed rate, tool overlapping, rotational speed, state of initial blank).

The Experimental Investigation

All the experiments were carried out on aluminium alloy AA 1090-F blanks with 1.1 mm thickness aimed to the production of cone-like shapes. The chemical compositions of the sheet material are analyzed by "spectrometer elements analysis" and the chemical compositions listed in Table (1). the flow stress curve of the sheet material is fitted to the empirical power equation as:

$$\sigma = 68.89 \in^{0.4} \quad \text{…….. (1)}$$

Table (1): Chemical composition of the Aluminum sheet AA 1090-F (% of Mass).

Element	Al	Si	Fe	Cu	Mn	Mg	Ti	V	Zn	Ni	Ca
Com.	99.256	0.047	0.575	0.002	0.002	0.059	0.017	0.007	0.005	0.004	0.006

The CAD model of the cone-like shapes that represent type from the revolved surface generated from the rotation of the generatrix cubic Bezier curve is shown in figure (1). The ration of the height (h = 50 mm) to radius (r = 50 mm) of the curve is one (h/r = 1). The iso-parametric tool path is used for all the trails of a cone –like shape. In this work, a hemispherical head of the cylindrical tool manufactured from medium carbon steel with diameter (10 mm) is utilized in order to form or sculpture the sheet metal according to tool path generation. To increase the hardness and mechanical properties of forming tool, the author proposes to use hard chromium electroplating.

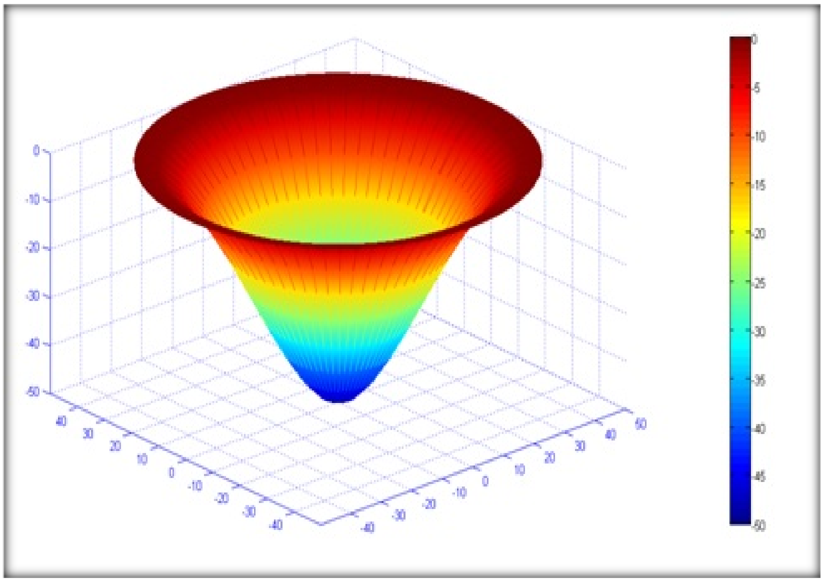

Figure (1): The surface of revolution approach of generator Bezier curve.

The experimental campaign was carried out according to a proper design of experiments (DOE) [8]. Two levels matrix is used, accordingly each variable is studied based on two levels. In order to reduce the number of experiments, maintaining, in the mean time and cost, the statistical consistency of the results, a D-optimal design was carried out instead of a Full Factorial Designs [9]. Therefore, the sixteen trails is performed in order to show the influence of the control factors that used in this study. Table (2) reports the considered main process parameters and the extremes of the experimental plan.

Table (2): Control parameters and their levels.

No.	**Parameter**	**Unit**	**Levels**			
			Original		Coded	
			Low	High	-1	1
1	Number of forming stages (A)	-	Single stage	Double stage	-1	1
2	Feed rate (B)	mm/min	Constant feed rate	Variable feed rate	-1	1
3	Overlapping (C)	-	84%	88%	-1	1
4	Rotational speed (D)	r.p.m	200	600	-1	1
5	State of initial blank (E)	-	Flat	Curved	-1	1

Vertical arrangement (VA) has a balanced property in which every factor setting occurs in the same number of times for every setting of all other factors in the experiment. Figure (2) shows the experimental setting used in this study and the cross section of the final product.

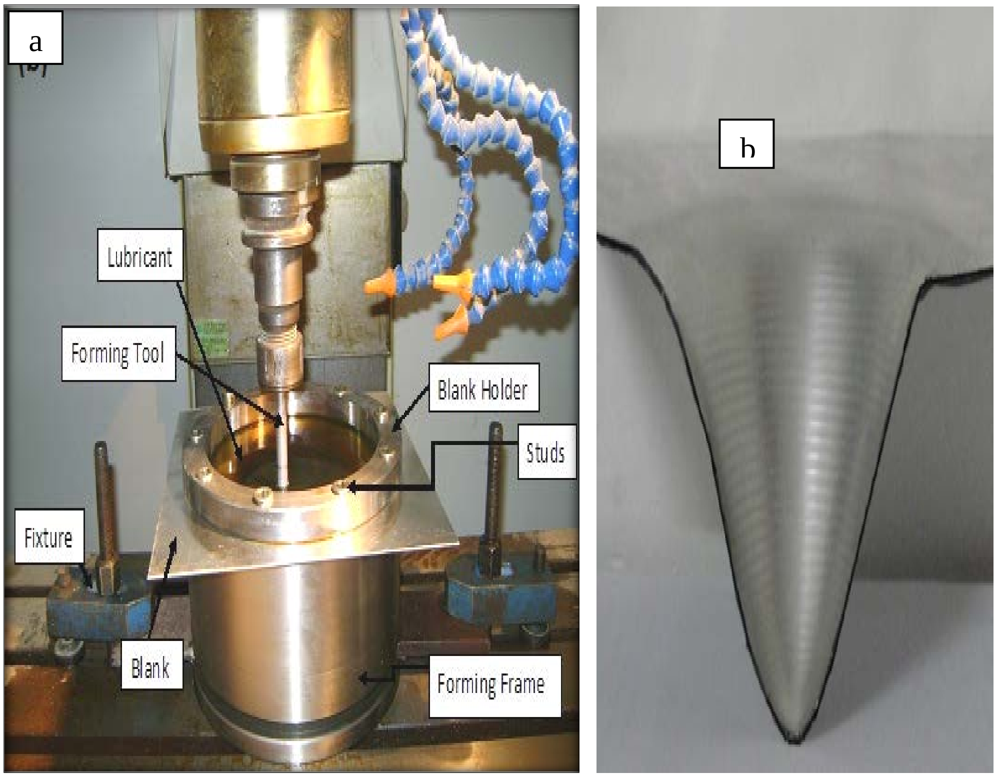

Figure (2): (a) Experimental setting used in this study, (b) Cross section of the cone like shape.

Results and Discussion

Sixteen experiments are conducted based on the selected L_{16} D-optimal Design that is utilizing the C-tek 3-axes CNC milling machine. Table (3) illustrates the results of the performed experiments.

Table (3): Design matrix and corresponding output response.

Expt. No.	Coded Value					Original Value					Measured Output
	A	B	C	D	E	Forming Stages	Feed Rate	Tool Overlap	Rotational Speed r.p.m	Initial Blank	Roughness Ra (μm)
1	1	1	1	-1	1	Double	Variable	88%	200	Curved	2.26
2	-1	-1	1	1	1	Single	Constant	88%	600	Curved	2.74
3	-1	-1	-1	1	1	Single	Constant	84%	600	Curved	4.06
4	-1	1	-1	1	-1	Single	Variable	84%	600	Flat	3.34
5	1	1	1	1	-1	Double	Variable	88%	600	Flat	2.44
6	-1	-1	-1	-1	-1	Single	Constant	84%	200	Flat	3.68
7	-1	1	1	-1	-1	Single	Variable	88%	200	Flat	2.28
8	-1	1	1	1	1	Single	Variable	88%	600	Curved	2.04
9	1	-1	-1	1	-1	Double	Constant	84%	600	Flat	2.42
10	1	1	-1	1	1	Double	Variable	84%	600	Curved	2.9
11	1	-1	1	1	1	Double	Constant	88%	600	Curved	2.14
12	-1	-1	1	1	-1	Single	Constant	88%	600	Flat	2.6
13	-1	-1	1	-1	1	Single	Constant	88%	200	Curved	3.22
14	1	-1	1	-1	-1	Double	Constant	88%	200	Flat	2.58
15	1	-1	-1	-1	1	Double	Constant	84%	200	Curved	2.32
16	-1	1	-1	-1	1	Single	Variable	84%	200	Curved	3.28

The average roughness Ra has been examined by using surface roughness tester brand “TALYSURF4” England making, and 0.01 μm accuracy. This parameter is chosen because Ra is widely used as a parameter for the surface roughness. A full experimental campaign is carried out and for each sample; five line measures are recorded along the internal face of the cone in order to avoid errors linked to any anisotropic behavior in terms of sheet roughness. The surface roughness has measured perpendicular to the direction of the tool movement. In general, it is observed that the surface roughness tends to decrease as the tool move from the flange of the product towards it's center. This is because the topology of the shape transformed from convex to concave shape. The tool touches the convex region at a single point. On the other hand, the forming tool touches the concave region (at the center of the product) at an arc of contact. That is why the surface roughness tends to be reduced as the tool head into the internal surface.

This part contains analyzing the data extracted from the practical experiences to determine the influence of the dominant factors on the accuracy investigation represented by the surface roughness. The systematic data analysis includes:

Response Table and Response Graph of Surface Roughness

The influence of parameters on surface roughness has been explored using response table. Response tables are used to simplify the calculations needed to analyze the experimental data. In response table, the effect of each factor on a response variable (surface roughness) is shown as the change in the response when each factor goes from its low to its high level [10].

The complete response table for a two level, 16 runs D-optimal design is shown in table (4). The graphical display such as response graph can be used, in conjunction with a response table to identify appropriate settings for SPIF parameters to minimize the average surface roughness. The effect of single and interaction factors derived from response table can be estimated by ($\ell_H - \ell_L$) where ℓ_H is the high level and ℓ_L is the low level for each factor and their interactions. The estimated effect graph is a fruitful tool to analyze the effect of the process variable which uses the absolute effect. The plot of the estimated effects of five control factors and their ten interactions for surface roughness is shown in figure (3).

According to the estimated effect graph for surface roughness measurements, it is inferred that the larger the vertical line, the larger the change in surface roughness. Therefore, tool overlapping (*C*) has the greatest effect on the surface roughness followed by number of forming stages (*A*), Feed rate type (*B*), Rotational speed (*D*) and finally State of initial blank (*E*). It will be pointed out that the statistical significance of the factor is directly related to the length of the vertical line as shown figure (3). Consequently, the interaction between number of forming stage and feed rate (AB), and the interaction between number of forming stage and tool overlapping (AC) have the greatest effect on surface roughness in the middle of the other interactions.

Table (4): Response table for mean surface roughness.

		SINGLE EFFECTS													
Exp. No.	(R_a) µm	A		B		C		D		E		AB		AC	
		-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	-1
1	2.26		2.26		2.26		2.26	2.26			2.26		2.26		2.26
2	2.74	2.74		2.74			2.74		2.74		2.74		2.74	2.74	
3	4.06	4.06		4.06		4.06			4.06		4.06		4.06		4.06
4	3.34	3.34			3.34	3.34			3.34	3.34		3.34			3.34
5	2.44		2.44		2.44		2.44		2.44	2.44			2.44		2.44
6	3.68	3.68		3.68		3.68		3.68		3.68			3.68		3.68
7	2.28	2.28			2.28		2.28	2.28		2.28		2.28		2.28	
8	2.04	2.04			2.04		2.04		2.04		2.04	2.04		2.04	
9	2.42		2.42	2.42		2.42			2.42	2.42		2.42		2.42	
10	2.9		2.9		2.9	2.9			2.9		2.9		2.9	2.9	
11	2.14		2.14	2.14			2.14		2.14		2.14	2.14			2.14
12	2.6	2.6		2.6			2.6		2.6	2.6			2.6	2. 6	
13	3.22	3.22		3.22			3.22	3.22			3.22		3.22	3.22	
14	2.58		2.58	2.58			2.58	2.58		2.58		2.58			2.58
15	2.32		2.32	2.32		2.32		2.32			2.32	2.32		2.32	
16	3.28	3.28			3.28	3.28		3.28			3.28	3.28			3.28
Total	44.3	27.24	17.06	25.76	18.54	22	22.3	19.62	24.68	19.34	24.96	20.4	23.9	20.52	23.78
Value	16	9	7	9	7	7	9	7	9	7	9	8	8	8	8
Avg.	2.77	3.03	2.44	2.86	2.65	3.14	2.48	2.80	2.74	2.76	2.77	2.55	2.99	2.57	2.97
Effect		-0.59		-0.21		-0.66		-0.06		0.01		0.44		0.4	

Table (4): Continued.

INTERACTION EFFECTS															
AD		**AE**		**BC**		**BD**		**BE**		**CD**		**CE**		**DE**	
-1	**1**	**-1**	**1**	**-1**	**1**	**-1**	**1**	**-1**	**1**	**-1**	**1**	**-1**	**1**	**-1**	**1**
2.26			2.26		2.26	2.26			2.26	2.26			2.26	2.26	
2.74		2.74		2.74		2.74		2.74			2.74		2.74		2.74
4.06		4.06			4.06	4.06		4.06		4.06		4.06			4.06
3.34			3.34	3.34			3.34	3.34		3.34			3.34	3.34	
	2.44	2.44			2.44		2.44	2.44			2.44	2.44		2.44	
	3.68		3.68		3.68		3.68		3.68		3.68		3.68		3.68
	2.28		2.28		2.28	2.28		2.28		2.28		2.28			2.28
2.04		2.04			2.04		2.04		2.04		2.04		2.04		2.04
	2.42	2.42			2.42	2.42			2.42	2.42			2.42	2.42	
	2.9		2.9	2.9			2.9		2.9	2.9		2.9			2.9
	2.14		2.14	2.14		2.14		2.14			2.14		2.14		2.14
2.6			2.6	2.6		2.6			2.6		2.6	2.6		2.6	
	3.22	3.22		3.22			3.22	3.22		3.22			3.22	3.22	
2.58		2.58		2.58			2.58		2.58	2.58		2.58			2.58
2.32			2.32		2.32		2.32	2.32			2.32	2.32		2.32	
	3.28	3.28		3.28		3.28			3.28		3.28	3.28		3.28	
21.94	22.36	22.78	21.52	22.8	21.5	21.78	22.52	22.54	21.76	23.06	21.24	22.46	21.84	21.88	22.42
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.74	2.8	2.84	2.69	2.85	2.69	2.72	2.81	2.82	2.72	2.88	2.66	2.81	2.73	2.74	2.80
0.06		-0.15		-0.16		0.09		-0.1		-0.22		-0.08		0.06	

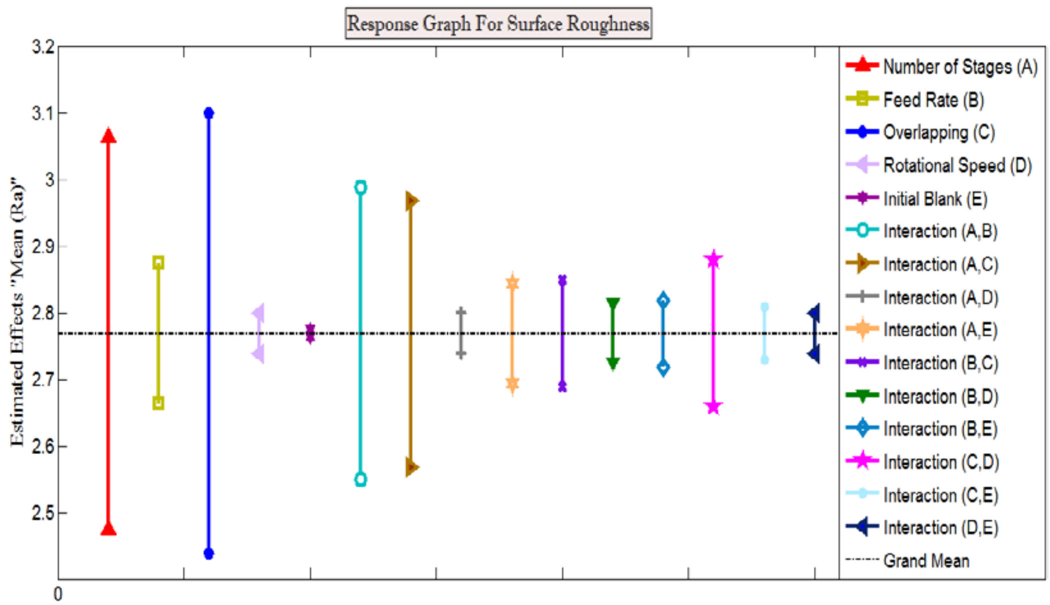

Figure (3): Response graph of estimated effects of the five control factors and their interaction on surface roughness.

Normal Probability Table and Normal Probability Plot

In response graph, it is found that the effects of some of the factors are larger than the other, but it is not clear, whether these effects are significant or not. To identify the significance of effect, normal probability plot is used. The normal probability of each estimated effect can be calculated using the subsequent equation [11]:

$$\text{Probability (Pi)} = \frac{100(i - 0.5)}{n} \qquad \text{..................... (2)}$$

Where i is the rank rising of i^{th} factor based on effect, n is the number of control factors and their interactions (n=15).

The calculations needed for plotting normal probability are summarized in table (5) for surface roughness response. Normal probability calculations are obtained by arranging the estimated effects in ascending order as shown in table (5).

Based on normal probability plots, the effects of factors which are close to the central middle line represent a chance effect (insignificant effect). On the contrary, effects of factors which are far away from the center line represent real effect or significant effect. Figure (4) shows the normal probability of surface roughness.

Table (5): Normal probability calculations for surface roughness.

Factor	Estimated Effects (Roughness)	Rank Order (i)	Probability (P_i) = 100(i – 0.5) / 15
C	-0.66	1	3.333
A	-0.59	2	10
CD	-0.22	3	16.667
B	-0.21	4	23.333
BC	-0.16	5	30
AE	-0.15	6	36.667
BE	-0.1	7	43.333
CE	-0.08	8	50
D	-0.06	9	56.667
E	0.01	10	63.333
AD	0.06	11	70
DE	0.06	12	76.667
BD	0.09	13	83.333
AC	0.4	14	90
AB	0.44	15	96.667

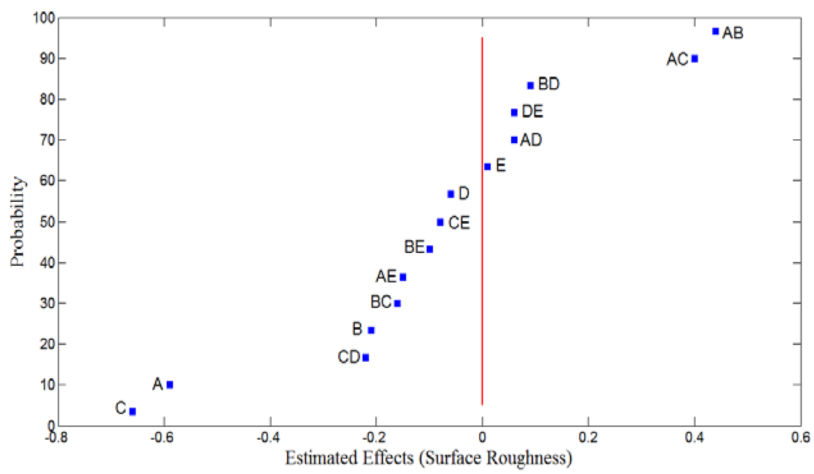

Figure (4): Normal probability plot for surface roughness.

As per the normal probability plot (Figure (5.3)), points (*CD, B, BC, AE, BE, CE, D, E, AD, DE, BD*) which are close to the central line represent estimated factors which do not demonstrate any significant effect on the surface roughness. On the other hand, the points (*C, A, AC, AB*) appear to be far away from the central line and they are likely to represent the real factor effects on the roughness. In brief of the above overlapping, number of forming stage and the interaction (of number of forming stage/overlapping, number of forming stage/feed rate) have significant effect on surface quality.

Roughness Analysis of Variance

The normal probability plot has the disadvantage of not providing a clear criterion for what values for estimated effects indicate significant factor or interaction effects, i.e., how far must a point be from the straight-line pattern before it is judged an outlier? In addition how do we measure amount of departure from the straight-line pattern. *Analysis of Variance (ANOVA)* meets this need by how much an estimate must differ from zero in order to be judged “statically significant” [12]. ANOVA is a method of portioning variability into identifiable sources of variation (process variables and their interactions) to investigate which source of variation significantly affects the response [11].

The current study is controlled by five control factors and ten interactions; therefore, there would be fifteen sources of variation control the required surface roughness. Therefore, ANOVA has a sharp criterion to select the significant parameter or interaction from fifteen sources by analyzing the significant effect through F- Fisher test or probability value P- value. Five way ANOVA is used in this study, as the number of control factors studied is five. This analysis is carried out for the level of confidence of (β=95%), therefore the level of significance is (α=5%). Thus the source of variation is considered to be significant if its P-value $\leq$ 0.05. Table (6) shows the ANOVA results test for surface roughness response.

Table (6): ANOVA results test for surface roughness response.

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
A	2.3675	1	2.36749	16.19*	0.001*
B	0.2422	1	0.24221	1.66	0.2164
C	3.8198	1	3.81985	26.13*	0.0001*
D	0.0737	1	0.07373	0.5	0.4879
E	0.0054	1	0.00541	0.04	0.8499
AB	2.8037	1	2.80371	19.18*	0.0005*
AC	1.06	1	1.05997	7.25*	0.016*
AD	0.0006	1	0.00065	0	0.9477
AE	0.3232	1	0.32321	2.21	0.1565
BC	0.3395	1	0.33949	2.32	0.1471
BD	0.0737	1	0.07373	0.5	0.4879
BE	1.0834	1	1.08339	7.41*	0.0151*
CD	0.2708	1	0.27085	1.85	0.1924
CE	0.0092	1	0.00925	0.06	0.8046
DE	0.0986	1	0.09857	0.67	0.4237
Error	2.3394	16	0.14621		
Total	14.9109	31			

$F_{T\ (0.05,\ 1,\ 16)}$ = 4.494 for single and interacted factors.

The source of variation is considered significant if it assures the condition in equation (5.5):

$$F \geq F_{T\ (\alpha,\ v1,\ v2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where F is the calculated F-ratio of a given source of variation as illustrated in table (6), and F_T is the tabulated F-ratio, α is the level of significance used in the test (α = 0.05), v1 is the degree of freedom of a given source (v1 =1) and v2 is the degrees of freedom error (v2 = 16).

The tabulated F_T ratio for all factors and interaction that based on 5% level of significant and degree of freedom is {F_T (0.05, 1, 16) = 4.494}. For this reason, based on ANOVA table (table 6), number of forming stage (*A*), tool overlapping (*C*), interaction between number of forming stage and feed rate type (*A* and *B*), interaction between number of forming stage and tool overlapping (*A* and *C*), and interaction between feed rate and state of initial blank (*B* and *E*) are considered to be significant factors of surface roughness response. These results confirm to large extent the results of normal probability plot.

Interaction Effect Plot (IEP)

The interaction effect plots confirm the significance of interactions of factors.Interaction occurs when one factor does not produce the same effect on the response at different levels of another factor. Since the interaction effects of *AB*,*AC*,and *BE* seem to be significant to the surface roughness as concluded from ANOVA test,the average values of this response are calculated for all the combinations and are presented in tables(7)through(9).By using the values in interaction tables, interaction graphs are drawn for each combination of levels.The interaction graphs are presented in figures(5) through(7).

From the interaction graphs of surface roughness, it is noticed that the most meaningful interaction of surface roughness response is the interaction between the number of forming stages and the tool overlapping. As the number of forming stages and the tool overlapping increased, the value of surface roughness decreased so the surface quality of the product improved as clarified in figure (6).

Table (7): Calculations for *AC* interaction.

		C	
		-1	1
A	-1	4.06	2.74
		3.34	2.28
		3.68	2.04
		3.28	2.6
			3.22
		3.59	2.58
	1	2.42	2.26
		2.9	2.44
		2.32	2.14
			2.58
		2.55	2.35

Table (8): Calculations for *AB* interaction.

		B	
		-1	1
A	-1	2.74	3.34
		4.06	2.28
		3.68	2.04
		2.6	3.28
		3.22	
		3.26	2.735
	1	2.42	2.26
		2.14	2.44
		2.58	2.9
		2.32	
		2.365	2.533

Table (9): Calculations for *BE* interaction.

		E	
		-1	1
B	-1	3.68	2.74
		2.42	4.06
		2.6	2.14
		2.58	3.22
			2.32
		2.82	2.9
	1	3.34	2.26
		2.44	2.04
		2.28	2.9
			3.28
		2.69	2.62

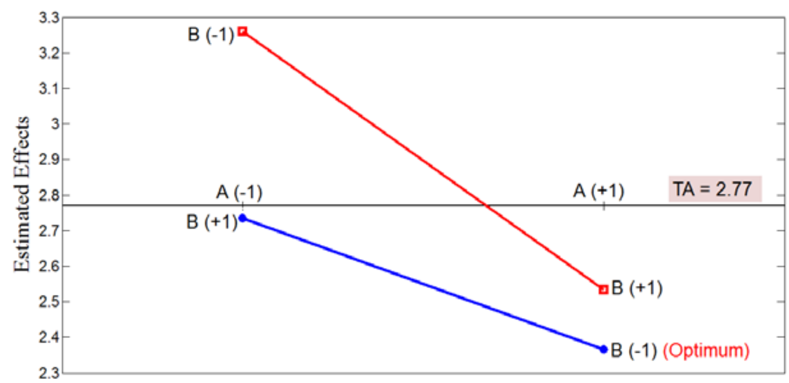

Figure (5): Interaction between *A* and *B*.

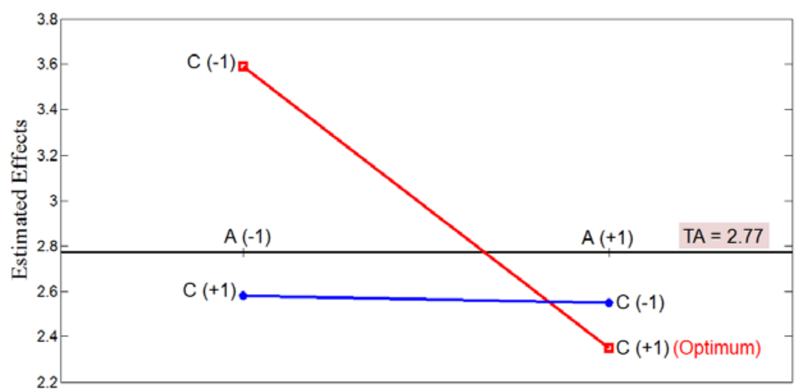

Figure (6): Interaction between *A* and *C*.

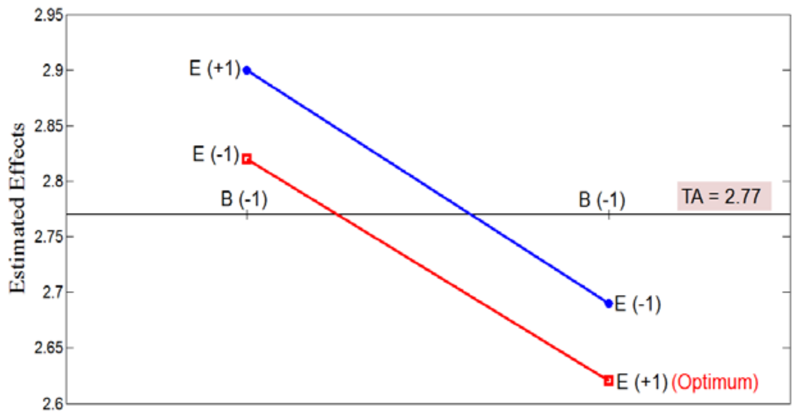

Figure (7): Interaction between *B* and *E*.

CONCLUSIONS

In modern manufacturing industry, flexibility of production technologies is becoming more important. Implementation of the technological process of incremental sheet metal forming is intended for rationalization of small batch production. Using it, the time necessary for prototype making can be shortened. Depending on the results of this work, the following remarks can be concluded:

1. The presented D-optimal design parameters are professional methods for designing experiments to cover all the process variables with minimum cost and effort.
2. The five way ANOVA is an efficient tool to extract the significant process variables and significant interactions between process variables.
3. The most effective factors for surface roughness are the tool overlapping followed by the number of forming stages. High level of these factors decreases the unwanted surface roughness. Therefore, these two factors are proportional to the surface roughness.
4. The maximum and minimum surface roughness, which is achieved from all the 16 experiments is (R_a = 4.06 & R_a = 2.04 µm) respectively.
5. There is a correlation between the surface roughness and the topology of the product. The surface roughness decreases radialy as the tool moves towards the center of the blank.

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