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MINIMIZATION OF THE SURFACE ROUGHNESS AND FORM ERROR ON THE MILLING OF FREE-FORM SURFACES USING A GREY RELATIONAL ANALYSIS

MINIMIZACIJA HRAPAVOSTI POVRŠINE IN OBLIKOVNE NAPAKE PRI OBDELAVI PROSTIH POVRŠIN Z UPORABO GREY ODVISNOSTNE ANALIZE

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The aim of this paper is to assess an experimental analysis of different tool-path strategies with respect to their influences on surface roughness and dimensional machining errors during free-form surface machining using experimental works. For this purpose, the machining of Al7075-T651 material, which is used in the production of free-form surfaces for the die-sinking sector, in particular, was examined using a ball-end mill in a 3-axis CNC machine. The effects of the tool diameters and of the rough and finished machining strategies on the presence and character of form errors and surface roughness were investigated and the results were optimized using a Grey Relational Analysis.
The results obtained from these experiments clearly indicate the influence of tool-path strategies and tool diameters on form errors, as well as the importance of the appropriate strategies for reducing the surface roughness.

Keywords: milling, free-form surface, form error, surface roughness

Namen tega dela je bil ovrednotenje analize različnih strategij orodja s stališča vpliva na hrapavost površine in dimenzijsko napako pri prosto oblikovni obdelavi na podlagi preskusov. S tem namenom je bila raziskana zlitina Al7075-T651, ki se uporablja pri izdelavi prosto oblikovanih površin, predvsem pri poglabljanju utorov, z orodjem s kroglasto glavo na tri osnem CNC stroju. Vplivi strategij premera glave orodja, grobe in končne obdelave na prisotnost in naravo napak in hrapavost površine so bili raziskani in rezultati optimizirani z uporabo Grey odvisnostne analize.
Rezultati preskusov jasno kažejo vpliv strategije poti in premera orodja na napako oblike in pomen strategij, primernih za zmanjšanje hrapavosti površine.

Ključne besede: obdelava, prosto oblikovana površina, napaka oblike, hrapavost površine

1 INTRODUCTION

Many products are designed with free-form surfaces to improve their aesthetics, which is important for customer satisfaction, particularly in the electronic and automotive industries. Furthermore, these products can have complicated surfaces to meet functional requirements, which necessitate specific aerodynamic, optical, medical, structural and processing characteristics.

The machining of free-form surfaces is a process that is both time-consuming and costly. There are more than 10,000 tool movements observed in a typical example of free-form surface machining. For this reason, the manufacture of free-form surfaces is defined as an "*error-prone*" process[1]. Consequently, selecting and controlling the cutting conditions, the cutting tools used and the strategies employed, each of which has an effect on product quality, is particularly important in order to minimize errors in the machining of free-form surfaces. Some examples of free-form surfaces and their machining are shown in **Figure 1**.

An algorithm for generating product-sensitivity-based tool paths designed for free-form surfaces was developed in the study conducted by Y-K. Choi et al.[2] The experiments were carried out under various machining conditions and the machined surfaces and designed surfaces were compared by scanning the machined parts. It was determined that the developed model and the experimental results matched.

Figure 1: Free-form surface and its machining[1]
Slika 1: Prosto oblikovana površina in njena obdelava[1]

The effects of the cutting diameter and the machining direction on the cutting force and the form error in the milling of curved surfaces were investigated in the study performed by K.K. Desai and P.V.M. Rao[3]. A theoretical model for the evaluation of the forces in the ball-end milling of curved surfaces was presented by B.W. Ikua et al.[4] Kim et al.[5] calculated the cutting force in the ball-end milling of free-form surfaces. In their study, the cutter contact area was determined from the z-map of the surface geometry and the current cutter location. It was shown that the proposed method predicted the cutting force effectively for any geometry, including sculptured surfaces with cusp marks and a hole.

Kaymakci and Lazoglu[6] have developed a new model that can be utilized as a tool incorporated with CAM software to predict 3D surface topographies, allowing the appropriate selection of the tool paths in free-form surfaces. V.G. Dhokia et al.[7] provided a predictive model using a design-of-experiments strategy to obtain optimized machining parameters for a specific surface roughness in the ball-end machining of polypropylene. This study reports on the use of new manufacturing knowledge to machine polypropylene using ball-end tooling in order to generate personalized sculptured surface products.

Antoniadis et al.[8] proposed a system for the prediction of surface topomorphy and roughness in ball-end milling for aerospace components and mould manufacture with a prediction system developed.

The literature research revealed that a large number of studies were carried out related to the machining of free-form surfaces, and these studies are still being conducted.

The majority of these studies focus on tool-path generation and the detection of and compensation for dimensional machining errors. The most important dimensional machining errors are described as the deviation from the actual geometry. A comparison method is used for the detection of the form error. This comparison method can provide a numerically designated indication of the differences between the designed surface and a scan of the machined surface[9].

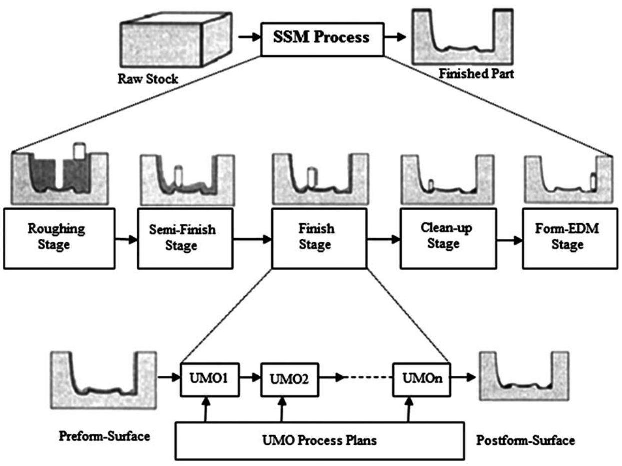

Figure 2: Stages in free-form surface machining[10]
Slika 2: Stopnje pri obdelavi prosto oblikovanih površin[10]

2 MACHINING OF FREE-FORM SURFACES

Before a surface's final form is approached, the bulk of the unecessary material must be cut away. In preparation for this process, a standard operation called a roughing cut is employed first. Afterwards, an operation called semi-roughing is carried out in order to leave a uniform amount of chip for the finishing operation. An attempt to achieve the designed surface is made by applying the finishing operation. Afterwards, any chips remaining (particularly in the curved areas and the places where the cutting tools cannot reach) are removed with a clean-up process. Finally, the areas that cannot be machined by cutting tools are worked to designated tolerances by an EDM machine[10]. These common stages in free-form surface machining are presented in **Figure 2**.

Form error is one of the most significant machining errors in free-form surface machining. Form error is defined as the deviation from an ideal geometric shape. In general, the form error varies with respect to the cutting-tool geometry, the machining strategies and the condition of the machined surface. Essentially, form error is the result of cutting forces and the displacement that these forces bring about in the cutting tool. Another critical error in terms of product quality is the surface

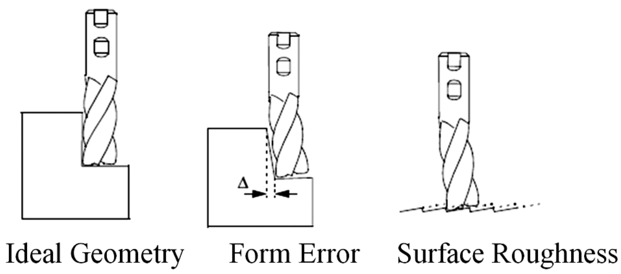

Figure 3: Effect of tool deflection on the form error and the surface roughness[11]
Slika 3: Vpliv upogiba orodja na napako oblike in hrapavost površine[11]

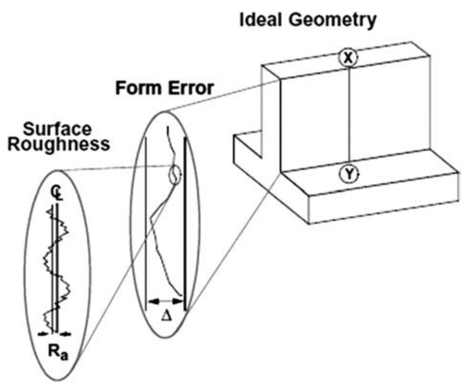

Figure 4: Deviations in form and surface quality[11]
Slika 4: Odstopanja oblike in kakovosti površine[11]

Table 1: Chemical composition and mechanical properties of the Al 7075-T6 material
Tabela 1: Kemična sestava in mehanske lastnosti zlitine Al 7075-T6

Chemical composition *w*/%	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Sn	V	Al
	0.393	0.260	1.26	0.044	1.94	0.288	0.027	5.92	0.086	0.0035	0.0087	89
	Ag	B	Be	Bi	Ca	Co	Li	Na	Pb	Sr	Zr	Cd
	0.0067	0.005	0.0028	0.001	0.048	0.032	0.347	0.015	0.0058	0.211	0.0014	0.0001
Mechanical properties	Tensile strength (MPa)			Yield strength (MPa)		Elongation (%)		Shear modulus (MPa)		Tensile modulus (GPa)		
	503			434		13		303		72		

roughness. The surface roughness and form error are shown in **Figures 3** and **4**.

3 MATERIAL AND METHOD

3.1 Workpiece Materials and Cutting Tools

The cutting tools used were chosen from the Helix Tools Catalog[12] to machine Aluminum 7075-T651. The chemical composition and mechanical properties of the Al 7075-T6 material are given in **Table 1**. Cutting tools of 6, 8 and 12 mm diameters, with two teeth, were employed for milling the experimental surfaces. Details of the tools are given in **Figure 5** and **Table 2**. The cutters were held in a BT-40 taper tool holder.

Table 2: The dimensional and mechanical properties of the cutting tools
Tabela 2: Dimenzije in mehanske lastnosti orodja

Tool diameter (d_1)	d_2	l_1	l_2	No. of Teeth	Helix Angle
6	6	80	13	2	30°
8	8	100	19	2	30°
12	12	100	26	2	30°

The experiments were conducted using a CNC Johnford VMC Model three-axis CNC milling machine equipped with a maximum spindle speed of 12,000 rpm and a 10-kW drive motor, as shown in **Figure 6**. This machine was designed to make 3-axis linear and circular interpolations via ISO format programs in metric and imperial units. Its control unit was a FANUC series O-M. The measurement of the cutting forces occurring during the machining was performed with a Kistler 9265B transducer. The CNC part-manufacturing programs were created by employing CATIA V5 R17 software on a personal computer containing an Intel Pentium IV chip and operating at 2.80 GHz. A cutting experiment was

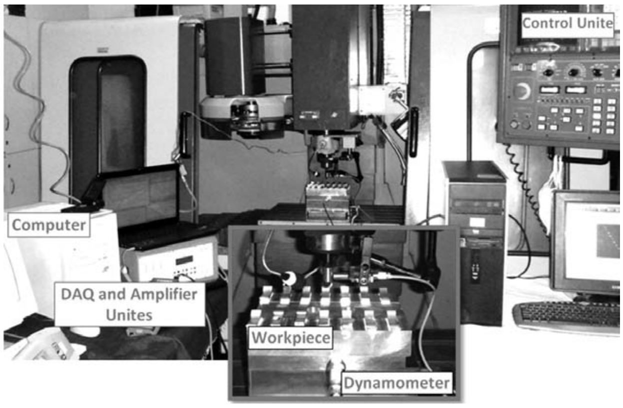

Figure 6: Experimental set-up
Slika 6: Eksperimentalna postavitev

developed to measure the tool forces using a Kistler 9257A three-axis load cell. The cutting forces were generated during free-form surface machining with a ball-end mill. The experiment involved the collection of three orthogonal channels of force data while cutting the free-form surface in a piece of Al 7075-T651 alloy using different tool path strategies and employing 6, 8 and 12 mm diameter ball-end mills.

Several program packages were used in the evaluation of the data and in the experimental design of the study. The specimen was designed in CATIA V5 R17,which is a universal software used in various industries, including aerospace, construction, machinery, and electronics.The same software was also employed, on a personal computer containing an Intel Pentium IV chip and operating at 2.80 GHz, for the creation of the CNC part-manufacturing programs used in the study. Minitab 15, Matlab and Office software programs were employed for the generation of the graphics, the analysis of the outcomes and the experimental design. Rapidform X0V2 software was used for obtaining the numerical values and the determination of the form error.

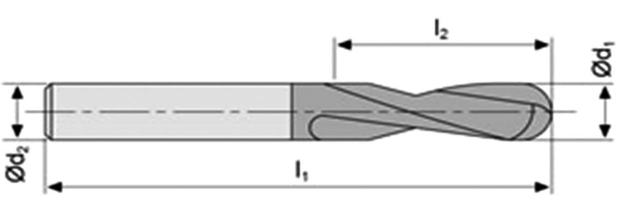

Figure 5: The ball-end milling tool
Slika 5: Orodje s kroglasto glavo

3.2 Method

G-codes were produced using a program package under machining conditions that were determined through experimental design. The remaining chip analyses after the roughing cut and the finishing operation were conducted during machining simulation in the program package. The cutting force was measured and

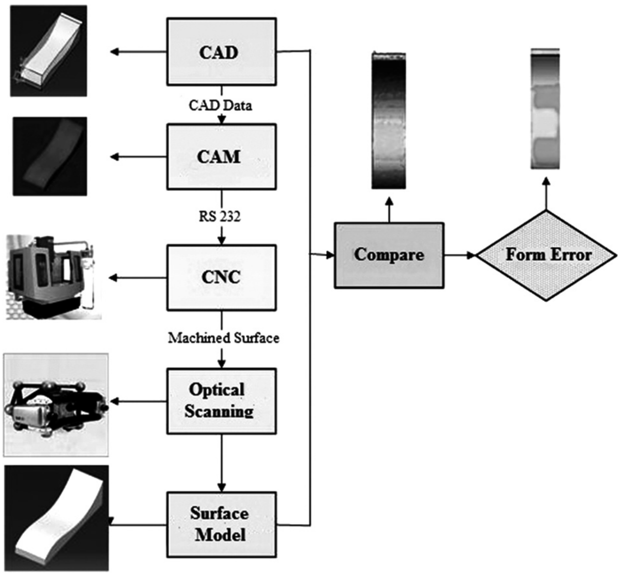

Figure 7: Stages of the form-error determination
Slika 7: Stopnje določanja napake oblike

the correlation between the remaining chips and the cutting force was determined. The comparison method used was one frequently used in previous studies for a determination of the form error in machined surfaces. In addition, surface roughness measurements were conducted. Then, the minimization of the surface roughness and the form error was achieved using a Grey Relational Analysis. The resultant form errors, the surface roughness, the correlation between form errors and cutting force and the relationship between remaining chip and the cutting force were analyzed.The stages in the determination of the form error are presented in **Figure 7**.

3.3 Grey Relational Analysis Method

While only one outcome is optimized in the Taguchi method, multiple outcomes can be optimized in a Grey Relational Analysis[8]. For this reason, the Grey Relational Analysis method, allowing optimization of multiple outcomes, was chosen in the study and the optimization process was carried out in the following three phases.

1. Normalization of experiment results (the lowest is the best)
2. Calculation of the Grey relational coefficient
3. Calculation of the Grey relational degree

The normalization operation, the first step, was conducted using the below equation according to "the-lowest-is-the-best" approach[13].

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \tag{1}$$

Here, $x_i(k)$ refers to the value at the i series and k row after normalization, min $y_i(k)$ refers to the minimum value at the i series, max $y_i(k)$ refers to the maximum value at the i series and $y_i(k)$ refers to the original value at the i series and k row[9].

A calculation of the Grey Relational coefficient, which is the second step, is done using the equation[13]:

$$\xi_i(k) = \frac{\Delta\min + \xi\Delta\max}{\Delta 0_i(k) + \xi\Delta\max} \tag{2}$$

Here, ξ is a distinguishing coefficient between 0 and 1. Studies demonstrate that the value of ξ does not affect the sorting that will occur after the calculation of the Grey Relational degree. $\Delta 0_i$ is the amount of deviation between the reference series and the normalization values. Δmin refers to the minimum value of the deviation sequence from the reference series and Δmax refers to the maximum value of deviation sequence from the reference series.

The third step, the calculation of the Grey Relational degree, determines the level of correlation between the γ_i reference series and the comparison series.This degree is estimated with the following equation[14]:

$$\gamma_i = \sum_{k=1}^{n} \xi_i(k) \tag{3}$$

3.4 Experimental Design

The cutting conditions in **Table 3** were determined by taking into account the constraints of the measurement instruments, the recommendations of the cutting-tool manufacturer and the related literature. Furthermore, the hold height was detected as five times the diameter of ball-end mill; the chip depth was determined as 0.2 times the diameter of ball-end mill maximum in the roughing cut; and the chip share left for the finishing operation was detected as 0.3 mm. The cutting speed was selected as 45 m/min for the roughing cut and 55 m/min for the

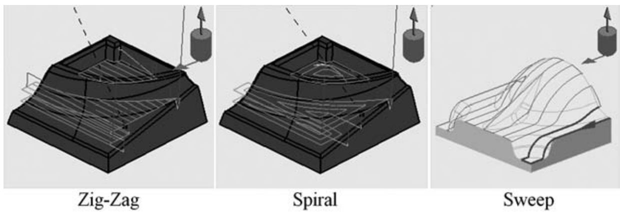

Figure 8: Machining strategies
Slika 8: Obdelovalne strategije

Table 3: Determined factors and their levels
Tabela 3: Določeni faktorji in njihovi nivoji

	Factors		
	A Cutting tool diameter (mm)	B Roughing cut	C Finishing operation
Level 1	6	zigzag_ longitudinal	sweep_upward
Level 2	8	zigzag_ latitudinal	sweep_downward
Level 3	12	spiral	sweep_latitudinal

finishing operation. Moreover, while the machining sensitivity was detected as 0.1 mm for the roughing cut, it was determined as 0.01 mm. for the finishing operation. In the experimental design method the L9 orthogonal array was selected for 3 factors and the condition, in which each factor has 3 levels (**Table 4**).

In the experiments, a zigzag and a spiral were employed as a machining strategy in the roughing cut and sweep was used in the finishing operation. The machining strategies are given in **Figure 8**.

Table 4: Experimental design according to the L9 orthogonal array
Tabela 4: Načrtovanje preskusov skladno z ortogonalno porazdelitvijo L9

Exp. No.	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

4 RESULTS AND DISCUSSION

4.1 Measurement of the Form Errors and the Surface Roughness

A comparison method was exercised, which is one of the most preferred methods for a determination of the form error in recent years. This method is based on a comparison of design surface (**Figure 9**), called the original surface, and the surface obtained by scanning using an optical method after the machining.

In order to determine the machining errors of the workpieces, a BreuckmannoptoTOP-HE coded structured light system was used. A three-dimensional optical measuring system with a strong light source drops on the fringes of the different textural properties to the body. These coded lights on the surface of the body are deformed depending on the direction of the characteristic features of the object. The coded lights are directed

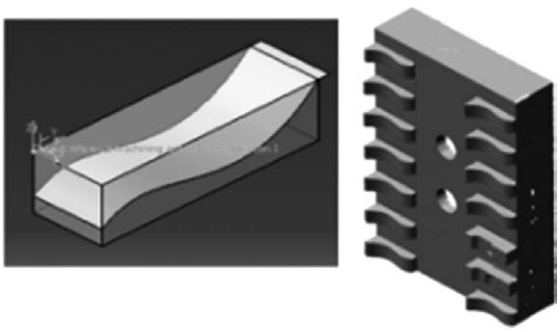

Figure 9: Test part designed in Catia V5 R17
Slika 9: Preskusni deli, načrtovani s Catia V5 R17

Figure 10: Machined real surface using different tool-path strategies
Slika 10: Realne površine, obdelane z različno strategijo poti orodja

towards the surface of the workpiece in order to have a special angle (**Figure 10**). This angle is referred to as triangulation. By an analysis of the information about the fringe projection's deformation, up to 1 million points of 3D coordinates are obtained within few seconds. Therefore, the point cloud that contains information in the surface of the object is created. With the help of computer, it is possible to measure the reference of the object or the point-cloud surface. Then, CAD modeling, an application of reverse engineering, is possible with the help of the point cloud. Also, digitization systems are used during the process of resolving as a technological convenience. As a result of optical scanning, the point cloud and polygon mesh data were obtained. Finally, the scanned data were registered into the CAD data to calculate and display the deviations of the two data sets by using the software.[15]

As understood in the section Experimental Design, nine experiments were conducted and the image of the machined surfaces was obtained via optical scanning.

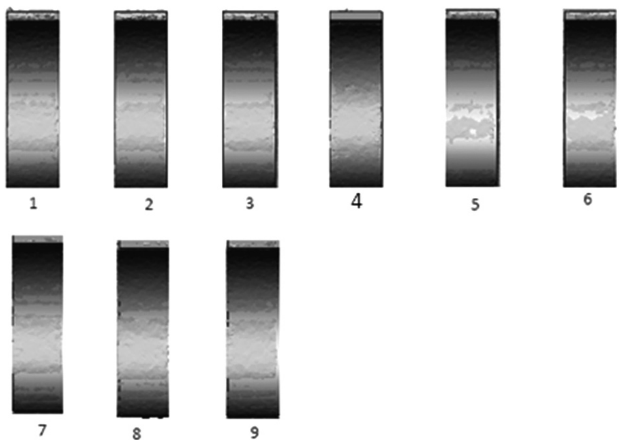

Figure 11: Superimposition of the design surface and the machined surface via scanning
Slika 11: Superpozicija načrtovane in obdelane površine s skeniranjem

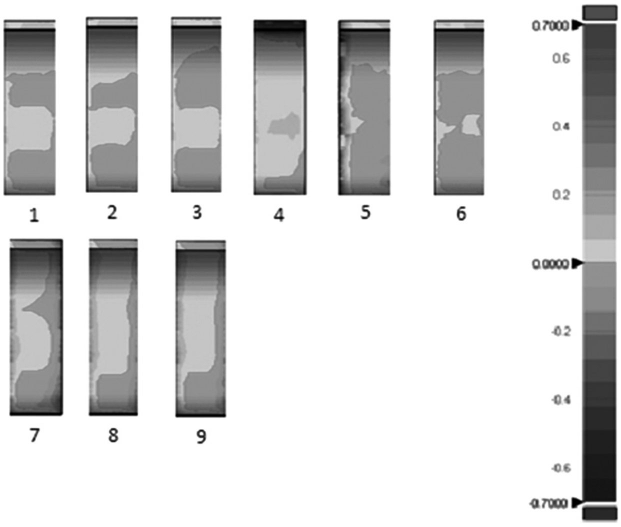

Figure 12: Machining surface errors
Slika 12: Napake obdelave površine

A comparison method will be employed to determine the form error. Therefore, the surfaces obtained from the machined surface via the scanning and design surface will be compared (**Figure 11**). Therefore, the surfaces should be overlapped in a precise manner. By screening the design surface (nominal data) and the machined surface via scanning (scanning data) and using the Rapidform package program, they are superposed precisely (best fit). Afterwards, an analysis to determine the difference among all the surfaces, in other words, the form error denominated as a deviation from the main form was conducted (**Figure 12** and **Table 5**).

Finally, control points with equal intervals of 0.5 mm were assigned across the surface in such a way that they will pass through the midpoint of the machined surface for each piece and the numerical values of the form error in each of these points were obtained (**Figure 13**).

The surface roughness values were measured using MahrPerthometer Concept roughness measuring instrument.

Table 5: Form error and roughness values obtained from the experiments
Tabela 5: Napake oblike in hrapavosti, dosežene pri preskusih

Exp. No.	A	B	C	Surface Roughness *Ra* (µm)	Form Error (mm)
1	1	1	1	1.130	0.086
2	1	2	2	1.100	0.099
3	1	3	3	2.550	0.096
4	2	1	2	1.150	0.120
5	2	2	3	2.170	0.147
6	2	3	1	1.360	0.089
7	3	1	3	1.660	0.098
8	3	2	1	0.850	0.172
9	3	3	2	1.240	0.124

4.2 Influence of the Machining Strategies on the Form Error

The machining strategies have a significant influence on the form error in free-form surface machining. Free-form surfaces usually demand extremely long tool paths, because of the surface complexity, that results in extreme values of the form error. Various cutter paths have different path lengths, though they remove an identical amount of workpiece material. Removing nearly the same amount of material in a shorter time reduces the cycle time; however, it raises the machining forces and the tool deflection.

After machining free-form surfaces by using the CNC machine that was mentioned in Section 4.1, the surface errors were measured with a 3-dimensional optical measuring system. The details of the experimental set-up were given in Section 3.1. The measured data points on the surface were compared with the CAD

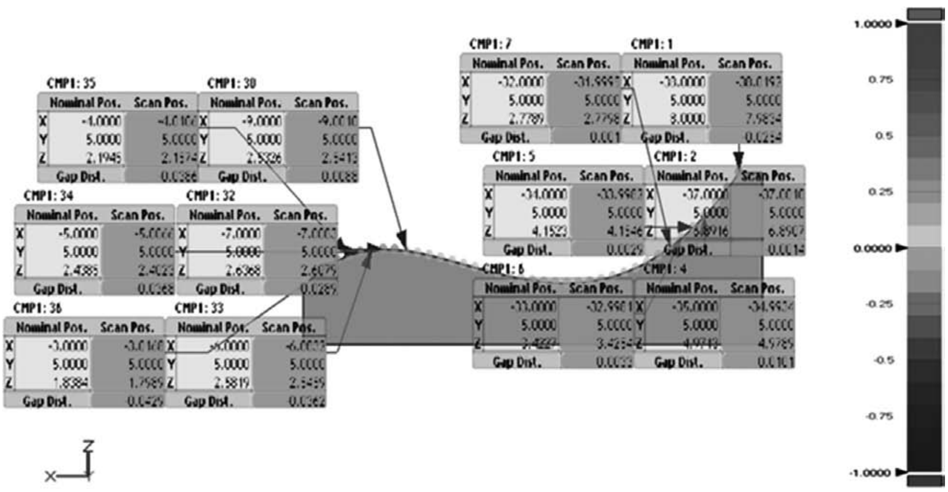

Figure 13: Assigned control points and numerical outcomes
Slika 13: Pripadajoče kontrolne točke in numerično dosežene

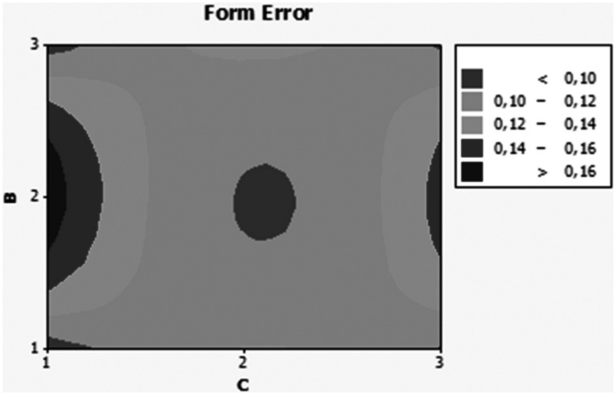

Figure 14: The effect of the roughing-cut strategy (B) and the finishing-operation strategy (C) on the form error
Slika 14: Učinek strategije grobe (B) in fine obdelave (C) na napako oblike

data, which is obtained in the first step. It should be noted that these surfaces are machined with a roughing-cut strategy, since we were expecting the surface errors to be large compared to the finishing operation strategy case. The effect of the roughing-cut strategy (B) and the finishing-operation strategy (C) on the form error results, which are the deviation from the CAD model, are presented in **Figure 14**.

4.3 Influence of the Cutting Tool Diameter on the Form Error

In rough machining strategies, when a ball-end mill with a large diameter is used, the form error increases (**Figure 15**). In particular, in the Zigzag_latitudinal machining method, with a 12-mm-diameter cutting tool, the form-error values increase. When an 8-mm-diameter cutting tool is used in the sweep_latitudinal process method, a finishing strategy, the form error had high values (**Figure 16**). These high values show that the cutter tool started machining from the workpiece and the machining is on the entries and exits where the process is finished.

4.4 Form Error and Surface Roughness Optimization

Implementations of the Grey relational analysis method, whose implementation steps were presented in the previous section, were made. First of all, normalization was performed according to the "lowest-is-the-best" approach and then, deviations from the reference series were calculated. Afterwards, the Grey relational degree of each experiment was calculated and the experiments were sorted with respect to their Grey relational degrees.

When the experimental results given in the table are normalized according to the "lowest-is-the-best" approach, the values in **Table 6** are obtained.

Table 6: Normalization outcomes
Tabela 6: Normalizirani izsledki

Exp. No.	Surface Roughness *Ra* (μm)	Form Error (mm)
1	0.835	1.000
2	0.853	0.849
3	0.000	0.884
4	0.824	0.605
5	0.224	0.291
6	0.700	0.965
7	0.524	0.860
8	1.000	0.000
9	0.771	0.558

Table 7: Values of the deviation from the reference value
Tabela 7: Deviacije od referenčme vrednosti

Exp. No.	Surface Roughness *Ra* (μm)	Form Error (mm)
1	0.165	0.000
2	0.147	0.151
3	1.000	0.116
4	0.176	0.395
5	0.776	0.709
6	0.300	0.035
7	0.476	0.140
8	0.000	1.000
9	0.229	0.442

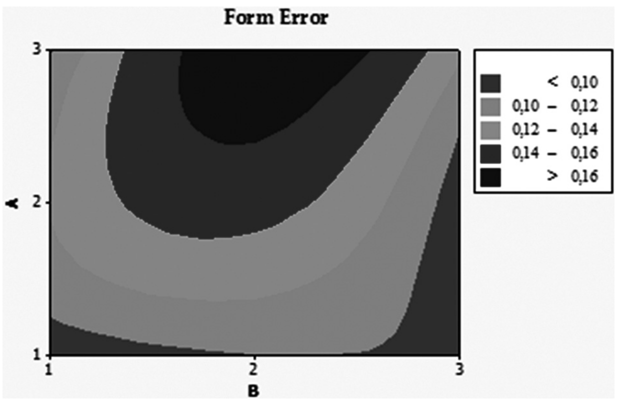

Figure 15: The effect of the cutting-tool diameter (A) and the roughing-cut strategy (B) on the form error
Slika 15: Vpliv premera orodja (A) in strategije grobe obdelave na napako oblike

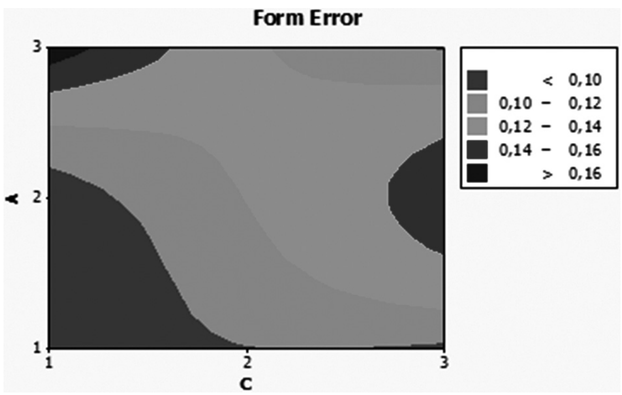

Figure 16: The effect of cutting-tool diameter (A) and the finishing-operation strategy (C) on the form error
Slik 16: Učinek premera orodja (A) in strategije kočne operacije (C) na napako oblike

The deviation values, which were obtained by removing the normalization outcomes of the surface roughness and the form error calculated from the reference value, are given in **Table 7**.

The Grey relational coefficient values of each output variable are given in **Table 8**.

Table 8: Grey relational coefficients
Tabela 8: Koeficienti Grey odvisnosti

Exp. No.	Surface Roughness *Ra* (μm)	Form Error (mm)
1	0.752	1.000
2	0.773	0.768
3	0.333	0.811
4	0.739	0.558
5	0.392	0.413
6	0.625	0.935
7	0.512	0.782
8	1.000	0.333
9	0.685	0.531

The Grey relational degrees related to each experiment are presented in **Table 9**.

Table 9: Grey relational degrees
Tabela 9: Stopnje Grey odvisnosti

Exp. No.	Grey Relational Degree	Sorting
1	0.876	1
2	0.770	3
3	0.572	8
4	0.649	5
5	0,403	9
6	0.780	2
7	0.647	6
8	0.667	4
9	0.608	7

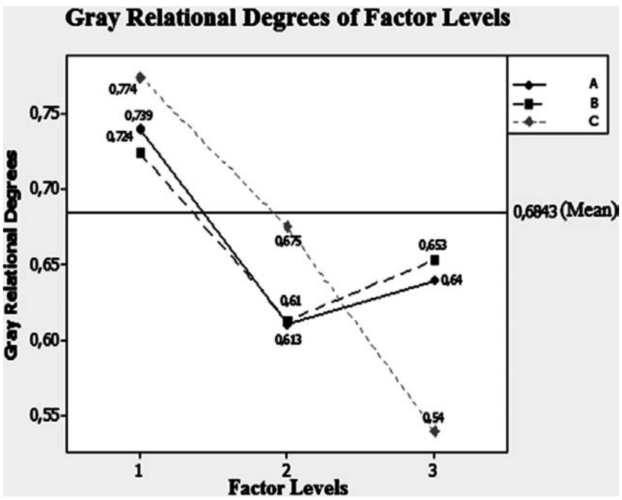

Figure 17: Grey relational degrees of factor levels
Slika 17: Stopnja odvisnosti za nivoje faktorjev

The calculated Grey relational degrees of the factor levels are presented in **Figure 17** and **Table 10**.

Table 10: Grey relational degrees of the factor levels
Tabela 10: Nivoji faktorjev Grey odvisnosti

	Factors		
	A	B	C
Level 1	0.739	0.724	0.774
Level 2	0.610	0.613	0.675
Level 3	0.640	0.653	0.540

As seen in the table, A1, B1 and C1 were detected as the most effective parameters on the outcome. The factor levels that will represent the lowest form error and surface roughness value under the conditions for the machining parameters and the limitations in the experimental design were determined in the above-mentioned way.

4.5 The Correlation between the Cutting Force and the Form Error

The cutting forces for the roughing cut and finishing operation were measured with a Kistler 9265B transducer during the cutting operation. Cutting forces occurred during the finishing operation, which has an actual impact on the form error, were the evaluated and the correlation between form error and cutting force were examined.

When the cutting force values obtained from the finishing operation were examined, it was determined that the greatest cutting force was obtained in the fifth and the eighth experiments. From the analysis of the remaining chips it was observed that the maximum number of chips remained in the fifth and eight experiments after the roughing cut and as a result of this situation. This leads to the highest cutting force having taken place in the afore-mentioned experiments.

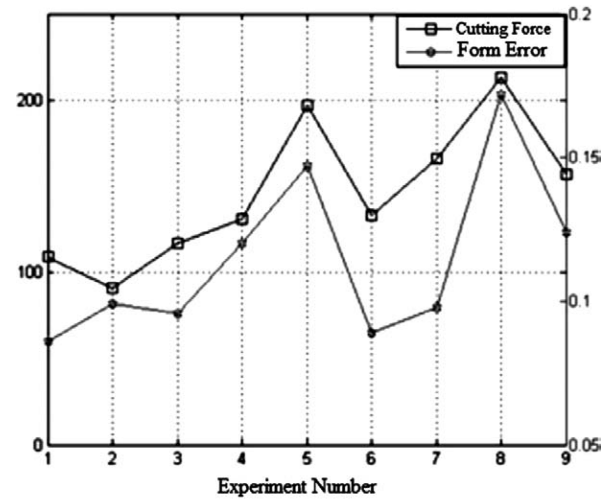

Figure 18: Graphical illustration of the relationship between the cutting force and the form error
Slika 18: Grafični prikaz odnosa med silo rezanja in napako oblike

The correlation between the cutting force and the form error is graphically exhibited in **Figure 18** and also numerically displayed in **Table 11**.

Table 11: Numerical illustration of the relationship between the cutting force and the form error
Tabela 11: Številčni prikaz odnosa med silo rezanja in napako oblike

Exp. No.	A	B	C	Cutting Force (N)	Form Error (mm)
1	1	1	1	109	0.0859
2	1	2	2	91	0.0991
3	1	3	3	117	0.0958
4	2	1	2	131	0.1203
5	2	2	3	197	0.1471
6	2	3	1	133	0.0890
7	3	1	3	166	0.0978
8	3	2	1	213	0.1721
9	3	3	2	157	0.1239

5 CONCLUSIONS

It was determined that surfaces are perfect within the limits of the machining tolerance, and that differences exist between the design and machined surface. This stems from the displacement that occurred in the cutting tool, on which the forces during cutting have an effect and a uniform chip thickness is not conserved. For the finishing operation when a SSYI operation with two schemas is performed, before a semi-roughing operation in the package programs, different amounts of chips remain, depending on the roughing-cut strategy and the cutting-tool diameter. This situation leads to an increase in the cutting forces during the finishing operation and, consequently, to a directly proportional increase in the form error. Therefore, in this case, the use of a semi-roughing operation will decrease the form error and the maximum number of chips remained in experiments numbers 5 and 8 (roughing cut strategy: Zigzag_latitudinal). As result, the maximum form error was obtained in experiments 5 and 8 and there is a proportional relationship between the cutting force and the form error. In addition, it was found that, as the cutting-tool diameter increases, the roughness decreases considerably. The optimum parameters were found to be A1, B1 and C1 through the Grey relational analysis method.

In further studies, an algorithm may be developed for a compensation of the form error that can be integrated into the CAM programs and so its validity can be checked.

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