International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 04 Issue: 07 | July -2017 www.irjet.net p-ISSN: 2395-0072

COMPUTER AIDED MANUFACTURING FACTORS AFFECTING REDUCTION OF SURFACE ROUGHNESS AND THICKNESS IN INCREMENTAL SHEET FORMING PROCESS

Deepak[1], Sanjeet Singh [2]

[1]*M. Tech. Research scholar, Department of Mechanical Engineering, CBS Group of Institutions, Fatehpuri, Jhajjar, Haryana, India (124103)*
[2] *Assistant Professor, Department of Mechanical Engineering, CBS Group of Institutions, Fatehpuri, Jhajjar, Haryana, India (124103)*

---***---

Abstract - *Incremental sheet forming (ISF) has established its great potential to form complex three-dimensional parts without using a matching die. The process locally deforms sheet metal using a moving tool head attaining higher forming limits than those of conventional sheet metal stamping process. The die-less nature in incremental forming provides a viable substitute for economical and effective fabricating low-volume functional sheet products. Various application areas include aerospace engineering, customized products in biomedical engineering and prototyping in the automotive engineering. This paper presents a review on experimental investigation of ISF process factors or parameters like feed rate, speed, tool diameter, sheet thickness, lubrication, step size and tool path affecting surface roughness and thickness reduction.*

***Key Words*: Incremental sheet forming (ISF), single point incremental sheet forming, roughness, thickness reduction, tool path.**

1. INTRODUCTION

Incremental Sheet Forming (ISF) process is sustainable in small scale production to deal with the various needs like customization, low tooling cost and setup time. The conventional forming processes already used in the industry (like deep drawing, stamping) need high investment cost and long die-preparation times for small scale production [1]. Therefore, ISF is a process which is, now a days, available for small batch production or prototyping as it deals with the issues in the conventional forming process.

ISF is a forming technique of sheet metal process based on layered manufacturing principle. The sheet part is locally deformed through horizontal slices. The moving locus of forming tool (tool path) in these slices is performed by the CNC milling machine. The tool path is generated directly from CAD model of final product by using CAM system.
Surface roughness is reduced to increase the surface quality of parts (e.g. reflexive surfaces for headlights) and to reduce friction between mating parts like production dies and mould surfaces etc. Thickness reduction defines both Geometrical accuracy as well as the strength of the forming parts. Uniform thickness distribution leads to better geometrical accuracy and better strength.

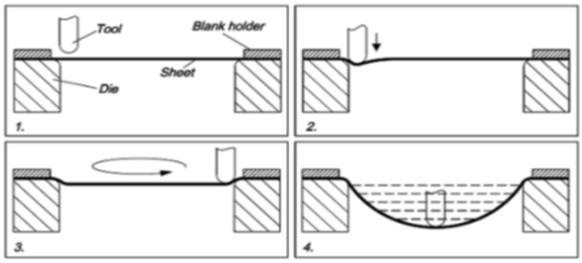

Fig -1: Principle of Incremental Sheet Forming [1]

1.1 Classification of Incremental Sheet Forming

The ISF can be classified as

- Single Point Incremental Forming (SPIF)
- Two Point Incremental Forming (TPIF)

1.1.1 Single Point Incremental Forming (SPIF)

In SPIF type of incremental forming, the blank is clamped along its edges and the tool (generally a spherical tool) moves along the sheet surface, as shown in fig - 2. Hence no die is used and even asymmetrical parts can be easily formed. This method can be executed using a conventional CNC milling machine, including a CAD/CAM system to produce the tool path [2].

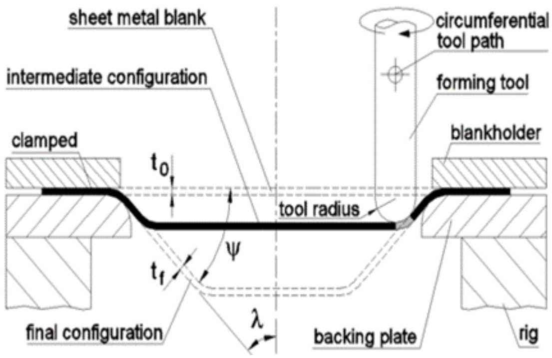

Fig -2: Single Point Incremental Sheet Forming [2]

1.1.2 Two Points Incremental Forming:

In Two Point Incremental Forming (TPIF) the blank is clamped in the blank holder which can be adjusted in the Z axis. The forming tool is similar to the tool in SPIF and performs a trajectory of the outer surface of the part, from top to bottom of the geometry. In TPIF a die is used below the blank & die has the same function as the supporting plate only and increase the geometry accuracy.

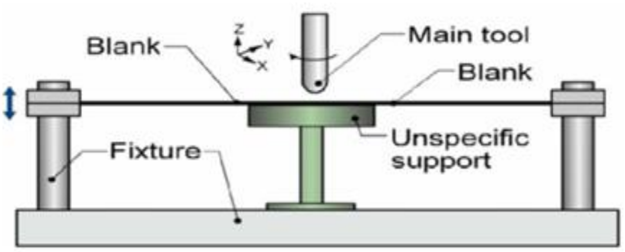

Fig -3: Two Point Incremental Sheet Forming [3]

1.2 CAM factors / process parameters used for Incremental Sheet Forming are :

(i) *Tool diameter* *(ii) Step size* *(iii) Feed rate (iv) Speed (v) Sheet Thickness (vi) Lubrication (vii) Tool path*

In ISF the process parameters (like speed, feed rate, incremental step size, lubrication, tool diameter, sheet thickness, material, and tool path) are affecting the surface roughness, and thickness reduction as described below from the previous study:

Surface roughness:

Factors have greatly influenced the surface quality in incremental sheet forming. J. Kopac, Z. Kampus (2005) [6] presented the processes controlled by CNC milling machine tool with CAD/CAM. Surface roughness of aluminum sheet is lower that steel because steel is highly deformable and subjected at minimum hardening. I. Cerro, E. Maidagan (2006) [7] stated that roughness is lower in the tool advancing direction than in perpendicular one. Roughness can be decrease by decreasing axial step size.

Thickness reduction:

Factors mainly affecting thickness reduction are sheet thickness, step size and feed rate. Ambrogio et al. (2005) [5] and Young and Jeswiet (2004) [4] found that wall thickness initially greater than the sine low thickness then reduces to less than the sine low thickness across the formed region of copper plates. This suggests that thinning beyond the sine low prediction as a result of material being pushed towards the center of geometry.

2. EXPERIMENTAL SETUP

2.1 CNC Machine: All the experiments were performed at CTR (central tool room) Ludhiana, Punjab. Where precise machines are available and CNC Milling Machine is readily available. CNC Vertical Milling Machine (VMC2216XV) used for the experimentation purpose of ISF As shown in Fig -4(a)

Fig -4(a): Overview of CNC milling machine (VMC) and **Fig -4(b):** Stainless steel tool of diameter 20 mm

2.2 Forming Tool: Forming tool used are basically are made of hardened stainless steel. Tool diameter is 16mm, 18mm and 20mm. Tool with tool holder shown in fig -4(b).

2.3 Fixture and Clamping system for SPIF: Single point incremental sheet forming performed on hollow fixture as shown in figure. A static frame is composed with using clamping devices. Assembly drawing for the SPIF clamping system and its overview is shown in the fig - 5. A blank holder is fixed with fixture using bolts, to holds the sheet over the blank. Total working area of the machine is 240 x 240 mm2 in this process

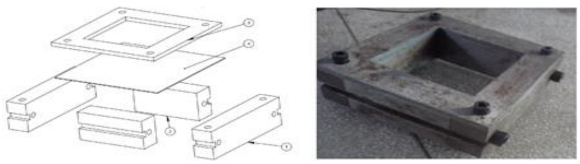

Fig -5 Assembly drawing for the SPIF Clamping System

2.4 Material used: Aluminium grade Al-2014 is used for forming process with three different thicknesses 1.2, 2 and 2.3 mm. Specification of material is described in table 1

Table 1 Material Specification:

Aluminum	Balance
Chromium	0.1 max
Copper	3.9-5
Iron	0.7 max
Magnesium	0.2-0.8
Manganese	0.4-1.2
Silicon	0.5-1.2
Titanium	0.15 max
Titanium + Zinc	0.2 max
Zinc	0.25 max

2.5 Dynamometer: It is used for measuring the force during the forming process. A load cell up to 1000 kg is used for measuring the force applied by the tool on sheet during forming. Dynamometer is directly connected with fixture which holds the sheet as shown in Fig -6.

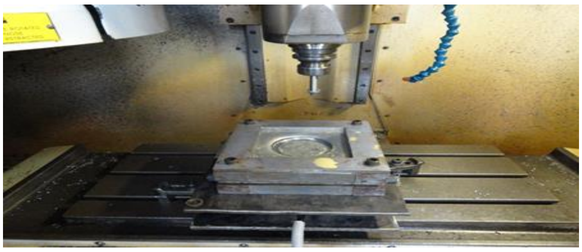

Fig – 6: Overview of Dynamometer

2.6 Lubricants: In this work, coolant, oil and grease are used as lubricants. WD-40 is used as oil and water- iscible fluid including soluble oil is used as coolant. Lubrication system used during ISF shown in fig - 7.

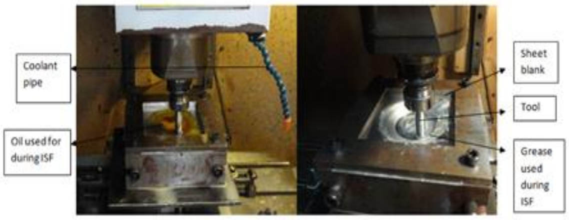

Fig -7: Lubrication system used during ISF

2.7 Actual experiment:

Actual experiments were conducted by varying all the process parameters using orthogonal array to study their effects on forming results. The forming results are surface roughness, thickness reduction and force based failure. All the responses are measured using different instruments. The formed parts of actual experiments are shown in Fig-8

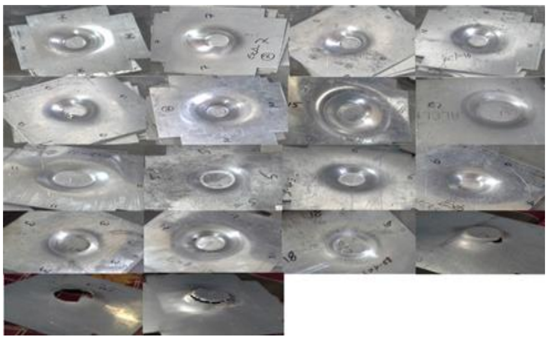

Fig -8: Picture representation of all eighteen experiments

2.8 Instrument Used:

Surface Roughness Tester: Instrument used in this work for measurement of surface Roughness is itutoyoSurftest SJ-201P as shown in fig-9 The surftest SJ-201P (mitutoyo) is a shop–floor type surface-roughness measuring instrument, which traces the surface various machine parts and calculates the surface roughness based on roughness standards, and displays the results.

Fig -9 MitutoyoSurftest SJ-201P (Surface Roughness Tester)

The work piece is attached to the detector unit of the SJ-201P will trace the minute irregularities of the work piece surface. The vertical stylus displacement during the trace is processed of the SJ-201P as shown in figure 10

Fig 10: SJ-201P surface roughness testing of formed part

3. Experimental Design Strategy

In this work, Taguchi method is used to select number of experiments and to investigate the effects of process parameters on the responses like surface roughness, thickness reduction and forming force. Seven parameters viz. tool path, tool diameter, sheet thickness, step size, spindle speed, feed rate and lubrication are considered and represented at different levels.

In the Taguchi method, the results of the experiments are analyzed to achieve one or more of the following objectives:

•To estimate the best or the optimum condition for a product or process.
•To estimate the contribution of individual parameters and interactions.
•To estimate the response under the optimum condition.
The optimum condition is identified by studying the main effects of each of the parameters. The analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiments in determining the percent contribution of each parameter against a stated level of confidence.

4. RESULT AND DISCUSSION

4.1 Experimental Results:

Experiments of SPIF were performed on the basis of selected orthogonal arrays (L18) for studying the effect of parameters whose values are assigned in table 2. In the present work all the experimental results are obtained using Minitab 17 Statistical software.

Table 2: Taguchi L18 Orthogonal Arrays with response mean and S/N ratio

Trial No.	Tool path	Tool Diameter (mm)	Sheet thickness (mm)	Step Size (mm)	Spindle Speed (rpm)	Feed Rate (mm/min)	Lubrication	Response (Raw data)		S/N Ratio
								R_1	R_2	S/N(1)
1.	1	1	1	1	1	1	1	-	-	-
2.	1	1	2	2	2	2	2	-	-	-
3.	1	1	3	3	3	3	3	-	-	-
4.	1	2	1	1	2	2	3	-	-	-
5.	1	2	2	2	3	3	1	-	-	-
6.	1	2	3	3	1	1	2	-	-	-
7.	1	3	1	2	1	3	2	-	-	-
8.	1	3	2	3	2	1	3	-	-	-
9.	2	3	3	1	3	2	1	-	-	-
10	2	1	1	3	3	2	2	-	-	-
11	2	1	2	1	1	3	3	-	-	-
12	2	1	3	2	2	1	1	-	-	-
13	2	2	1	2	3	1	3	-	-	-
14	2	2	2	3	1	2	1	-	-	-
15	2	2	3	1	2	3	2	-	-	-
16	2	3	1	3	2	3	1	-	-	-
17	2	3	2	1	3	1	2	-	-	-
18	2	3	3	2	1	2	3	-	-	-

R1 and R2 are repeated values of response. Where 1, 2 and 3 represent the values of 1st, 2nd and 3rd level for each factor respectively.

4.2 Analysis and discussion of result:

All the SPIF experiments are conducted using the parametric approach of Taguchi method to measure the effects of individual process parameters on the response. The mean and S/N ratio data for different level are calculated from experimental results and then the effects of process parameters for both mean and S/N ratio data are plotted. The response curves are used for examine the effect of parameters on the response characteristics. The analysis of variance (ANOVA) of mean and S/N ratio data is used to categorize the significant variable and to measure their effects on the response characteristics. The optimum value of process variables in terms of mean are established by analysing response curve and ANOVA table.

4.2.1 Effect on Surface Roughness:

The effects of process parameters on Surface roughness of formed part is calculated by using mean and S/N ratio of each row where Surface roughness for each level of experiment is established in orthogonal array. Orthogonal array with mean and S/N ratio data is shown in table 3.

Table 3 Orthogonal array for result of Surface roughness with mean & S/N ratio data

Trial No.	ool ath	Tool Diameter (mm)	Sheet thickness (mm)	Step Size (mm)	Spindle Speed (rpm)	Feed Rate (mm/min)	Lubri-cation	Surface Roughness (µm)		Mean	S/N Ratio
								R_1	R_2	M_1	S/N(1)
1.	piral	16	1.2	0.3	0	1500	Coolant	1.395	1.59	1.4925	-3.49678
2.	piral	16	2	0.5	1000	2000	Oil	0.9	0.82	0.86	1.300646
3.	piral	16	2.3	0.75	2000	3000	Grease	1.39	1.4	1.395	-2.89154
4.	piral	18	1.2	0.3	1000	2000	Grease	0.64	0.73	0.685	3.267486
5.	piral	18	2	0.5	2000	3000	Coolant	1.26	1.26	1.26	-2.00741
6.	piral	18	2.3	0.75	0	1500	Oil	1.26	1.29	1.275	-2.1108
7.	piral	20	1.2	0.5	0	3000	Oil	1.08	1.17	1.125	-1.02999
8.	piral	20	2	0.75	1000	1500	Grease	1.16	1.18	1.17	-1.36403
9.	piral	20	2.3	0.3	2000	2000	Coolant	1.22	1.16	1.19	-1.5137
10	Helica	16	1.2	0.75	2000	2000	Oil	0.94	0.96	0.95	0.445047
11	Helica	16	2	0.3	0	3000	Grease	1.13	1.21	1.17	-1.36879
12	Helica	16	2.3	0.5	1000	1500	Coolant	1.06	1.05	1.055	-0.46515
13	Helica	18	1.2	0.5	2000	1500	Grease	0.64	0.65	0.645	3.808545
14	Helica	18	2	0.75	0	2000	Coolant	1.22	1.21	1.215	-1.6916
15	Helica	18	2.3	0.3	1000	3000	Oil	1.45	1.45	1.45	-3.22736

16	Helica	20	1.2	0.75	100	3000	Coolant	0.72	0.67	0.695	3.154688
17	Helica	20	2	0.3	200	1500	Oil	0.75	0.74	0.745	2.556679
18	Helica	20	2.3	0.5	0	2000	Grease	2.38	2.31	2.345	-7.40382

Selection of optimal levels:

Effect of process parameters over surface roughness is calculated by using response tables. The response table 4 and 5 shows the average of each surface roughness characteristic of each level for every factor. Surface roughness "smaller is better" type quality characteristic. From chart-1 it found that second level of tool path (A2), second level of tool diameter (B2), first level of sheet thickness (C1), third level of step size (D3), second level of spindle speed (E2), first level of feed rate (F1) and second level of lubrication (G2) are optimum values. S/N ratio and Mean data of surface roughness for each corresponding level is shown in table 4 and 5.

Table 4 Response table for S/N ratio of Surface Roughness (Smaller is better)

Level	Tool Path	Tool Dia.	Sheet Thickness	Step Size	Spindle Speed	Feed rate	Lubrication
1	-1.09401	-1.07943	1.02483	-0.63041	-2.85030	-0.17859	-1.00332
2	0.46575	-0.32686	-0.42909	-0.96620	0.44438	-0.93266	-0.34430
3		-0.93336	-2.93540	-0.74304	0.06627	-1.22840	-0.99203
Delta	0.62826	0.75257	3.96023	0.33579	3.29468	1.04981	0.65903
Rank	6	4	1	7	2	3	5

Table 5 Response table for Mean of Surface Roughness (Smaller is better)

Level	Tool Path	Tool Diameter	Sheet Thickness	Step Size	Spindle Speed	Feed rate	Lubrication
1	1.1614	1.1537	0.9321	1.1221	1.4371	1.0638	1.1513
2	1.1411	1.0883	1.0700	1.2150	0.9858	1.2075	1.0675
3		1.2117	1.4517	1.1167	1.0308	1.1825	1.2350
Delta	0.0203	0.1233	0.5196	0.0983	0.4512	0.1437	0.1675
Rank	7	5	1	6	2	4	3

Main effect plots for S/N ratio and Mean data are shown in chart 1 and 2 respectively, to predict the effect of process parameters for different levels on the surface roughness for same factor.

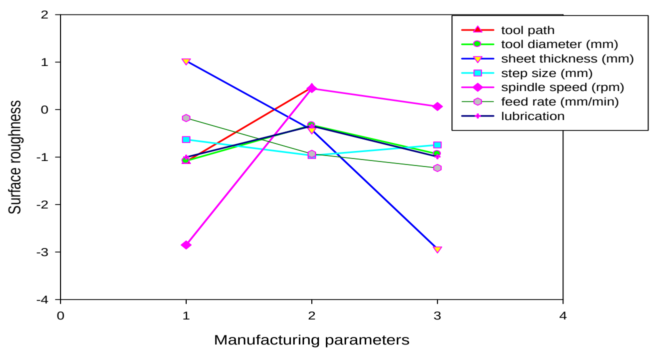

Chart-1 Effect of plot for S/N ratio (for Surface roughness)

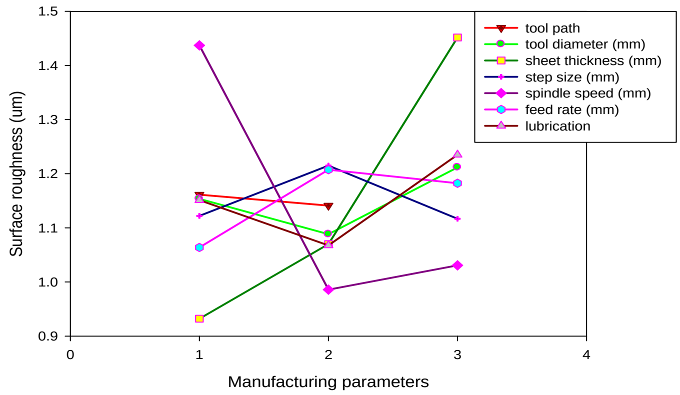

Chart-2 Effect of plot for Mean (for Surface roughness)

Analysis of variance for Surface Roughness (SR):

To study the significance of process parameters over Surface roughness analysis of variance (ANOVA) is performed in design of experiment. For 95% confidence level value of P should be less than 0.05. Therefore, from table it is clearly signified that all the process parameters affects the surface roughness. As Surface roughness "smaller is better" type quality characteristic. So, smaller value of surface roughness is considered as optimal. The raw data of ANOVA is given in table 6 using MINITAB17.

Table 6 Analysis of Variance for SR, using Adjusted SS (for Surface roughness)

Source	DF	Adj SS	Adj MS	F	P
Tool Path	1	0.00370	0.003701	0.05	0.831
Tool Dia.	2	0.09138	0.045690	0.57	0.572
Sheet Thk.	2	1.73863	0.869315	10.92	0.001
Step Size	2	0.07333	0.036665	0.46	0.637
Spindle Speed	2	1.48276	0.741381	9.31	0.001
Feed Rate	2	0.14156	0.070781	0.89	0.425
Lubrication	2	0.16834	0.084169	1.06	0.364
Error	22	1.75187	0.079630		
Total	35	5.45157			

S = 0.282189, R-sq = 67.86%, R-sq(adj) = 48.88%& R-sq(pred)= 13.95% R-sq(pred)= 13.95%

Most influential factor for Surface roughness can be decided using rank. According to the ascending order of rank, value the most effective process parameter is sheet thickness followed by spindle speed, lubrication, feed rate, tool diameter, step size and tool path. Thus optimum values can easily find out for better surface roughness.

4.5.2 Effect on Thickness Reduction:

In order to see the effect of process parameters on thickness reduction we used the orthogonal array as shown in table 7 with Mean and S/N ratio data.

Table 7 Orthogonal array for Thickness reduction with Mean and S/N ratio data

S. N.	Tool path	Tool Dia. (mm)	Sheet thickness (mm)	Step Size (mm)	Spindle Speed (rpm)	Feed Rate (mm)	Lubrication	hickness eduction %/30mm		Mean	S/N Ratio
								1	2	M1	S/N(1)
1.	Spiral	16	1.2	0.3	0	1500	Coolant	6.5	1.42	38.935	-31.8245
2.	Spiral	16	2	0.5	100	2000	Oil	1.5	1.12	51.485	-34.2338
3.	Spiral	16	2.3	0.75	200	3000	Grease	2.5	5.62	33.885	-30.6115
4.	Spiral	18	1.2	0.3	100	2000	Grease	5.4	9	47.42	-33.524
5.	Spiral	18	2	0.5	200	3000	Coolant	8.1	9.88	28.945	-29.236
6.	Spiral	18	2.3	0.75	0	1500	Oil	4.7	3.65	29.06	-29.3729
7.	Spiral	20	1.2	0.5	0	3000	Oil	9.1	6.45	43.13	-32.7212
8.	Spiral	20	2	0.75	100	1500	Grease	8.7	6.26	17.165	-24.7049
9.	Spiral	20	2.3	0.3	200	2000	Coolant	8.	0.6	29.75	-29.4733
10	Helical	16	1.2	0.75	200	2000	Oil	6.7	7.72	46.895	-33.4239
11	Helical	16	2	0.3	0	3000	Grease	6.	2.94	39.87	-32.0386
12	Helical	16	2.3	0.5	100	1500	Coolant	1.9	4.45	33.22	-30.4339
13	Helical	18	1.2	0.5	200	1500	Grease	5.	9.46	37.58	-31.51
14	Helical	18	2	0.75	0	2000	Coolant	8.5	7.08	47.815	-33.5923
15	Helical	18	2.3	0.3	100	3000	Oil	5	8.11	46.555	-33.3642
16	Helical	20	1.2	0.75	100	3000	Coolant	3.1	0.26	41.935	-32.4585
17	Helical	20	2	0.3	200	1500	Oil	7.1	4.83	16.07	-24.146
											1
18	Helical	20	2.3	0.5	0	2000	Grease	2.3	0.6	41.415	-32.3448

Selection of optimal levels:

Using the response table 8 and 9, selection of optimum parameters has been made and the effect of process parameters over thickness reduction is calculated. Thickness reduction is also a "smaller is better" type quality characteristic. Therefore, from figure 4.4 it is found that first level of tool path (A1), third level of tool diameter (B3), second level of sheet thickness (C2), third level of step size (D3), third level of spindle speed (E3), first level of feed rate (F1) and third level of lubrication (G3) are optimum values. Table 8 and 9 shows the S/N ratio and Mean data of thickness reduction for each corresponding level.

Table 8 Response table for S/N ratio of Thickness reduction (Smaller is better)

Level	Tool Path	Tool Dia.	Sheet Thickness	Step Size	Spindle Speed	Feed rate	Lubrication
1	-30.63	-32.09	-32.58	-30.73	-31.98	-28.67	-31.17
2	-31.48	-31.77	-29.66	-31.75	-31.45	-32.77	-31.21
3		-29.31	-30.93	-30.69	-29.73	-31.74	-30.79
Delta	0.85	2.79	2.92	1.05	2.25	4.10	0.42
Rank	6	3	2	5	4	1	7

Table 9 Response table for Mean of Thickness reduction (Smaller is better)

Level	Tool Path	Tool Diameter	Sheet Thickness	Step Size	Spindle Speed	Feed rate	Lubrication
1	35.53	40.71	42.65	36.43	40.04	28.67	36.77
2	39.04	39.56	33.56	39.30	39.63	44.13	38.87
3		31.58	35.65	36.13	32.19	39.05	36.22
Delta	3.51	9.14	9.09	3.17	7.85	15.46	2.64
Rank	5	2	3	6	4	1	7

The effect of process parameters on thickness reduction for different level and same factor using S/N ratio and Mean data are plotted in chart 3 and 4.

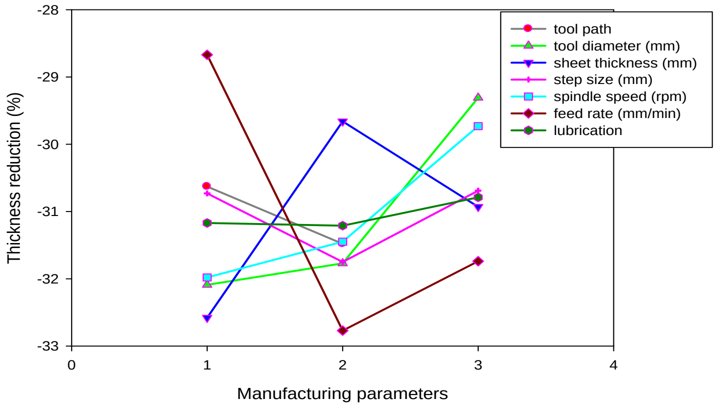

Chart -3 Effect of plot for S/N ratio (for thickness reduction)

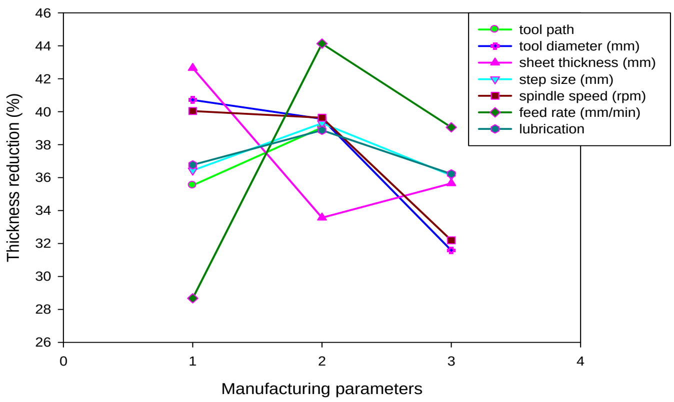

Chart -4 Effect of plot for Mean (for Thickness reduction)

Analysis of variance for Thickness Reduction (TR):

From table 10, it is clearly signified that all the process parameters affects the thickness reduction because for 95% confidence level value of P should be less than 0.05. Thickness reduction "lower is better" type quality characteristic. So, smaller value of thickness reduction is considered as optimal.

Table 10 Analysis of Variance for TR, using Adjusted SS (for Thickness reduction)

Source	DF	Adj SS	Adj MS	F	P
Tool Path	1	110.81	110.811	7.71	0.011
Tool Dia.	2	594.33	297.165	20.66	0.000
Sheet Thk.	2	544.12	272.062	18.92	0.000
Step Size	2	73.35	36.675	2.55	0.101
Spindle	2	468.72	234.359	16.30	0.000
Feed Rate	2	1490.05	745.023	51.81	0.000
Lubrication	2	46.76	23.380	1.63	0.220
Error	22	31.638	1.4381		
Total	35	3644.51			

S = 3.79219, R-sq = 91.32%, R-sq(adj)= 86.19%& R-sq(pred)= 76.76%

According to ascending order of rank value the most effective process parameter is lower value of rank. Therefore, most effective parameter in case of thickness reduction is feed rate followed by tool diameter, sheet thickness, spindle speed, tool path, step size and lubrication. Thus optimum values can easily find out for better thickness reduction.

4.5.3 Effect on forming Force:

To predict the effect of process parameters on forming force using Mean and S/N ratio data. Mean and S/N ratio data of forming force with its orthogonal array is shown in table 11.

Table 11 Orthogonal array for forming Force with Mean and S/N ratio data

Trial No.	Tool path	Tool Dia (mm)	Sheet thick-ness (mm)	Step Size (mm)	Spindle Speed (rpm)	Feed Rate (mm/min)	Lubri-cation	Forming Force(N)	Mean	S/N Ratio
								R_1	M_1	S_1
1	Spiral	16	1.2	0.3	0	1500	Coolant	1751.26	1751.26	-64.867
2	Spiral	16	2	0.5	100	2000	Oil	2058	2058	-66.2689
3	Spiral	16	2.3	0.75	200	3000	Grease	6007.4	6007.4	-75.5737
4	Spiral	18	1.2	0.3	100	2000	Grease	1127	1127	-61.0385
5	Spiral	18	2	0.5	200	3000	Coolant	5439	5439	-74.7104
6	Spiral	18	2.3	0.75	0	1500	Oil	7203	7203	-77.1503
7	Spiral	20	1.2	0.5	0	3000	Oil	1244.6	1244.6	-61.9006
8.	Spiral	20	2	0.75	100	1500	Grease	5262.6	5262.6	-74.424
9.	Spiral	20	2.3	0.3	200	2000	Coolant	7350	7350	-77.3257
10	Helical	16	1.2	0.75	200	2000	Oil	1156.4	1156.4	-61.2622
11	Helical	16	2	0.3	0	3000	Grease	4057.2	4057.2	-72.1645
12	Helical	16	2.3	0.5	100	1500	Coolant	5635	5635	-75.0179
13	Helical	18	1.2	0.5	200	1500	Grease	1185.8	1185.8	-61.4802
14	Helical	18	2	0.75	0	2000	Coolant	2077.6	2077.6	-66.3

										512
15	Helical	18	2.3	0.3	100	3000	Oil	6076	6076	-75.6724
16	Helical	20	1.2	0.75	100	3000	Coolant	1342.6	1342.6	-62.5589
17	Helical	20	2	0.3	200	1500	Oil	5450.6	5450.6	-75.344
18	Helical	20	2.3	0.5	0	2000	Grease	6310	6310	-76.0828

Selection of optimal levels:

Selection of optimum parameters and the effect of process parameters over forming force are calculated by using response table 12 and 13. As the forming force "smaller is better" type quality characteristic, it is found that second level of tool path (A2), first level of tool diameter (B1), first level of sheet thickness (C1), second level of step size (D2), second level of spindle speed (E2), second level of feed rate (F2) and second level of lubrication (G2) are optimum values of forming force to minimize the forming force during manufacturing process.

Table 12 Response table for S/N ratio of forming Force (Smaller is better)

Level	Tool Path	Tool Diamete	Sheet Thicknes	Step	Spindle	Feed rate	Lubrication
1	-70.3	-69.19	-62.18	-71.0	-69.75	-71.3	-70.14
2	-69.5	-69.40	-71.54	-69.2	-69.16	-68.0	-69.60
3		-71.27	-76.14	-69.5	-70.95	-70.4	-70.13
Delta	0.81	2.08	13.95	1.83	1.79	3.33	0.54
Rank	6	3	1	4	5	2	7

Table 13 Response table for S/N ratio of forming Force (Smaller is better)

Leve	Tool	Tool	Sheet	Step	Spindl	Fee	Lubricatio
1	416	3444	1301	436	3784	448	3933
2	375	3851	4124	365	3584	335	3931
3		4570	6440	384	4498	402	4002
Delt	410	1126	5139	713	915	112	70
Ran	6	2	1	5	4	3	7

Main effect plot for S/N ratio and Mean data are shown in chart 5 and 6 respectively.

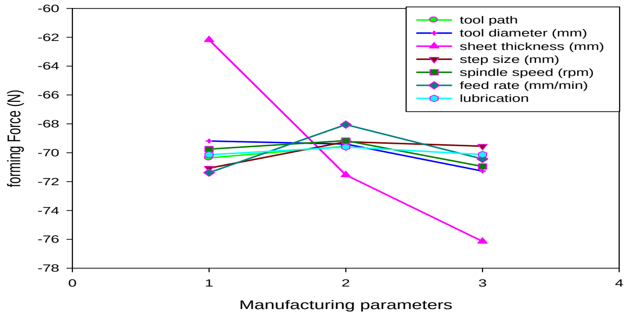

Chart -5 Main effect plot for S/N ratio (forming Force)

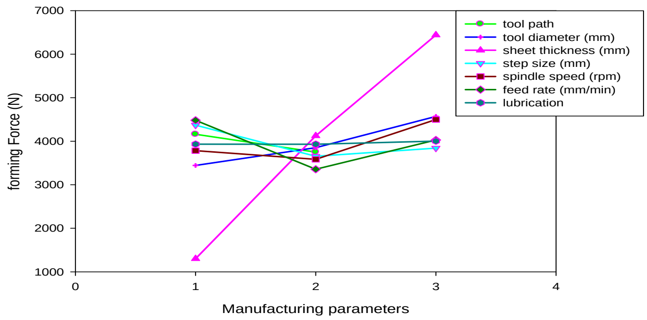

Chart -6 Main effect plot for Mean (forming Force)

5. CONCLUSIONS

1. Sheet thickness is most influential process parameter on surface roughness followed by spindle speed and lubrication where feed rate, tool diameter, step size and tool path have little influence over surface roughness. The optimal experimental condition are determined as tool path (helical), tool diameter (18mm), sheet thickness (1.2mm), step size (0.75mm), spindle speed (100rpm), feed rate (1500mm/min) and lubrication (oil) with minimum surface roughness (0.64μm), which is efficiently confirmed by validation experiment.
2. Feed rate is highly influential factors in case of thickness reduction followed by tool diameter, sheet thickness, spindle speed but tool path, step size and lubrication have little influence on thickness reduction. The optimal experimental condition for thickness reduction are determined as tool path (spiral), tool diameter (20mm), sheet thickness (2mm), step size (0.75mm), spindle speed (200rpm), feed rate (1500mm/min) and lubrication (grease) with minimum thickness reduction (14.83%).
3. Most influential process parameter on forming force is sheet thickness followed by tool diameter, spindle speed, feed rate, step size while tool path and lubrication little influence on forming force. The optimal experimental condition for forming force are determined as tool path (helical), tool diameter (16mm), sheet thickness (1.2mm), step size (0.5mm), spindle speed (100rpm), feed rate (2000mm/min) and lubrication (oil) with minimum forming force (1,127N).

4. Al-2014 is high strength and hardness alloy, hence large amount of forming force (7350 N) is calculated during ISF, which cause of abrupt failure in case of thick sheet. So, it is estimated that low hardness and thin sheet have good formability for ISF.
5. For overall performance including surface quality, thickness distribution and forming force, sheet thickness is most influential process parameter in ISF and for better quality product it should be used between 1.2mm to 2mm.

REFERENCES

[1] G. Fan, L. Gao, G. Hussain, & Z. Wu (2008). "Electric hot incremental forming: A novel technique." International Journal of Machine Tools and Manufacture, 48(15), 1688–1692.
[2] J. R. Duflou, B. Callebaut, J. Verbert, & H. De Baerdemaeker (2007). "Laser Assisted Incremental Forming: Formability and Accuracy Improvement." Annals - Manufacturing Technology, 56(1), 273–276.
[3] F. Micari, G. Ambrogio, & L. Filice (2007). "Shape and dimensional accuracy in Single Point Incremental Forming: State of the art and future trends." Journal of Materials Processing Technology, 191(1-3), 390–395.
[4] Young and J. Jeswiet 2004. "Wall thickness variations in single-point incremental forming. J. Eng. Manufact." Part B 218, 1453–1459.
[5] G. Ambrogio, 2005. "Sheet thinning prediction in single point incremental forming." 05 International Conference on Sheet Metal, Germany, pp. 479–486.
[6] J. Kopac (2005), "Incremental sheet metal forming on CNC milling machine-tool." Journal of material processing technology 162-163 (2005) 622-628
[7] Cerro, E. Maidagan, J. Arana, A. Rivero & P. P. Rodríguez, (2006). "Theoretical and experimental analysis of the dieless incremental sheet forming process." Journal of Materials Processing Technology, 177(1-3), 404–408.