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An Experimental Study on the Effect of Process Parameters on Surface Roughness in Single Point Incremental Forming

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Abstract— **Incremental forming process has become more and more popular because of its ease of forming and capability to produce different part shapes using same machine setup. This paper describes an experimental study on the influence of process parameters in single point incremental forming (SPIF) on the surface roughness of formed part. Experiments are performed on cold rolled steel sheets (DC04) on a 3-axis CNC milling machine. Hemispherical headed tool of high speed steel material is used to study the effect of tool diameter, pitch, feed rate and spindle speed on the surface roughness (R_a) of formed part. Design of experiment full factorial plan is used for experimentation and results are plotted using ANOVA. Based on the experimental results, the equation (model) for R_a is developed using regression analysis. This model can be used to predict surface roughness of part to be formed. Considerable effect of tool diameter and pitch is found on the surface quality of formed part.**

Keywords—*Single point incremental forming (SPIF), surface roughness, ANOVA.*

I. Introduction

Sheet metal parts are important structural members of car bodies, aircraft, beverage cans, home appliances, telecommunication equipment and medical implants. These parts are generally manufactured on press tools. A press tool consists of a punch and a matching female die. The cost of designing and manufacturing of press tools is high and it is only economical for producing large number of parts. Therefore, there is a need to find an alternate of press tools which must be flexible and cost effective for producing small number of sheet metal parts. Incremental sheet forming (ISF) is an emerging sheet metal forming and rapid prototyping technology. This process offers flexibility in the part forming and has shorter setup time as well as lower production cost. Therefore, this process can be used for batch production. Also, forming forces involved in ISF are very small as compared to conventional sheet metal forming because of localized deformation of sheet. The ISF setup is simple and does not need costly dies. It requires 3-axis CNC or conventional milling machine or water jet machine to produce complex sheet metal parts without using conventional press tools [1]. The machine spindle holds a hemispherical- headed forming tool and a fixture holds the blank. For ISF part geometry can be modeled in software platforms like CATIA, UG/NX etc. and using the part geometry tool path of CNC machine can be easily generated. The plastic deformation is accomplished layer-by-layer through the movement of simple CNC controlled forming tool. On completion of each layer, the tool moves down a small increment along the z-axis and continues to process the subsequent layers until all layers are formed. It is also called as die-less NC forming process as it does not use a dedicated die.

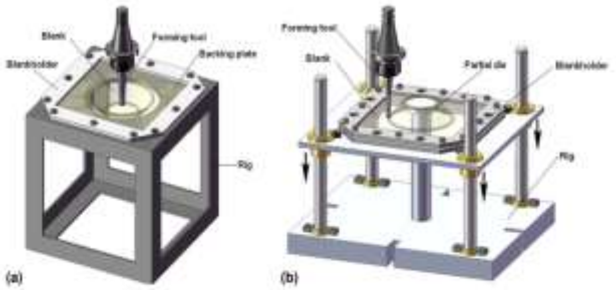

Figure 1. (a) Single point incremental forming, (b) Two point incremental forming [2]

ISF process has two major variants – (i) Single point incremental forming (SPIF), and (ii) Two point incremental forming (TPIF) as shown in Fig. 1 [2]. In SPIF process, the sheet is held on the fixture and a hemispherical tool forms the sheet. The sheet is free to move in working area. In TPIF process, a counter tool (also called as secondary tool) or a partial die or a full die is used. Therefore, the sheet has some constraints for movement in working area. The ISF process was developed as a method for prototyping and forming of sheet metal parts in small batches for the needs of automobile manufacturers [3], but nowadays, it is also being used by many other industries such as aeronautical industry, medical applications [4] etc. Metal as well as polymer sheets can be formed using ISF. Marques et al. [5] performed experiments on four different commercial thermoplastic materials and successfully formed conical parts using SPIF process. A variety of asymmetric complex shapes were made as rapid prototypes for the automotive industry. ISF has also found numerous applications in aerospace industries, biomedical applications and appliances (e.g. solar cooker). A distinct application of SPIF process is demonstrated by Jackson et al. [6] for forming of sandwich panels. Vihtonen et al. [7] investigated the effect of SPIF and TPIF and found that more thinning (i.e. decrease in thickness of formed sheet material) takes place in case of SPIF. Some researchers [8-10] investigated the enhanced formability and geometrical accuracy of formed parts.

In the present work an experiments are performed to study the influence of process parameters in SPIF on the surface roughness of formed part of cold rolled steel sheet (DC04).

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II. Experimental Setup

CNC Machine: SPIF process can be performed on any machine with numeric control or using numerically controlled robot arm. This significantly reduces the tooling cost of process and makes the process more flexible and easy to use. The same tooling setup can be used to form different part geometries. CNC machine setup used for the present experimental work is a 3-axis vertical milling machine as shown in Fig. 2.

Figure 2. CNC machine with experimental setup

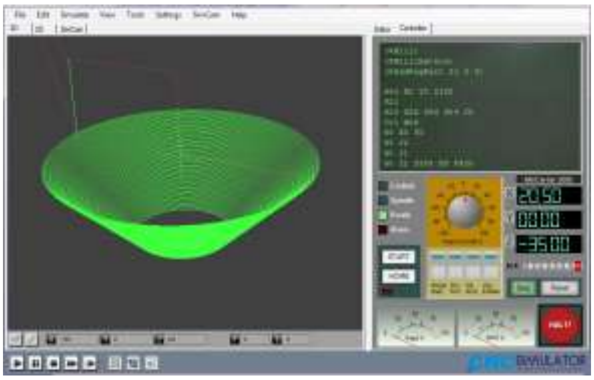


Figure 3. Tool Path simulation using CNC Simulator Pro

Forming tool and blank sheet: In the present work, forming tool of high speed steel is used. The end of the tool is hemispherical in shape. Two different tools having diameters 8 mm and 12 mm are used. The reason behind using these two tools is to find out the effect of tool diameters on surface quality and thickness variation on the part formed by these tools. Most of researchers have focused on a small set of materials, namely, aluminum [11], thermoplastic materials [12], magnesium AZ31 [13], and titanium [14]. For the present work cold rolled annealed steel sheet (DC04) of 0.5 mm thickness is used. This material is most widely used to produce the automotive body parts and panel, and home appliances.

Tool path: profile tool path is used in the present experimental work. Tool path is generated using C–program. This can also be generated using commercial software like CATIA, MASTERCAM, UG/NX, DELCAM etc. For the ease of generating CNC code/tool path, a C – program is written which produces a CNC tool path. Tool path generated using this program is then simulated using CNC tool path simulation software CNC Simulator Pro Version 1.0.6.6 Beta as shown in Fig. 3.

Figure 4. Formed conical part using SPIF

Fixture: Fixture used for holding the blank in present work consists of a frame made up of two C-shaped plates welded together. The lubricant used in present work is Castrol gear oil. Part formed by SPIF is depicted in Fig. 4.

For the plan of experiment, four process parameters namely tool diameter (d), pitch (P), feed rate (f) and spindle speed (s) are used. Full factorial design of experiment (DOE) plan is selected for experimentation. The high and low values of the process parameters are given in the table I. Other parameters like forming angle also called as wall inclination angle, maximum forming depth, and tool path etc. are kept constant. Table II lists constant process parameters and their values.

TABLE I. PROCESS PARAMETERS AND THEIR LEVELS

Parameters	**Level**	
	Low level (1)	**High level (2)**
Tool diameter (mm)	8	12
pitch (mm)	0.2	0.5
Feed rate (mm/min)	700	1300
Spindle speed (rpm)	1000	2000

TABLE II. CONSTANT PROCESS PARAMETERS AND THEIR VALUES

Parameters	**Units**	**Value**
Forming angle	Degrees	45
Maximum forming depth	mm	30
Tool path	-	Profile tool path

III. Results and Discussion

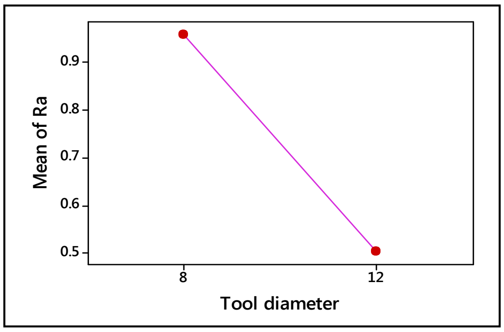
Full factorial DOE plan is selected for the experimentation. Four factors, each with two levels are selected for the experiment, which results in sixteen experiments. Parts are successfully formed using SPIF process without a single fracture. The formed parts are cut into rectangular strips for easy measurement of surface roughness. Before measuring the surface roughness, the strip is cleaned properly so as to remove any lubricating oil present on the surface which is used during experimentation. Three readings are recorded on each sample i.e. top, middle and bottom. Average of these three values (R_a Avg.) is used for further analysis. Table III shows the design matrix for surface roughness in the standard run order. Experiments are performed according to the standard run order.

TABLE III. DESIGN MATRIX FOR SURFACE ROUGHNESS

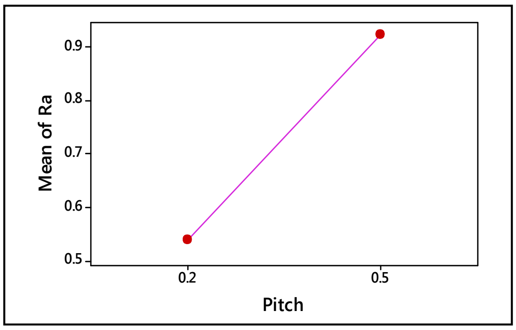
Run No.	Tool dia.(d)	Pitch (p)	Feed rate(f)	Spindle speed (s)	R_a AVG. (µm)
1	8	0.2	700	1000	0.6533
2	12	0.2	700	1000	0.3193
3	8	0.5	700	1000	1.1546
4	12	0.5	700	1000	0.6866
5	8	0.2	1300	1000	0.7523
6	12	0.2	1300	1000	0.3856
7	8	0.5	1300	1000	1.1110
8	12	0.5	1300	1000	0.6523
9	8	0.2	700	2000	0.9026
10	12	0.2	700	2000	0.3240
11	8	0.5	700	2000	1.1643
12	12	0.5	700	2000	0.6970
13	8	0.2	1300	2000	0.6723
14	12	0.2	1300	2000	0.2920
15	8	0.5	1300	2000	1.2550
16	12	0.5	1300	2000	0.6610

ANOVA is performed to find out the significant variables and to quantify their effect on response characteristics. Main effects plot and their interaction plots are used to examine the parametric effect of listed process parameters on response characteristics. All the results are analyzed using Minitab 17.0 statistical software. A cone with major diameter of 150 mm, depth of 30 mm, and wall inclination angle of 45^0 is formed. The surface roughness is measured using surface roughness measurement stylus. The surface roughness obtained is in the range of 0.292 µm to 1.255 µm. This analysis is carried out at confidence level of 95%.

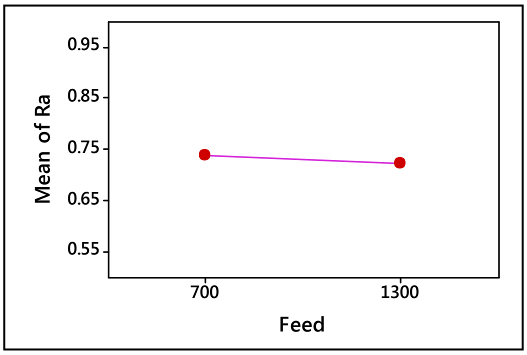
The effect of tool diameter on the surface roughness is shown in the Fig. 5 (a). From the main effects plot, it is observed that as tool diameter decreases, surface roughness increases and vice versa. It happens because when using the smaller tool diameter, tool penetrates easily into the sheet and some pieces of chip are spited out. Thus leaving behind the small peak and valleys and surface becomes rough. Hence to obtain the smooth surface with minimum peak and valleys, larger tool diameter should be used.



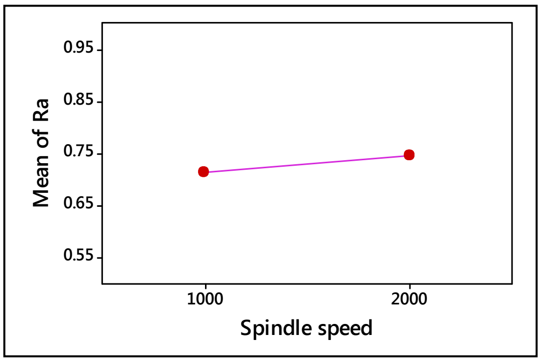
(a) Main effects plot R_a V/s d



(b) Main effects plot R_a V/s P



(c) Main effects plot R_a V/s f



(d) Main effects plot R_a V/s s

Figure 5. Main effects plot - effect of process parameter on surface roughness

While using smaller diameter tool, smaller pitch value should be used in order to obtain good surface. From the investigation it is found that, as pitch (depth of penetration) increases from 0.2 to 0.5 surface roughness increases as shown in Fig. 5 (b). It happens because when pitch is decreases, the numbers of forming cycles are increased.

Repeated contact of the forming tool results in the improved surface quality of the formed part.

From Fig. 5 (c) and 5 (d) it is observed that there is negligible effect of feed rate and spindle speed on surface quality in terms of surface roughness. At any range of feed rate and spindle speed surface roughness found to be almost constant. It happens because in incremental forming, local deformation of sheet metal takes place, which is not dependent on spindle speed or feed rate. Increasing spindle speed and feed rate will result in generation of heat at tool – sheet contact zone. The generated heat will increase the formability of sheet metal. Also higher feed rate reduces the forming time considerably without affecting the surface quality of formed part.

A. *Design of Regression Model*

Regression analysis is a statistical forecasting model that is concerned with describing and evaluating the relationship between a given variable called the dependent variable and one or more other variables usually called the independent variables. In the present work, independent variables (factors) considered are tool diameter, pitch, feed and spindle speed and measured response variable (dependent variable) is surface roughness. Minitab software is used to generate various regression models.

For present investigation four independent variables are used hence it is multiple linear regressions analysis. Table IV is ANOVA table for regression. This table shows the p-value for regression model and four dependent variables - tool diameter, pitch, feed and spindle speed. Given ANOVA analysis for regression is carried out at 95% confidence level. Hence if p-value obtained for given parameter is less than 0.05 then it is assumed that given parameter is significant.

From table IV, it is observes that p-value for constant, coefficient of tool diameter and coefficient pitch is less than 0.001. Hence all the coefficients are highly significant and these coefficients pass the test for p. Whereas p-value for coefficient of feed and spindle speed is greater than 0.05, hence these parameters are insignificant.

TABLE IV. ANOVA TABLE FOR REGRESSION ANALYSIS

Source	SS	DF	MS	F Value	P value	Remarks
Regression	1.42953	4	0.357381	68.47	0.000	significant
Tool diameter	0.83159	1	0.831592	159.32	0.000	significant
Pitch	0.59303	1	0.593029	113.62	0.000	significant
Feed	0.00091	1	0.000905	0.17	0.685	
Spindle speed	0.00400	1	0.004001	0.77	0.400	
Error	0.05741	11	0.005220			
Total	1.48694	15				

Standard Deviation	R^2	R^2_{Adj}
0.0722464	96.14%	94.73%

Where,

SS – Sum of squares

DF – Degrees of freedom

MS – Mean Square

Table V lists the coefficients of regression model for surface roughness. It is observed that the coefficient of feed and spindle speed is very small. Hence these parameters are insignificant as compared to tool diameter and pitch.

TABLE V. COEFFICIENTS OF REGRESSION MODEL FOR SURFACE ROUGHNESS

Predictor	Coeff.	SE Coeff.	T-Value	P-Value
Constant	1.399	0.130	10.78	0.000
Tool diameter	-0.11399	0.00903	-12.62	0.000
Pitch	1.283	0.120	10.66	0.000
Feed	-0.000025	0.000060	-0.42	0.685
Spindle speed	0.000032	0.000036	0.88	0.400

Predictive model for the data using regression techniques is given by (1):

$$R_a = 1.399 - 0.11399 \times \text{Tool diameter} + 1.283 \times \text{Pitch} - 0.000025 \times \text{Feed} + 0.000032 \times \text{Speed} \qquad (1)$$

From the ANOVA table for regression and coefficients of regression model for surface roughness table, it is observed that feed and spindle speeds are the insignificant parameters which unnecessarily increasing the value of R^2 and decreasing R^2 adjusted. Therefore these parameters should be removed. Table VI depicts the analysis of variation of regression after removing the insignificant terms.

TABLE VI. ANOVA TABLE FOR REGRESSION AFTER REMOVING INSIGNIFICANT PARAMETERS

Source	SS	DF	MS	F Value	P value	Remarks
Regression	1.42462	2	0.712310	148.59	0.000	significant
Tool diameter	0.83159	1	0.831592	173.47	0.000	significant
Pitch	0.59303	1	0.593029	123.71	0.000	significant
Error	0.06232	13	0.004794			
Total	1.48694	15				

Standard Deviation	R^2	R^2_{Adj}
0.0692379	95.81%	95.16%

All the coefficients' value is less than selected p-value, hence coefficients of tool diameter and pitch are significant, constant term is also significant. Table VII shows the coefficients of regression model after removing insignificant parameters. Thus, the fitted equation for the data using regression techniques is given by (2),

TABLE VII. COEFFICIENTS OF REGRESSION MODEL AFTER REMOVING INSIGNIFICANT PARAMETERS

Predictor	Coef	SE Coef	T-Value	P-Value
Constant	1.4209	0.0971	14.64	0.000
Tool diameter	-0.1139	0.0086	-13.17	0.000
Pitch	1.2830	0.1150	11.12	0.000

$$R_a = 1.4209 - 0.11399 \times \text{Tool diameter} + 1.28 \times \text{Pitch} \quad (2)$$

TABLE VIII. COMPARISON BETWEEN ACTUAL AND PREDICTED SURFACE ROUGHNESS

Exp. No	Experimental Surface Roughness	Predicted surface roughness	% Error
1	0.653333	0.76558	17.18
2	0.319333	0.30962	3.04
3	1.154667	1.15048	0.36
4	0.686667	0.69452	1.14
5	0.752333	0.76558	1.76
6	0.385667	0.30962	11.71
7	1.111000	1.15048	3.55
8	0.652333	0.69452	6.40
9	0.902667	0.76558	10.18
10	0.324000	0.30962	4.43
11	1.164333	1.15048	1.18
12	0.697000	0.69452	0.35
13	0.672333	0.76558	9.86
14	0.292000	0.30962	6.03
15	1.255000	1.15048	8.32
16	0.661000	0.69452	5.07

Table VIII gives comparison between actual (experiment) and predicted surface roughness using developed regression model. To measure the accuracy for regression model, percentage error is calculated using (3),

$$\% \text{ Error} = 100\text{x}\{[R_a(\text{exp.}) - R_a(\text{pr.})]/ R_a(\text{exp.}) \} \quad (3)$$

Where, R_a(exp.) – Avg. surface roughness of formed part

R_a(pr.) – Avg. surface roughness predicted by model

From table VIII it is observed that, the predictive model developed using the regression analysis is in good agreement with the experimental results. There is a maximum 17% and minimum 0.35% prediction error in the surface roughness value. Therefore, this model is useful for prediction of surface roughness of part to be formed using SPIF for the given set of process parameters.

IV. Conclusion

The present experimental study is focused on studying the effect of various process parameters on the surface roughness of formed parts using SPIF. Four process parameters namely tool diameter, pitch, feed rate and spindle speed are selected for experimentation. It is found that tool diameter and pitch have major effect on the surface quality. To obtain better surface quality, large tool diameter and low pitch should be used. It is also observed that feed rate and spindle speed have very little effect on surface quality of formed part. Therefore higher feed rate can be used while forming parts using SPIF process without affecting surfae quality. This will lead to rduced forming time.

From the experimental results, it is observed that SPIF can form parts with considerable accuracy and desired surface quality. This study can be extended to optimize parameters affecting the part accuracy and surface quality. The present experimental study is also required to find the effet of listed process parameters on different sheet materials. Mathematical correlations should be built in order to predict the surface quality for different materials.

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