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# INFLUENCE OF TECHNOLOGICAL PARAMETERS ON MACHINING ACCURACY IN INCREMENTAL FORMING

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***Abstract:*** The practise of single-point incremental forming (SPIF) is an advanced flexible manufacturing process initiated during the early 2000s, and since then, extensive research has been conducted in this area. Sheets can be formed incrementally, which not only reduces the amount of energy needed and raw materials, but also allows for multiple products types to be made using the same set of resources. Investigations existed have helped provide a thorough understanding of the macro SPIF deformation mechanism. In the present paper the following aspects have been highlighted: the execution accuracy of the incrementally formed part; determining the part surface roughness; ANOVA analysis of the factors influence on precision and surface roughness. The observed deformations in the shape of the part, can be attributed to the kinematics of the forming process. These deviations are evident in the curvature radius of the part side wall, the presence of a radius of connection between the wall and the bottom of the part, and the dimensional variations indicated by the forming depth. With regards to the surface smoothness, it was noticed that the TiN coated tool yielded the most favourable roughness outcomes.
***Key words:*** SPIF, Al 3003 sheet, ANOVA analysis, influence of tehnological parameters, TiN-coated tool.

## 1. INTRODUCTION

Single point incremental forming (SPIF) is an emerging technique in the field of sheet metal forming that exhibits considerable promise in terms of its economic viability for applications such as quick prototyping and small-scale production. A simple tool with round-tipped, parabolic, flat, or hemispherical head, typically ranging in diameter from 5 to 20 mm, shape the sheet by sequential peripheral movements, in one direction, in alternate directions or in the form of a spiral, programmed on a robot arm or a CNC machine that generates the tool path. The sheet is securely fastened within the horizontal plane, while the tool is maneuvered in both horizontal and vertical directions to accurately trace the shape of the component being fabricated. As the tool undergoes movement, it gradually penetrates the sheet by incremental measurements, typically 1 mm in depth, during each traversal, thereby achieving the intended form, [1]. Numerous academic research underlined issues like geometrical inaccuracy, extreme thinning, and inhomogeneous wall thickness produced by poor forming procedures, [1, 2]. There are many sheet metal-forming processes which reflects both advantages and weaknesses, for example: *hot press forming* (hot stamping) – exhibit impact durability, less springback and distortion in geometry than cold-stamped parts; *hydroforming* - hydroforming-limit diagrams, hydro-deep drawing of bimetallic sheets, and quick tooling; *severe plastic deformation* - ultrafine grain refinement with notable improvement of mechanical characteristics; *flexible forming* - achieved by moving dies like in strip rolling without changing tooling; *light metal matrix composites* - improve constituent material properties, the newest methods being based on nanotechnology and laser sintering; *peen forming* - flexible forming process but with sheet deflection and residual stresses; *cross wedge rolling* - excellent performance in terms of efficiency, material use, mechanical characteristics but, issues such as central cavities appearance or cross-rolled goods' soundnessl, [3, 2].
Another grouping of the ISF process can be categorized into conventional and hybrid techniques, as shown in Figure 1. A concise description of the hybrid method follows.
*SPIF - Single point incremental forming* is a manufacturing technique that involves the use of a single tool to shape or deform a sheet through a sequence of small progressive deformations. This process continues until the required shape is achieved, [5-7].
*TPIF - Two-point incremental forming* is a manufacturing process that involves the use of two forming tools. One of these tools is responsible for deforming the sheet into the desired geometry, while the other tool provides support to the sheet from the back, [8-10].

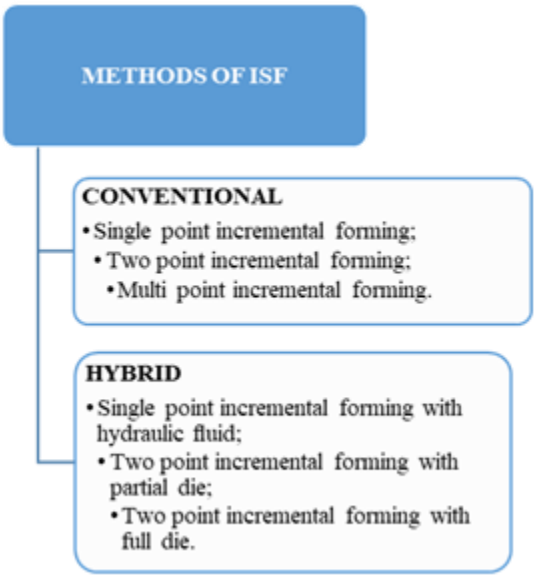



Fig.1. Classification of incremental sheet forming process, [4]

*MPIF - Multi-point incremental forming* is a flexible three-dimensional manufacturing process commonly employed for large sheets. This process involves the utilisation of two opposing rigid dies, namely the lower and upper dies. These dies are equipped with multiple punches that possess a high level of precision. The desired shape is achieved through the movement of these punches, which is facilitated by linear actuators, [11-13].
*SPIF with hydraulic fluid* process consiste in positioning a forming tool on one side, while hydraulic fluid is pumped to a high pressure on the opposite side, [14-16].
*TPIF with partial die* involves the utilisation of a partial die on one side of the sheet and a moving forming tool on the opposite side, [17-19]. On the other hand, two-point incremental forming with full die entails the application of a complete die on one side of the sheet, while the forming tool rotates on the other side, [20-22].
A comprehensive understanding of the process factors is essential for effectively controlling the incremental forming process. This information not only aids in safeguarding the integrity of the equipment and machinery employed in the process but also assumes paramount significance when utilising a robot as the forming platform. Undoubtedly, a robot is commonly characterised by a lack of rigidity in its structure. Consequently, under the influence of external forces, the robot undergoes deflection, leading to significant deviations in the tool path. These deviations, in turn, give rise to faults in the geometric properties of the produced components. One crucial measure to address in the resolution of this issue involves incorporating appropriate compensation for the anticipated deflection in the tool path, [23, 24].
The accurate estimation of the maximal forming force of the SPIF and comprehending the impact of the input parameters on this force is of utmost importance. This knowledge facilitates the proper selection of the machine equipped with the necessary nominal force. If the forming force above a specific threshold, it has the potential to cause harm for exemple to the robot arm involved in the incremental forming process [25, 26]. The research conducted by [27] demonstrated that the thickness of the sheet material significantly influences the vertical and horizontal components of the forming force in the SPIF method. The examination of the impact of various parameters on the resulting forming force necessitates considering the influence of the workpiece's wall angle, as well as the lubricant and its corresponding coefficient of friction, which should not be disregarded, [28]. Also, it has been shown, [29], that magnitude of the vertical component of the forming force is considerably greater than that of the two horizontal components. The paramount consideration in evaluating the loading of the sample is comprehending the impact of parameters on the maximal vertical force component. Regardless, the horizontal components have a crucial role in determining the strain on the drives and guides of the chosen machine.
During the process of incremental forming, the thickness of the sheet metal decreases causing fracture occurrence Typically, the greatest degree of thinning is observed in the wall segment of the workpiece, particularly in proximity to its lower radius or bottom corner. The thinning process is affected by several factors, including the initial thickness of the sheet metal, the diameter of the tool, and the vertical forming step, which refers to the tool's descent to the subsequent level [30-34]. When assessing the impact of factors on thinning, it is crucial to consider the material parameters [33, 34]. Additional phenomena such as deflection of the clamped sheet metal towards the forming direction and wrinkling of the sheet metal in the direction of its rolling can appear, [35]. In order to

enhance the precision of sheet metal formation or minimise excessive deflection in the direction of forming, it is important to position the clamping of the flange material as proximate as feasible to the initial contour of the tool path, [36].
Residual stresses in the context of SPIF are an additional component that is investigated by researchers in this field. Therefore, the issues that have been addressed include: generation of residual stresses in parts and their dependence on tool diameter and feed rate - it was observed that increasing the tool diameter resulted in a decrease in residual stresses, while the tool feed rate did not have a significant effect on this ones, [37]; residual stresses in double frustums of a cone and a pyramid - increasing the tool diameter and spindle speed led to a decrease in residual stresses, whereas increasing the tool step-down and feed rate resulted in an increase in residual stresses [38, 39]; X-ray diffraction to measure residual stresses on the inner and outer surfaces of the side walls of a pyramidal frustum - residual stresses exhibit a tension-compression nature, causing a notable amount of distortion upon unclamping and trimming, [40].
In the scholarly literature, several ways have been proposed to enhance geometrical accuracy by mitigating residual stress intensity. Moreover, enhancing geometrical precision can be achieved by the use of a smaller tool diameter, a reduced tool step-down, and thicker sheets [41-43].
The present study investigates the influence of tehnological parameters on the SPIF obtained results. In this regard an ANOVA analysis regarding the maximum components of force was used.

## 2. MATERIALS AND METHODS

The semi-finished products selected to be incremental formed was EN AW 3003 aluminium alloys. The sheet geometric characteristics were: 1.8mm - thickness; before cutting 6000mm – length and 2000mm – width; after cutting 240mm - length and 200mm - width; 20mm - forming depth; 85mm -side of pyramid trunk; 55° - pyramid wall inclination angle. The physical properties of the sheet are available on the producer website, [44].
Experiments were conducted following a full factorial experimental design with three influencing factors each on 2 levels: increment step [mm] - 0.28 (-1) and 0.56 (+1); feed rate [mm/min] – 5500 (-1) and 8500 (+1); tool – uncoated (-1) and coated with TiN (+1). Table 1 highlight the experimental plan of the present research.

Table 1. Experimental plan of the study

| No. exp. | Tool | Feed rate, *Vs [mm/min]* | Forming step, *Pi [mm]* |
|---|---|---|---|
| 1 | -1 | -1 | -1 |
| 2 | -1 | -1 | +1 |
| 3 | -1 | +1 | -1 |
| 4 | -1 | +1 | +1 |
| 5 | +1 | -1 | -1 |
| 6 | +1 | -1 | +1 |
| 7 | +1 | +1 | -1 |
| 8 | +1 | +1 | +1 |

ANOVA method with MiniTab software package (17.1.0 version) was used for statistical processing and determining the influence of factors.
The Kuka KR210-2 6-axis robot was chosen for the purpose of tool movement in the incremental forming process. The robot came with a KR C2 controller, specifically utilizing SprutCam software in its X version. The assessment of wall thinning and deformations was conducted using the Aramis measurement system.
Two types of tools with a diameter measuring Ø12mm were utilised in this study: an uncoated tool (that exhibits a hardness level ranging from 55 to 60 HRC) and a tool coated with titanium nitride (TiN) that exhibits a superficial hardness of 2300 HV.
The Erichsen method was employed to conduct tensile and compression tests on the semi-finished product. The samples utilised in the punching test were rectangular in shape, featuring dimensions of 50mm on one side and 300mm on the other side. The condition of the test sample is determined by the corresponding material standards. Prior to conducting the test, no machining of the samples was performed due to the potential impact on the material's drawability and subsequent influence on the test outcomes.

## 3. RESULTS AND DISCUSSION

### 3.1. Execution accuracy of the incrementally formed part

To measure the depth of the piece, a theoretical straight area (dotted green line) was considered as a basis, as can be seen in Figures 2 and 3.

The current investigation indicates the formation of a deviation in wall structure that is defined by a convex curvature of the wall. The occurrence of this form deviation can be attributed to variations in the forming force during the process, an increase in cold hardening (resulting from reduced spring back), and material thinning. Consequently, at the processing initial stages, the magnitude of $F_z$ is smaller, resulting in lower material deformation and subsequently a smaller forming angle. At the point of maximum forming depth, the thinning of the wall reaches its maximum extent. Simultaneously, the force required for the forming process also reaches its highest value. This force is a determining factor in achieving a larger degree of deformation, ultimately resulting in the attainment of the maximum forming angle.

This variation in the forming depth can be attributed to the phenomenon of spring back, which is particularly pronounced in the Single Point Incremental Forming (SPIF) process. Two potential methods can be proposed: counter-tool use and the implementation of a thermal system capable of regulating the temperature within the deformation area. One additional factor contributing to deviations is the utilisation of robotic systems, as opposed to milling computer numerical control (CNC) machines. As stated in references [23, 45], the employment of robots might result in positional inaccuracies of the tool centre due to the elastic deformations experienced by the robot during the machining process.

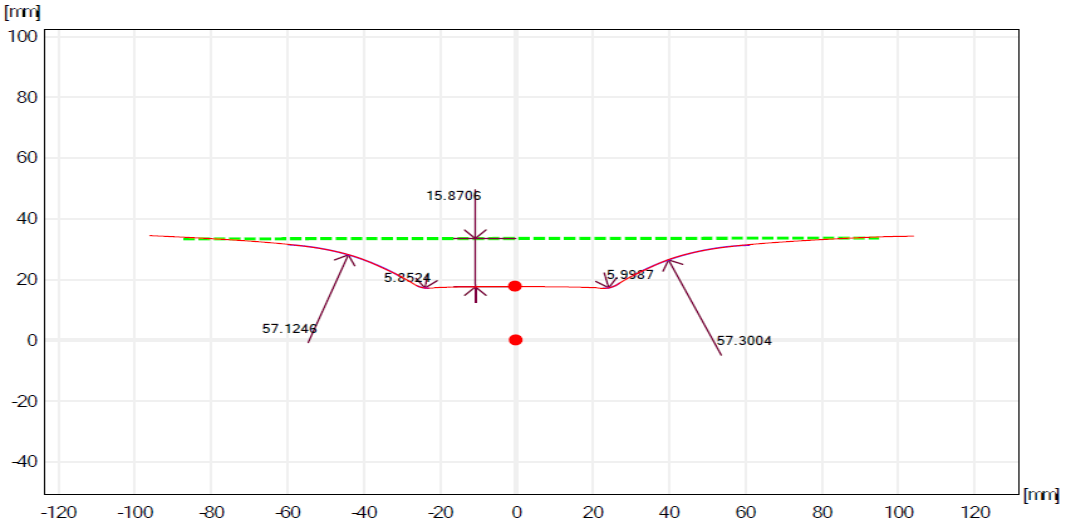



Fig. 2. Profile measurement of the obtained part, 1st experiment (uncoated tool)

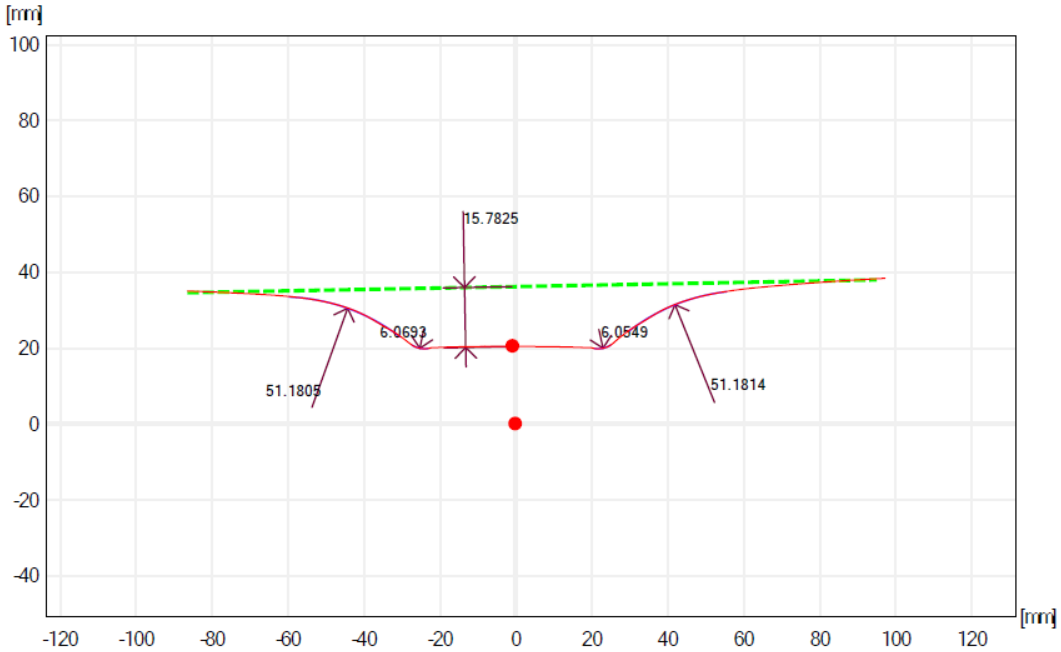
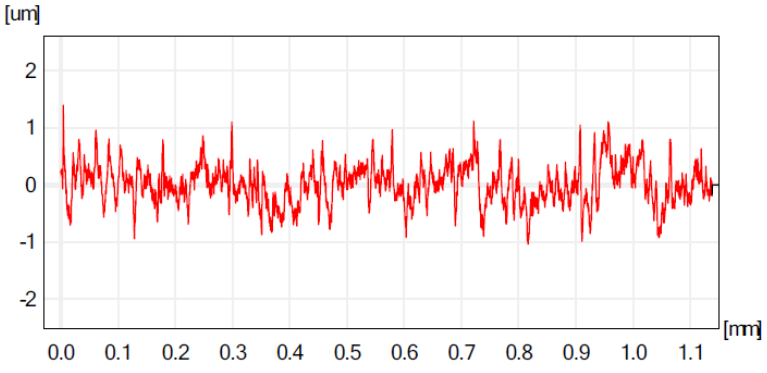



Fig. 3. Profile measurement of the obtained part, 5th experiment (coated tool)

### 3.2. Determining the part surface roughness

The surfaces achieved by the incremental forming process are subject to various elements that impact their quality, including the surface quality of both the sheet and the die, as well as any irregularities in their respective shapes. Another crucial aspect to consider is the selection and optimisation of process parameters and the the presence or absence of lubrication. The last one, is crucial because to the potential temperature rise resulting from friction between the tool and the sheet, which can significantly impact the roughness of the machined surface. In this study, an aluminium alloy sample was utilised, together with a 10W40 engine oil. To assess the surface quality of the produced parts, measurements of roughness parameters $R_a$ (µm) and $R_z$ (µm) were conducted for all experimental samples, but, in the present study are presented only experiments 1 and 5, first for the uncoated tool and the second for the titanium nitride coated tool, (Figures 4 and 5). It is evident that the utilisation of a TiN coated tool resulted in improved surface smoothness of the produced components.

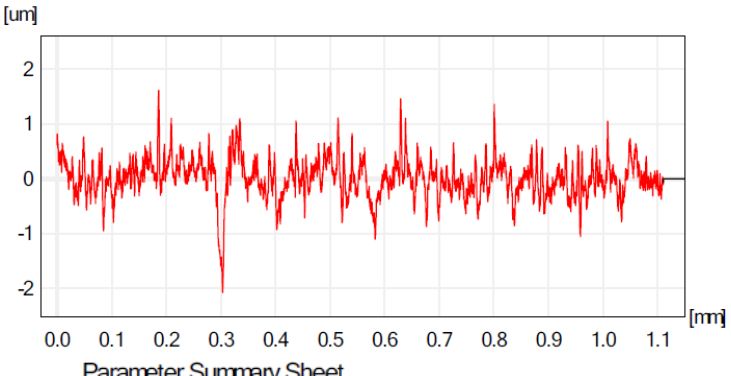
The tool case with the TiN coating achieved enhanced surface smoothness as a result of its higher superficial hardness, which effectively decreased local deformation in the contact area between the tool and semi-finished product. Thus, the tool coated with TiN had a reduced roughness (Ra = 0.26µm) compared to the uncoated tool, which had a roughness value of Ra = 0.27µm.




Parameter Summary Sheet

| Parameter | Profile=R_VDA - Section=[1] | Average Value |
|---|---|---|
| Ra (um) | 0.2749 | 0.2749 |
| Rz (um) | 2.0425 | 2.0425 |
| RSm (mm) | 0.0261 | 0.0261 |

Fig. 4. Roughness values for the part from 1st experiment (uncoated tool)




Parameter Summary Sheet

| Parameter | Profile=R_VDA - Section=[1] | Average Value |
|---|---|---|
| Ra (um) | 0.2630 | 0.2630 |
| Rz (um) | 2.5076 | 2.5076 |
| RSm (mm) | 0.0252 | 0.0252 |

Fig. 5. Roughness values for the part from 5th experiment (coated tool)

### 3.3. ANOVA analysis of the factors influence on precision and surface roughness

For the analysis of the factors variance on the roughness of incrementally formed parts, the Ra parameter was used.

Table 1 shows the measured part profile values for each experiment.

Table 1. Values of dimensional and shape deviations, roughness of the incrementally formed part

| No. exp. | Forming depth deviation (mm) | Left large radius Rms (mm) | Right large radius Rmd (mm) | Roughness Ra (μm) |
|---|---|---|---|---|
| 1 | 4.129 | 57.125 | 57.300 | 0.275 |
| 2 | 4.482 | 63.096 | 64.095 | 0.313 |
| 3 | 4.086 | 55.990 | 57.612 | 0.298 |
| 4 | 4.933 | 60.120 | 60.061 | 0.384 |
| 5 | 4.218 | 51.181 | 51.181 | 0.263 |
| 6 | 4.300 | 59.434 | 57.694 | 0.438 |
| 7 | 3.938 | 56.983 | 56.205 | 0.221 |
| 8 | 4.374 | 58.048 | 58.080 | 0.328 |

### *Influence on the deviation from the forming depth, Δh*

To determine the precision of the forming depth, the deviation from the forming depth, Δh, was used as the difference between the value prescribed in the drawing (20mm) and the actual one, defined by measurement. The ANOVA study of the factors variance on the deviation from the formation depth, Δh, is presented in Table 2.

Table 2. Analysis of the factors variance on the deviation from the forming depth, Δh

| Factor | Freedom degrees (DF) | Adj. MS | F value | Significance threshold, p | Statistical significance* |
|---|---|---|---|---|---|
| Tool | 1 | 0.369198 | 7.77 | 0.049 | S |
| Feed rate, Vs | 1 | 0.002464 | 0.05 | 0.831 | NS |
| Forming step, Pi | 1 | 0.089973 | 1.89 | 0.241 | NS |

* S - statistically significant; NS - not statistically significant

The only variable that exhibits statistical significance is the used instrument type with p = 0.049. Figure 6 illustrates the impact of several factors on the deviation from the cure depth, denoted as Δh. The utilisation of a titanium nitride (TiN) coated well results in a decrease in the deviation from the cure depth.

### *Influence of factors on left large radius, Rms*

The part wall that is being formed incrementally is curved, which shows that the shape is not straight. Most of the time, to find this deviation, it should be measured the longest arrow that connects the part's real (curved) profile to its theoretically straight wall. This is hard to do, so the radius of the curve was found, keeping in mind that a big radius means the profile is getting closer to being straight.

In Table 3, it can be seen the outcomes of the ANOVA test that looked at the differences between the factors on the left large radius, Rms. The tool type is the only factor that is statistically important, p = 0.047.

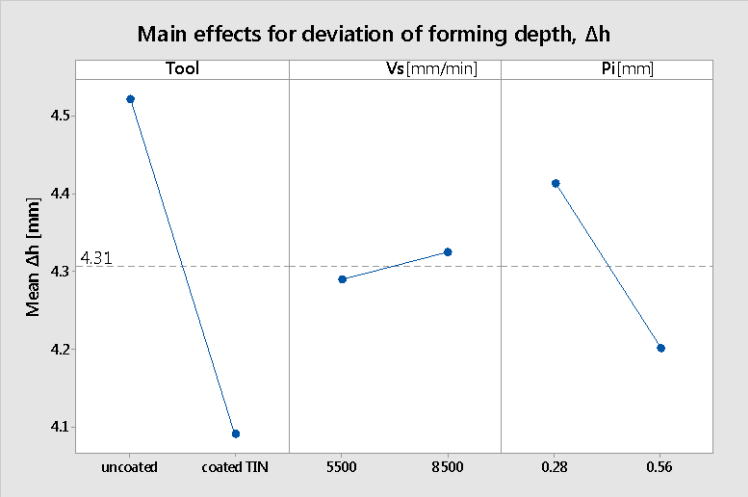



Fig. 6. Influence of factors on the forming depth deviation

Figure 7 is a graph that shows how the factors changed the left large radius, Rms. When it is used as an uncoated tool, it can obtain a big radius, which means the profile is closer to what it should be. This difference goes down as well when the increment step is increased.

Table 3. Analysis of factors variance on the left large radius, Rms

| Factor | Freedom degrees (DF) | Adj. MS | F value | Significance threshold, p | Statistical significance* |
|---|---|---|---|---|---|
| Tool | 1 | 47.144 | 8.04 | 0.047 | S |
| Feed rate, Vs | 1 | 3.574 | 0.61 | 0.479 | NS |
| Forming step, Pi | 1 | 10.195 | 1.74 | 0.258 | NS |

* S - statistically significant; NS - not statistically significant

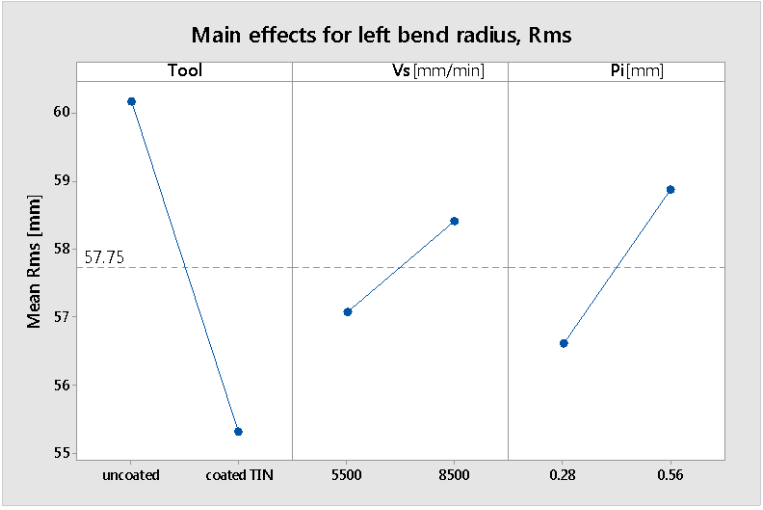



Fig. 7. Influence of factors on the left large radius, Rms

***Influence on roughness, Ra [µm]***

The Ra parameter was used to look at how different factors affected the parts roughness that were made in steps. The ANOVA test results are shown in Table 4. The only thing that has a statistically significant effect on roughness is the type of tool used.

Table 4. Analysis of factors variance on the roughness, Ra

| Factor | Freedom degrees (DF) | Adj. MS | F value | Significance threshold, p | Statistical significance* |
|---|---|---|---|---|---|
| Tool | 1 | 0.020574 | 7.39 | 0.05 | S |
| Feed rate, Vs | 1 | 0.001673 | 0.60 | 0.481 | NS |
| Forming step, Pi | 1 | 0.000049 | 0.02 | 0.901 | NS |

* S - statistically significant; NS - not statistically significant

Figure 8 is a graph that shows how the factors change the roughness parameter of the part that is being formed incrementally.

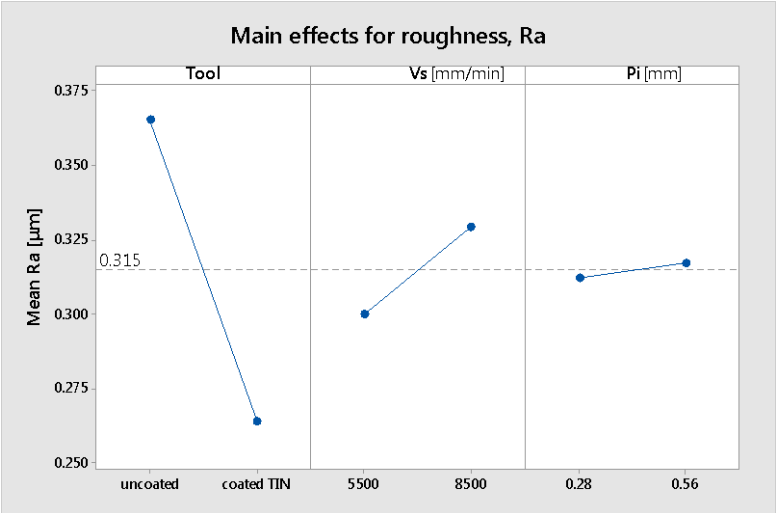



Fig. 8. Influence of factors on the roughness, Ra

## 4. CONCLUSIONS

When talking about the experimental studies, the following can be emphasised:
- the base of the part keeps tracks of the largest movement;
- the ANOVA test shows that the tool is the only factor that has a statistically significant effect on the principal-specific deformations; using a TiN-coated tool guarantees high principal-specific deformations;
- the single-point incremental forming process causes shape and size changes, mostly because of the deformed material's elastic spring back;
- using a robot to move the tool instead of a CNC machine lowers the accuracy of the machining; the robot arm is less rigid than the machine tool spindle, and it also makes mistakes with positioning.
- the measurements showed that the shape of the workpiece wall generator wasn't straight; this deviation shows up as a curve with a certain radius of curvature; the closer the workpiece wall profile is to a straight shape, the larger the radius of curvature; the machined parts, the radius of curvature of the workpiece wall profile is between 51.18 and 64.1 mm.
- a study of the factors that affect this deviation found that only the type of tool has a statistically significant effect on the radius of the curve; When a TiN-coated tool is used for machining, the radii of curves get smaller;
- because of the less stiffness and elastic spring-back of the technology, deviations of 3.94 to 4.93 mm from the depth of the boring happen. To lower these deviations, two-point incremental boring methods (such as using a counterbore, a partial die, etc.) must be used. There are also constructive solutions that use two robots facing each other and moving one forming bar at the same time.
- the factor that affect the deviation from the depth is the tool type and has a statistically significant effect. Using a TiN-coated tool lowers the deviation from the depth of probing.
- the surface roughness parameter Ra of surfaces that have been processed by incremental tooling is between 0.2 and 0.43 μm; the type of tool used is the only statistically significant factor that affects the roughness parameter Ra; surfaces that have been processed with TiN-coated tooling have lower roughness.

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