EFFECTS OF PROCESS PARAMETERS ON THE QUALITY OF PARTS PROCESSED BY SINGLE POINT INCREMENTAL FORMING

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Abstract: The objective of this study is to inspect the quality of SPIF-ed parts obtained by varying different process parameters. The effect of four parameters, namely tool radius, step size, feed rate and spindle speed on the dimensional accuracy and surface roughness is experimentally investigated. A Taguchi's orthogonal array is used to design the experiments and the ANOVA method is employed to statistically analyse the results. From the performed analysis resulted that the step size and tool radius have a significant effect on the quality of parts processed by SPIF, both in terms of dimensional accuracy and surface roughness.
Key words: SPIF, process parameters, quality of parts

1. INTRODUCTION

Single point incremental forming (SPIF) is a very simple, flexible and cost-saving alternative to the classical forming processes of metal sheets when low volume batches, customized parts or prototypes have to be manufactured (Attanasio, A. et al., 2008, Emmens, W.C., et al., 2010, Hussain, G., et al., 2009). This technology does not require dedicated expensive tools. On the contrary, the metal sheets, tightly held at the periphery by a frame situated on the worktable of a CNC milling machine, is formed by a rigid tool programmed to follow, usually, a succession of planar contours or a single spiral contour (fig. 1), (Dejardin, S., et al., 2010, Iseki, H., 2001, Park, J.J., Kim, Y.H., 2003). Since, in SPIF, the largest part of the material is unconstrained during the process, the final geometry may be very different with respect to the desired CAD geometry. Thus, the main drawback of tooling simplicity is the lack of accuracy.

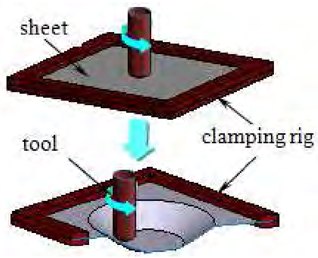


Fig. 1. The SPIF working principle [12]

A solution to overcome this inconvenient is to analyse the process parameters, to determine to what extend each of them affects the quality of the formed parts in order to find out their optimum values that lead to the expected geometry. The process parameters that are usually of interest in SPIF are: thickness of the sheet, size of the vertical step down (Δz), tool size, tool speed (spindle speed and feed rate), lubrication and material properties (fig. 2). The results presented in the specialty literature are sometimes contradictory and the influence of some process parameters on the quality of formed part is still debated. For instance some researchers claim that the size of the vertical step down does not influence formability but rather it affects surface roughness and time processing (Ham, M., Jeswiet, J., 2006) while others claim the contrary, (Jeswiet, J., et al., 2005). As concern the feed rates, according to some authors (Strano, M., 2005), slower feed rates are preferable while in a recent study (Hamilton, K., Jeswiet, J., 2010) it is shown that SPIF can be done at high feed rates, making it much more attractive to manufacturers.

The aim of this paper was to inspect the quality of SPIF-ed parts, expressed in terms of dimensional accuracy and surface roughness, obtained by varying different process parameters. Four process parameters, namely tool radius (r), step size (Δz), feed rate (v) and spindle speed (ω) were varied according to a predifenid experiment design. The results were statistically analysed by using the ANOVA technique.

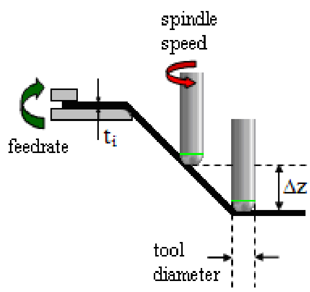
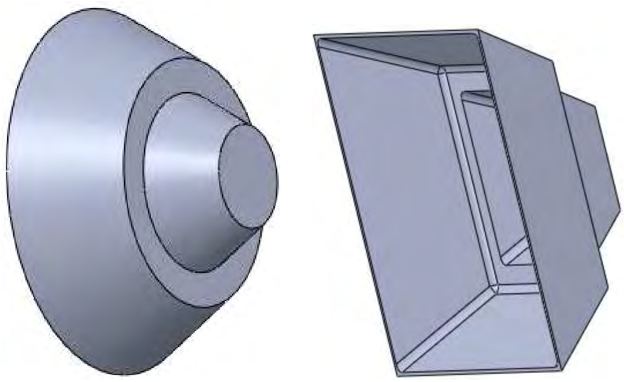


Fig. 2. The main process parameters

2. RESEARCH METHODOLOGY

2.1 Material used and geometry of part

A DC01 mild steel sheet (EN 10130:2006), with the thickness of 0.6 mm, was used as the experimental material. Two kinds of geometry were considered – a double frustum of cone and a double pyramid frustum (fig. 1) - in order to examine if the influence of the above mentioned parameters differs with the part shape.



a. b.

Fig. 3. Geometry of parts

2.2 Design of experiments and the experimental equipment

The range over which the four parameters were investigated is presented in table 1. These settings were decided after a preliminary documentation from the specialty literature and by considering the CNC machine capacity and the factor “productivity” – it is well known that the SPIF process is a time consuming process.

The experiments were designed by using a Taguchi’s orthogonal array (table 2). The tests at various combinations of process parameters were carried out on a RAPIMILL 700 CNC milling machine, equipped with a 802D Siemens numerical command. A clamping rig was mounted on the worktable of the CNC milling machine, in order to lock metal sheet during the forming process, while a spherical tool was mounted on the mandrel (fig. 4).

Fig. 4. Experimental equipment

Table 1. Variation range of process parameters

Parameter	Level	
	Low (1)	High (2)
Tool radius [mm]	3	5
Step size [mm]	0.05	0.5
Feed rate [mm/min]	1500	3000
Spindle speed [rot/min]	500	1000

Table 2. Design of experiments

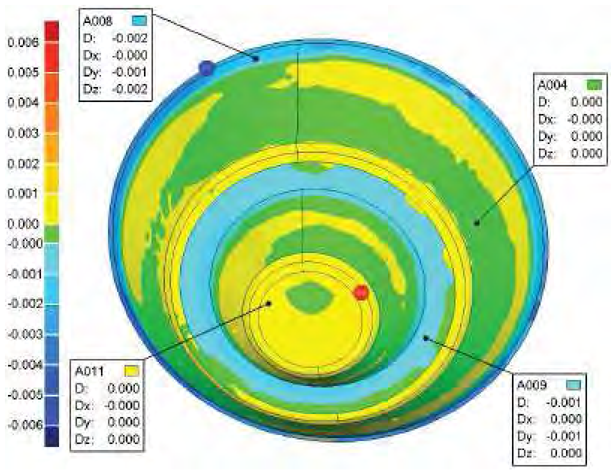
Run	r [mm]	Δz [mm]	ν [mm/min]	ω [rot/min]
1	1	1	1	1
2	1	1	1	2
3	1	1	2	1
4	1	1	2	2
5	1	2	1	1
6	1	2	1	2
7	1	2	2	1
8	1	2	2	2
9	2	1	1	1
10	2	1	1	2
11	2	1	2	1
12	2	1	2	2
13	2	2	1	1
14	2	2	1	2
15	2	2	2	1
16	2	2	2	2

3. OBTAINED RESULTS AND STATISTICAL ANALYSIS

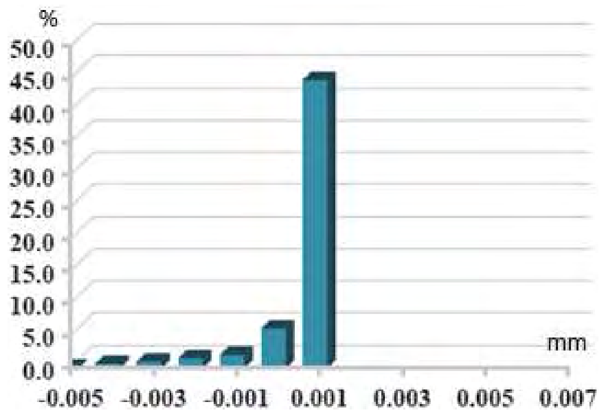
3.1 Inspection of the dimensional accuracy

In order to determine the dimensional accuracy of the obtained parts, they were scanned by using a FARO laser scanner.

The discrepancies between the obtained and designed profiles were determined with the help of Geomagic Qualify software. It allows to determine the maximum and minimum deviation, the average deviation, the standard deviation as well as the deviation distribution for the entire part (fig. 5).



a.deviations in arbitrary points of a conical part



b. deviation distribution

Fig. 5. Deviations of a part from the designed profile

Moreover, by using the sectioning option, the discrepancies from the designed CAD profile can be determined in different zone of interest (fig. 6).

The standard deviations from the designed profile of the 16 obtained parts (see table 1) are shown in figure 7. As can be seen, the standard deviations vary from 0.797 to 1.322 mm. As regard the distribution of the deviations from the designed profile, two regions could be highlighted as responsible for the bigger deviations (see fig. 6). In the region 1, the deviation of parts had values up to 5.483 mm, due to the elastic springback of material (no backing plate was used to support the metal sheet during forming). In the region 2, the deviation of parts had values up to 2.748 mm.

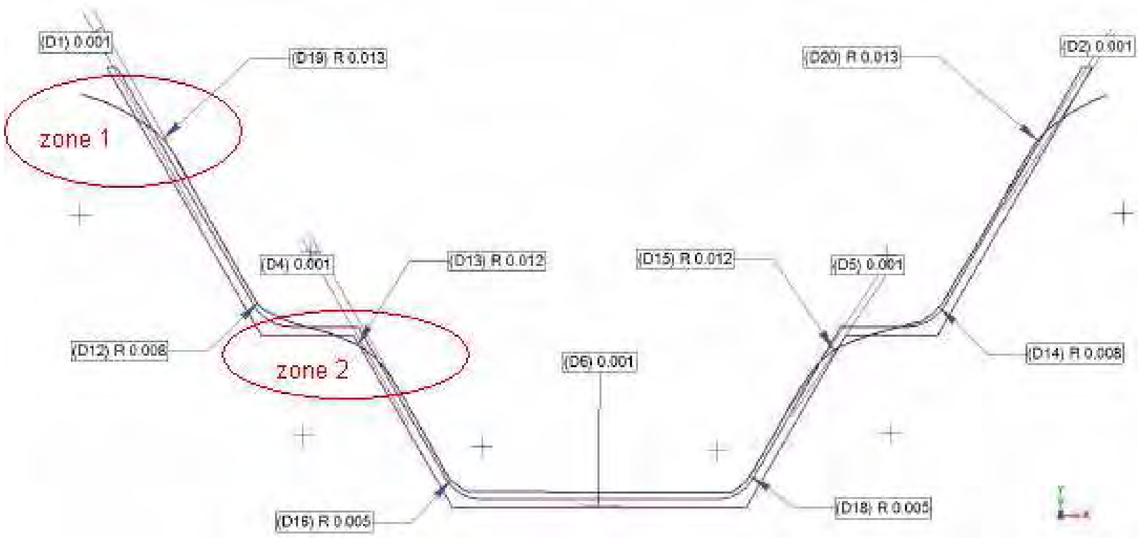


Fig. 6. Comparation between the obtained and the CAD profile in the case of the frustum of cone

It must be noted that in the case of the current geometry, it was not observed the "pillow effect" highlighted by some researches (Hussain, G., et al., 2011) when a simple truncated cone was analysed. This must be due to the smaller dimension of the part bottom, to the smaller thickness of the sheet, to the larger wall angle and to the material properties (in this study DC01 mild steel is used instead of aluminium alloy like in (Hussain, G., et al., 2011).

The effects plot of the considered factors of influence is presented in figure 8.

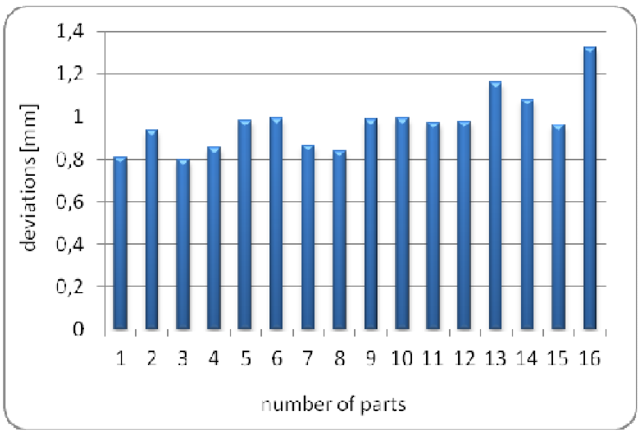


Fig. 7. Standard deviations of parts from the desired profile

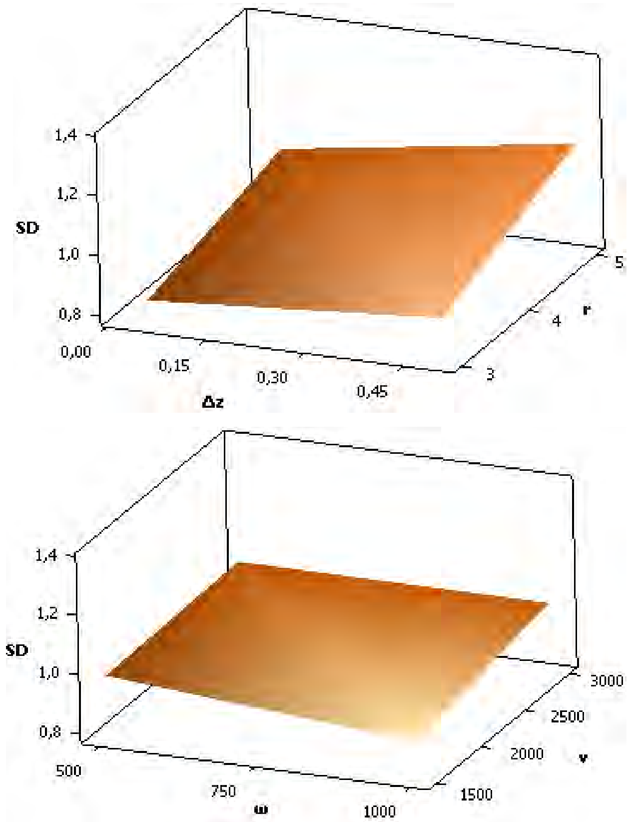


Fig. 8. Plots of the process parameters effects

The ANOVA analysis indicated that the step size and the tool radius are the most significant parameters (compared against an alpha value of 0.05). For the step size resulted a “p” value of 0.008 and for the tool radius the “p” value was equal to 0.014.
From the figure 8 it can be seen that the profile accuracy increase with a decrease in tool radius and step size. Furthermore, an increase of the spindle speed leads to positive effects related to the part accuracy while the increase of feed rates has an opposite effect.

In the case of the pyramid frustum, the deviations from the designed profile are bigger than in the case of the conical shape. Larger deviations resulted at the level of the first pyramid where a pronounced springback occurred and curved the four faces of the pyramid (fig. 9). Thus the part resulted smaller than the designed profile, the deviations being mostly negative (fig. 10). As in the case of the conical shape, no pillow effect was observed at the bottom of the pyramidal part, as was reported in (Ambrogio, G. et al., 2007).

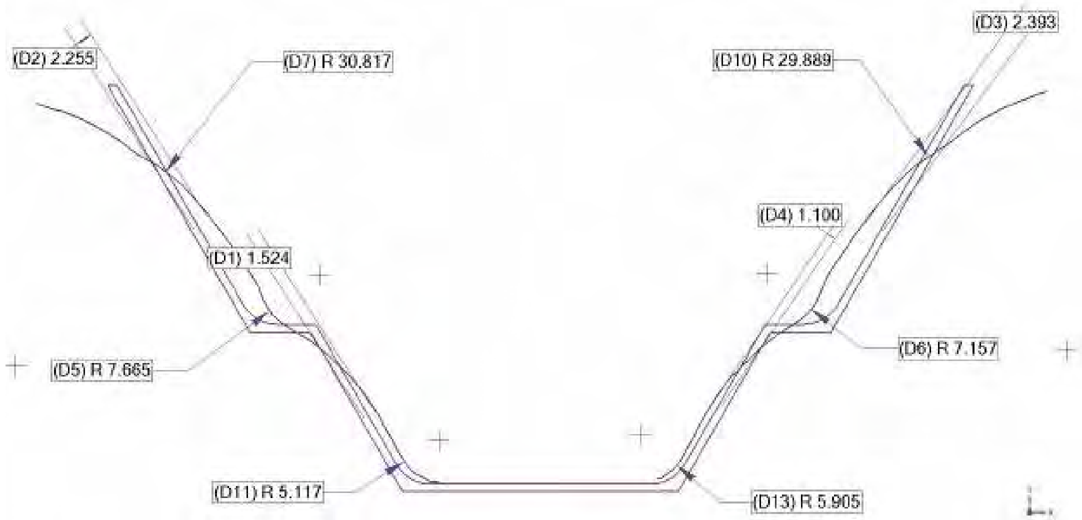
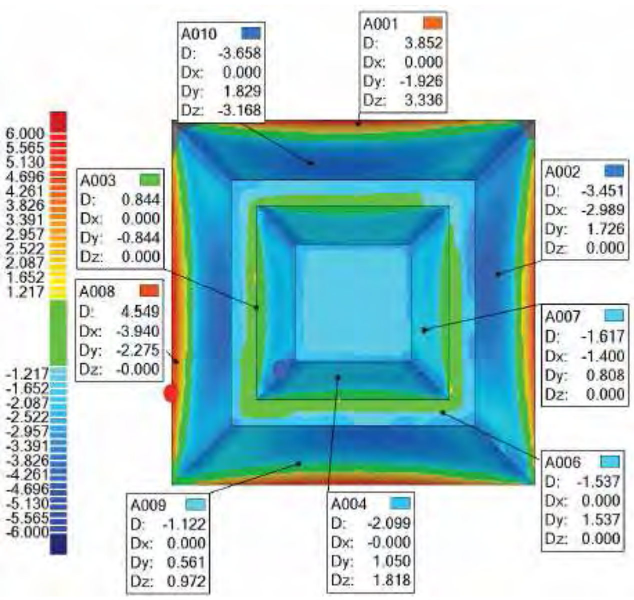
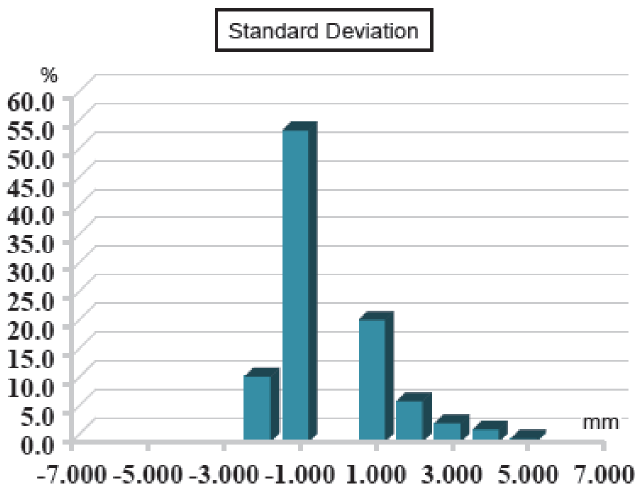


Fig. 9. Comparation between the obtained and the CAD profile in the case of the pyramid frustum

The standard deviations from the designed profile of the 16 prismatic parts are shown in figure 11. As can be seen, the values of deviations vary from 1.531 mm to 1.810 mm.
The effects plot of the four analysed factors of influence is presented in figure 12. From the ANOVA analysis resulted that again the tool radius and the step size are the most significant parameters, their corresponding p-values being equal with 0.025 for the tool radius and 0.065 for the step size. The spindle speed and the feed rate have a lower influence on the part accuracy, almost similar as intensity but opposite as effect: the part accuracy increase with the increase of spindle speed and the decrease of feed rates.



a.deviations in arbitrary points of a prismatic part



b. deviation distribution

Fig. 10. Deviations of a part from the designed profile

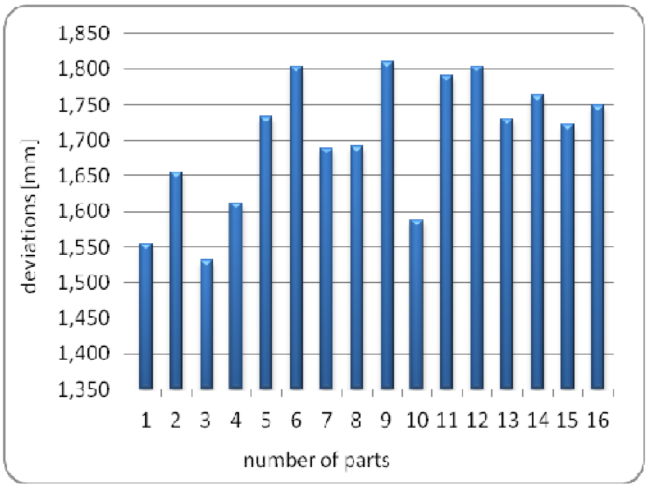


Fig. 11. Standard deviations of parts from the designed profile

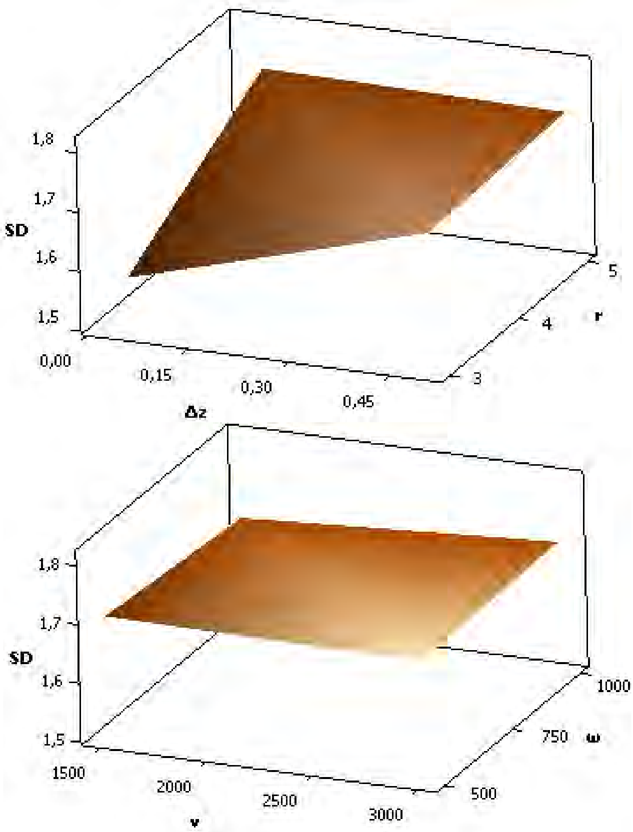
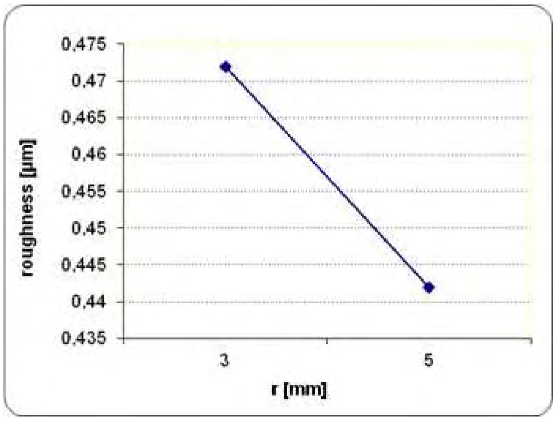


Fig. 12. Plots of the process parameters effects

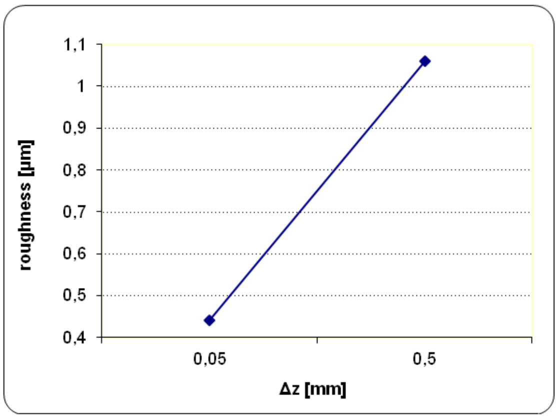
3.2 Roughness of sourface

In order to evaluate the effect of the analyzed factors on the surface roughness, measurements were made with a Mitutoyo roughness device. The investigated surface was the inner surface of the part, the one that has been in contact with the tool. Samples from different regions of the parts were cut (fig. 13) and three measurements were performed on each sample. The average of the three measured values was considered for the analysis of surface roughness. Figure 14 shows the influence of the process parameters on the roughness of the inner surface. It can be observed that an increase in tool radius and tool speed (both, spindle speed and feed rate) leads to a better surface of the formed part. On the contrary, an increase in step size determines, as it was expected, an increase of the surface roughness.

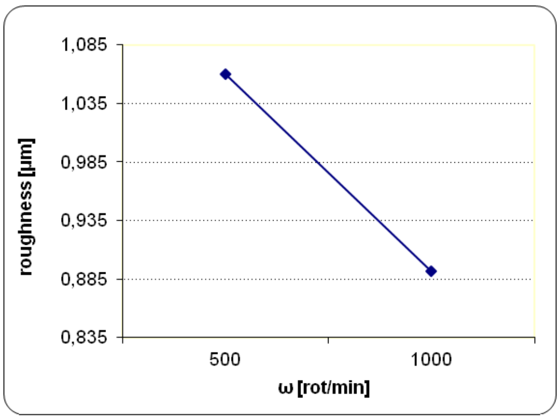

Fig. 13. Samples used for the roughness measurements



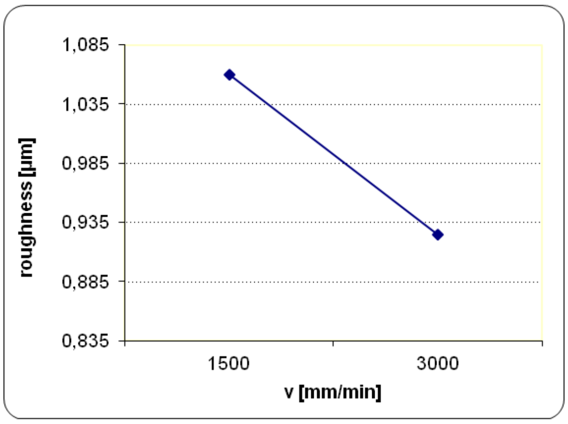
a.influence of tool radius



a.influence of step size



c. influence of spindle speed



d. influence of feed rate

Fig. 14. The influence of process parameters on the roughness of the inner surface

10. CONCLUSIONS

In this paper, the effect of four process parameters (tool radius, vertical step down, spindle speed and feed rate) on the quality of parts, expressed in terms of dimensional accuracy and surface roughness, was investigated. Two geometries of part were considered: a double frustum of cone and a double pyramid frustum.

The following aspects were highlighted:

- in the case of the pyramid frustum the deviations are larger than in the case of the frustum of cone, especially at the level of the first pyramid, where a pronounced sprigback occurred.
- among the four studied parameters, the most significant effect on the quality of parts, expressed both in terms of dimensional accuracy and surface roughness, has the tools radius and the vertical step down.
- based on the obtained results, further researches have to be carry out in order to find optimum process parameters that lead to more accurate profiles and better surface quality.

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