ISSN: 0974-5823 Vol. 6 No. 3 October-December, 2021

International Journal of Mechanical Engineering

Effect of Process Parameters on Wall Thickness Variation in Deformation Machining Stretching Mode

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Date of Submission: 09th April 2021 Revised: 20th September 2021 Accepted: 26th October 2021

How to Cite: **Parmar, et.al (2021). Effect of Process Parameters on Wall Thickness Variation in Deformation Machining Stretching Mode. International Journal of Mechanical Engineering 6(3), pp.1713-1719**

***Abstract* - Deformation Machining is a metal forming process where thin floor like structure is produce by milling, and then the forming of this thin floor is being carried out with single point incremental forming tool. In this process the deformation may be perpendicular to the axis of tool known as bending mode or may be along the axis of the tool known as stretching mode. Forming of thin structure is always a difficult task, and literature shows significant work in the area where sheet and plate like structure is form by die and press. In recent time single point incremental forming process as a flexible forming process is also developed where the required feature in the sheet like structure is formed by localized deformation of points. In this work objective is to develop the tooling required and to study the effect of process parameters on the wall thickness achieved. Experiments are performed on AA 6061 plate like structure on 3-axis CNC machine. DOE is used and results are plotted using ANOVA. Results show the significant effect of spindle speed, feed rate, incremental step depth and tool diameter on the thickness.**

Index Terms – Deformation machining; thin structure manufacturing; single point incremental forming; design of experiment, AA 6061.

INTRODUCTION

In many application areas such as aerospace, it is desirable to have thin metallic structures and AA 6061 is widely use in aerospace industry. The machining of such thin components can be done by deformation machining process and this can replace large number of assembly operations. In the metal forming processes variation in the thickness due to deformation zone affect the strength and formability and in general the functioning of the part. Incremental single point forming was patented in year 1967 by Leszak [3] and also feasible was checked by Kitazawa et al.[4] in forming rotational symmetric parts. Capability study of special designed machine tool apparatus was performed by Jeswiet [5] and Filice [6]. Incremental forming has higher formability compared with other conventional forming processes [7,8] due to its highly localized plastic deformation. Research in this area is related to feasibility of the process and different tooling requirement for the process. The sheet is deformed by the moving tool controlled by numerical codes previously programmed and imported [9]. The process time, forces generated during the process, geometry of the part produced, micro structural study and the responses of different materials are the areas which are still open to work on. Current state-of-the-art for metal forming by localized deformation is carried out by implementing the modification in the conventional spinning and shear forming[10]. Single point incremental forming process is also used to manufacture a complex product like customised ankle support. Process slowness and the low accuracy are still to be considered open points [11].

So far as deformation machining stretching mode is concern preliminary results in feasibility study of the process are encouraging, and point to a broad range of industrial applications. Starting from plate stock, thin features like walls, floors, or even pins are created by machining operations. Then using a forming tool SPIF process is followed to create deformations of the thin sections in two different ways, either bending or stretching the features. By switching between the cutting tool and the deformation tool, it is possible to make interesting features which are thinner, lighter, or less expensive than the structures they replace. In addition, it is possible to produce geometries that would be difficult or impossible to create using other processes [12]. Two modes of deformation machining process are shown in figure 1 and 2. Thin structure are widely use in aerospace industry and force collected data shows that the process is within the capability of existing machine tools, and deformation forces are similar in magnitude to cutting forces. The thin Wall/floor structure may be bent to form any type of lip or overhang, a C-channel, a U-channel, or selectively and progressively bent along its transverse direction to form an impeller blade or the like and the possibilities the same are virtually endless [13].

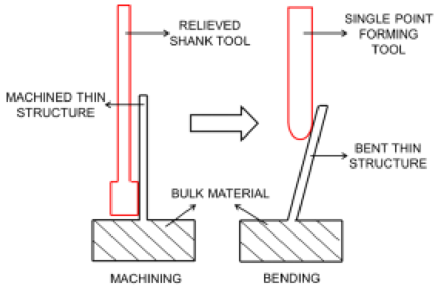

FIGURE 1
SCHEMATIC OF DEFORMATION MACHINING BENDING MODE [6]

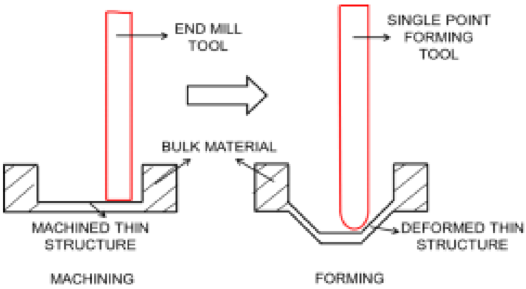

FIGURE 2
SCHEMATIC OF DEFORMATION MACHINING STRETCHING MODE [6]

DM process is not providing tight tolerances like standard milling process. This may be due to the spring back and local variations in material properties which influence the yield strength and results in spring back. However, the components created by this process found more repeatable compare to similar components created with sheet metal using SPIF, but less repeatable than components created by conventional bending of sheet metal[14]. The dimensional repeatability of the process largely depends on the accuracy of the machined floor, and other factors affecting are elastic deformation, residual stresses, spring back and highly localized yielding. The role of residual stresses in this process could be seen as a new research scope [15]. The feed rate, dimensional attributes like wall thickness, bent angle, H/L ratio have significant bearing on the elastic spring back. The future scope is to develop correlations with the various aspects of elastic spring back and developing holistic experimental model, incorporating wide range and levels of parameters for accurate prediction of spring back [16]. Residual stresses have significant effect on fatigue life, strength, corrosion resistance and overall product life of component. Residual stresses are induces in the component by deformation machining during the machining as well as forming [17]. Substantial reduction in deformation forces in deformation machining and single point incremental forming was found over conventional forming. The work provides initial insights to commercialize the process as a replacement of conventional forming [18].

Desired formed thickness along with considerable uniform profiles across the forming depth was achieved by employing a varying thin section machining compensation strategy, prior to incremental forming. This would probably enhance the formability limits and strength of the formed monolithic components. Future work in structural thinning and compensation would be its extension to varied profiles, geometries with variable forming angles [19]. The influence of shape of the formed component on the average resultant forces has also been studied and found to be dependent on the geometry [20]. Process parameters such as forming tool diameter, forming angle, and incremental depth have a significant effect on the average radial error in DM stretching mode components in comparison to dimensional attributes like floor thickness and floor size. The future work in this direction could be finding ways and techniques to eliminate the geometrical discrepancies in order to achieve acceptable level of accuracy and for this the process is still need to study for improvement[21]. It is found that profile tool path have higher surface roughness and thinning compared to helical tool path [22]. Ham and Jeswiet [23] carried out a experiments to study the effect of process parameters on the forming angle. Also, CapeceMinutolo et al. [24] successfully evaluated the formability of both truncated pyramids and cones by using the maximum forming wall angle. A set of experiments was designed by Bhattacharya et al. [25] found that formable angle first increases and then decreases with step down size. Ham [26] performed 46 experimental tests that consider five factors which include material type, sheet thickness, tool size, step down size and formed shape. Hagan and Jeswiet [27] analysed the influence of several forming variables, such as step-down size and spindle speed, on surface roughness in ISF process. Powers et al. [28] investigated the surface morphology through a SPIF case analysis. Some of the established process parameters in SPIF are related to the material type and thickness, incremental depth, tool speed, tool diameter, tool path shape, feature compensation, spring back compensation, and multi-stage forming [6, 24, 25, 26, 27, 28]. Bhattacharya et al. shows idea about tool path for higher dimensional accuracy as well as better surface finish [29,30]. Presently, the geometric accuracy for ISF products is still one of the biggest challenges for both academic researchers and industrial users. Choices with respect to the tool path strategies affect the outcome of SPIF, specifically the geometric accuracy, residual stress, surface finish, distribution of sheet thickness, and material formability.

EXPERIMENTAL WORK

I. Machining center and process parameter selection

Process was performed to get conical shape from thin wall floor up to the depth of 30mm. Machining center (Vertimach V-650) of TAL manufacturing solutions ltd. was used for the machining and forming. Programme for tool travel was prepared in NX 12 manufacturing as per the path required for machining and forming constants [15]. As the DM stretching mode is combination of two processes i.e. machining and forming, for the machining operation[13], [14] fixed process parameters were selected and for forming after concrete literature review four controllable parameters were selected to study [8], [9], [10], [12]. Literature review shows that one factor at a time approach can be used to study the effect of process parameters.

TABLE I
FIXED LEVEL OF MACHINING PARAMETER FOR THIN FLOOR MACHINING

Process Parameters	Level
Tool material	Tungsten carbide
Tool diameter	12mm

Spindle speed	60m/min
Transverse feed	0.5m/min
Depth of cut	0.5mm

TABLE II
VARIABLE LEVEL OF FORMING OPERATION

Process Parameters	Level
Spindle speed	60,80,100 rpm
Feed rate	2000,4000,6000 mm/min
Tool diameter	8,10,12mm
Incremental step depth	0.10,0.20,0.30mm
Depth of cut	0.5mm

II. Machining tool, forming tool and workpiece material

For machining of thin floor solid carbide end mill is used. Forming tools are manufactured from HCHCR material as a single point incremental forming tool. Figure 3 shows the part drawing of the component. Aluminium alloy AA 6061 plate of dimension 150X150X10mm is milled to produce thin floor of 2mm thickness and 70mm diameter. This milled thin floor is formed by single point incremental forming tool to achieve 30mm depth. Experiments were performed as per Table III.

The setup for the process was prepared (FIGURE 4) which consists of four column, base plate, top plate, clamping with nut and bolt. The top plate was milled about 8mm deep so that 150X150X10mm component can accommodate, and at the centre 80mm diameter bore is created to have required spaced for forming the floor thickness.

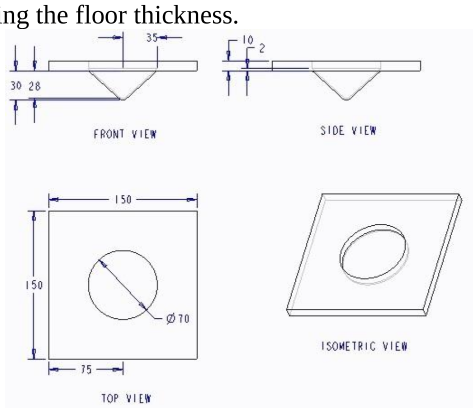

FIGURE 3
PART DRAWING OF THE COMPONENT

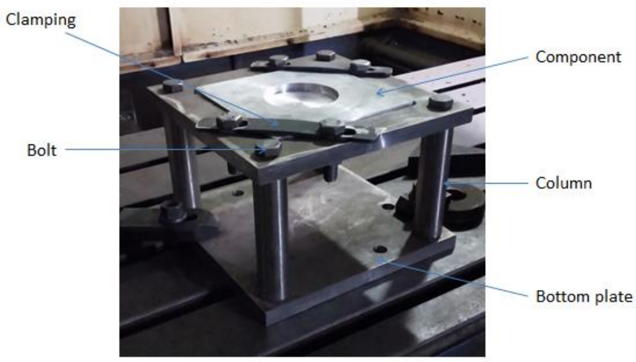

FIGURE 4
SETUP FOR DM STRETCHING MODE

III. DOE Plan 2^4 full factorial

DOE is a useful method to identify significant parameters affecting the response. The method is useful to develop the experiments between ranges from uncontrollable factors, which will be introduced randomly to controlled parameters. In the experimental work 2^4 full factorial plan is used to study the effect of various parameter on the thickness achieved.

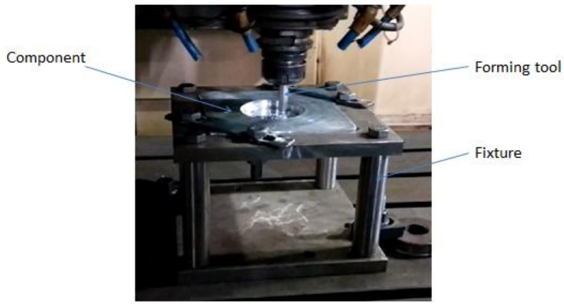

FIGURE 5
FORMING OPERATION

Figure 5 showing DM stretching mode operation where single point incremental forming tool is forming the machined floor thickness. Experiment is carried out with 2^4 full factorial plans and the same is mentioned in Table III.

TABLE III
2^4 FULL FACTORIAL DESIGN OF EXPERIMENT

Sr. No.	Spindle Speed (RPM)	Feed (mm/min)	Incremental Step Depth (mm)	Tool Diameter (mm)	Form/Failure
1	60	2000	0.10	8	Form
2	100	2000	0.10	8	Form
3	60	6000	0.10	8	Form
4	100	6000	0.10	8	Form
5	60	2000	0.30	8	Failure
6	100	2000	0.30	8	Failure
7	60	6000	0.30	8	Form
8	100	6000	0.30	8	Form
9	60	2000	0.10	12	Failure
10	100	2000	0.10	12	Form
11	60	6000	0.10	12	Form
12	100	6000	0.10	12	Failure
13	60	2000	0.30	12	Form
14	100	2000	0.30	12	Failure
15	60	6000	0.30	12	Failure
16	100	6000	0.30	12	Failure
17	80	4000	0.15	10	Form
18	80	4000	0.15	10	Form
19	80	4000	0.15	10	Form
20	80	4000	0.15	10	Form

FIGURE 6
PARTS FORM BY DEFORMATION MACHINING STRETCHING MODE

IV. New2^{4-1} DOE plan with revised process parameter levels

Observation shows that some of the components get failure. So in the next experiment work the process parameter is changed and 2^{4-1} DOE plan is prepared and components are manufactured. So far as to measure the thickness, component must not get failure before achieving shape. But here 7 out of 20 components get failure. The observation (Table III) shows that component get failure at higher tool diameter, incremental depth and higher spindle speed. So, new set of parameter are chosen which is given in the Table IV.

TABLE IV
REVISED VARIABLE LEVEL FOR FORMING OPERATION

Process Parameters	Level
Spindle speed	40,60,80 rpm
Feed rate	2000,4000,6000 mm/min
Tool diameter	6,8,10mm
Incremental step depth	0.08,0.10,0.12mm

Figure 7 shows the component produced with 2^{4-1} DOE plan according to new set of process parameter level and all components formed successfully. The thickness for all this components is measured on CMM after having cross sectional cut. Thickness is measured at 2mm interval depth and average of the same is shown in the Table V.

TABLE V
2^{4-1} FULL FACTORIAL DESIGN OF EXPERIMENT

Sr. No.	Spindle Speed (RPM)	Feed (mm/ min)	Incremental Step Depth (mm)	Tool Diameter (mm)	Form/ Failure	Average Thickness (mm)
1	40	2000	0.08	6	Form	1.738
2	80	2000	0.08	10	Form	1.69
3	40	6000	0.08	10	Form	1.711
4	80	6000	0.08	6	Form	1.721
5	40	2000	0.12	10	Form	1.672
6	80	2000	0.12	6	Form	1.681
7	40	6000	0.12	6	Form	1.702
8	80	6000	0.12	10	Form	1.668
9	60	4000	0.10	8	Form	1.712
10	60	4000	0.10	8	Form	1.714
11	60	4000	0.10	8	Form	1.715
12	60	4000	0.10	8	Form	1.71

FIGURE 7
PARTS FORM BY WITH NEW SET OF PROCESS PARAMETERS

RESULTS AND DISCUSSION

Analysis of variance (ANOVA) is performed to check the significant parameters and to quantify their effect on the thickness. Main effect plot and interaction plot are used to examine the parametric effect on response. Total 12 components were produced according to 2^{4-1} DOE plan, and to study the effect of process parameter components were cut symmetrical and thickness is measured at 2mm depth up to its total depth, i.e. 30mm. The wall thickness variation was measured on coordinate measuring machine (CMM) at different forming depth after cutting and average of the thickness are taken into consideration for further analysis. Measured value of thickness at different depth shows that at the starting of the forming bending region is form, which is followed by thinning and at the middle region section is observed.

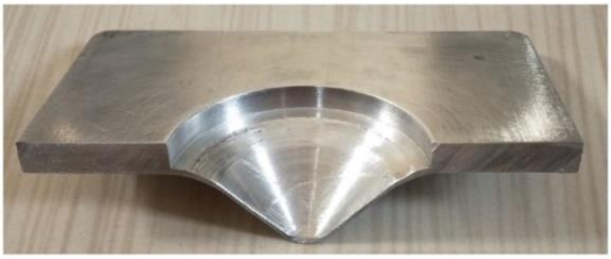

FIGURE 8
CUT SECTION OF THE PART

TABLE VI
ANALYSIS OF VARIANCE

Term	Effect	Coef	SE Coef	T	P
Constant		1.69788	0.000784	2165.78	0.000
Spindle Speed (RPM)	-0.01575	-0.00787	0.000784	-10.05	0.002
Feed Rate (mm/min)	0.00525	0.00263	0.000784	3.35	0.044
Incremental Step Depth (mm)	-0.03425	-0.01713	0.000784	-21.84	0.000
Tool Diameter (mm)	-0.02525	-0.01263	0.000784	-16.10	0.001
Spindle Speed (RPM)* Feed Rate (mm/min)	0.00375	0.00187	0.000784	2.39	0.097
Spindle Speed (RPM)* Incremental Step Depth (mm)	0.00325	0.00163	0.000784	2.07	0.130
Spindle Speed (RPM)* Tool Diameter (mm)	0.00325	0.00162	0.000784	2.07	0.130
Ct Pt		0.01488	0.001358	10.95	0.002

From figure 8 shows the cut section view of the component manufactured. At different interval of depth the thickness of the feature is measured on CMM, and average of the thickness is taken into consideration for further analysis.

R-Sq = 99.70%   R-Sq(adj) = 98.88%

The regression equation is
Average Thickness (mm) = 1.86 - 0.000394 Spindle Speed (RPM)+ 0.000001 Feed Rate (mm/min)- 0.856 Incremental Step Depth (mm)- 0.00631 Tool Diameter (mm)

Table VI for ANOVA is show for thickness, values which are less than 0.05 indicate the parameter affecting significantly to the response characteristic. From this table it is concluded that incremental step depth and tool diameter have more significant effect on the thickness compared to other two process parameters. The difference between R-Sq (99.70%) and R-Sq(adj) (98.88%) is very less which shows reasonable agreement.

Figure 9 shows the 3D surface plot for the thickness versus spindle speed and feed rate. Higher value of spindle speed and lower value of feed rate tends to decrease the thickness achieved. The 3Dsurface plot for the thickness versus spindle speed and incremental step depth is shown in figure 10. It can be interpreted from the figure that in order to have lower incremental step depth and lower value of spindle speed is suggested to have lower variation the thickness.

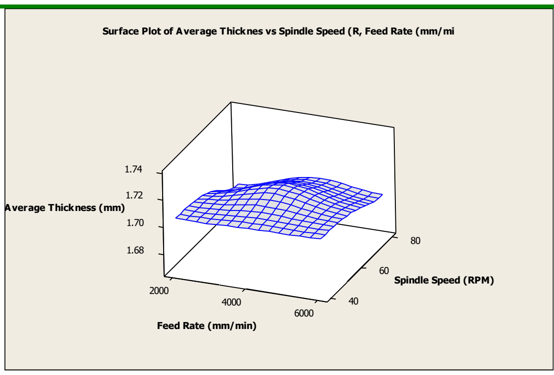

FIGURE 9
AVERAGE THICKNESS VS FEED RATE AND SPINDLE SPEED

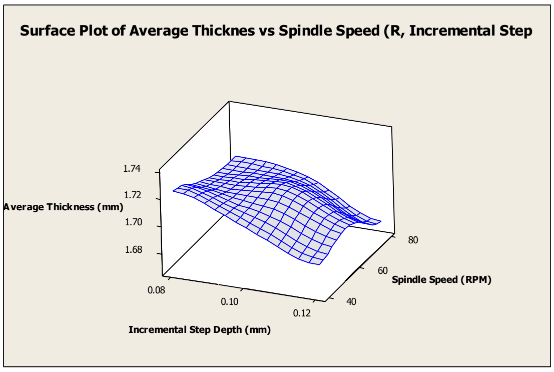

FIGURE 10
AVERAGE THICKNESS VS INCREMENTAL STEP DEPTH AND SPINDLE SPEED

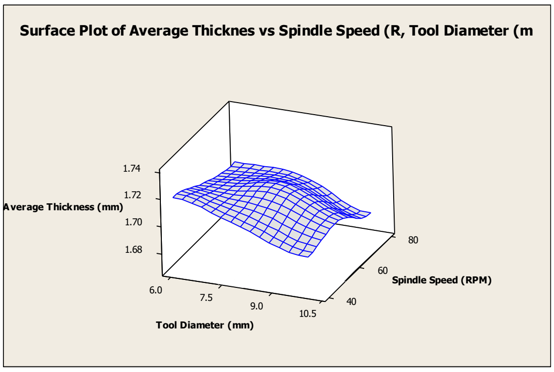

FIGURE 11
AVERAGE THICKNESS VS TOOL DIAMETER AND SPINDLE SPEED

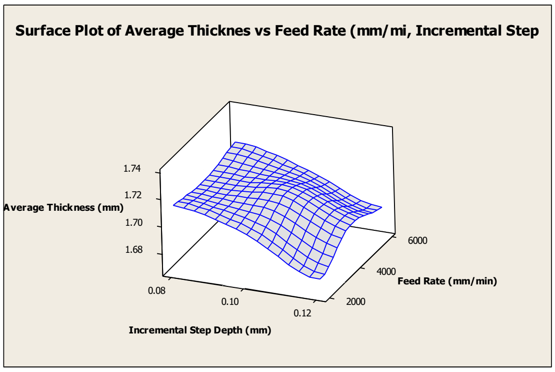

FIGURE 12
AVERAGE THICKNESS VS INCREMENTAL STEP DEPTH AND FEED RATE

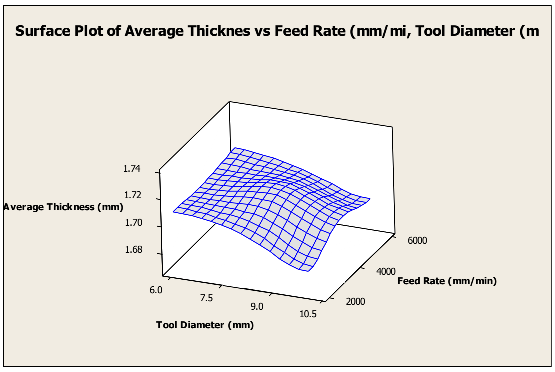

FIGURE 13
AVERAGE THICKNESS VS TOOL DIAMETER AND FEED RATE

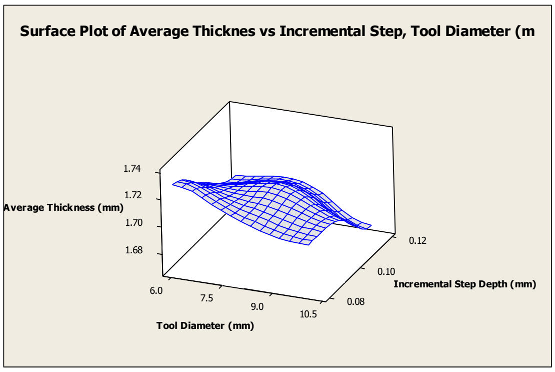

FIGURE 14
AVERAGE THICKNESS VS TOOL DIAMETER AND INCREMENTAL STEP DEPTH

Surface plot in figure 11 for thickness versus spindle speed and tool diameter shows lower value of both the parameters are contributing to have lower variation in the thickness of the part. In figure 12 the surface plot of thickness versus tool diameter and feed rate is shows that lower value of parameters are contributing to have uniform thickness or lower variation in the thickness. Figure 13 shows the plot of thickness versus tool diameter and feed rate it can be seen from the plot that lower tool diameter and higher feed rate is giving less variation in thickness. Figure 14 shows the 3D surface plot for thickness versus incremental step depth and tool diameter. It shows that effect of tool diameter and incremental step depth have more effect on thickness variation compare to other two parameter, this might be due to higher value of forming forces for higher tool diameter and higher incremental step depth [9].

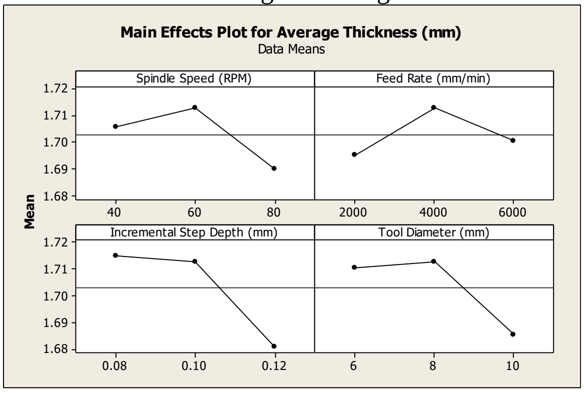

FIGURE 15
MAIN EFFECT PLOT FOR SPINDLE SPEED, FEED RATE, INCREMENTAL STEP DEPTH AND TOOL DIAMETER

It can be seen from figure 15 that incremental step depth plays very important role for variation in thickness. And form the ANOVA table it can also be concluded that incremental step depth have highest effect on the response followed by tool diameter, spindle aped and feed rate. Increase of the incremental step depth decreases the thickness. Figure 16 shows that for selected level of parameters no interaction is found.

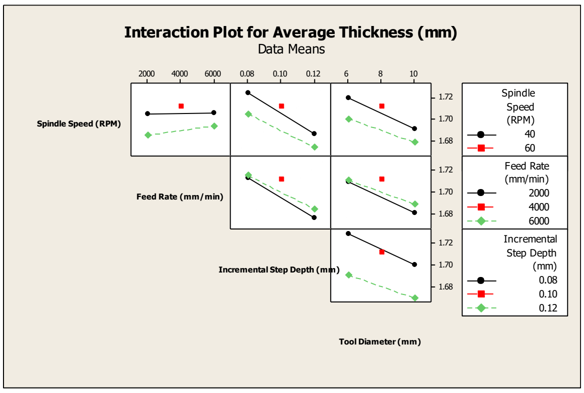

FIGURE 16
INTERACTION PLOT FOR SPINDLE SPEED, FEED RATE, INCREMENTAL STEP DEPTH, AND TOO DIAMETER

CONCLUSION AND FUTURE SCOPE

Tooling required for DM stretching mode is developed and experiment is carried out according to DOE plan for DM stretching mode to see the effect of different process parameters. Wall thickness variation is analysed through measurement on CMM. Under this study it is found that spindle speed, feed rate, tool diameter and incremental step depth have significant effect on the wall thickness of the formed feature. Data can be used to implement the compensation strategy to achieve desired or uniform thickness for proper functioning of the parts. Below are some conclusion made after studying the process parameters:

- It is found that at the staring of the forming, bending of floor is observed which is followed by reduction in thickness and then thickness remains steady at the bottom of the cone produced.
- From the plots it is concluded that lower spindle speed, higher feed rate, smaller tool diameter and smaller

incremental step depth is recommended to have lower variation in thickness.

- At higher spindle speed, reduction in thickness is more, and in case of feed rate higher feed rate is recommended for lower variation in wall thickness.
- Incremental step depth has more significant effect in the variation of the wall thickness because at higher incremental step depth the formability of the material decreases.
- Less reduction in the wall thickness can be achieved at lower tool diameter; this may be due to higher resultant force and also because smaller tool size gives increased formability.
- This data may be useful to apply different compensation strategy to have uniform thickness after forming.

Further analysis is underway for thickness compensation strategy, micro-structural and surface integrity study for the feature produced.

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