Determining the effect of process parameters on surface roughness in two point incremental sheet metal forming process using the Taguchi method

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Abstract:

The main aim of this study is determining the effect of process parameters on surface roughness in two point incremental sheet metal forming process using the Taguchi method. The experimental plan and analysis were based on the mixed L18 Taguchi orthogonal array with four forming parameters, tool radius (r), feed rate (f), stepover (Δz) and type of support (full and partial support) were analyzed and pyramid shape was used (57°) wall angle. The influence of the process parameters has been investigated and optimum forming condition for minimizing the surface roughness is evaluated. The analysis results show that the stepover has the highest effect on the surface roughness and followed by tool radius, feed rate and die. The result shows that the error of predicted accuracy for the surface roughness is (1.2%).

Keyword: Two Point Incremental Forming (TPIF), Surface Roughness, Taguchi Method.

دراسة تأثير عناصر العملية على الخشونة السطحية في عملية التشكيل التزايدي ثنائي التماس بإستخدام طريقة تاكوجي

الخلاصة:

الهدف الرئيسي للبحث هو دراسة تاثير عناصر العملية على الخشونة السطحية في عملية التشكيل التزايدي ثنائي التماس بإستخدام طريقة تاكوجي. خطة العمل والتحليل بالإستناد الى طريقة تاكوجي بإجراء 18 تجربة نوع مختلط مع اربع عناصر مختلفة للعملية: نصف قطر العدة, معدل التغذية, مسافة الانتقال بين خطوتيين, نوع الإسناد (قالب جزئي وكامل) والمنتج المستخدم ذو شكل هرمي يمتلك زاوية جدار (57°) . تأثيرعناصر العملية وإيجاد أفضل ظروف لتقليل الخشونة السطحية تمت دراستها. نتائج التحليل اظهرت ان مسافة الانتقال بين خطوتين تمتلك التأثير الأكبر على الخشونة السطحية ومن ثم نصف قطر العدة ومعدل التغذية واخيرا نوع الإسناد .كذلك بينت النتائج ان قيمة الخطأ للقيمة المتنبئة للخشونة السطحية هي (1.2%) .

الكلمات المرشدة: التشكيل التزايدي ثنائي التماس , الخشونة السطحية, طريقة تاكوجي

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INTRODUCTION

The incremental sheet metal forming process (ISMF) is a novel sheet metal forming process which is characterized by high flexibility and lower cost with new concept of manufacturing with simple tool numerically controlled which moves along the contours of part to be formed according to a programed toolpath imposes deformation locally on the sheet and achieving a simple and complex shape with higher forming limits than deep drawing and stamping process [1,2].

The surface roughness is an essential requirement in determining the surface quality of a product and widely used index of product quality and in most cases a technical requirement for mechanical products. Surface roughness is defined as the irregularities of any material resulting from machining or forming operations. It is denoted by Ra – namely, average roughness. Ra is theoretically derived as the arithmetic average value of departure of the profile from the mean line along a sampling length. Surface roughness have been obtained in both the tool advancing direction and in the perpendicular one. The obtained values are always lower in the tool advancing direction than in the perpendicular one [3]. So, most researchers measured the roughness perpendicular to direction of the tool movement.

Generally, surface roughness in incremental forming is regarded as a weak point when compared to the traditional processes. And it is important variable to be taken into account in global process evaluation [4] because the nature of process which depends upon local contact zone that moving along entire part. The surface roughness is affected primarily by the tool radius, step size, material thickness, forming angle, rotational, feed speeds and lubricant [5]. In the present work, the influence of process parameters on surface roughness is investigated by means of statistical methods.

Experimental investigation

In this work, the experimental tests have been performed in 3- Axis CNC milling machine model (C-tek KM-80D) which belongs to the turning unit at Training Center and laboratories in the University of Technology as shown in Figure (1). The experimental set up of TPIF process consist of: the sheet metal blank, the blankholder, movable frame, post guide sliding bush and partial die and the experimental setup is shown in Figure (2).

A forming tool for TPIF process is a solid hemisphere head that was made from hardened steel material three radii (5, 6 and 7 mm).the geometry of the forming tools is shown in Fig (3(a)). The tools were inserted into tool holder of the CNC milling machine. The tool holder is attached to the CNC milling machine and the tool shank is attached to the collet of tool holder as shown in Figure (3(b)).

The material used for the investigation is a square aluminum sheet (Al 1050) and the initial size of the sheet was 280 x 280 x 0.9 mm. The chemical composition of the sheet material is listed in Table (1). Its composition studied in State Company for Inspection and Engineering Rehabilitation activities (S.I.E.R)). Material properties obtained by a uniaxial tensile test are shown in Table (2).In this test; pyramid shape was used as test geometry to evaluate the part. A frustum of pyramid, with 40 mm side length and 45 mm height was used. The contour toolpath with a rectangular trajectory, the geometrical details of the pyramid are shown in Figure. (4). In this study the tool path is generated by the commercial CAD/CAM software (UG NX-5). Engine oil and bearing oil as a mixture of (75% and 25% respectively) was used as lubricant at interface between the tool and the sheet.

The surface roughness of the samples were measured with the help of Surface Roughness Tester; pocket Surf® III I ABSOLUTE MOBILITY. Measuring ranges (Ra 0.03 μm to 6.35 μm) with display resolution 0.01 μm. The device is shown in figure. (5). So this study will measure in perpendicular direction only.

Taguchi technique

The Taguchi method was developed by presented a method for designing experiments to investigate how different parameters affect the mean and variance of process performance characteristics by developed fractional factorial experimental designs that use a limited number of experimental runs

In any forming process, it is most important to determine the optimal settings of parameters aiming at reduction of production costs, time and achieving the desired product quality. The signal-to-noise (S/N) ratio, mean effect and the analysis of variance (ANOVA) were employed to study the performance characteristics, evaluate the effect of selected variables (process parameters) and determine the optimum parameter level. The signal-to- noise ratio(S/N ratio) is a measurement of Taguchi robust design in the Design. It's the logarithmic function of desired outputs. In this technique, the term 'signal' refers to the desirable value (mean) for the output characteristic and the term 'noise' refers to the undesirable value (standard deviation). The determination of S/N ratio differs according to objective function. Taguchi categorizes performance characteristics into three different kinds, such as the nominal the better (NB), the smaller the better (SB), and the larger the better (LB), There are several S/N ratios available depending on type of characteristics [6,7,8]

The signal-to-noise ratio for the larger-the better is

$$S/N = -10 \log 1/n \left(\sum_{i=1}^{n} 1/Y^2\right) \quad ...(1)$$

The signal-to-noise ratio for the smaller-the better is

$$S/N = -10 \log 1/n \left(\sum_{i=1}^{n} Y^2\right) \quad ...(2)$$

The signal-to-noise ratio for the nominal-the better is

$$S/N = -10 \log (S^2) \quad ...(3)$$

Where

S^2 is variance and the Y is the value of response (quality characteristic)

Experimental procedure

This section discusses the use of Taguchi method for minimizing the surface roughness in TPIF process with four forming parameters, tool radius (r), feed rate (f), step over (Δz) and type of support (full and partial support) were analyzed on the basis of the mixed standard L18 (2*1 3*3) Taguchi orthogonal array as shown in Table (3) . This orthogonal array is chosen due to its capability to unequal levels of process parameter with the help of the commercial software package MINITAB 16 (statistical software) to collect and analyze the experiential result. Pyramid shape with 57° wall angle was used in Taguchi method. The quality characteristics for calculation of S/N ratio of surface roughness are taken as of lower-the-better type of the average surface roughness (Ra, μm) of machined specimens measured. Table (4) shows the results obtained for all experimental work.

Results and discussion

Analysis of means (57° wall angle).

The average values of the surface roughness (main effects) for each parameter at level L1, L2 and L3 are calculated and given in Table (4), respectively. The values have been plotted in Figure (6).

Figure. (6) (die effect) shows the variation of surface roughness with respect to the type of support that was used in experiment. The result shows that surface roughness is obtained when full die (L2) is used as support is higher. Also it is noted that surface roughness decrease with the use of partial die (L1). This is due to in the case that partial die uses the higher springback it found compared with full die, so the region of sheet that is located above the tool radius/ sheet contact goes backward to create another contact region with the tool because of springback and this phenomenon leads to increase the length of contact between sheet and tool, this leads to decrease the surface roughness. Because the contact length increases this leads to reduce the effect of height of scallops that was obtained during forming on surface.

From Figure.(6)(tool radius effect) it can be observed that the surface roughness decreases as tool radius increases. However, the lowest value of surface roughness can be obtained with third level (L3). From the results, it is noted that with increasing tool radius the length contact increases and this leads to decrease the surface roughness. The surface roughness of part depends on the tool radius and it is effect on Ra. Figure. (6)(Stepover Δz) shows the variation of surface roughness with respect to stepover (Δz). It can be noted that the best surface roughness is obtained when the smallest value is selected from the set parameter (L1) which gives the lowest value of Ra. Scallop height and surface finish are two measurements that are used for characterizing surface finish. When several scallops are created in a row the peaks and valleys occur in the surface. So the surface finish directly relates to the roughness of the surface. Scallop height is one of the most important factors that have effect on surface roughness and depend on the tool path stepover (Δz) and the tool radius.

Figure. (6)(feed rate) presents the effect of feed rate on surface roughness, as its indicated, when increasing the feed rate, Ra increases, so the feed rate have significant effect on process.

From Table (5) the result of rank represents the arrangement of parameters affecting the characteristic response. The ranks indicate the relative importance of each factor to the response. The stepover (rank1) is parameter that has large effect and is followed by tool radius (rank2), feed rate (rank3) and die (rank4) respectively.

Analysis of variance for means (ANOVA).

The purpose of ANOVA in this study is to determine the significant process parameters and to measure their effects on the surface roughness. ANOVA was performed using the mean as the response. The means for the levels of each control factor are computed and tabulated in Table. (6) to determine the relative significances of the different parameters. In ANOVA, the ratio between the variance of the process parameter and of the error called F test determines whether the parameter has a significant effect on the quality characteristic. This process is carried out by comparing the F test value of the parameter with the standard F table value (F0.05) at the 5 % significance level. If the F test value is greater than F0.05, the process parameter is considered significant or else it is considered non-significant [9].

From the ANOVA analysis of the means in Table (6), it is observed that step over plays significant role in determining the surface roughness. Furthermore, the type of die, tool radius, and feed rate is non-significant parameters according to analysis of means. Although the step over has only the significant effect on the surface roughness it is noted that other control factors have percentage contributions of effects on surface roughness.
Figure. (7) represents the percent of contributions of effects of control factors. It is noted from figures the stepover is a significant factor and has most effect on surface roughness with percentage contribution of (27.27%) and is followed by tool radius (17.77%), feed rate (13.74%) and type of die (11.2 %). There are other factors which affect surface roughness and are not considered in this study like type of lubricant and temperature effects.

Analysis of the signal-to-noise ratio

The factors that influence the response characteristic of any process can be classified into main groups: control factors that are controllable process variables and noise factors that are uncontrollable factors which cause significant variation in response characteristics [10]. Figure (8) presents plots of the S/N ratio for the four control parameters die, tool radius, stepover and feed rate, studied at their levels for the surface roughness. By using Eq (2) the smallest the better As is clearly seen, by using partial die the sensitivity of the system to noise factors increases.

Figure (8) shows that the S/N ratio is high when the partial die (L1) is used as compared with that for full die (L2). So from this result it is noted the partial die has a higher value of S/N ratio at this type of supporting and gives higher signal and less noise and this leads to an optimum result of these parameters.

Also the results show that the S/N ratio is high for tool radius that has third level (L3) and little noise, this leads to the surface roughness of part depends on the tool radius and it is effect on Ra. This due to with increases tool radius the length contact increase and this lead to decrease the surface roughness. The S/N ratio is a highest value for small level (level1) of stepover with high signal with less noise. Fig (8) (feed rate effect) presents the effect of feed rate of surface roughness. Results show that the surface roughness depends on the feed rate and it has effect on Ra which is important and when feed rate decreases a high signal with less noise result. A signal to noise ratio (SNR) analysis is conducted to find the optimal settings and factor levels.so, the level corresponding to higher S/N value is the optimum level for surface roughness. Further, from Figure (8) it can be seen that the optimal forming parameter performance for the mean (minimum) is obtained at partial die (Level 1), tool radius 7 mm (Level 3), stepover 0.3 mm (Level 1) and feed rate 600 mm/rev (Level1) settings.

In Table.(7) the result of rank represents the arrangement of parameters effect on characteristic response. The ranks indicate the relative importance of each factor to the response. The stepover (rank1) is parameter that has large effect and is followed by tool radius (rank2), feed rate (rank3) and die (rank4) and this agrees with that obtained when means is calculated as shown in Table (5).

Analysis of variance for S/N ratios (ANOVA).

In Table. (8) the results show that the stepover have significant effect. And the type of die, the tool radius and feed rate have non-significant influence on the surface roughness but have percentage contribution effect.

The percentage contributions of control factors have influence means and are represented in fig (9). It is evident from the figure that the stepover is a significant factor and has most effect on surface roughness with percentage contribution of (26.91%) and is followed by tool radius (14.3%), feed rate (14.17%) and type of die (14.3%).

Prediction and optimization of expected response

In the Taguchi method the optimization involves finding the factor level combination that gives the optimal response. So, Best factor level is selected and optimal performance level is predicted. The surface roughness value is “the smaller, the better,” so will find a set of factor level combinations that gives a minimum surface roughness. The main effect analysis in Figure (6) shows the level of each factor that gives the aim of the experiment. The aim of this test is to find the effects of process parameters on surface roughness and levels that reduces the surface roughness. The low level of factors is selected. The main effect of S/N ratio at different levels of parameter is shown in Figure (8). The ideal set of levels that give minimum surface roughness must have largest S/N ratio which reflection of the minimum variation in surface roughness would be the optimal response.

To find the best levels that give suitable characteristic response there are two ways. The first is the main effects of mean and other is the mean effect of S/N ratio. The required optimization criteria for surface roughness are the smallest value of mean effects and the largest value of S/N ratio. The graphs in Figure (6) and Figure (8) are used to determine the optimal set of levels for the experimental design that are used in Taguchi method. From figures the significant levels can be selected that give the optimal condition as shown below:

- The type of die at first level = partial.
- The tool radius at third level= 7 mm.
- The step over at first level = 0.3 mm.
- The feed rate at first level = 600 rpm.

The best value of surface roughness can be obtained by using the optimal levels that are selected based on Figures (6) and (8). The best mean response and S/N ratio in optimal condition can be predicted by using this equation [10,11]

$$\text{Mean (opt)} = \bar{A}_1+\bar{B}_3+\bar{C}_1+\bar{D}_1-(\text{number of factor} -1) *(\bar{T})$$

where $A_{1,}$ $B_{3,}$ $C_{1,}$ D_1 are mean response for level and T mean all response characteristic

Mean (opt) = Die $_{(1)}$ +Tool radius $_{(3)}$ +Step over $_{(1)}$ +feed rate $_{(1)}$ -3*T
= 0.64+0.6106+0.5917+0.6228- 3*(0.6811)
Mean (opt) = 0.421667 μm

Verification experiments

The verification experiments are performed by conducting tests with specific combination of the factors and levels previously evaluated. The purpose of the verification experiments is to validate accuracy of the predictive model. In this study, after determining the optimum conditions and predicting the response under these, a new experiment was prepared and achieved with the optimum levels that were selected of the TPIF process. So, finally the predicted experiment on improvement of the performance characteristic is verified. The results of experimental confirmation using optimal forming parameters are shown in table (9)

To verify the proposed model another set of experiment has been carried out as shown in Table (9) Prediction error in this table has been defined as follows [8]:

$$\text{Prediction error\%} = \frac{(\text{Predicted result} - \text{Exp result})}{\text{Exp result}} \times 100$$

From result it is noted that the surface roughness is greatly improved by using Taguchi approach and this method has a powerful technique that can be applied in TPIF process to determine the optimal levels of factors that are used in this study which has effect on the process by using few experiments to select better process control factor, cost reduction, robustness and predictable processes.

Conclusion:

1-A mixed standard L18 orthogonal array and analysis of means, signal-to-noise (S/N) and variance (ANOVA) were employed to analyze the effect of TPIF process parameters, by using Taguchi method for designing a robust experiment.

2-The result shows that surface roughness obtained when full die (L2) is used as support is higher than that of partial die (L1) and it is observed that the surface roughness decreases as tool radius increases. Also it is noted that the best surface roughness is obtained when selecting the largest value of tool radius and the smallest value of step over. Also when the feed rate increases, Ra increases, so the feed rate has significant effect on process.

3-The result of rank represents the arrangement of parameters affected on surface roughness. The stepover (rank1) is parameters that have large effect of (27.27%) percentage contribution and is followed by tool radius (rank2), feed rate (rank3) and die (rank4) and from the ANOVA analysis of the means; it is observed that step over only plays significant role in determining the surface roughness.

4-Taguchi approach was applied to find the optimum condition for quality characteristic by predicting the response. Verification experiments were performed to validate the accuracy of the predicted model; the results show that the predicted accuracy for the surface roughness and shape deviation are (1.2%) error.

Figure. (1). 3-Axis CNC milling machine used in experimental work. (1) CNC milling machine. (2) Machine controller. (3) Tool holder. (4) Forming frame. (5) Forming tool.

Figure. (2) Schematic representation of the experimental set up of TPIF process: the sheet metal blank, theblankholder, movable frame, post guide sliding bush and partial die

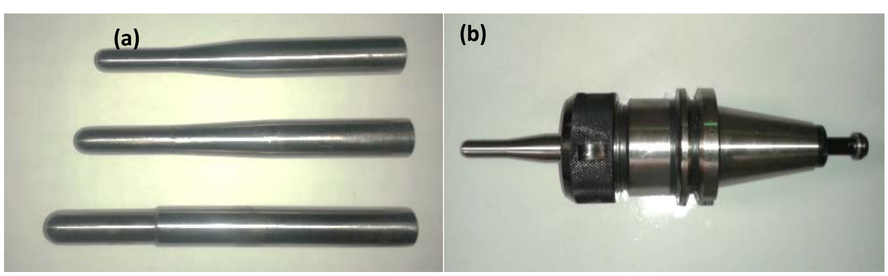

Figure. (3). (a) Tool geometry. (b) Forming tool clamped with tool holder.

Table. (1). The chemical composition of the aluminum sheet (% of mass).

Element	Al	Si	Fe	Cu	Mn	Mg	Ti	V	Zn
Com.	99.5	0.093	0.32	0.015	0.02	0.024	0.**011**	0.01	0.007

Table. (2). Mechanical Properties for Al-1050 Sheet.

material	Tensile strength (Mpa)	Yield strength (Mpa)	Elastic modulus (Gpa)	Poisson's Ratio	Density (kg/m3)	Total elongation (%)	Max elongation (mm)	Percent elong. at max load (%) (mm)
Al-1050	105	70	70	0.33	2700	4	1.89	1.5

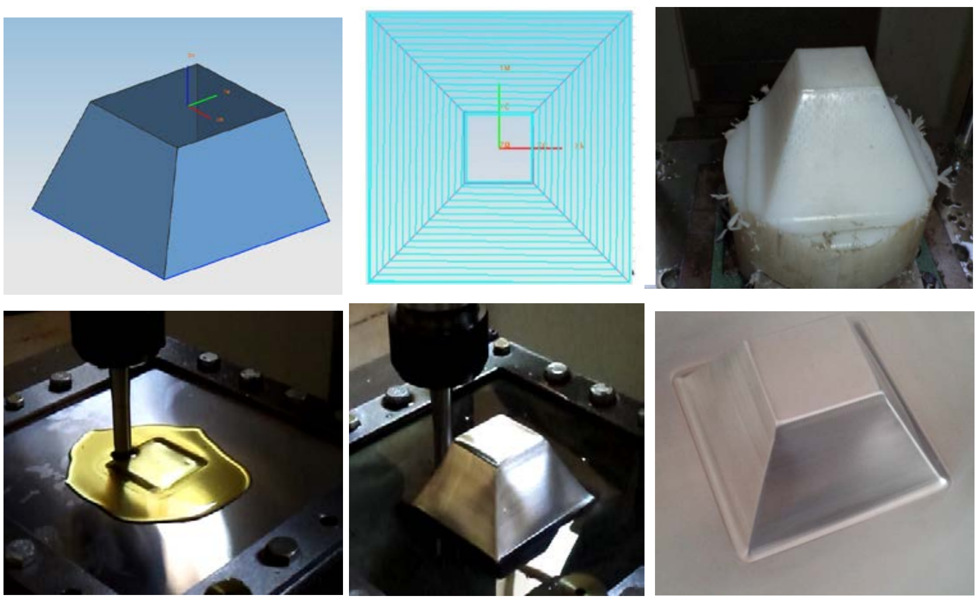

Figure. (4) (a) test geometry of pyramid shape. (b) square toolpath for pyramid shape. (c) full die support, (d) the experimental stages for incremental forming. (e) Formed shape.

factor	parameters	levels		
		L1	L2	L3
A	Tool radius (mm)	5	6	7
B	Step over (mm)	0.3	0.5	0.7
C	Feed rate(mm/mim)	600	800	1000
D	Die	Partial	Full	

Figure. (5) Surface roughness measurement.

Table. (3) Design factors and their levels for the present experimental work

Table (4) Experimental results, mean and the corresponding *S*/*N* ratios for surface roughness.

NO	Original value				Coded value				Surf.. Rough. mean (57°) (µm)	Surf. rough. S/N (57°) (dB)	Surf.. Rough. mean (66°) (µm)	Surf. rough. S/N (66°) (dB)
	Die.	Tool rad. (mm)	Step over. (mm)	Feed rate. (mm/ min)	A	B	C	D				
1	Partial	5	0.3	600	1	1	1	1	0.450	6.934	0.35	9.0880
2	Partial	5	0.5	800	1	1	2	2	0.883	1.056	0.5467	5.2374
3	Partial	5	0.7	1000	1	1	3	3	0.763	2.341	0.7067	3.0010
4	Partial	6	0.3	600	1	2	1	1	0.530	5.511	0.39	8.1088
5	Partial	6	0.5	800	1	2	2	2	0.823	1.686	0.4433	7.0413
6	Partial	6	0.7	1000	1	2	3	3	0.747	2.528	0.33	9.6190
7	Partial	7	0.3	800	1	3	1	2	0.507	5.891	0.41	7.7083
8	Partial	7	0.5	1000	1	3	2	3	0.570	4.849	0.3233	9.7922
9	Partial	7	0.7	600	1	3	3	1	0.487	6.250	0.3333	9.5389
10	Full	5	0.3	1000	2	1	1	3	0.770	2.261	0.54	5.3521
11	Full	5	0.5	600	2	1	2	1	0.773	2.229	0.3833	8.3042
12	Full	5	0.7	800	2	1	3	2	0.760	2.381	0.6367	3.9208
13	Full	6	0.3	800	2	2	1	2	0.677	3.391	0.3433	9.2750
14	Full	6	0.5	1000	2	2	2	3	0.653	3.694	0.36	8.8739
15	Full	6	0.7	600	2	2	3	1	0.767	2.306	0.4167	7.5903
16	Full	7	0.3	1000	2	3	1	3	0.617	4.191	0.56	5.0353
17	Full	7	0.5	600	2	3	2	1	0.730	2.731	0.36	8.8583
18	Full	7	0.7	800	2	3	3	2	0.753	2.460	0.4067	7.8041

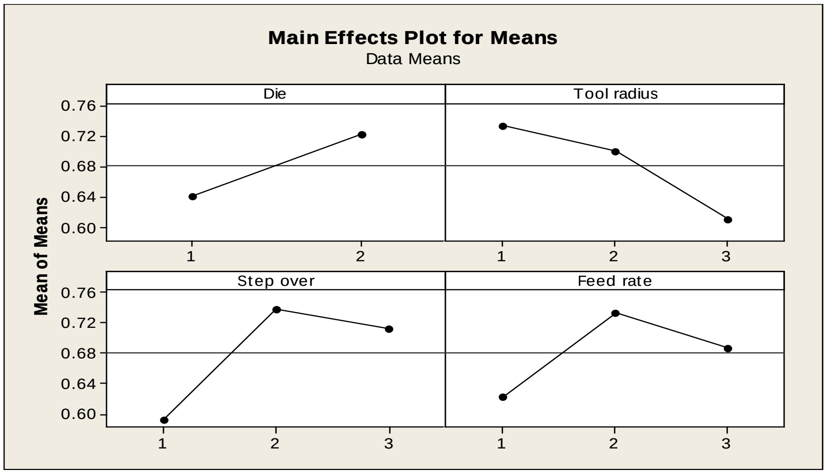

Figure.(6) Main effects plot of factor effects on surface roughness (57° wall angle).

Table. (5) Response table for means smaller is better (57° wall angle).

Level	Die	Tool radius	Stepover	Feed rate
1	0.6400	0.7333	0.5917	0.6228
2	0.7222	0.6994	0.7389	0.7339
3		0.6106	0.71278	0.6867
Delta	0.0822	0.1228	0.1472	0.1111
Rank	4	2	1	3

Table. (6) ANOVA for means analysis for surface roughness (57° wall angle).

Source	DF	Seq SS	Adj MS	F	P	Percentage contribution
Die	1	0.03042	0.030422	3.73	0.082	11.2%
Tool radius	2	0.04825	0.024124	2.96	0.098	17.77 %
Stepover	2	0.07405	0.037024	4.54	0.039*	27.27%
Feed rate	2	0.03731	0.018657	2.29	0.152	13.74%
Residual Error	10	0.08148	0.008148			30.0%
Total	17	0.27151				100%

*f (0.05, 1, 10) =4.96 and f (0.05, 2, 10) = 4.102

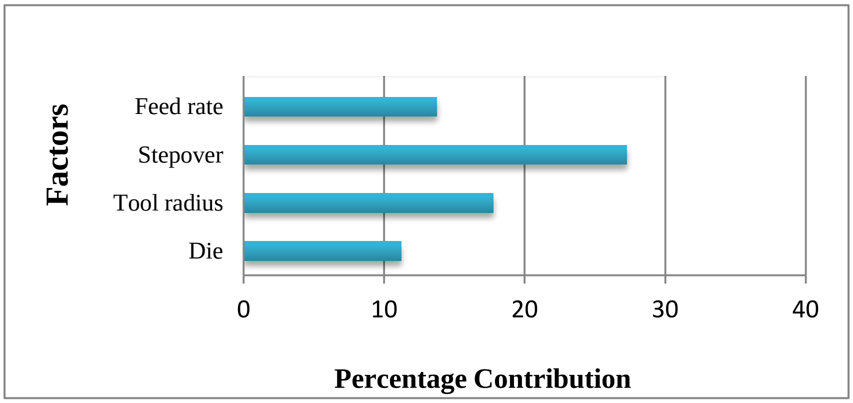

Figure. (7) Percentage contributions of means (57° wall angle).

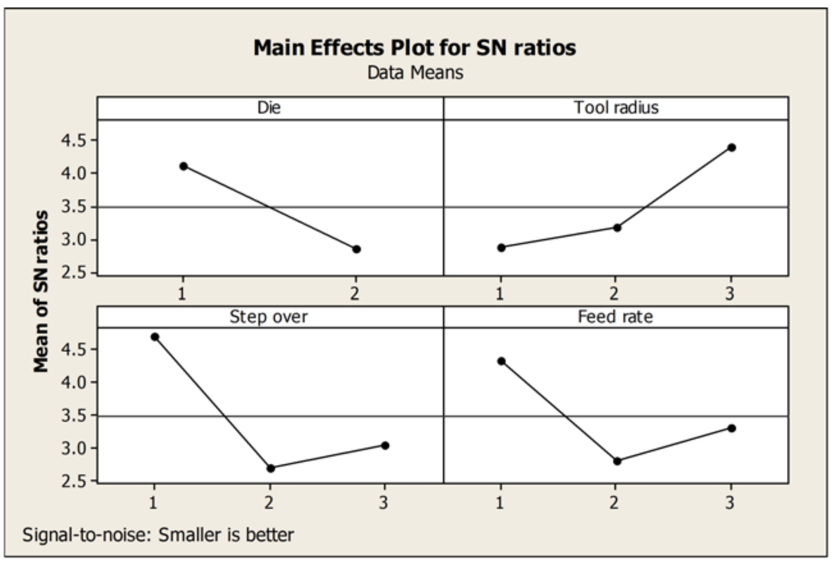

Figure. (8) Main effects plot for S/N ratios of factor effects on surface rough (57°wall angle).

Table. (7).Response table for Signal to Noise Ratios of smaller is better (57° wall angle).

Level	Die	Tool radius	Stepover	Feed rate
1	4.117	2.867	4.697	4.327
2	2.850	3.186	2.708	2.811
3		4.396	3.045	3.311
Delta	1.267	1.528	1.989	1.516
Rank	4	2	1	3

Figure. (8) Main effects plot for S/N ratios of factor effects on surface rough (57°wall angle).

Source	DF	Seq SS	Adj MS	F	P	Percent contribution
Die	1	7.224	7.224	4.90	0.051	14.3%
Tool radius	2	7.800	3.900	2.65	0.119	15.44%
Stepover	2	13.596	6.798	4.62 *	0.038	26.91%
Feed rate	2	7.162	3.581	2.43	0.138	14.17%
Residual Error	10	14.730	1.473			29.16%
Total	17	50.511				100%

*f (0.05, 1, 10) =4.96 and f (0.05, 2, 10) = 4.102

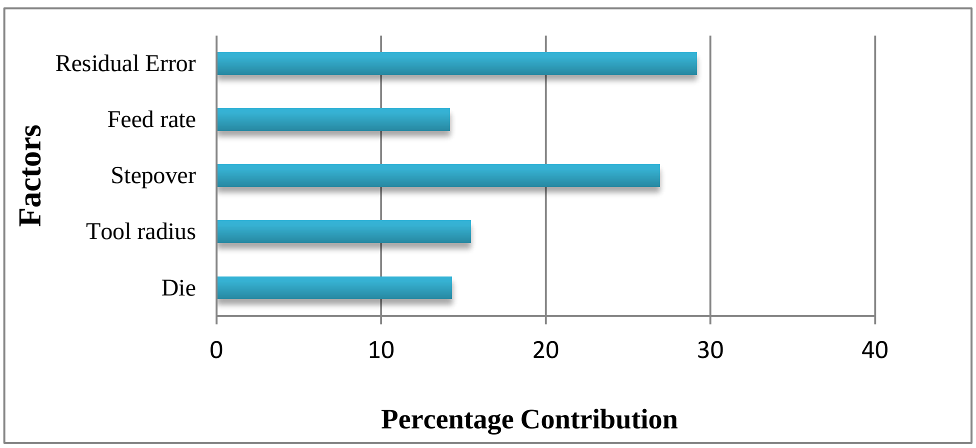

Figure. (9) Percentage contributions of S/N ratio (57° wall angle).

Table (9). Results of the experimental confirmation for optimization results.

Optimal forming parameters			
	Prediction	**Experiment**	**Error %**
Optimal Levels	$D_1T_3S_1F_1$	$D_1T_3S_1F_1$	
Mean µm	0.42167	0.4167	1.2

References:

[1].Y.H.Kim, J.J.Park “Effect of processes parameters on formability in incremental forming of sheet metal” Journal of Materials Processing Technology (2002) 130-131 42-46.

[2]. Jong-Jin Park, Yung-Ho Kim ”Fundamental studies on the incremental sheet metal forming technique” Journal of Materials Processing Technology 140 (2003) 447–453.

[3]. I. Cerro, E. Maidagan, J. Arana, A. Rivero, P.P. Rodr´ıguez “Theoretical and experimental analysis of the dieless incremental sheet forming process “ Journal of Materials Processing Technology 177 (2006) 404–408.

[4].M. Durante, A. Formisano, A. Langella, F. Memola Capece Minutolo ”The influence of tool rotation on an incremental forming process" Journal of Materials Processing Technology 209 (2009) 4621–4626.

[5]. K. Hamilton, J. Jeswiet” Single point incremental forming at high feed rates and rotational speeds: Surface and structural consequences” CIRP Annals - Manufacturing Technology 59 (2010) 311–314.

[6]. Şefika Kasman & I. Etem Saklakoglu ”Determination of process parameters in the laser micromilling application using Taguchi method: A case study for AISI H13 tool steel” Int J Adv Manuf Technol (2012) 58:201–209

[7]. Roy .R.K “A primer on taguchi method” Van Nostrand Reinhold, New York. 1990.

[8]. T. A. El-Taweel & M. H. El-Axir “Analysis and optimization of the ball burnishing process through the Taguchi technique“ Int J Adv Manuf Technol (2009) 41:301–310.

[9]. Kai Yang Basem S. El-Haik "Design for Six Sigma A Roadmap for Product Development" Second Edition 2009 McGraw-Hill.

[10]. M. J. Haddad , M. Tajik , A. Fadaei Tehrani, A. Mohammadi ,M. Hadi “An experimental investigation of cylindrical wire electrical discharge turning process using Taguchi approach” Int J Mater Form (2009) 2:167–179

[11]. Rohit Garg “Effect of process parameters on performance measures of wire electrical discharge machining“ Ph.D. ,mechanical engineering department National institute of technology, haryana, india 2010.