http://doi.org/10.24867/JPE-2022-02-006

Journal of Production Engineering
Vol.25 No.2

JPE (2022) Vol.25 (2) Original Scientific Paper

Sredanović, B., Čiča, Đ., Borojević, S., Tešić, S., Kramar, D.

EXPERIMENTAL ANALYSIS AND OPTIMIZATION OF THIN-WALLED TUBULAR PARTS MILLING

Received: 19 May 2021 / Accepted: 17 August 2021

Abstract: *A certain percentage of mechanical parts in the engineering (parts in automotive industry, medical and measuring devices, parts in energetic sector, and etc.), refers to thin-walled structures with optimized shapes and dimensions. In addition to the requirements for a special shape of the structure, there are also requirements related to the dimensional accuracy and surface quality. In this paper, the milling of thin-walled tubular parts is analyzed. Workpiece of mentioned parts was C45E (AISI 1045) steel. Experimental analysis and optimization is based on Taguchi's experimental plan. The influence of cutting process parameters, depth of cut, feed per tooth and radial depth of cut, was analyzed. As the output cutting parameters, the dimensional accuracy and machined surface quality parameters, were measured and analyzed. Based on experimental data, modeling and optimization were performed. The obtained results defined the optimal input cutting process parameters, which give the best results in milling.*
Key words: *thin-walled structure, milling, experiment, optimization*

Eksperimentalna analiza i optimizacija glodanja tankozidnih cevnih delova. *Određeni procenat mehaničkih delova u mašinstvu (delovi u automobilskoj industriji, medicinski i merni uređaji, delovi u energetskom sektoru i dr.), odnosi se na tankozidne konstrukcije optimizovanih oblika i dimenzija. Pored zahteva za posebnim oblikom konstrukcije, postoje i zahtevi koji se odnose na tačnost dimenzija i kvalitet površine. U ovom radu je analizirano glodanje tankozidnih cevastih delova. Radni predmet navedenih delova je čelik C45E (AISI 1045). Eksperimentalna analiza i optimizacija zasnovana je na Tagučijevom eksperimentalnom planu. Analiziran je uticaj parametara procesa rezanja, dubine reznja, pomaka po zubu i radijalne dubine rezanja. Kao izlazni parametri rezanja, mereni su i analizirani parametri tačnosti dimenzija i kvaliteta obrađene površine. Na osnovu eksperimentalnih podataka urađeno je modeliranje i optimizacija. Dobijeni rezultati su definisali optimalne ulazne parametre procesa rezanja, koji daju najbolje rezultate pri glodanju.*
Ključne reči: *tankozidna struktura, glodanje, eksperiment, optimizacija*

1. INTRODUCTION

Thin-walled structures are most often used as structural parts in engineering due to their homogeneity and excellent load-to-weight ratio. Examples of such components are ribs, partitions, supports. These structures are technologically very complex because they are made of a wide materials range, have a complex geometry, and often relatively large dimensions. Many thin-walled structures forms have been developed, which can generally be divided into the next following types: line shapes, triangular shapes, rectangular shapes, hexagonal shapes, circular shapes and complex shapes. Complex forms of thin-walled structures are widely present in almost all branches of the metalworking industry (automotive, aerospace, energy, medicine devices, measuring devices, and etc.). They are most often used for the production of other assembly parts housings, as a base or supporting part for other parts in the assembly. These structures became technologically extremely complex, if stronger and harder materials are used for their production. The most common production technologies thin-walled structures are: casting and welding, in case simpler, bigger or non-functional surfaces on parts, and cutting technologies, in case of complex, smaller, or functional surfaces on parts.

Thin-walled structures, despite their simple design, bring problems to the machining in terms of technology and workability [1, 2, 3]. Although they have high rigidity in the vertical direction (wall extension direction), the most common cause of problems in their processing is their low rigidity in the perpendicular direction to the wall [4, 5]. Aluminum and its alloys are the dominant material of thin-walled structures, bust other materials are often used. Other types of materials, such as steels or special alloys, are especially used in cases where the thin-walled structure construction requires higher strength, hardness, heat loads resistance, wear resistance, and etc. In addition to the problems in terms of manufacturability, this also complicates the problems in terms of materials machinability. In the case of the application of cutting technology in the production of thin-walled structures from stronger materials, high machining accuracy and the machined surface quality are often required. If harder materials are used, the aforementioned machining problems became very complicated. Cylindrical shapes of thin-walled structures, made of relatively stronger and harder materials, are most often used as parts in the process industry, as parts of measuring devices, nozzles, burners, heaters, tools for plastics casting, tools in the

Note: The manuscript was presented at the 14. International Scientific Conference MMA held in Novi Sad, Serbia, 23.-25. September, 2021.

textile and wood industry and the like. The milling is dominant method for machining of tubular thin-walled structures, due to the possibility of performing complex cutting tool movements, adequate precision and productivity. During machining, relatively higher cutting forces occur, which more intensively deform the thin walls (Figure 1).

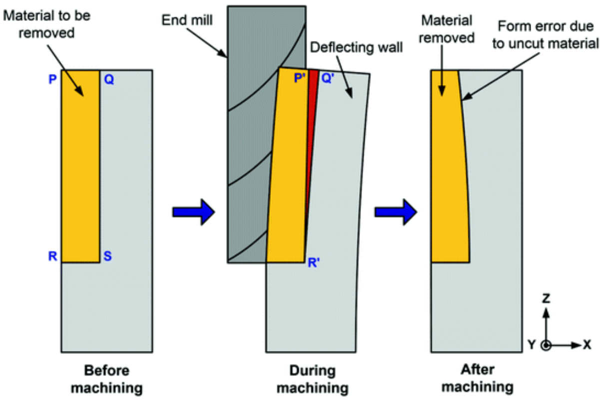

Fig. 1. Thin-walled structure deformation [3]

The action of a relatively higher cutting force on the thin and high structure wall, leads to a large deviation of dimensions and shapes due to elastic and plastic deformations of the thin walls of the structure [6]. The deviation of the dimensions of the cylindrical thin-walled structure is specific, and is reflected in the changes in wall thickness in vertical direction, and deviations in terms of circularity and cylindricality. Higher cutting forces and a large height/base ratio of the structure causes the higher vibrations, and leads to poorer machined surface roughness.

In this paper, experimental investigates on influence of technological parameters on the machining accuracy and quality in milling of cylindrical thin-walled structures are shown. The surface roughness, wall thickness deviation and circularity of the wall were analyzed. Based on experimental obtained data, modeling and optimization are performed.

2. EXPERIMENTAL SETUP

The experiment were performed on three-axis milling machining center Emco Concept MILL 450 equipped with a Sinumerik 810D/840D control unit with Windows platform (Figure 2). Power of machine is 11 kW, and maximum main spindle revolutions per minute is 11000. The programming of the machining center was performed using the SolidCAM software. Movement on linear axis have acceleration of 2 m/s². A milling cutter, marked as Dormer S814HA, was used to machining the experimental samples. The cutter has four teeth. The diameter of the cutter is d_c = 16 mm. The length of the cutter body is of l_1 = 92 mm, while the cutting length of the tool is l_2 = 32 mm. The overhang of the tool was set to l_3 = 40 mm. The tool mounting was performed with an ER32 elastic sleeve with an axial nut system, which is mounted in the ISO 40 holder.

Carbon steel C45E (Č.1530, DIN 17200, EN 10083) was used as the workpiece material for experimental research. This structural steel is used for the production of responsible parts, where increased wear resistance and strength are required. It has the possibility of heat treatment, such hardening and annealing. Workpiece was tubular, with outer diameter 40 mm, height 40 mm, and wall thickness 1.5 mm (Figure 3).

Fig. 2. Experimental setup

The machined surface roughness was measured after workpiece samples machining, using a mobile measuring device Mitutoyo Surftest SJ 301. Measurement of wall thickness and circularity deviations was performed on Carl Zeiss Duramax 5/5/5 CNC coordinate measuring machine. Measurement accuracy of this device is ± 2.3 µm, while repeatability is 1.7 µm. The measurement on machined workpiece was performed at five different points in height direction of the thin-walled structure, starting from 5 mm, with a step of 5 mm, to a height of 35 mm.

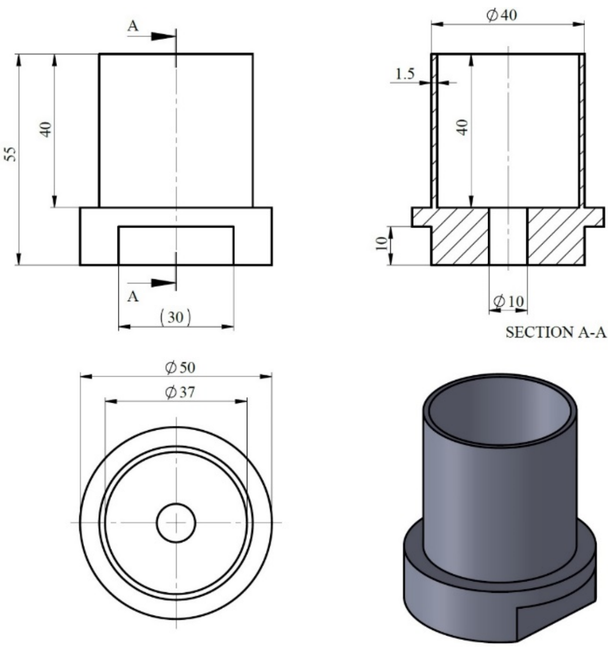

Fig. 3. Workpiece

Taguchi's orthogonal L9 (3²) experimental plan was used as the design of experiment. There was nine combinations of the three cutting process parameters at three levels, varied on three level (Table 1). All machining parameters, variable and constant, were adopted according to the recommendations of the cutting tool manufacturer. The depth of cutting (a_p), as the first parameter (P1) was varied at three levels: 2, 4 and 6 mm; feed per tooth (f_z), as the second parameter (P2) at three levels: 0.06, 0.12 and 0.18 mm/tooth, and as the third parameter (P3) milling width (a_e), at three levels: 0.5, 1.0, and 1.5 mm.

No.	P1	P2	P3	a_p (mm)	f_z (mm/tooth)	a_e (mm)
1	-1	-1	-1	2.0	0.06	0.5
2	-1	0	0	2.0	0.12	1.0
3	-1	+1	+1	2.0	0.18	1.5
4	0	-1	0	4.0	0.06	1.0
5	0	0	+1	4.0	0.12	1.5
6	0	+1	+1	4.0	0.18	0.5
7	+1	-1	+1	6.0	0.06	1.5
8	+1	0	-1	6.0	0.12	0.5
9	+1	+1	0	6.0	0.18	1.0

Table 1. Experiment runs

The cutting speed was kept at constant level for all combinations, on value of v_c = 120 m/min. As a cooling and lubrication technique, flooding on the outside of the tool through two nozzles was used. A synthetic emulsion diluted in water, with a content of 5%, was used. The fluid pressure was 5 bar, and the flow was 40 l/min with recirculation of the fluid.

3. RESULTS AND DISSCUSIONS

The analysis of machining accuracy includes the analysis of the wall thickness deviation δ (mm) from the nominal value of 1.5 mm, and the measurement of the mean circularity K (mm). Both parameters were measured at several points at five heights in the vertical direction of the thin-walled structure. Intervals between heights, starting from the bottom of the structure, was 5 mm. The analysis of the machined surface roughness included measurements in the vertical direction, along the height of the thin-walled structure R_{av} (μm); and in the horizontal direction, in the direction of planar movement of the cutter R_{ah} (μm). Machining time t (min), as economical parameter, was measured also.

No.	a_p	f_z	a_e	δ (mm)	K (mm)	R_{av} (μm)	R_{ah} (μm)	t (min)
1	2.0	0.06	0.5	0.136	0.027	0.90	0.72	26.53
2	2.0	0.12	1.0	0.266	0.034	1.40	0.83	7.47
3	2.0	0.18	1.5	0.216	0.039	1.88	1.06	3.78
4	4.0	0.06	1.0	0.216	0.029	1.37	0.70	7.47
5	4.0	0.12	1.5	0.230	0.046	1.74	0.89	2.95
6	4.0	0.18	0.5	0.214	0.041	0.78	1.14	4.82
7	6.0	0.06	1.5	0.144	0.039	1.71	0.79	3.95
8	6.0	0.12	0.5	0.135	0.033	0.84	0.92	5.03
9	6.0	0.18	1.0	0.165	0.061	1.02	1.16	2.10

Table 2. Experiment results

Figure 4 shows that measured wall thickness depends on the combination of the cutting parameters of the milling process and the measuring point height, along the vertical of the cylindrical thin-walled structure. Based on the diagram, it can be concluded that the thickness was the highest at a height of 5 mm, and then decreased. After the mentioned decreasing, it slightly increased at the measuring point at a height of 25 mm.

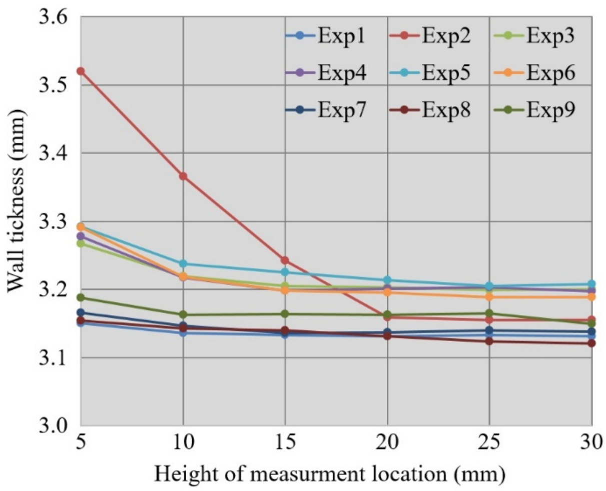

Fig. 4. Wall thickness for different experiment runs

The highest value of the mean deviation of the wall thickness of 0.266 mm was obtained using the cutting parameters a_p = 2.0 mm, f_z = 0.12 mm/tooth and a_e = 1.0 mm, while the lowest value of 0.135 mm for the processing parameters a_p = 6.0 mm, f_z = 0.12 mm/tooth and a_e = 0.5 mm. Higher deviation values were obtained for smaller depths of cutting. Based on the measuring, recalculating of circularity data was performed. Figure 5 shows diagrams of measured mean circularity.

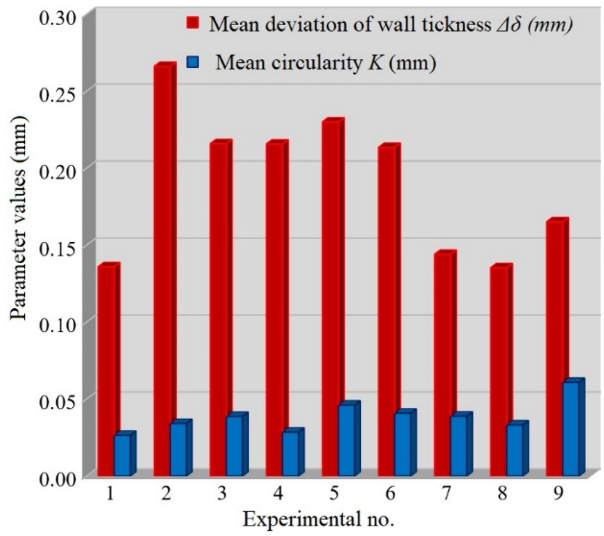

Fig. 5. Mean circularity for different experimental runs

The highest value of the mean circularity 0.061 mm, was obtained using the cutting parameters a_p = 6.0 mm, f_z = 0.18 mm/tooth and a_e = 1.0 mm, while the lowest value of 0.029 mm with the cutting parameters a_p = 4.0 mm, f_z = 0.06 mm/tooth and a_e = 1.0 mm

(Figure 6). Higher mean circularity values were obtained for greater depths of cutting and cutting widths.

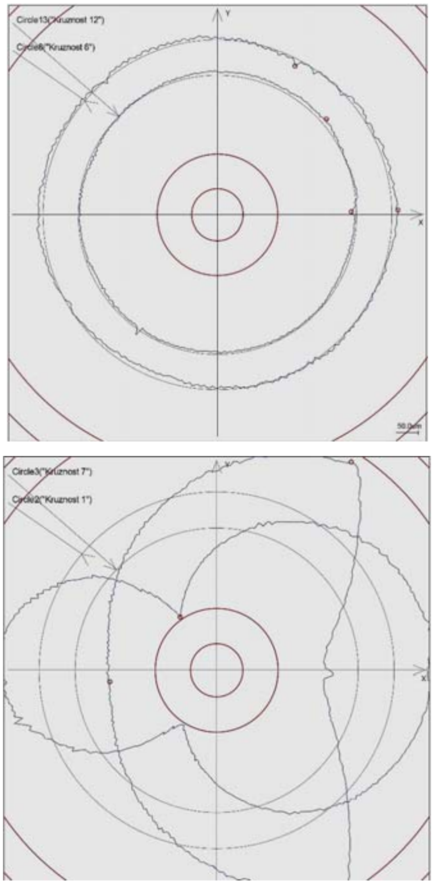

Fig. 6. The lowest (above) and highest (below) mean circularity measuring plot

The measured values of horizontal and vertical surface roughness depending on the combination of cutting parameters are shown in Figure 7.

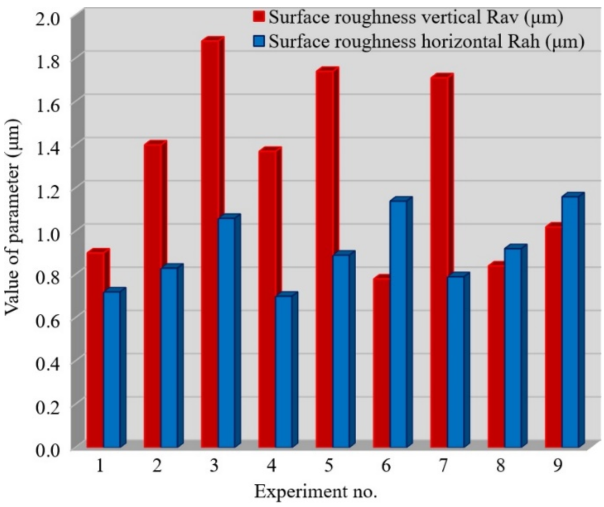

Fig. 7. Surface roughness for different experimental runs

The appearance of the machined surface, taken under a tool microscope Mitutoyo TM505, is shown in Figure 8. In the picture of the machined surface with the worst roughness, dark parts can be seen, which represent the waves created by the movement of the cutter. In the picture of machined surface with finest roughness, in some places, can be seen places of plunged and poorly separated material of the workpiece.

Fig. 8. The worst (above) and finest (below) machined surface under microscope

The highest value of the measured vertical roughness is 1.88 μm, which was obtained using the processing parameters a_p = 2.0 mm, f_z = 0.18 mm/tooth and a_e = 1.5 mm, while the lowest value is 0.78 μm, obtained with the parameters a_p = 4.0, f_z = 0.18 mm/tooth and a_e = 0.5 mm. Higher values of vertical roughness were obtained for larger machining widths. The highest value of horizontal roughness is 1.16 μm, which was obtained with machining parameters a_p = 6.0 mm, f_z = 0.18 mm/tooth and a_e = 1.0 mm, The lowest value is 0.70 μm, is obtained with a_p = 4.0 mm, f_z = 0.06 mm/tooth and a_e = 1.0 mm. Higher values of horizontal roughness were obtained for larger steps per tooth.

3.1 Modeling of output parameters

For statistical analysis of experimentally measured data, and model generating, the software DesignExpert 7.1 was used. Statistical analysis is based on analysis of variance (ANOVA). Based on the measured, entered and untransformed experimental obtained values, the software proposed an appropriate models using the least sum of squares method. Determination of input parameters significance was based on F values (target is greater than 15) and P values (target is less than 0.05). The adequacy of the models was determined based on the coefficient of regression, signal-to-noise ratio, mean value and standard deviation. According to the previously presented results, statistical analysis and modeling of the following quantities were performed:

- mean deviation of wall thickness
- mean circularity
- surface roughness in vertical direction
- surface roughness in horizontal direction

Based on the mean values of the wall thickness deviation Δδ, the software for statistical analysis proposed a model with the interaction of two parameters versus linear (2FI vs Linear). The P-value of the model is 0.028, while the most influential parameter is depth of cutting, whose P-value is 0.006. According to the analysis of variance, a mean value of $\bar{x} = 0.19$, and standard deviation of SD = 0.009 were obtained. The signal-to-noise ratio is S/N = 15.61, and the regression coefficient is R^2= 0.99. Based on these values, it is concluded that the model is adequate. By the surface response method (RSM), a mathematically formalized dependence of the mean deviation of the wall thickness depending on cutting parameters was obtained in form:

$$\Delta\delta = -0.107 - 0.028 \cdot a_p + 0.648 \cdot f_z + 0.719 \cdot a_e + 0.499 \cdot a_p \cdot f_z - 0.068 \cdot a_p \cdot a_e - 2.936 \cdot f_z \cdot a_e \quad (1)$$

The software proposed a model with the interaction of two parameters versus linear for model of mean circularity *K*. Calculated model P-value is 0.028, while the most influential parameter is feed, with P-value 0.003. Mean value is $\bar{x} = 0.039$, and standard deviation is SD = 0.00082. The signal-to-noise ratio is S/N = 47.39, and the regression coefficient is R^2 = 0.99. Based on these values, it is concluded that the model is adequate. Mathematically model was obtained in form of:

$$K = 0.035 - 0.008 \cdot a_p + 0.066 \cdot f_z + 0.004 \cdot a_e + 0.062 \cdot a_p \cdot f_z + 0.003 \cdot a_p \cdot a_e - 0.024 \cdot f_z \cdot a_e \quad (2)$$

Model response diagrams for mean values of the wall thickness deviation and mean circularity are shown on Figures 8 and 9, respectively.

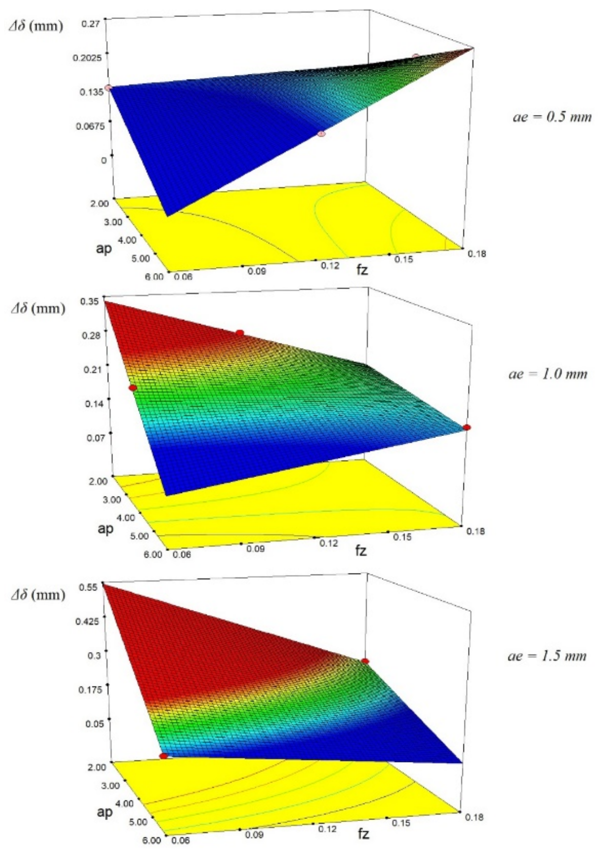

Fig. 8. Model response for Δδ

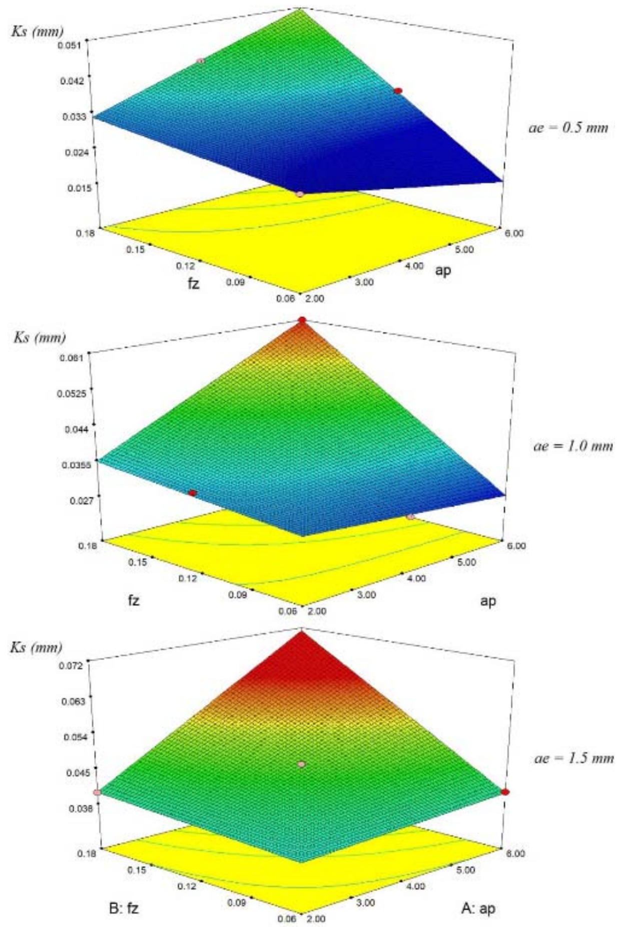

Fig. 8. Model response for ΔK

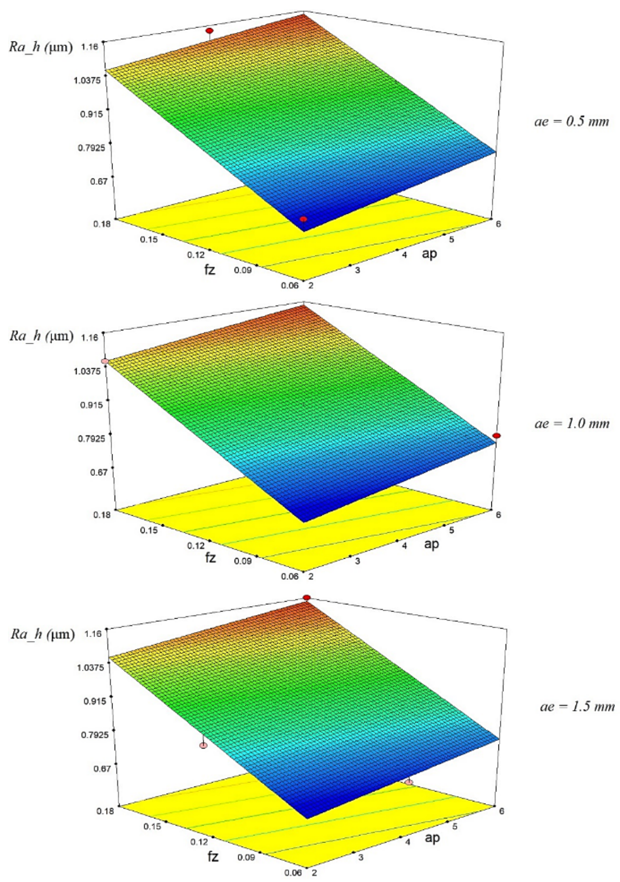

Fig. 9. Model response for R_{ah}

For both surface roughness parameters R_{av} and R_{ah}, the software proposed a model with the interaction of two parameters versus linear. P-values for model of R_{av} is 0.0002, and for R_{ah} is 0.0001. Most influential parameters for vertical surface roughness is milling width (P-value is 0.0001), and for horizontal surface roughness is feed per tooth (P-value is 0.0001 also). Mean values is $\bar{x} = 1.29$ and standard deviation is SD = 0.057, for vertical surface roughness. Mean values is $\bar{x} = 0.91$ and SD = 0.036, for horizontal surface roughness. Signal to noise ratio is 26.96 for vertical and 22.78 for horizontal surface roughness. Coefficients of regression is 0.991 and 0.97, respectively. The software gave a mathematical form of dependence between input and output parameters:

$$R_{av} = 0.348 + 0.053 \cdot a_p - 1.699 \cdot f_z + 1.353 \cdot a_e - 0.104 \cdot a_p \cdot a_{ee} \quad (3)$$

$$R_{ah} = 0.442 + 0.022 \cdot a_p + 3.194 \cdot f_z \quad (4)$$

Using the previous mathematical formulas, a diagram or response surface is formed for horizontal surface roughness (Figure 9).

3.2 Optimisation of process parameters

For the case of perform finish milling a cylindrical thin-walled structure, the minimum roughness of the machined surface, the minimum mean deviation of the wall, and the minimum mean circularity are chosen as the optimization target functions. The mathematical framework of optimization, according to the mentioned requirements, is given in Table 3.

Para-meter	Target	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Para. W
a_p	In range	2.0	6.0	1	1	3
f_z	In range	0.06	0.18	1	1	3
a_e	In range	0.5	1.5	1	1	3
R_{av}	Minimized	0.026	0.061	1	1	3
R_{ah}	Minimized	0.78	1.88	1	1	3
$\Delta\delta$	Minimized	0.7	1.16	1	1	3
K	Minimized	0.135	0.266	1	1	3

Table 3. Optimisation framework

The optimization procedure, based on the previous mathematical framework, gave 27 possible solutions. As the optimal solution for finish milling, the cutting parameters a_p = 2.13 mm, f_z = 0.066 mm/tooth and a_e = 0.5 mm were obtained. For these parameters, the desirability of optimization targets is 96.8%. Optimization solution desirability depending on the depth of cutting and feed at most (Figure 10). From the diagram, can be concluded that smaller values of cutting parameters should be used in finish milling. Higher values of depth of cutting can be used, which must be accompanied by a significant reduction in feed per tooth.

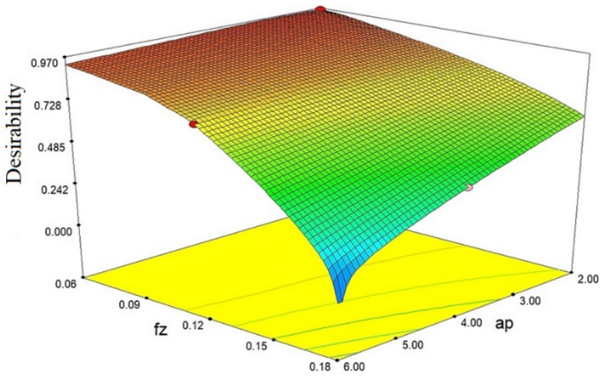

Fig. 10. Desirability for different parameters

4. CONCLUSSIONS

There was conducted experimental investigations of the influence of milling parameters: processing depth, feed per tooth and milling width, on the output parameters in milling of tubular thin-walled structure. The outputs are: deviation of wall thickness, circularity, and surface roughness.

Based on the analysis of variance, the significance of cutting parameters on the output parameters was determined. Linear models with a parameters combination, which describes the influence of the values of cutting parameters, have been developed. There is noted that the increase of cutting parameters, through the increase of cutting force, leads to a decrease in machining accuracy, according increase of the wall thickness and structure circularity. As a result of optimization, optimal technological parameters were obtained. However, further research should focus on the analysis of the machining of thin-walled parts made of special materials.

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ACKNOWLEDGMENTS: This paper is results of collaboration between Laboratory for cutting at FME Ljubljana and Laboratory for cutting technologies and machining systems at FME Banja Luka. Collaboration is supported by the ministries of the host countries.

Authors: **Assist. Prof. Branislav Sredanović, Full Prof. Đorđe Čiča, Assoc. Prof. Stevo Borojević, MSc. Saša Tešić,** University of Banja Luka, Faculty of Mechanical Engineering, Department of Production and CAx Technologies, Bulevar Vojvode Stepe Stepanovića 75, 78000 Banja Luka, Republic of Srpska, Bosnia and Herzegovina, Phone: +387 51 433 001, Fax: +387 51 465 085,
E-mails: branislav.sredanovic@mf.unibl.org,
djordje.cica@mf.unibl.org,
stevo.borojevic@mf.unibl.org,
sasa.tesic@mf.unibl.org,
Assoc. Prof. Davorin Kramar, University of Ljubljana, Faculty of Mechanical Engineering, Department of Machining Technology Management, Aškerčeva 6, 1000 Ljubljana, Slovenia, Phone: +386 1 477 14 38, Fax: +386 1 477 17 68,
E-mail: davorin.kramar@fs.uni-lj.si