An experimental investigation on the influence of process parameters on the surface roughness of incrementally deformed sheet (AA 8011-H14).

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ABSTRACT
Incremental Sheet Forming is a versatile process used to manufacture components which are well suit for small batch production of Asymmetric 3D Shapes. This research work represents an experimental investigation on the influence of process parameters on the surface roughness of incrementally deformed sheet (AA 8011-H14) under selected tool paths (Spiral and Contour). An experiment based on Single point incremental forming (SPIF) was performed on AA 8011-H14 (200 x 200 mm) sheet in 3-axis vertical milling machine. Selected process parameters are Speed (rpm), Feed (mm/min), Tool Diameter (mm) and Depth of cut (mm). The experiment is conducted at room temperature with three different sizes of hemispherical headed (SS-304) tools are used to plastically deform the aluminium sheet. ANOVA is the statistical tool which has been used for the analysis of experimental results and it's found that tool dia has the maximum influence on the surface roughness of manufactured component (Truncated cone) compare to all other selected process parameters.

Index Terms - SPIF, Process parameters, Surface roughness, AA 8011-H14, Plastic deformation, ANOVA.

1. INTODUCTION

Sheet metal forming is a manufacturing process in which the forces are applied on sheet metal to transform its geometry into a required component, without removing any material during the process. The applied force generates stresses that stretch the sheet metal beyond its yield strength, because of which the sheet metal deforms plastically without fail. In traditional sheet forming method we need specialized dies and punch addition with huge amount of mechanical forces to deform the metal sheet into the required geometry. Due to the high manufacturing cost of the die and punch the overall cost related to traditional sheet manufacturing component becomes very high, because of which it is only suitable for mass production. In today's world because of the higher cost disadvantage of traditional sheet metal forming method the companies are focusing on new and innovative techniques which have higher flexibility and can minimize the overall cost of manufacturing of a component from sheet metal.

Incremental Sheet Forming also known as dieless forming is a numerically controlled versatile process used to manufacture components which are well suit for small batch production of Asymmetric 3D Shapes. Incremental sheet forming process provides the required flexibility during manufacturing of the component and has shortened the set-up time because it doesn't need any specialized dies like in traditional process which in turn cuts the overall costing of the manufactured component. One of the major advantage that Incremental sheet forming provides is the forming forces needed to deform the sheet metal is very low compared to the traditional sheet forming method.

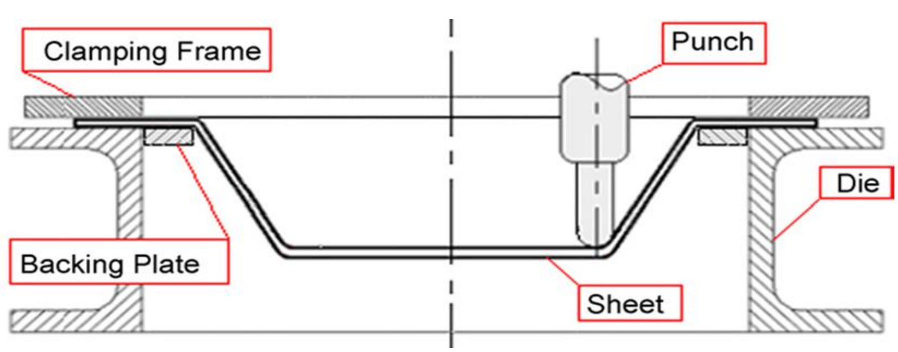

Figure No. 1 Incremental Sheet forming configuration [14].

Basically, there are two major types of ISF – (i) single point incremental forming (SPIF) (ii) two-point incremental forming (TPIF) [1]. In Single point incremental forming method, the sheet metal blank is grasped on the fixture along its edges and a tool of hemispherical shape is used to deform the sheet plastically into the required shape. Two point incremental forming method, where a partial die is used to press the metal blank simultaneously, hence it is known as TPIF. In both cases, we have a single point forming tool whose motion normally represents in terms of Cartesian coordinates, with tool movement in the horizontal plane mark as the x-axis and y-axis, and the vertical z-axis being the direction in which deformation tends to happen [1].

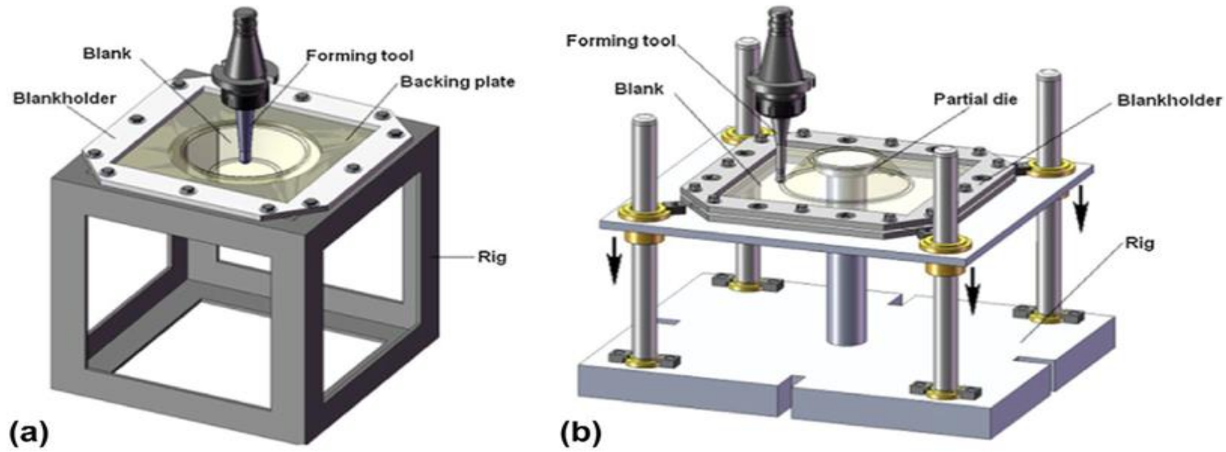

Figure No. 2 (a) Single point incremental forming (b) Two point incremental forming [18]

In incremental sheet forming tool path a has major impact on the dimensional accuracy of the component, surface finish, formability, thickness variation and processing time of the component [1]. This current research work mostly focuses on the effect of processes parameter on surface roughness with respect to Contour and the Spiral tool path. These two tool paths have been selected for the manufacturing of truncated cone component under current experimental work.

Contour tool path is the most familiar tool path used during incremental forming of sheet metal. Because of discrete motion the tool in contour tool path, the tool stops at every adjustment point between two layers to give depth of cut in the z-direction, because of which it leaves the scar marks over the surface of the component, which leads to the generation of poor quality of surface roughness [3]. But in case of Spiral tool path, since the motion of tool is continuous because of which it does not produce any scar marks, hence the surface quality of the product produced with spiral tool path has relatively better surface quality. Tool paths are generated with the help of commercial computer-aided manufacturing (CAM) software's [21].

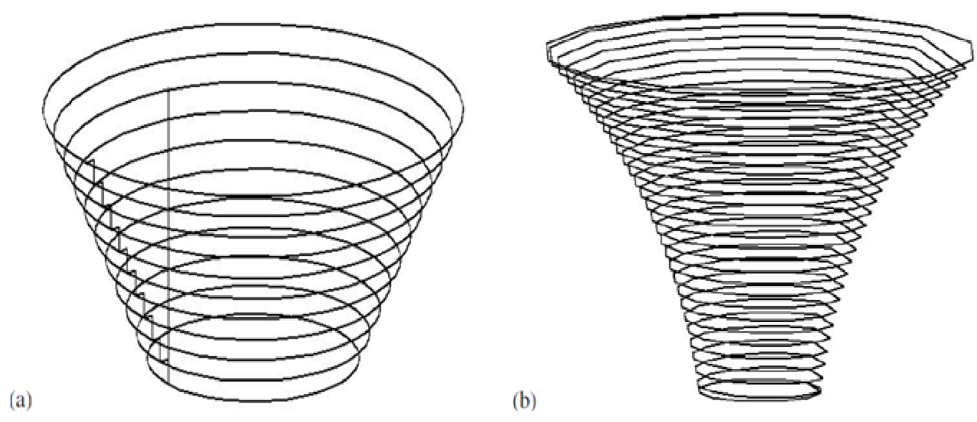

Figure No. 3 (a) Contour tool path (b) Spiral tool path [21]

2. DEFORMATION MECHANISM

Under the incremental sheet forming method, the sheet is deformed due to the advancement of highly localized plastic deformation, which is generated at the contact point between the tool and the workpiece. Moreover, because of localized deformation, the formability achieved in incremental sheet forming is higher than the traditional forming process and requires comparatively less amount of force to deform the sheet metal [1]. The mechanism of deformation in incremental sheet forming is stretching in the plane normal to the tool advancement direction and with shear in the plane parallel to the tool advancement direction. The deformation rate grows after every subsequent lap, and the most influencing parameter for sheet deformation is shearing parallel to the tool advancement direction. The experimental evidence and analysis are concluded that the formability of the ISF process is mainly influenced by four major parameters: depth of step, tool RPM, tool diameter and sheet thickness.

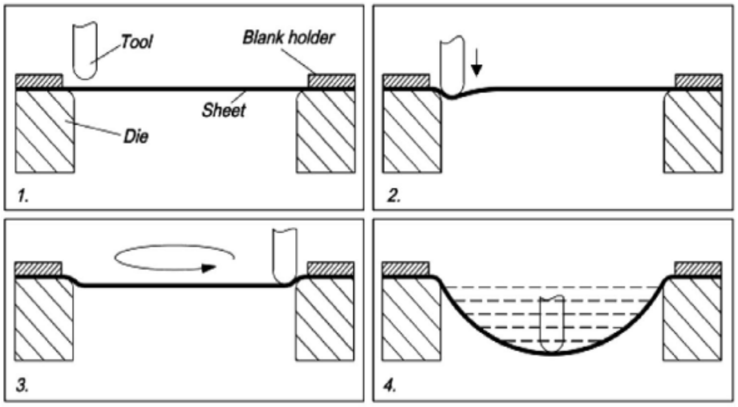

Figure No. 4 Deformation mechanism of SPIF [18].

3. WORKING PRINCIPLE OF SPIF

SPIF process demands 3-axis NC Milling machine to produce asymmetric 3D sheet metal parts without the use of dedicated dies. In this process of incremental forming, CNC machine spindle grasps a hemispherical-headed forming tool and a fixture holds the sheet along its edges. Different 3D geometrical parts can be designed with the help of software such as ANSYS, CATIA etc. and by using the part geometry different tool paths of CNC milling machine can be generated. The tool moves over the sheet with the help of preset 3D tool path (Contour and Spiral), because of which a highly localized plastic deformation zone generated at the contact point between tool and workpiece. After completion of each lap, the tool moves in z-direction for the subsequent lap with a small increment along the *z*-axis and run the process until the required shape is achieved.

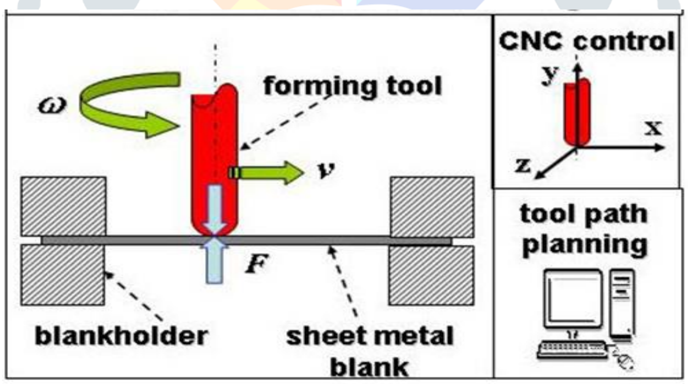

Figure No. 5 Working Principle of Single point incremental forming [1].

4. METHODOLOGY:

For the current experimental work, SPIF process is performed on a 3-axis NC Vertical milling machine. This remarkably minimizes the overall tooling cost and makes the SPIF process more adaptable and easy to work. Moreover, the same set-up can be utilized for production of different non-identical part geometries.

Figure No. 6 3-Axes NC Milling Machine. [CIPET, Valsad].

4.1 MATERIAL SELECTION

The selected material for present research work is **AA 8011-H14** 1 mm thick sheet of aluminium alloy having dimension 200x200 mm. The material is widely used for bottle safety closure for spirits. It has moderate ultimate strength and good corrosion resistance. The Chemical composition of the material is given below in Table no.1.

Table No. 1 Chemical composition of AA 8011-H14 material [MakeItForm.com]

Elements	Percentage %
Aluminum (Al)	97.5 to 99.1
Iron (Fe)	0.5 to 1.0
Silicon (Si)	0.4 to 0.8
Manganese (Mn)	0 to 0.1
Chromium (Cr)	0 to 0.1
Zinc (Zn)	0 to 0.1
Copper (Cu)	0 to 0.1
Magnesium (Mg)	0 to 0.1
Titanium (Ti)	0 to 0.050
Residuals	0 to 0.15

4.2 FORMING TOOL

In the present experimental study, a forming tool of stainless steel (SS-304) possess the hardness of 91 HRB is used. CNC lathe machine is used to manufacture a hemispherical headed tool of different diameter (8, 10, 12 mm). Three different tool sizes are selected to verify the effect of tool dia over the surface roughness of the manufactured component.

Figure No. 7 Stainless Steel SS 304 bar tool

4.3 FIXTURES

Fixtures are used to clamp the sheet metal along the edges. It consists of different size backup plates to hold the sheet metal in the right position during the experimental work. Backup plates help to improve the geometrical accuracy of the component by not allowing the sheet to bend abnormally along the periphery of the component.

Figure No. 8 Fixtures and Backup plates

4.4 TOOL PATH

Under this current experimental work two different tool path have been used – **Contour tool path** and **Spiral tool path**. These two tool paths are generated with the help of MASTERCAM software. The reason behind using of two different tool paths is to inquiry the effect of tool path over the surface quality and machining time, of the manufactured component by varying the process parameters, which are Tool speed (RPM), Feed rate (mm/min), Depth of cut (mm) and Tool Diameter (mm).

4.5 EXPERIMENTAL PLAN

The experimental work was carried out at CIPET, Valsad-396007 on an **MTAB Maxmill+ CNC** milling machine. A truncated cone a having base diameter of 100 mm and depth of 20 mm was manufactured on a 1 mm thick aluminium sheet (AA 8011- H14). Two different tool paths Contour and Spiral tool path have been selected, by varying the process parameters Speed, Feed, Depth of cut and Tool dia we can inquire the overall effect on surface quality and machining time of the product. DOE Taguchi method is used for optimization of the process parameter. With three levels and four factors, the number of the experiment to perform can be calculated using a full factorial DOE plan (**L9 Orthogonal array**).

Table No. 2 Response parameters

Variable Parameters	**Levels**		
	1	2	3
Speed (RPM)	1000	1500	2000
Feed rate (mm/min)	1000	1500	2000
Depth of Cut (ΔZ) (mm)	0.2	0.4	0.6
Tool Diameter (mm)	08	10	12
Fixed Parameters			
Sheet Thickness	1 mm		
Wall Angle	60^0		
Lubrication	Soluble oil (2 lt. /20 lt. of water)		

Table No. 3 DOE L9 Orthogonal array

Exp No.	**Parameters**			
	SPEED	**FEED**	**DEPTH**	**DIA**
1	1000	1000	0.2	8
2	1000	1500	0.4	10
3	1000	2000	0.6	12
4	1500	1000	0.4	12
5	1500	1500	0.6	8
6	1500	2000	0.2	10
7	2000	1000	0.6	10
8	2000	1500	0.2	12
9	2000	2000	0.4	8

Figure No. 9 Truncated Cone manufactured from Spiral tool path [Height 20mm, Wall angle 60^0, Dia 100 mm]

Figure No. 10 Truncated Cone manufactured from Contour tool path [Height 20mm, Wall angle 60^0, Dia 100 mm]

Experiment no. 7 of the design of experiment L9 orthogonal array has been shown above and the components are manufactured with different tool paths namely Spiral and Contour. [Speed 2000 rpm, Feed 1000 mm/min, depth of cut 0.6 mm and tool dia is 10mm]

5. RESULT AND DISCUSSION: Taguchi Method

Data collection for the surface roughness measurement of the components produced from Spiral and Contour tool path is done with the help of Surface roughness tester. The collected data is then analyzed with the help of a statistical tool known as Taguchi method. Taguchi method helps in studying the variation of the quality attribute in the process, by converting the incremental sheet metal forming roughness data into signal-to-noise ratio, where term signal and noise constitute magnitude of the mean of a process to its variation. For the current research work, 'smaller is better' is assumed as the lower value of surface roughness is desired in the component.

Table No. 4 Surface roughness data for Spiral tool path component.

S. No	Speed (rpm)	Feed (mm/min)	Depth of cut (mm)	Tool dia (mm)	Avg. Roughness (Ra) μm	S/N Ratio (dB)	Production time (min)
1	1000	1000	0.2	8	1.5650	-3.89029	26'50''
2	1000	1500	0.4	10	1.3770	-2.77868	9'15''
3	**1000**	**2000**	**0.6**	**12**	**1.2440**	**-1.89641**	**6'12''**
4	1500	1000	0.4	12	0.9567	0.38448	13'22''
5	1500	1500	0.6	8	2.6190	-8.36271	7'10''
6	1500	2000	0.2	10	1.1780	-1.42291	13'20''
7	2000	1000	0.6	10	1.3900	-2.86030	9'24
8	**2000**	**1500**	**0.2**	**12**	**0.9190**	**0.73369**	**16'41''**
9	2000	2000	0.4	8	1.8010	-5.11027	7'52''

Table No. 5 Surface roughness data for Contour tool path component.

S. No	Speed (rpm)	Feed (mm/min)	Depth of cut (mm)	Tool dia (mm)	Avg. Roughness (Ra) μm	S/N Ratio (dB)	Production time (min)
1	1000	1000	0.2	8	1.9371	-5.7430	28'48''
2	1000	1500	0.4	10	1.5770	-3.9566	10'24''
3	**1000**	**2000**	**0.6**	**12**	**1.2916**	**-2.2226**	**6'40''**
4	1500	1000	0.4	12	1.0183	-0.1575	14'20''
5	1500	1500	0.6	8	3.3430	-10.4827	8'46''
6	1500	2000	0.2	10	1.4776	-3.3911	14'21''
7	2000	1000	0.6	10	1.7073	-4.6462	11'00''
8	**2000**	**1500**	**0.2**	**12**	**0.9526**	**0.4218**	**19'15''**
9	2000	2000	0.4	8	2.2840	-7.1739	8'9''

Table No. 6 Response Table for S/N Ratio and Avg. Surface Roughness of Spiral tool path component

Response Table for Signal to Noise ratio					Response Table for Mean				
Smaller is better									
Level	**Speed**	**Feed**	**Depth**	**Tool Dia**	**Level**	**Speed**	**Feed**	**Depth**	**Tool dia**
1	-2.8551	-2.1220	-1.5265	-5.7878	**1**	1.395	1.304	1.221	1.995
2	-3.1337	-3.4692	-2.5015	-2.3540	**2**	1.585	1.638	1.378	1.315
3	-2.4123	-2.8099	-4.3731	-0.2594	**3**	1.370	1.408	1.751	1.040
Delta	0.7214	1.3472	2.8466	5.5283	**Delta**	0.215	0.334	0.530	0.955
Rank	4	3	2	1	**Rank**	4	3	2	1

Table No. 7 Response Table for S/N Ratio and Avg. Surface Roughness of Contour tool path component

Response Table for Signal to Noise ratio Smaller is better					Response Table for Mean				
Level	**Speed**	**Feed**	**Depth**	**Tool Dia**	**Level**	**Speed**	**Feed**	**Depth**	**Tool dia**
1	-3.9741	-3.5156	-2.9041	-7.7999	**1**	1.602	1.554	1.456	2.521
2	-4.6771	-4.6725	-3.7627	-3.9980	**2**	1.946	1.958	1.626	1.587
3	-3.7994	-4.2625	-5.7838	-0.6528	**3**	1.648	1.684	2.114	1.087
Delta	0.8777	1.1569	2.8797	7.1471	**Delta**	0.344	0.403	0.658	1.434
Rank	4	3	2	1	**Rank**	4	3	2	1

From the above Table no. 6 and Table no. 7 (Analysis of S/N ratio), It shows that from all the four considered process parameters, Tool diameter has the greatest effect on the surface roughness of the component (for both the cases of Spiral and Contour tool path). As tool dia increases the surface roughness of the component minimizes. Moreover, the second parameter which has the next highest effect on the surface roughness of the component is the depth of cut, as the depth of cut increases the roughness over the surface gets maximized.

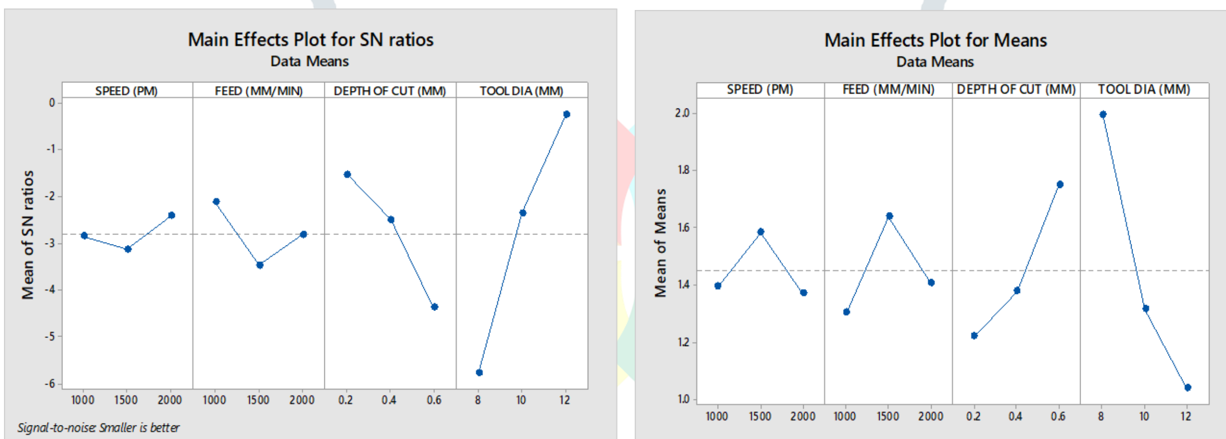

Figure 11 S/N ratio and Avg. Roughness Graphs for Spiral tool path component.

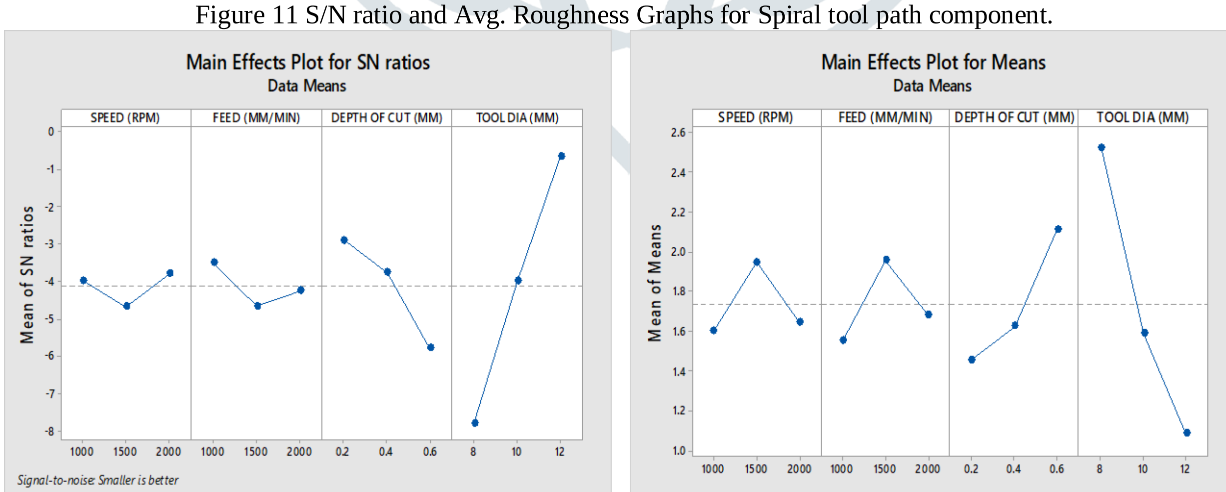

Figure 12 S/N ratio and Avg. Roughness Graphs for Contour tool path component.

5.1 ANOVA Analysis

ANOVA stands for Analysis of variance, is a statistical tool which helps to interpret the disagreement between the group means in a sample. The analysis of variance is calculated by dividing the measured sum of squared deviations from the total mean S/N ratio with the contribution of each process parameter and the errors.

Table No. 8 Analysis of Variance of Spiral tool path component.

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**% C**
TOOL DIA	1	45.8439	45.8439	51.12	0.088	72.98%
SPEED	2	0.7942	0.3971	0.44	0.728	1.264%
FEED	2	2.7228	1.3614	1.52	0.498	4.334%
DEPTH OF CUT	2	12.5570	6.2785	7.00	0.258	19.99%
Error	1	0.8968	0.8968			1.427%
Total	8	62.8147				100.0%

Model Summary			
S	R-sq	R-sq(Adj)	R-sq(pred)
0.946991	98.57%	88.58%	0.00%

Table No. 9 Analysis of Variance of Contour tool path component.

Source	**DF**	Adj SS	Adj MS	F-Value	P-Value	**% C**
TOOL DIA	1	76.6223	76.6223	734.79	0.023	82.21%
SPEED	2	1.2951	0.6476	6.21	0.273	1.389%
FEED	2	2.0645	1.0323	9.90	0.219	2.215%
DEPTH OF CUT	2	13.1148	6.5574	62.88	0.089	14.07%
Error	1	0.1043	0.1043			0.112%
Total	8	93.2010				

Model Summary			
S	R-sq	R-sq(Adj)	R-sq(pred)
0.322922	99.89%	99.10%	86.41%

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6. CONCLUSION:

The current experimental work on Single point incremental forming process (AA 8011-H14) concentrates on the effect of four process parameters, which are Speed, Feed, Depth of cut and Tool dia on the surface roughness of the component produced from two different tool paths (Spiral and Contour). Statistical tools such as ANOVA analysis has been used to determine the optimum process parameters for improvement of surface roughness of the component. The results from the analysis of variance and Signal to Noise ration helps to interpret the data and also helps to draw the conclusion for the current experimental work on Single Point Incremental forming of AA 8011-H14 Sheet.

- It has been observed that under identical machining conditions Spiral tool path produces better surface finish compared to the Contour tool path. Moreover, it has been found (for both the cases) that increase in tool dia leads to the better surface finish. As the tool dia increases the contact area between tool and the sheet increases, because of which after every lap when tool goes for next subsequent lap it overlaps the previous lap and tends to reduce the scars marks which are generated during the former lap, which in turns help to improve the surface quality of the product. ANOVA analysis also concludes that, 12 mm dia tool with 0.2 mm (lowest value) depth of cut, better surface quality can be achieved. [Figure No. 6 and 7].
- From Figure No. 11 and 12, analysis of S/N ratio and Avg. roughness data concludes that after tool dia, depth of cut has the next highest influence over the surface finish of the product and tool speed (rpm) has minimum effect. As the depth of cut increases, the surface quality becomes poor. Moreover, the ANOVA analysis shows that with 0.6 mm depth of cut the surface quality produced for both spiral and contour tool path component is poorest.
- The machining time of the components with Spiral tool path is **108.46 min** compares to Contour tool path which is **121.04 min**, a difference of **12.58 min** less required in case of Spiral tool path, this happens because in case of Spiral tool path the tool motion is continuous, which is not in the case of Contour. [Table 4 and 5].
- From Table No. 5 and 6 of S/N ratio the optimum parameters for the process: tool dia 12 mm, depth of cut 0.2 mm, speed 2000 rpm and feed 1500 mm/min. [Spiral and Contour tool path].

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