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# Investigation on the Effect of Process Parameters During Hot Incremental Sheet Forming of Hard-to-Form Material

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**Abstract**: The manufacturing sector plays an essential role in satisfying society's needs and provides a catalyst for the country's progress. In the manufacturing and machining industry, there are new technologies. In the metal forming industry, the single point incremental forming is new technology. In SPIF single point tool is used to form the material without the use of an external die. Heat-assisted incremental forming is an advancement in single-point incremental forming, which enhances the formability of the material. In this experimental work, titanium material is formed by a heat-assisted single-point incremental process with the hemispherical tool at a different temperature, feed rate, step size, and lubricant on the vertical machining centre. The effect of these parameters on formability and surface roughness of material is analysed Using Taguchi design. ANOVA is used to assess which parameter substantially impacts the surface roughness of the material and assess the difference between statistical and mathematical experiment data for confirmation using regression analysis

**Keywords** Hot incremental sheet forming, lubricant, coil heating system, formability, spring back, surface roughness, sheet thinning.

## I. INTRODUCTION

A sheet metal component, often made by the form and dimensions of the component, is formed using dies and punching. This typical approach is suitable for mass production because a large number of products share the cost of dies and punches.[1] Incremental sheet forming is a process in which the deformation is done in steps. When the single point tool is used in the incremental forming process that’s called single point incremental forming. The technique of conversion of a flat sheet of metal into a contoured final geometry using one deformation point is a single point incremental forming (SPIF). It makes it possible to shape a sheet metal in three dimensions without a high-cost die. This property of die-less formation can lower the costs of small lots and prototypes drastically.[2] Using a Numerical Control (NC) machine and a part program, incremental forming is a die-less sheet metal forming method. The cumulative impact of the local deformations generated on sheet metal leads to the desired final shape. SPIF provides higher process flexibility and substantial potential to reduce costs for die fabrication in prototypes and low-volume production since the tooling is different from traditional farming. When compared to standard sheet metal forming, the incremental forming technique provides a higher formability limit.[3] Computer numerical control machines are used for the SPIF. The CAD model of the required part geometry is prepared and according to it, the part program is obtained. That part program is fed into the CNC machine and the tool is moved according to the part program. We get the required geometry at the end.

J. Jesweit et al. [4] have performed an Experiment with Al AA3003-O with a Hemispherical ended tool with different diameters and different part wall angles and evaluated formability and Surface roughness. Toshiyuki Obikawa et al. [5] have experimented with two different thicknesses and with water as a lubricant and evaluated the effect of that. G. Husaain et al. work with Titanium with a hemispherical tool with different Diameters and different too[6]l material and conclude that the HSS tool recommended for Ti and tool diameter has no remarkable effect. S. Dejardin et al.[7] compare the experimental profile, theoretical profile, and numerical profile and obtain that all profile is nearly the same. M. D. Vijayakumar et al.[8] have experimented with IS513Cr3 material with different tool materials, different spindle speeds, different feed rates, and different step sizes and evaluated the surface quality. G. Ambrogio et al.[9] work with the titanium grade 2 and grade 5 and evaluate the effect of feed on microstructure. Vikrant Sharma et al.[10] have experimented with different tool diameters, different step sizes, feed rates, and different program strategies and evaluated

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the effect of that parameter on formability. Sherwan M. Najm et al.[11] experiment with a flat-end tool with a different corner radius and conclude that the flat tool with a 0.1 mm corner radius gives the best result. Xu Ziran et al.[12] work with different tool shapes ( hemispherical and flat-ended) and concluded that a flat-end globe had better formability and profile accuracy. M. Durante et al.[13] experiment with aluminum alloy with different spindle speeds and concluded that with increasing spindle speed the coefficient of friction is decreased. Rahul jagtap et al.[14] experiment on Al-1050 with different tool diameters and step sizes and evaluate the surface quality. Andre Leohardt et al.[15] have to perform an experiment with global hot air heating on AZ31 and conclude that with heating forming force is reduced. Guoqiang Fan et al.[16] work on AZ31 with electric hot incremental forming with different step sizes, tool diameter, and feed rates and evaluate the formability. Gaoqiang Fan et al.[17] work on Titanium grade 5 with electric hot incremental forming with different lubricants and evaluate the surface quality. Xiaofan Shi et al.[18] have to perform electric hot incremental forming on low carbon steel with different current values and evaluate formability and surface quality. Amar Al-Obaidi et al.[19] experimented with hot incremental forming with an induction heating technique on DC04 steel and evaluated the formability and force. L. Galdos et al.[20] have to perform hot incremental forming with hot fluid on AZ31 and evaluate formability. Swarit Anand Sing et al.[21] have performed experiments with different combinations of lubricant and tool material and concluded that MoS2 as a lubricant and Tool steel for a tool is suitable for that. David Adms et al.[22] have to perform an experiment on titanium grade 5 with electric hot Spif with different tool diameters and spindle speeds and evaluate surface roughness. S. W. Kim et al.[23] have experimented with HISF with halogen heating with different temperatures, wall angles, and step size and evaluate the formability. Guoqiang Fan et al.[24] perform electric hot incremental forming on titanium grade 5 with different feed rates and evaluate the effect of it on temperature, current, and hardness. M. Honarpisheh et al.[25] have performed an experiment with electric heating on titanium grade 5 with different wall angles, step sizes, and tool diameter and concluded that increasing wall angle, step size, and tool diameter lead to a decrease the formability. S.Amini Najafabaf et al.[26] have experimented with electric heating incremental forming with different sheet thickness, spindle speed, and step size and concluded that increasing step down increases surface roughness, and roughness decrease with increasing sheet thickness. Christain S. Magnus[27] has experimented with the joule heating technique end evaluate spring back, formability, and force. P. A. P. Pacheco et al.[28] work on aluminum with the method of electric heating with different temperatures, punch dia, and wall angle and concluded that temperature increase reduces forming force. M. R. Sakhtemanian et al.[29] have performed an experiment on TC4Ti alloy heated by ultrasonic vibration with different step sizes and feed rates and evaluated the coefficient of friction and microstructure. Khanh Dien LE et al.[30] experimented on titanium with different tool diameters, step sizes, feed rates, and temperatures and evaluated spring-back, surface roughness, and formability. Zhiyuan Yang et al.[31] work on PEEK with thermal radian heating with different step sizes and temperatures and evaluate the forming force and twist angle. R. Mohanraj et al.[32] work with the titanium grade 2 with an electric heating technique with different step sizes, wall angles, and temperatures and evaluate formability. Manel Sbayti et al.[33] have to perform an experiment on titanium grade 5 with different tool diameters and temperatures and evaluate the geometric accuracy and formability.

## II. EXPERIMENTAL SETUP AND PROCESS PARAMETER

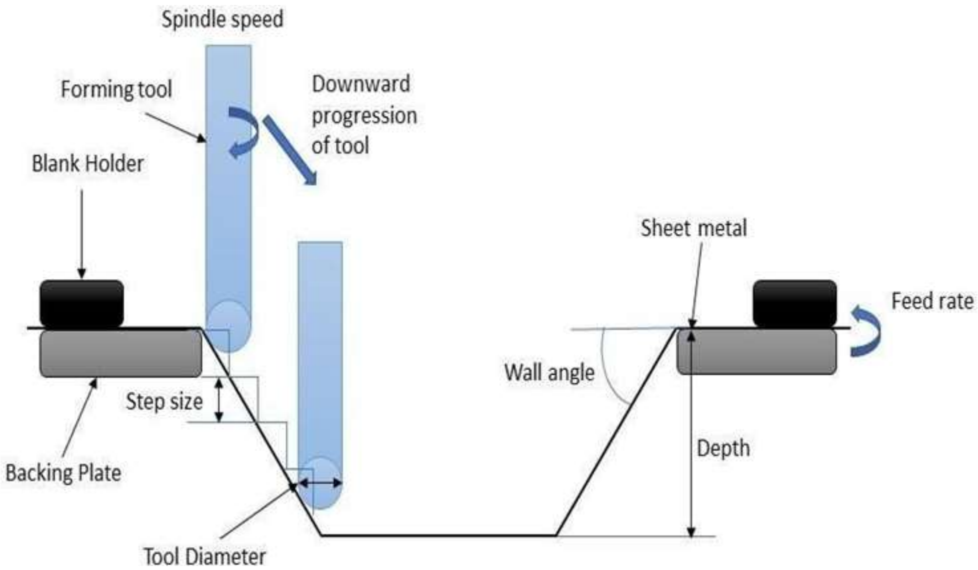


Fig. 1. Principle of single-point incremental forming

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The SPIF experimental setup with heating is shown in fig 2. The Titanium grade 2 blank material of 150 x 150 x 1.2 mm was used for the experimentation. The tool used for forming was made with tungsten carbide with a 10 mm diameter and 100 mm length.

Taguchi method is used for the design of the experiment and three input parameters as Temperature, spindle speed, and lubricant are selected same shown in table 1.

Table 1. Input parameters and their levels

| Parameter | Unit | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| **Lubricant** | | $MoS_2$ +Grease | Boron Nitride | Graphite +Grease |
| **Speed** | Rpm | 250 | 350 | 450 |
| **Temperature** | ˚C | 150 | 250 | 350 |

Mitutoyo SJ-210 surface roughness tester is used to measure the surface roughness value of the object formed. for formability, the grid marking dimension is measured with AutoCAD software and strain equations. The formed cone part is taken for the Water jet for cutting into two pieces and then the thinning was measured at the formed zone using a micrometre. spring back is measured with the help of tracing the geometry and compared with the target geometry with the help of a protector.

## III. RESULT AND DISCUSSION

The experiment was conducted on a VMC machine. The response parameter was surface roughness, formability, thinning, and spring back. The process parameter value and response parameter value are given in table 2. Formed specimens are shown in fig 3.

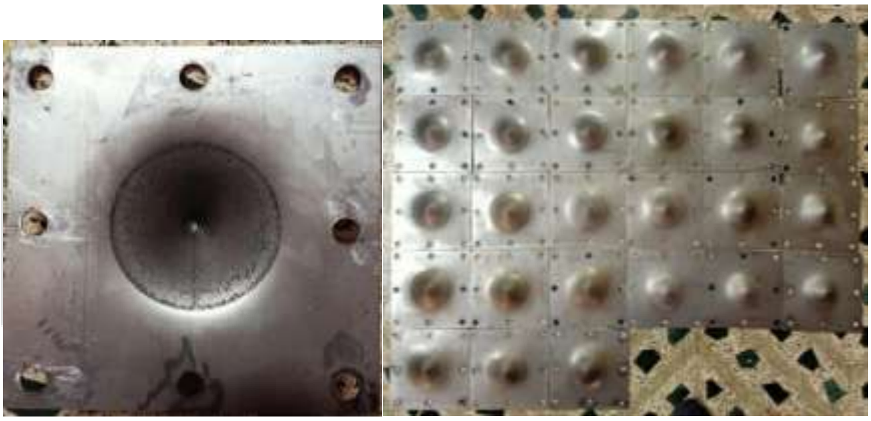

Fig. 2. formed specimen

Table 2. process parameter and Response

| No | Temperature (˚C) | Lubricant | Spindle speed (Rpm) | Surface roughness ( µm) | Major strain (%) | Minor strain (%) | Thinning (mm) | Springback (˚) |
|---|---|---|---|---|---|---|---|---|
| 1 | 150 | MoS2 + Grease | 250 | 3.365 | 12.5 | 8.56 | 0.21 | 4.363 |
| 2 | 150 | MoS2 + Grease | 350 | 4.345 | 22.5 | 2.5 | 0.24 | 4.212 |
| 3 | 150 | MoS2 + Grease | 450 | 5.055 | 20 | 2.5 | 0.27 | 3.305 |
| 4 | 150 | Boron Nitride | 250 | 6.278 | 22.5 | 2.5 | 0.23 | 3.289 |
| 5 | 150 | Boron Nitride | 350 | 7.015 | 20 | 0 | 0.25 | 3.898 |
| 6 | 150 | Boron Nitride | 450 | 8.063 | 20 | 2.5 | 0.28 | 3.351 |
| 7 | 150 | Graphite+ Grease | 250 | 2.932 | 20 | 0 | 0.22 | 3.347 |

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| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 8 | 150 | Graphite+ Grease | 350 | 2.974 | 22.5 | 7.5 | 0.245 | 4.206 |
| 9 | 150 | Graphite+ Grease | 450 | 4.376 | 20 | 5 | 0.275 | 4.187 |
| 10 | 250 | MoS2 + Grease | 250 | 2.906 | 20 | 2.5 | 0.245 | 3.263 |
| 11 | 250 | MoS2 + Grease | 350 | 3.697 | 20 | 2.5 | 0.265 | 3.245 |
| 12 | 250 | MoS2 + Grease | 450 | 4.204 | 20 | 0 | 0.3 | 2.881 |
| 13 | 250 | Boron Nitride | 250 | 6.982 | 17.5 | 0 | 0.26 | 2.663 |
| 14 | 250 | Boron Nitride | 350 | 6.208 | 22.5 | 5 | 0.28 | 3.145 |
| 15 | 250 | Boron Nitride | 450 | 7.722 | 22.5 | 5 | 0.31 | 3.043 |
| 16 | 250 | Graphite+ Grease | 250 | 2.834 | 25 | 5 | 0.255 | 3.231 |
| 17 | 250 | Graphite+ Grease | 350 | 3.242 | 20 | 2.5 | 0.272 | 2.197 |
| 18 | 250 | Graphite+ Grease | 450 | 3.714 | 20 | 2.5 | 0.305 | 1.96 |
| 19 | 350 | MoS2 + Grease | 250 | 4.302 | 20 | 5 | 0.265 | 2.375 |
| 20 | 350 | MoS2 + Grease | 350 | 4.775 | 20 | 2.5 | 0.28 | 2.283 |
| 21 | 350 | MoS2 + Grease | 450 | 4.946 | 20 | 2.5 | 0.32 | 2.227 |
| 22 | 350 | Boron Nitride | 250 | 6.374 | 25 | 2.5 | 0.28 | 3.226 |
| 23 | 350 | Boron Nitride | 350 | 8.982 | 20 | 0 | 0.3 | 2.56 |
| 24 | 350 | Boron Nitride | 450 | 9.213 | 17.5 | 5 | 0.32 | 1.563 |
| 25 | 350 | Graphite+ Grease | 250 | 4.131 | 17.5 | 5 | 0.27 | 1.489 |
| 26 | 350 | Graphite+ Grease | 350 | 5.135 | 17.5 | 2.5 | 0.29 | 1.102 |
| 27 | 350 | Graphite+ Grease | 450 | 4.533 | 17.5 | 2.5 | 0.3 | 0.396 |

### 3.1 Surface roughness

Surface roughness on the sheet is the **result of the friction between the tool and the blank material.**


Fig. 3. Surface roughness tester

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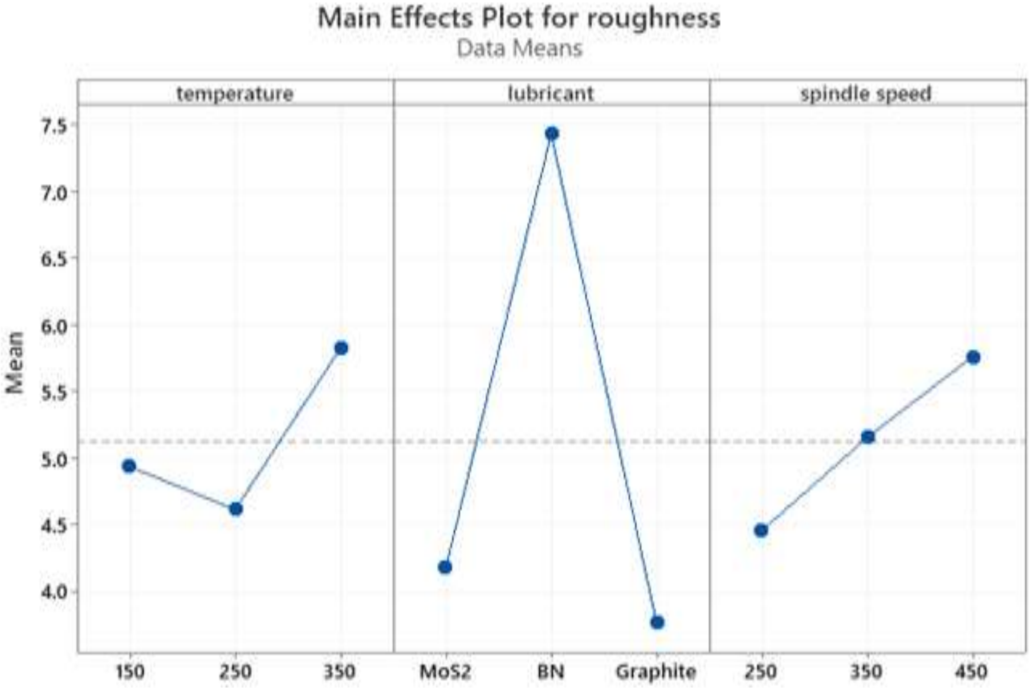


Fig. 4 Main effect plot for surface roughness

Fig. 4 shows the main effect plot for surface roughness of a 1.2 mm thick titanium grade 2 sheet formed by incremental forming with the varying value of temperature and spindle speed and different lubricants keeping incremental depth and feed constantly. Here all three parameters are significant to the surface roughness. It can be seen from this graph that by increasing the spindle speed from 250 rpm to 450 rpm there is an increase in surface roughness. This may be due to a decrease in relative motion between the tool and workpiece causing a reduction in surface roughness. There fore when the tool rotation speed is low, the surface becomes more and more polished.

From fig.4 also shows that by increasing the temperature from 150℃, 250℃, and 350℃ there is an increase in surface roughness.

Fig. 4 shows the use of graphite + grease as a lubricant to give a better surface finish because graphite is a good lubricant that withstands higher temperatures. Similarly, lubricant MoS2 + grease slightly greater value of surface roughness compared to graphite + grease. Boron nitride gives poor surface roughness as compared to the other two lubricants because the layer of boron nitride is removed during the incremental forming due to friction between the tool and the workpiece. So, the boron nitride is not recommended for hot incremental sheet forming.

The optimum condition for the minimum surface roughness is 2.834 microns for tool rotation speed 250 rpm, Temperature 250℃, and lubricant graphite + grease.

### 3.2 Formability

The formability of the workpiece is measured by the grid method according to the ASTM E2218-02. Measure the diameter with the use of AutoCAD. The elongated circle has two diameters major diameter and a minor diameter. The major diameter shows the major strain and the minor diameter shows the minor strain.

  

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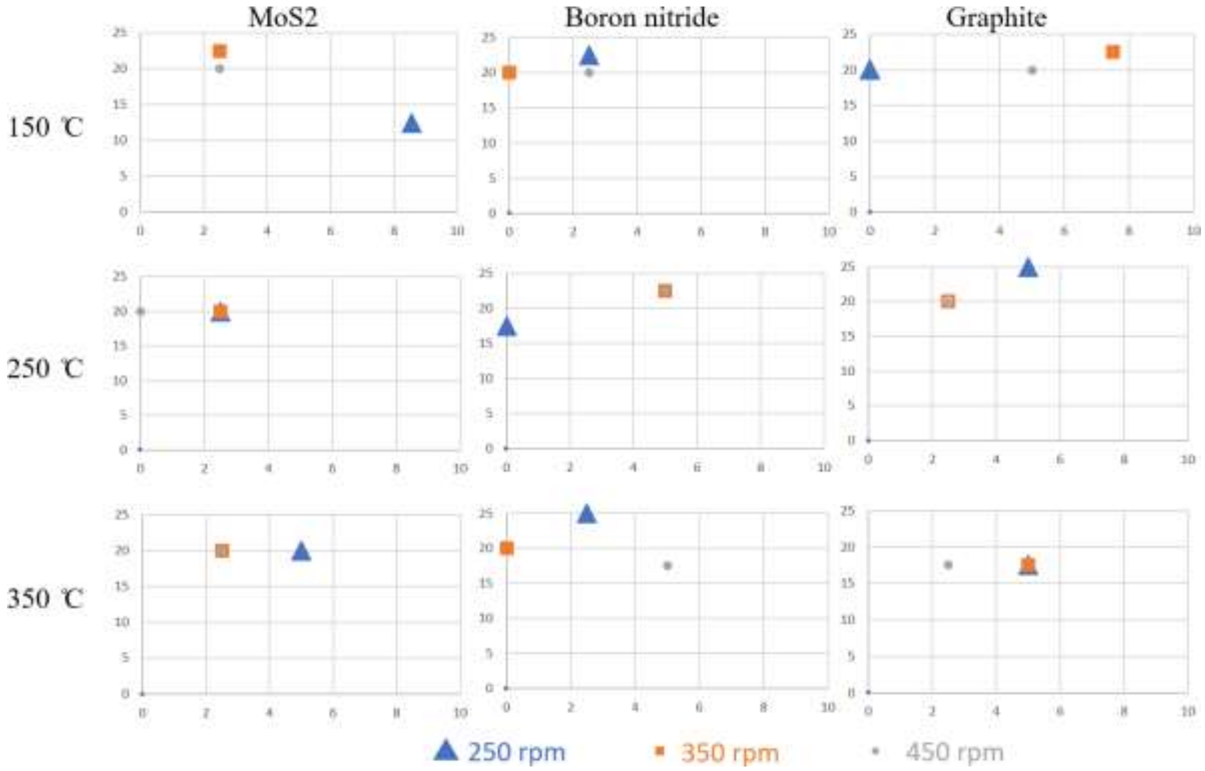

Fig. 5 Forming limit diagram (major strain vs minor strain)

Equations to measure major and minor strain

$$\text{Major strain} = \frac{(\text{Major axis length} - \text{Original circle diameter})}{\text{Original circle diameter}} \times 100 = \%\ \text{Elongation}$$

$$\text{Minor strain} = \frac{(\text{Minor axis length} - \text{Original circle diameter})}{\text{Original circle diameter}} \times 100 = \%\ \text{Elongation}$$

From the above equation, the major and minor strains are calculated, and according to it, the forming limit diagram is prepared which is shown in fig.5.

Fig. 5 shows that spindle speed has no significant effect on formability. Here the material is not formed up to the fracture limit so relative formability is observed. For lubricant graphite + grease as the temperature increases, the points on the graph shifted downward. It means that the point shifted away from the fracture line. So the material can further deform. so, can say that as the temperature increases the formability increase. This result is not shown for the $MoS_2$ + Grease and Boron nitride.

**3.3 Thinning**

The blank material during the process of incremental sheet forming undergoes some reduction in the thickness of the sheet to take the required shape. This reduction in sheet thickness is called thinning which is unavoidable in Hot incremental sheet forming but by understanding the influence of process parameters thinning could be controlled within the permissible limit. The thinning is one of the prime factors influencing the failure of the formed part.

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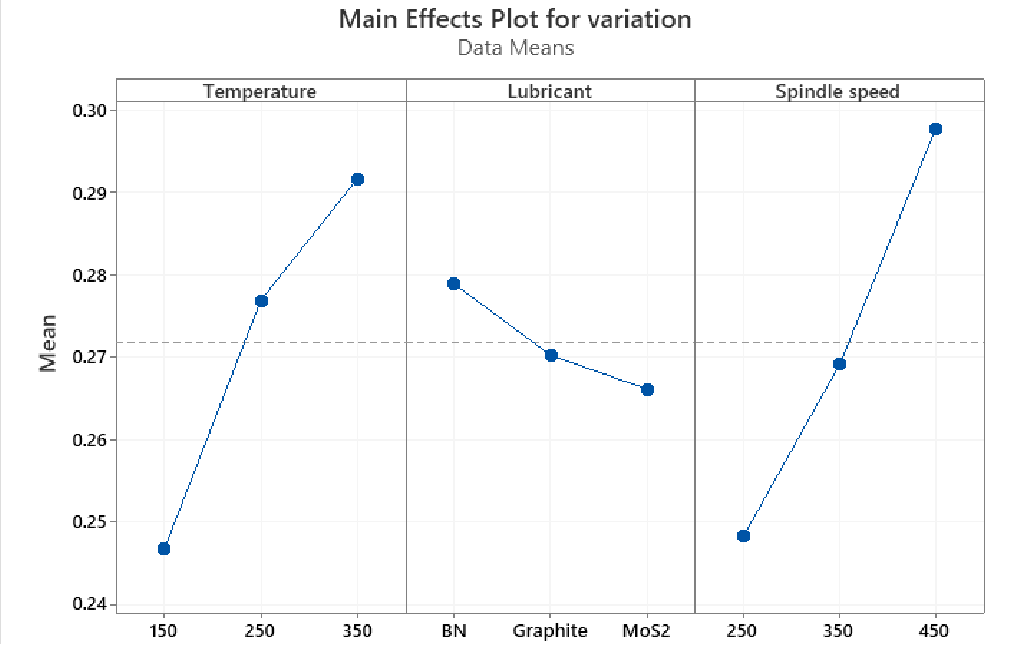


Fig. 6. Main effect plot for thinning

Fig. 6 shows the main effect plot for the thinning of a 1.2 mm thick titanium grade 2 sheet formed by incremental forming with the varying value of temperature and spindle speed and different lubricants keeping incremental depth and feed constant. It can be seen from the figure that with an increase in spindle speed, there is a reduction in the thickness means an increase in the thinning. Thickness reduction may be due to the shearing action of the tool.

Fig. 6 also shows that with an increase in temperature, there is a reduction in thinning means an increase in thinning. The increase in thinking may be due to the softening of material due to an increase in temperature which leads to more stretching of the material.

The optimized condition for minimum thinning of 0.21 mm for the temperature 150 ˚ C, spindle speed 250 rpm, and lubricant $MoS_2$ + grease.

### 3.4 Springback

Spring back is the geometric change made to a part at the end of the forming process when the part has been released from the forces of the forming tool. Here, the spring back is considered as the difference between the angle of the target geometry and the actual geometry.

Blank material during the process force is applied to the material and material is formed, after removal of the force the material tries to regain its original shape. But due to plastic deformation, the material can not come to its original shape. After plastic deformation, some of the elastic regions are present in the material due to this plastic stress the material shape is slightly changed is called spring back.

Target geometry = ϴ1
Actual geometry = ϴ2
Spring back = ϴ2 - ϴ1

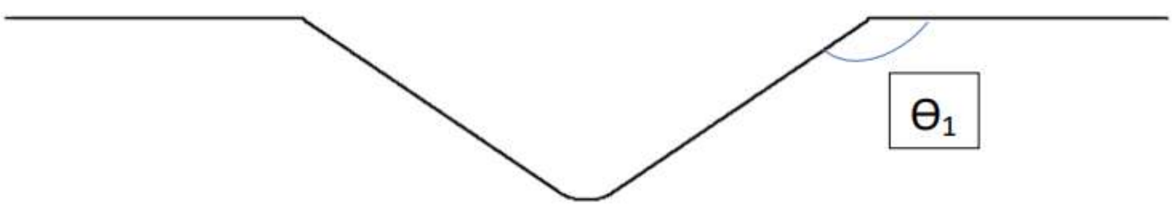


Fig. 7. Target Geometry

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Fig. 8. Actual geometry

Fig. 9 Comparison of target geometry and actual geometry

Fig. 7 shows the Target geometry of the sheet according to the part program. Fig. 8 shows the Actual geometry of the formed specimen and Fig. 9 shows the difference between the actual and target geometry.

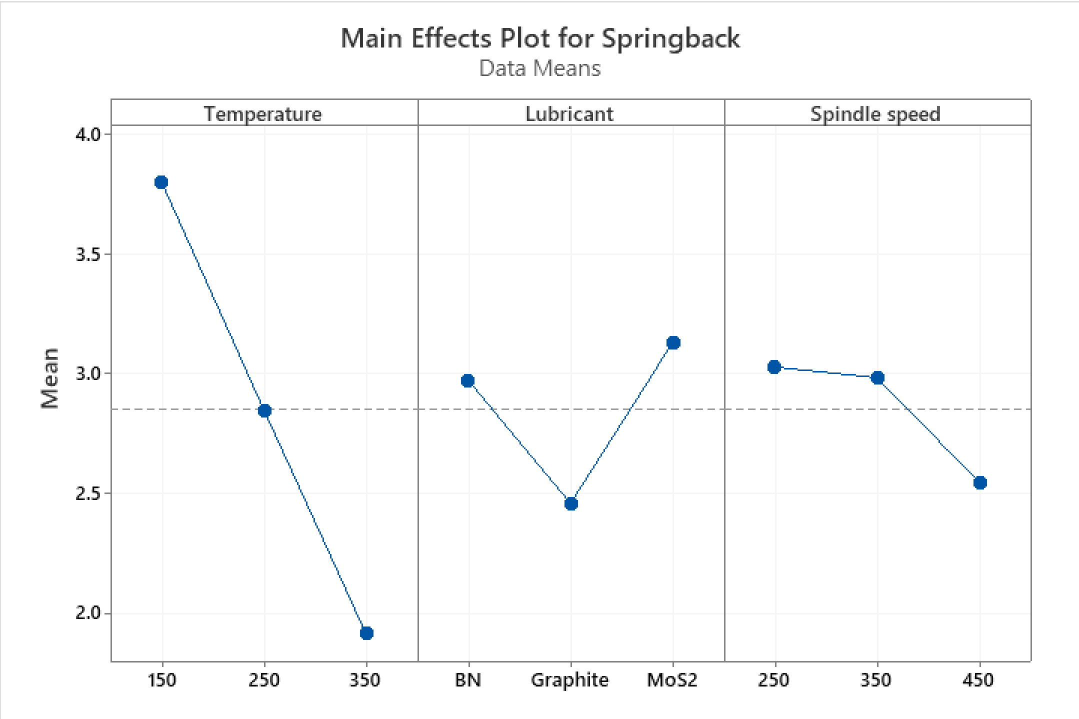


Fig. 10 Main effect plot for Springback

Fig. 10 shows the main effect plot for the Springback of a 1.2 mm thick titanium grade 2 sheet formed by hot incremental forming with the varying value of temperature and spindle speed and different lubricants keeping incremental depth and feed constantly. It can be seen from the figure that with an increase in temperature there is a reduction in the Springback means. Springback reduction may be due to temperature increase which leads to increased plastic deformation of the sheet metal.

Fig. 10 Also shows that the lubricant Graphite + Grease gives less spring back compare to the other two lubricants. Spindle speed is not significant to the spring back.

The optimized condition for minimum Springback is 0.396° for the temperature 350°C, spindle speed 450 rpm, and lubricant Graphite + grease.

## IV. CONCLUSION

In this work, the HISF behavior of titanium grade 2 sheet metal has been identified based on the effect of the process parameter selected for cone part geometry. For this work, the fixture, heating element, and hemispherical end tool used for forming are designed and fabricated. From the experiment, the observation of surface roughness, formability, thinning, and spring back are the response parameter that was discussed and tabulated.

a) The workpiece formed at a temperature of 250℃, a speed of 250 rpm; feed 1200mm/min using Graphite+Grease lubricant gives lower surface roughness of 2.834 µm as compared to the Boron Nitride and MoS2 +grease. As temperature and spindle speed increases the surface roughness of the sheet increases.
b) The major strain and minor strain are measured to evaluate the formability and concluded that as the temperature increases formability increases and there is no significant effect of lubricant on formability. There is a very marginal effect of spindle speed as compared to temperature.
c) Sheet thinning was measured to evaluate the thickness of the sheet after forming and evaluated that as temperature and spindle speed increases sheet thinning increases and a lubricant such alike MoS2 gives better sheet thickness as compared to graphite and boron nitride.
d) Spring back was measured to evaluate the deviation of the formed sheet dimension from its actual dimension and evaluated that as the temperature increases spring back decreases and graphite gives less spring back as compared to boron nitride and MoS2. Spindle speed has no significant effect on spring back

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