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An Experimental Study on Effect of Process Parameters on Surface roughness for Deformation Machining Stretching Mode

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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. Surface roughness plays crucial role in functioning of part. In this study objective is to study the effect of different process parameters on surface roughness of the part produced. Experimental set for the process is developed and design of experiment is used to carry out for the experimental run. Surface finish of the form feature is measured using surface roughness tester. ANOVA is used to find out significant process parameter affecting the surface roughness. Results shows that incremental step depth and feed rate have more significant effect on the surface roughness.

Keywords: Deformation machining, Thin structure manufacturing, Single point incremental forming, Design of experiment.

1. Introduction

Al 6061 is widely used in aerospace, automobile and medical industries. Forming of metal is always difficult task. Earlier forming is carried out with punch and die or press, and desired shape of product is achieved as per die used. But this process was costly as die and punch usage, and now a day same is replaced for majority of the product by dieless forming process known as single point incremental forming process. In this process deformation of metal is carried out by localised deformation. In single point incremental forming process sheet metal is formed locally and desired shape of product is achieved. Deformation machining is combination of two method i.e. thin floor machining followed by single point incremental forming. 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.

2.LiteratureReview

Incremental Sheet Forming (ISF) process significantly lowers the tooling costs as compared to other processes where dies are used to produce any product. Hence, for multi-variety components in small batches incremental forming is more advantageous[1]. As the service performance of the formed parts is unsatisfactory, the process has not been widely used for industrial application. Liretature focuses on improving the thickness distribution and mechanical properties (e.g., hardness, yield strength, and tensile strength) through process optimization[2]. Nowadays, CNC machines are being used by many medium scale and small-scale industries. Therefore, this process can be employed in these industries. The process is ideal for prototyping and producing small number of specialised parts. Advantages of ISF process such as ease of forming, small forming forces, and ability to form any part shape with minimal tooling requirement make it a viable option to conventional sheet forming processes[3].

Experimental study on the influence of process parameters in single point incremental forming (SPIF) on the surface roughness shows considerable effect of tool diameter and pitch on the surface quality of formed part[4]. In single-point incremental forming (SPIF) process, the inappropriate selection of parameters could be detrimental to process accuracy. The nature of effect of tool radius depends on the angle of forming: large tool radius proves beneficial when the angle is small and the same is detrimental when the angle is large[5]. But due to its high surface roughness, it is still not so popular in sheet metal industries. But when SPIF is performed with dummy sheet at the top of target sheet, then this limitation is eliminated to some extent [6]. The thickness of a sheet metal to be used can also be easily calculated using only the shape of a product[7]. Fundamental investigation regarding a new parameter blank stiffness, in the SPIF process also affect the formability[8]. Incremental forming applications are currently increasing in industry, especially for the production of small batches or single components. In fact, sufficient know-how is now available for the manufacture of simple products. However, further efforts are required to reduce the drawbacks of typical incremental forming processes, which compromise important advantages in terms of costs and flexibility[9]. The SPIF process has been accurately investigated both from a numerical and experimental point of view, with particular attention to the dimensional precision of the part obtained[10].

A methodology for identifying applications of a new production technology is proposed and tested. It is applied to the incremental sheet-forming process, showing a preference for low-volume high-value applications and identifying the importance of improving process accuracy[11]. In order to study metal behavior, it is very important to establish a method to create a large strain hardening curve based on the normal mechanical test[12]. A good prediction of the material springback can be obtained, for the particular problem, using a statistical approach[13]. A finite-element (FE) model has been used to investigate the effects of adding a backing plate, a supporting kinematic tool and modifying the final stage of the tool path. The results show that the backing plate will minimise the sheet bending near to the initial tool contact location; the additional kinematic tool will reduce springback; and the extension of the tool path across the base of the sheet will eliminate the pillow effect. The results contribute to a better understanding of springback in SPIF[14]. Optimization of the tool path in two point sheet incremental forming with full die, in a particular asymmetric sheet incremental forming configuration can also help in getting required dimensional accuracy[15].

However, the effective production design and optimization in ISF require the efficient prediction of forming force, especially the tangential force which is the actual force component that does plastic work during the forming process[16]. The dimensional accuracy of this process is determined by comparing parts manufactured using SPIF with the part drawings used to create the manufacturing toolpaths[17]. The final geometrical accuracy of a part formed by incremental sheet forming depends on the deformation mechanisms and the residual stresses created in the part. In this regard, several studies have been reported in the literature, which investigate the forming mechanisms of the single point incremental forming (SPIF) process. Depending on the condition and experimental set-up, different research groups revealed that either membrane stretching, bending or shear deformation modes prevails[18]. The formability of sheet metal appears better in incremental forming than in conventional forming [19].

A number of scientists are currently involved in Incremental Forming investigation, in order to better understand the process and to extend its applicability to industrial practice. Study on the the formability of Magnesium AZ31 is investigated in warm Incremental Forming, focusing the attention on the tools currently utilised for describing material formability. It is shown that Forming Limit Curves fail in this goal while a study of fracture, exploiting results of conventional tensile tests, supplies more appreciable results[20]. The forming parameters for incremental forming of aluminium alloy 3003 sheet shows that incremental forming can reach very high levels of plastic deformation and that the stress±strain curves can be analysed in a manner similar to that used by Ford for the plain strain compression test[21]. The idea of incremental forming technique has been investigated for production of sheet metals. In the present study, the formability of an aluminum sheet under various forming conditions was assessed and difficult-to-form shapes were produced with the technique. By utilizing knowledge and experience obtained during the present study, it became possible to produce some free surfaces[22]. Single point incremental forming (SPIF) is plagued by an unavoidable and unintended bending in the region of the sheet between the current tool position and the fixture. The effect is a deformation of the region of the sheet in benween the formed area and the fixture as well as deformation of the already formed portion of the wall, leading to significant geometric inaccuracy in SPIF. Double sided incremental forming (DSIF) uses two tools, one on each side of the sheet to form the sheet into the desired shape. Some work explores the capabilities of DSIF in terms of improving the geometric accuracy as compared to SPIF by using a novel toolpath strategy in which the sheet is locally squeezed between the two tools[23]. Applications of sandwich panels as 3D shells are limited by the high costs of tooling required for conventional forming operations. Experiments shows that ISF can be applied to sandwich panels which have ductile and largely incompressible cores[24]. Study of the effect of some important factors (incremental step size, product angle and tool rotational speed) on the surface hardness during single point incremental forming (SPIF) of truncated cone made from (1008-AISI) workpieceshows that surface hardness of the single point incremental forming (SPIF) product is affected by the forming parameters (incremental step size, spindle speed, and wall angle of the product). The most significant parameter influencing the hardness is the incremental step size[25].

The incremental sheet forming by using water jet (ISF-WJ), shows that if the forming pressure produced by water jet is too high, it may cause high levels of deformation in a localized area resulting in wrinkling of formed parts[26]. The features of the incremental sheet forming (ISF) process allow it to meet a wide array of customer preferences[27]. Incremental sheet forming (ISF) is a highly flexible sheet forming process, but it suffers from poor geometric accuracy. Work on a feedback control strategy using model predictive control (MPC) presents improved geometric accuracy in ISF. [28]. The effects of four working parameters, namely tool diameter, tool vertical step, feed rate, and spindle speed on the dimensional accuracy, surface roughness, and microstructure of parts processed by SPIF were experimentally investigated[29]. A 2^{4-1} fractional factorial design of experiments with three replications was performed to investigate the effects of forming parameters on material formability. Interactions between step size and tool size or tool size and feed rate have significant effects in the polymer formability. Additionally, an increase in spindle speed also contributes significantly to increase formability[30]. The tool size has a significant effect on formability of thermoplastic sheets[31]. The effects of four working parameters, namely tool diameter, tool vertical step, feed rate, and spindle speed on the dimensional accuracy, surface roughness, and microstructure of parts processed by SPIF were experimentally investigated by a conic and a prismatic shape[32]. It is hoped that critical literature review will give a quick idea about the research areas in incremental forming and will provide the researchers with a clear vision and indications for the research area that they should focus on[33]. It is reasonable to hypothesise that the research in this field will continue and improve in the next years: cost reduction and environmental impact of tooling manufacturing, in fact, will be always stronger constraints that will determine an increasing interest to flexible and simpler technologies[34]. Incremental sheet metal forming in general and Single Point Incremental Forming (SPIF) specifically has gone through a period of intensive development with growing attention from research institutes worldwide. The result of these efforts is significant progress in the understanding of the underlying forming mechanisms and opportunities as well as limitations associated with this category of flexible forming processes. Furthermore, creative process design efforts have enhanced the process capabilities and process planning methods[35]. Single Point Incremental Forming (SPIF) of sheet metals is an area where industry can focus in the future due to the enormous opportunities available for automated fabrication of sheet metal parts. The productivity in the SPIF of sheet metals is less[36]. A case study with a car fender section shows that the geometric accuracy of the final part can be improved compared to single-stage forming by a combination of multi-stage forming and stress-relief annealing before trimming[37].

As recent market analysis studies have shown, accuracy is one of the most important limiting factors for the deployment of SPIF in industrial applications. The case studies described that the state-of-the-art in achievable accuracy for a number of realistic parts having different geometric complexity and produced by different tool path strategies[38]. The residual stresses also have relationship with the accuracy of the parts processed by SPIF[39]. The overall conclusion is that ISF has received the attention of the world, in particular of the automotive industry, and that most proposed or suspected applications focus on the flexibility offered by the process[40]. Dimensional deviation is observed in the region of component opening (due to sheet bending) and at the wall as well as base regions[41]. Full factorial design of experiments is very well applicable to find out the eefect of different process parameters on the response[42]. The study on main cutting variables (spindle speed, feed rate and depth of cut) shows the comparision of full and fractional factorial design of experiments shows that fraction factorial gives good result with optimum set of combination of experiments among the different process parametrs. It is concluded that the use of fractional factorial design for analyzing cutting force in turning of titanium alloys leads to quite accurate results[43].

Study of the effect of the curvature of a part's generatrix on the formability of an aluminum sheet shows that the formability increases as the radius of curvature decreases[44]. Forming tool diameter, vertical tool pitch, feed rate, and support typehave also significant ffect on forming time. The analysis results have shown that the most important parameter that has the greatest effect on the forming time is the vertical pitch followed by the feed rate and then tool diameter. The confirmation experiments have shown that the interaction between the significant parameters plays a prominent role in the negative ISMF process[45]. DM process is not capable of holding tolerances as tight as a standard milling process. This may be due to local variations in material properties that influence the yield strength and the resulting spring-back, or frictional variations in the forming tool contact. However, it is notable that the repeatability of the DM bending mode process appears to be significantly better than for SPIF of sheet metal[46]. Deformation machining process enables the creation of structures that have geometries that would be difficult or impossible to create using any other processes. A feasibility study has been conducted exploring the toolpath planning and deformation force data was collected[47]. Comparative study on dimensional repeatability and accuracy for deformation machining stretching mode components with sheet metal components shows that Dimensional repeatability of conventionally formed sheet metal components is the better than that of DM components and SPIF sheet metal components. The poor repeatability of the DM and SPIF components could be attributed the uneven redistribution of residual stresses, however this could not be confirmed conclusively. The role of residual stresses in incremental forming could be seen as a new research scope[48]. Study helps in providing an accurate compensation in the tool path for incremental bending over a wide range of process parameters, to achieve necessary dimensional accuracy[49]. Overall, stresses inDM bending and stretching mode component were compressive innature due to the dominating effect of compressive surface residualstresses generated during the thin section machining[50]. Surface roughness plays crucial role in functioning of part. In this study objective is to study the effect of different process parameters on surface roughness of the part produced.

3. Experimental Work

I. Machining centre and process parameter selection

Al 6061 aluminium alloy with plate size 150X150X10mm is used; fixture for this dimension of plate is prepared. Fixture consist of four column, top plate and bottle plate, top plate is milled upto 8mm so that the workpiece is fixed rigidly. Hole with diameter 80mm is drilled in top plate to provide space for metal to form. Figure 2 shows the fixture for experimental work. The process was performed on Machining center (Vertimach V-650) to achieve cone shape geometry as shown in figure 1. The toolpath was spiral so far as to have more uniform thickness.The blank was clamped in fixture and set up is mounted on machine tool as shown in figure 2. After loading procedure milling operation is carried out to produce floor with 2mm thickness and this floor is then form by incremental forming tool.

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 [51]. As the DM stretching mode is combination of two processes i.e. machining and forming, for the machining operation[52], [53] fixed process parameters were selected and for forming after concrete literature review four controllable parameters were selected to study [50], [54]–[56].

Table.1. Fixed level of machining parameter

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.2. Variable level of 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

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 1 shows the part drawing of the component. Aluminium alloy Al 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 3.

Figure 3 showing DM stretching mode operation where single point incremental forming tool is forming the machined floor thickness.

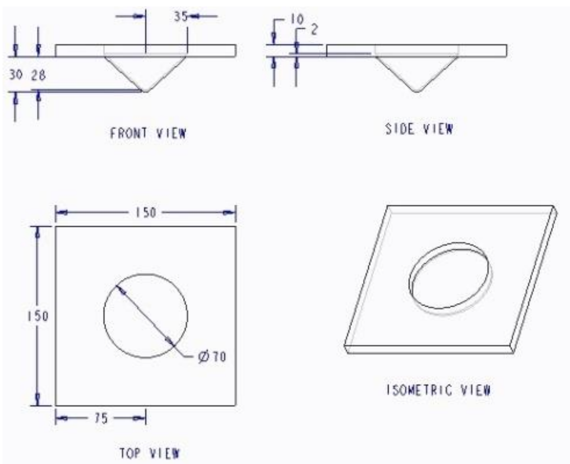

Figure.1. Part drawing of the component

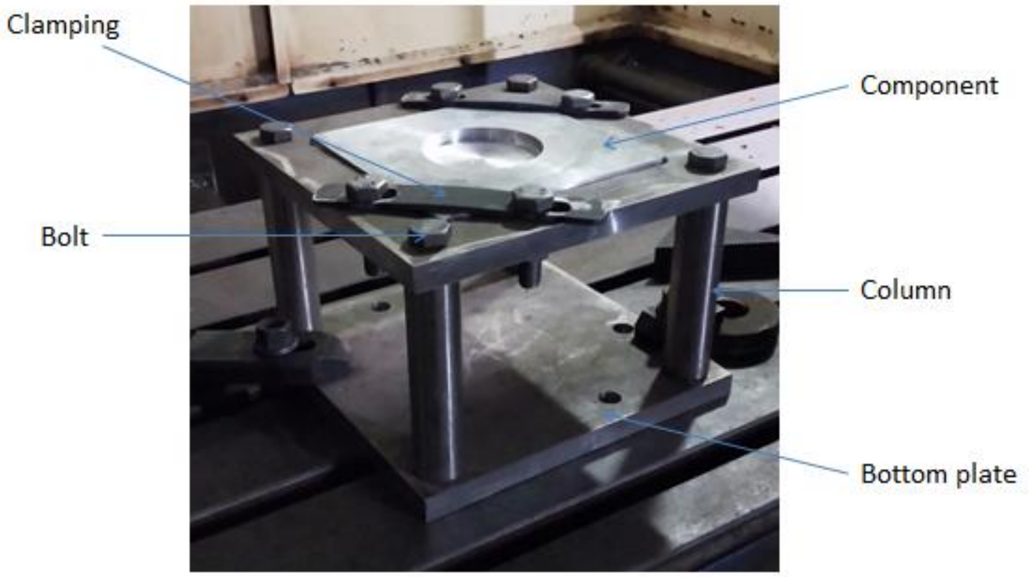

Figure.2. Setup for DM Stretching mode

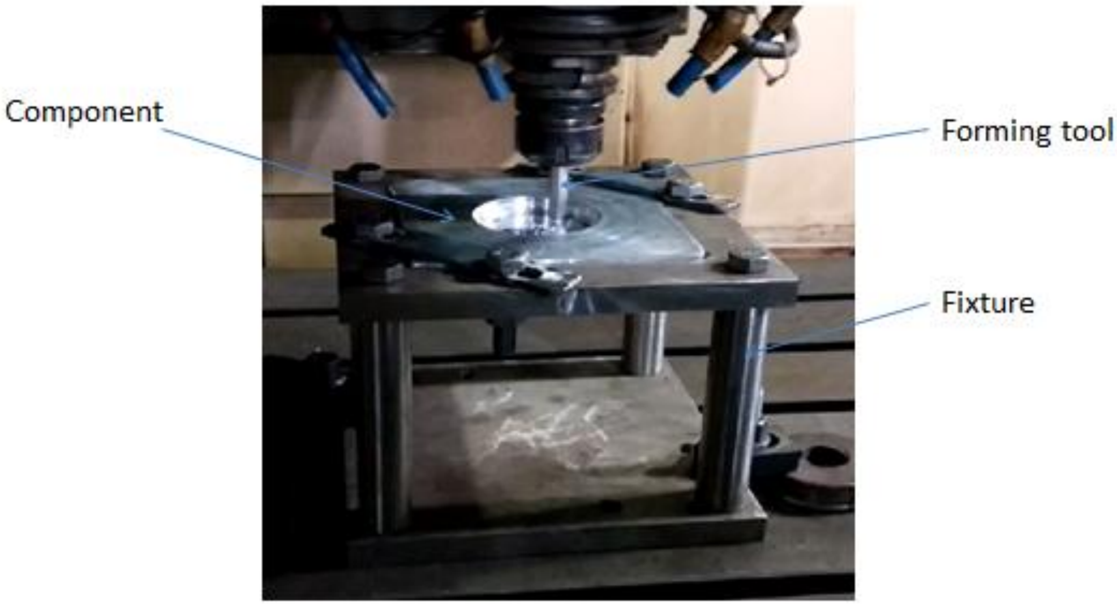

Figure.3. Forming operation

III. 2^{4-1} DOE plan with process parameter levels

To know the effect of different process parameters experimental plan is designed with 2 level of each parameter and 2^{4-1} plan is selected to optimize the experimental run. ANOVA is prepared after carrying out measurement of surface roughness. Figure 4 show the component produced with 2^{4-1} DOE plan according to the set of process parameter level and all components formed successfully. The surface roughness for all these components are measured on Surface roughness meter (Mitutoyo SJ210) the same is shown in the Table 3.

Table.3. Measured Response

Sr. No.	Spindle Speed (RPM)	Feed (mm/ min)	Incremental Step Depth (mm)	Tool Diameter (mm)	Average (μm) Ra
1	40	2000	0.08	6	1.941
2	80	2000	0.08	10	2.429
3	40	6000	0.08	10	3.665
4	80	6000	0.08	6	3.103
5	40	2000	0.12	10	3.195
6	80	2000	0.12	6	3.484
7	40	6000	0.12	6	3.285
8	80	6000	0.12	10	3.686
9	60	4000	0.10	8	2.892
10	60	4000	0.10	8	2.962
11	60	4000	0.10	8	2.922
12	60	4000	0.10	8	2.974

Figure.4. Parts form by with set of process parameters

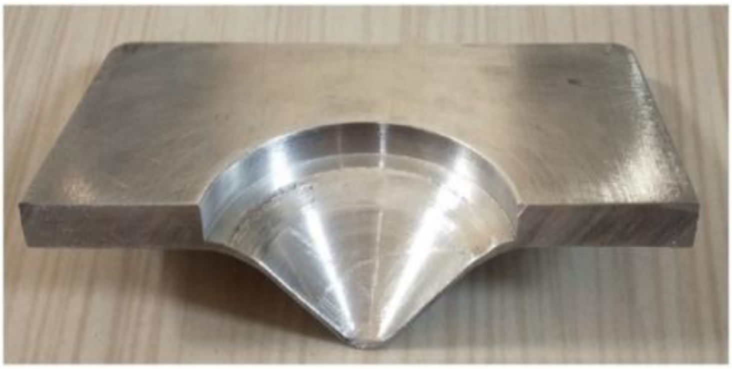

Figure.5. Cut section of the part

Table.4. Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	2.71596	0.339495	240.04	0.000
Linear	4	1.90949	0.477373	337.53	0.000
Spindle Speed (RPM), A	1	0.04743	0.047432	33.54	0.010
Feed (mm/min), B	1	0.90451	0.904513	639.53	0.000
Incremental Step Depth (mm), C	1	0.78877	0.788768	557.70	0.000
Tool Diameter (mm), D	1	0.16878	0.168781	119.34	0.002
2-Way Interactions	3	0.73735	0.245782	173.78	0.001
Spindle Speed (RPM), A*Feed (mm/min), B	1	0.10998	0.109981	77.76	0.003
Spindle Speed (RPM), A*Incremental Step Depth (mm), C	1	0.07296	0.072962	51.59	0.006
Spindle Speed (RPM), A*Tool Diameter (mm), D	1	0.55440	0.554405	391.99	0.000
Curvature	1	0.06912	0.069123	48.87	0.006
Error	3	0.00424	0.001414		
Total	11	2.72021			

Model Summary

S	R-sq	R-sq(adj)
0.0376076	99.84%	99.43%

Regression Equation in Uncoded Units:

Average Ra (µm) = -2.386 + 0.04435 Spindle Speed (RPM), A+ 0.000344 Feed (mm/min), B

+ 1.38 Incremental Step Depth (mm), C + 0.4675 Tool Diameter (mm), D

- 0.000003 Spindle Speed (RPM), A*Feed (mm/min), B

+ 0.2387 Spindle Speed (RPM), A*Incremental Step Depth (mm), C

- 0.006581 Spindle Speed (RPM), A*Tool Diameter (mm), D - 0.1610 Ct Pt

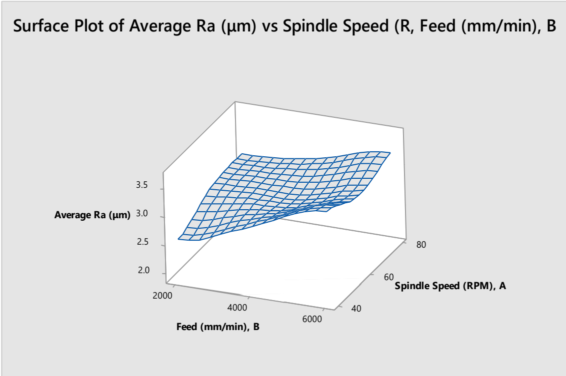

Figure.6. Average Ra vs Feed rate and Spindle speed

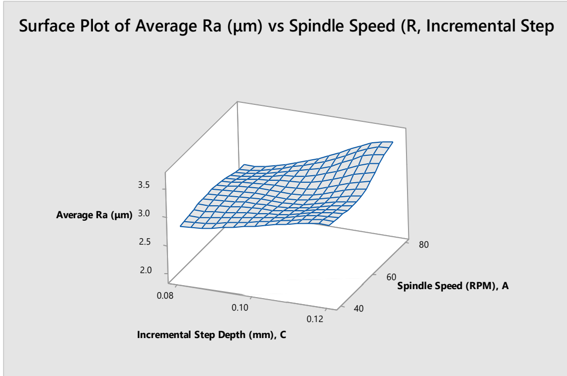

Figure.7. Average Ra vs Incremental step depth and Spindle speed

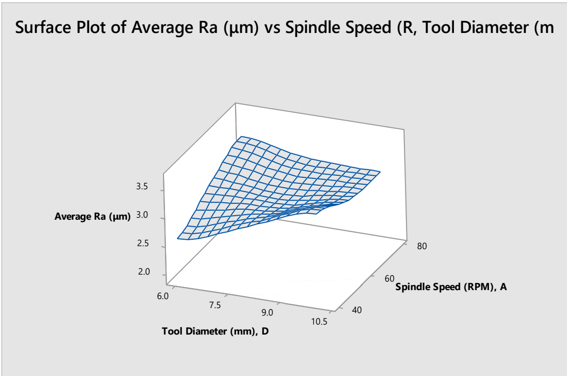

Figure.8. Average Ra vs Tool diameter and Spindle speed

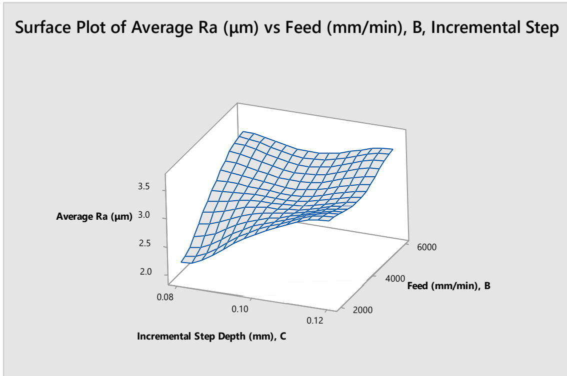

Figure.9. Average Ra vs Incremental step depth and Feed rate

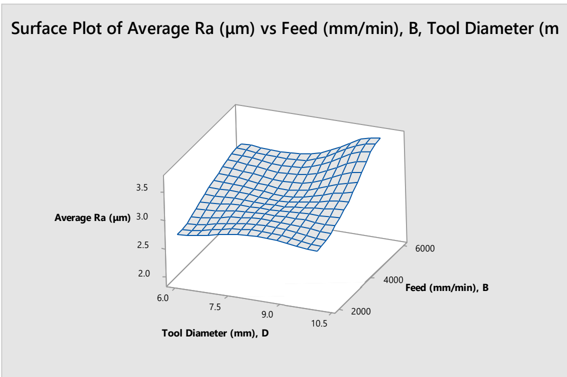

Figure.10. Average Ra vs Tool diameter and Feed rate

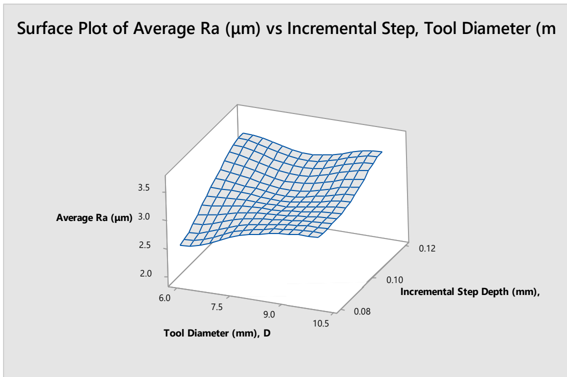

Figure.11. Average Ra vs Tool diameter and Incremental step depth

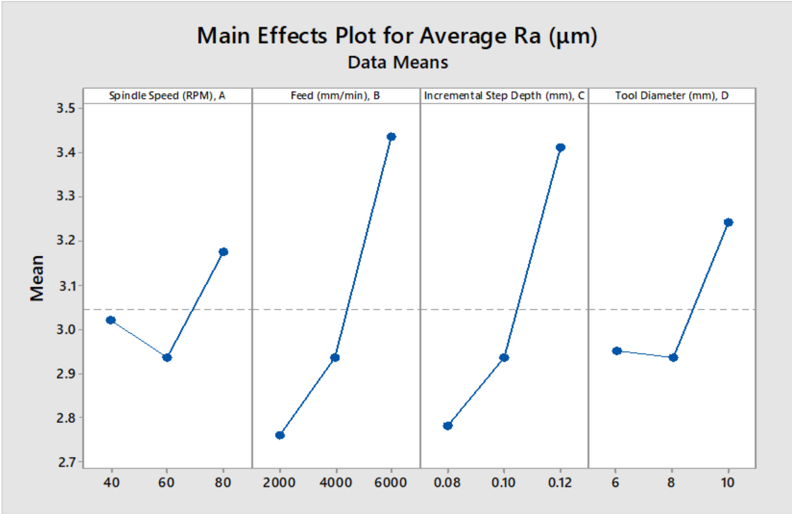

Figure.12. Main effect plot for spindle speed, feed rate, incremental step depth and tool diameter

4. Conclusion and Future Work

The design of experiment plan has been used to study the effect of different process parameters on surface roughness for the formed geometry in deformation machining stretching mode with Al 6061 plate. The results obtained is analysed through Minitab and conclusion is made from ANOVA table, main effect plot, surface plot and interaction plot.

- Spindle speed, feed rate, tool diameter and incremental step depth have significant effect on the responses.
- Feed rate and incremental step depth have more significant effect on the surface roughness followed by tool diameter and spindle speed.
- At higher incremental step depth surface roughness is more, and in case of feed rate also higher feed rate leads to more surface roughness value.
- Spindle speed and Tool diameter have less significant effect on surface roughness as compared to Feed rate and incremental step depth.
- This data may be useful to get desired surface finish for proper functioning of the form parts.

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