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ANALYSIS OF THE CUTTING TEMPERATURE AND SURFACE ROUGHNESS DURING THE ORTHOGONAL MACHINING OF AISI 4140 ALLOY STEEL VIA THE TAGUCHI METHOD

ANALIZA TEMPERATURE REZANJA IN HRAPAVOSTI POVRŠINE S TAGUCHI METODO PRI ORTOGONALNI STROJNI OBDELAVI LEGIRANEGA JEKLA AISI 4140

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In this research, the tool-chip interface temperature (T_{CTI}), the tool temperature (T_T) and the average surface roughness (R_a) were measured experimentally during the turning of AISI 4140 alloy steel with TiAlN-TiN, PVD-coated, WNVG 080404-IC907 tungsten carbide inserts using an IR pyrometer technique, a K-type thermocouple and a portable surface-roughness measurement device, respectively. The workpiece material was heat treated by an induction-hardening process and hardened up to a value of 50 HRC. The Taguchi method L18 (21 × 37) was used for the determination of the optimum control factors. The depth of cut, the cutting speed and the feed rate were taken as control factors. The analysis of variance was applied in order to determine the effects of the control factors on the tool-chip interface temperature, the tool temperature and the surface roughness. The optimum combinations of the control factors for T_{CTI}, T_T and R_a were determined as $a_2v_1f_3$, $a_1v_3f_2$ and $a_2v_3f_1$, respectively. Second-order predictive models were developed with a linear-regression analysis, and the coefficients of correlation for T_{CTI}, T_T and R_a were calculated as R^2 = 92.8, R^2 = 68.1 and R^2 = 82.6, respectively.

Keywords: tool temperature, thermocouple, pyrometer, machining, Taguchi method

V raziskavi so bile eksperimentalno izmerjenene tempetratura na stiku orodje-ostružek (T_{CTI}), temperatura orodja (T_T) in povprečna hrapavost površine (R_a) pri struženju legiranega jekla AISI 4140, z volfram karbidnimi vložki WNVG 080404-IC907 s PVD prevleko iz TiAlN-TiN, z uporabo IR pirometra, termoelementi vrste K in s prenosnim merilnikom hrapavosti. Obdelovanec je bil toplotno obdelan z indukcijskim ogrevanjem in hlajenjem na trdoto 50 HRC. Za določanje optimalnih kontrolnih faktorjev je bila uporabljena Taguchi metoda L18 (21 × 37). Globina rezanja, hitrost rezanja in hitrost podajanja so bile vzete kot kontrolni faktorji. Analiza variance je bila uporabljena za določanje vpliva kontrolnih faktorjev na temperaturo prehoda orodje-ostružek, temperaturo orodja in hrapavost površine. Določene so bile optimalne kombinacije kontrolnih faktorjev za T_{CTI}, T_T in R_a , kot $a_2v_1f_3$, $a_1v_3f_2$ and $a_2v_3f_1$. Z linearno regresijsko analizo so bili razviti modeli drugega reda za napovedovanje in izračunani so bili koeficienti korelacije za T_{CTI}, T_T in R_a kot R^2 = 92,8, R^2 = 68,1 in R^2 = 82,6.

Ključne besede: temperatura orodja, termočlen, pirometer, strojna obdelava, Taguchi metoda

1 INTRODUCTION

In order to overcome the difficulties in terms of efficiency and the quality of production encountered in the metal-cutting industries, all the stages of the machining process need to be monitored. During the metal-cutting processes, one of the key factors is the cutting temperature, which directly affects the surface quality, the tool wear, the tool life, and the cost of production. The amount of heat generated varies with the type of material being machined and the cutting parameters (especially the cutting speed, which had the biggest influence on the temperature).[1]

Temperature monitoring is one of the most difficult and complicated procedures in metal-cutting operations. It is extremely complex to develop a model for measuring the temperature due to the complexity of the different events at the point of contact between the tool and the workpiece. Therefore, an accurate and repeatable temperature prediction still remains as a challenge due to this complexity of the contact phenomenon.[2] It is quite difficult to measure the temperature since the heat in the region is very close to the cutting edge. Due to a lack of sufficient experimental data, it is not possible to verify a mathematical model. Numerous attempts have been made to measure the temperature during machining operations.[3]

Amongst the many experimental methods to measure the temperature directly, only a few systems have used the temperature as an indicator of machine performance and for industrial applications.[4] Therefore, the temperature can be controlled using the appropriate cutting parameters to design and develop the system and it will be beneficial to increase the efficiency in production.

In recent years, experimental studies related to metal-cutting processes have made use of the Taguchi method. This method has been used successfully for a determination of the appropriate cutting parameters and in the optimization of parameters related to tool wear, tool life, and the surface quality. The Taguchi method and Analysis of Variance (ANOVA) can conveniently optimize the cutting parameters with several experimental runs that are well designed. Taguchi parameter design can optimize the performance characteristics through the settings of the design parameters and reduce the sensitivity of the system's performance to the source of variation.[5] On the other hand, ANOVA is used to identify the most significant variables and interaction effects.[6,7]

In the Taguchi method, quality is measured by the deviation of a quality characteristic from its target value. Therefore, the objective is to create a design that is insensitive to all possible combinations of uncontrollable factors and is at the same time effective and cost efficient as a result of setting the key controllable factors at their optimum levels.[8] Taguchi's parameter design offers a simple and systematic approach that can reduce the number of experiments to optimize the design for performance, quality and cost. The signal-to-noise (*S*/*N*) ratio and the orthogonal array (*OA*) are two major tools used in robust design.[9]

A lot of research has been conducted for determining the optimal cutting parameters. W. H. Yang and Y. S. Tarng[10] employed the Taguchi method, and the optimal cutting parameters for the turning of S45C steel bars were successfully obtained. B. M. Gopalsamy et al.[11] applied the Taguchi method to find the optimum machining parameters while machining hard steel and used the L18 orthogonal array. The *S*/*N* ratio and ANOVA were used to study the performance characteristics of the machining parameters. F. Ficici et al.[12] used the Taguchi method to study the wear behaviour of boronized AISI 1040 steel. They used the *S*/*N* ratio to investigate the optimum setting parameters.

M. Adinarayana et al.[13] presented the multi-response optimization of the turning parameters for the turning of AISI 4340 alloy steel. The experiments were designed and conducted based on Taguchi's L27 orthogonal array design. They discussed an investigation into the use of Taguchi parameter design to predict and optimize the surface roughness, the metal removal rate and the power consumption during turning operations. E. D. Kirby[14] discussed an investigation into the use of Taguchi parameter design for optimizing the surface roughness generated by a CNC turning operation. He used a standard orthogonal array for determining the optimum turning parameters with an applied noise factor. The controlled factors include the spindle speed, the feed rate, and the depth of cut.

In this paper, the measurement of temperature during the turning of AISI 4140 alloy steel was performed using various cutting parameters. The tool-chip interface temperature T_{CTI} was measured by infrared thermometer, the tool temperature T_T was measured with a K-type thermocouple in the cutting zone, and the average surface roughness R_a was measured using a portable surface-roughness measurement device. The Taguchi design was selected to find the relationships between the control factors. The depth of cut (a_p), the cutting speed (v_c), and the feed rate (f) were taken as the control factors.

2 TEMPERATURES DURING METAL CUTTING

In the cutting process, nearly all of the energy dissipated during plastic deformation is converted into heat, which in turn raises the temperature in the cutting zone. Since the heat generation is closely related to the plastic deformation and friction, we can specify three main sources of heat when cutting:

- plastic deformation by shearing in the primary shear zone;
- friction on the cutting face and friction between the chips;
- tool on the tool flank.

Temperature results in dimensional errors on the machined surface. The cutting tool elongates as a result of the increased temperature, and the position of the cutting tool edge shifts towards the machined surface, resulting in a dimensional error of about 0.01–0.02 mm. Since the processes of thermal generation, dissipation, and solid-body thermal deformation are all transient, some time is required to achieve the steady-state condition.

Heat is mostly dissipated by: the discarded chip that carries away about 60–80 % of the total heat, the workpiece acts as a heat sink drawing away 10–20 % of heat, while the cutting tool draws away ~10 % of the heat. The balance between heat generation and heat dissipation during metal cutting is shown in **Figure 1**.

3 MATERIALS AND METHOD

3.1 Workpiece and cutting tool

The workpiece material is AISI 4140 alloy steel. The chemical composition of the workpiece material (in volume fractions) is shown in **Table 1**. The machining process was performed using a NR 2020K-08 tool holder

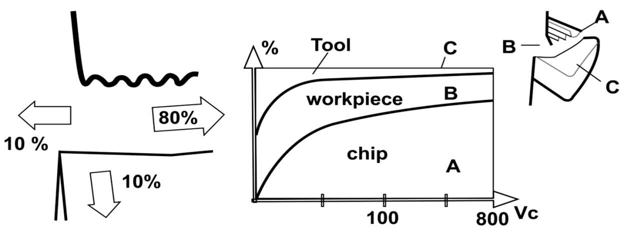

Figure 1: The balance of heat generation and heat dissipation during metal cutting

Slika 1: Izravnava med sproščeno in odvedeno toploto pri rezanju kovin

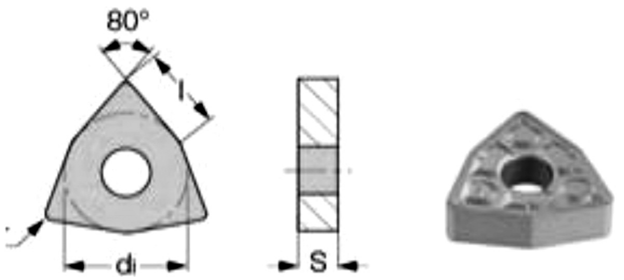

Figure 2: Schematic of tip geometry
Slika 2: Shema geometrije rezilne konice

and a TiAlN-TiN, PVD-coated, WNVG 080404-IC907 solid carbide insert. **Figure 2** and **Table 2** show a schematic of the tip geometry and the specifications of the insert.

Table 1: Chemical composition of AISI 4140 alloy steel (in volume fractions, *x*/%)
Tabela 1: Kemijska sestava legiranega jekla AISI 4140 (v volumenskih odstotkih, *x*/%)

C	Cr	Ni	Mn	P	S	Si	Mo
0.38	0.80	9.58	0.75	0.035	0.04	0.15	0.15

Table 2: The specifications of the insert
Tabela 2: Specifikacije vložka za rezanje

TiAlN-TiN PVD-coated WNVG 080404-IC907						
d_1	S	I	r	HRA	TRS	d
12.70	4.83	8.70	0.40	92.80	560	4.70
Property			Value			
ISO Range – P/M/K			(P10-P30)(M05-M20)			
ISO Range – H/S/N			(H05-H15)(S05-S20)			
Grade or coating type			PVD			
Coating layers			TiAlN-TiN			

3.2 Experimental conditions, temperature and surface-roughness measurements

In this study, two methods of tool-temperature evaluation are presented:

- the placement of the K-type thermocouple on the tool,
- the infrared pyrometer.

A schematic view of the experimental setup is shown in **Figure 3**. Cylindrical workpieces (Ø45 × 300 mm) were fixed between the chuck and the tailstock and were pre-machined using a separate insert. The workpiece samples were heat treated by induction hardening and a hardness of 50 HRC was maintained. The samples were then solution heat treated and oil quenched in order to achieve the proper hardness.

In this study, an Optris CF4 infrared thermometer was used to measure T_{CTI}. The maximum temperature (which was about 525 °C) was recorded around the cutting zone. A total of 18 trials were conducted throughout these experiments and brand new inserts were used for each temperature measurement. Hence, the cutting temperature increased with the cutting speed, the feed rate and the depth of cut. The experiments were repeated three times for the same cutting conditions and the measured values were averaged. T_T was measured using a K-type thermocouple. The thermocouple measurements were recorded every five seconds.

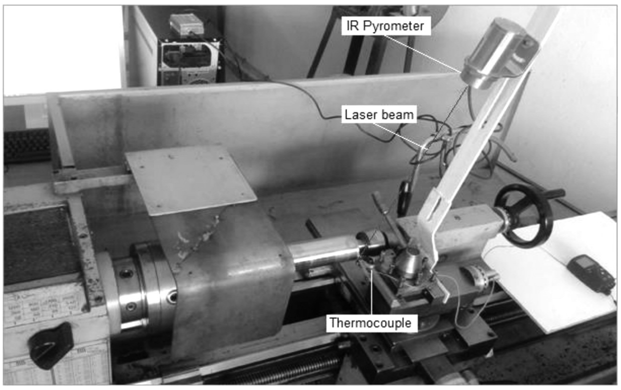

Figure 3: Thermocouple and IR pyrometer connections to the lathe
Slika 3: Povezava termočlena in IR-pirometra na stružnici

The R_a surface roughness was measured to characterize the surface quality. The R_a measurements were carried out using a Time TR 200 device by obtaining values from different points that were parallel to the workpiece axis at a cut-off length of 5.6 mm. According to the experimental design, three measurements were made on the surfaces at the specified values of the control factors, and the R_a values were determined by taking the average of the measurement results.

3.3 Experimental design using the Taguchi method

The Taguchi design was selected to find the relationships between the control factors and the quality characteristics. The cutting speed (v_c), feed rate (f) and depth of cut (a_p), whose levels are given **Table 3**, were selected as the control factors. The quality characteristics were the tool-chip interface temperature (T_{CTI}), the tool temperature (T_T) and the average surface roughness (R_a). As the total degree of freedom of the factor group was 5, a standard Taguchi experimental plan with the notation L18 ($2_1 \times 3_7$) was chosen as the orthogonal array. The rows in the L18 orthogonal array used in the experiment corresponded to each trial and the columns contained the factors to be studied. The first column consists of the depth of cut; the second and the third columns contain the cutting speed and the feed rate, respectively. In the Taguchi method, the experimental results are transformed into a *S/N* ratio. The *S/N* ratio is used while approaching or moving away from the desired value and measuring the quality characteristics.[15-18] The smaller-is-better (SB), the nominal-best (NB) and the larger-is-better (LB) approaches are found according to the results of the *S/N* ratio.[15-18] As the tool-chip interface temperature (T_{CTI}), the tool temperature (T_T) and the surface roughness (R_a) values were required to be the lowest, the *S/N* ratios of these quality characteristics were calculated in dB using Equation (1) according to the SB option in the study.[15–18]

$$S/N_{\mathrm{SB}} = -10 \cdot \lg\left(\frac{1}{2}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

In the Equation (1), n is the number of the experiment and yi is the ith data point obtained.[15–18] ANOVA was applied in order to determine the percentage effects of the control factors on T_{CTI}, T_{T} and R_{a}.

Table 3: Control factors and their levels
Tabela 3: Kontrolni faktorji in njihovi nivoji

Symbol	Control factors	Unit	Level 1	Level 2	Level 3	Degree of freedom (DoF)
a_{p}	Depth of cut	mm	0.40	0.60	–	1
v_{c}	Cutting speed	m/min	76	114	170	2
f	Feed rate	mm/rev	0.05	0.08	0.12	2

3.4 Predictive models for temperature and surface roughness with multiple regression analysis

Equations were developed for the prediction of T_{CTI}, T_{T} and R_{a} using the experimental results in a multiple regression analysis. The second-order linear models containing the main effects of the control factors and their interactions are signified with the Equation (2):

$$Y_1 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + \\ + b_3 x_3 + b_4 x_{12} + b_5 x_{13} + b_6 x_{23} \quad (2)$$

where Y_1 is the estimated answer of the second-order equation and y is the tool-chip interface temperature (T_{CTI}), tool temperature (T_{T}) or surface roughness (R_{a}) measured on a the logarithmic scale, $x_0 = 1$ is the fixed variable, the x_1, x_2 and x_3 control factors are the logarithmic transformations of the depth of cut, the cutting speed and the feed rate and, the x_{12}, x_{13} and x_{23} interactions of the control factors are the logarithmic transformations of the depth of cut–cutting speed, the depth of cut–feed rate and cutting speed–feed rate. The coefficient of the experimental error is ε, and the b values (b_0, b_1, b_2, b_3, b_4, b_5 and b_6) are the coefficients of related factors.

4 ANALYSIS OF THE RESEARCH RESULTS

The present study was performed to understand and evaluate the infrared- and thermocouple-based temperature measurements during metal cutting and to consider the practical difficulties. T_{CTI}, T_{T} and R_{a} were used as the quality characteristics. The experimental results are shown in **Table 4**.

The T_{CTI}, T_{T} and R_{a} measurement results from the turning of the quenched and tempered AISI 4140 steel with coated carbide tools were resolved and analyzed by means of the Minitab 16.0 package software. From **Table 4** it is clear that the overall means for T_{CTI}, T_{T} and R_{a} were calculated as 446.11 °C, 70.78 °C and 0.578 µm, respectively.

Table 4: The experimental results for the quality characteristics and *S/N* ratios
Tabela 4: Rezultati preizkusov za opis kvalitete in *S/N* razmerja

Exp. no	Control factors			Measured values			*S/N* Ratios (dB)		
	a_{p}	v_{c}	f	Tool-chip interface temperature, T_{CTI} (°C) (IR Pyrometer)	Tool temperature, T_{T} (°C) (Thermocouple)	Surface roughness, R_{a} (µm)	*S/N* T_{CTI}	*S/N* T_{T}	*S/N* R_{a}
1	0.4	76	0.05	410	57	0.295	–52.26	–35.12	10.60
2	0.4	76	0.08	405	66	0.483	–52.15	–36.39	6.32
3	0.4	76	0.12	410	72	0.958	–52.26	–37.15	0.37
4	0.4	114	0.05	460	65	0.484	–53.26	–36.26	6.30
5	0.4	114	0.08	465	61	0.579	–53.35	–35.71	4.75
6	0.4	114	0.12	425	67	0.988	–52.57	–36.52	0.10
7	0.4	170	0.05	520	65	0.410	–54.32	–36.26	7.74
8	0.4	170	0.08	500	67	0.492	–53.98	–36.52	6.16
9	0.4	170	0.12	475	71	0.872	–53.53	–37.03	1.19
10	0.6	76	0.05	400	72	0.489	–52.04	–37.15	6.21
11	0.6	76	0.08	390	80	0.530	–51.82	–38.06	5.51
12	0.6	76	0.12	395	76	0.720	–51.93	–37.62	2.85
13	0.6	114	0.05	430	80	0.429	–52.67	–38.06	7.35
14	0.6	114	0.08	435	75	0.547	–52.77	–37.50	5.24
15	0.6	114	0.12	420	83	0.722	–52.46	–38.38	2.83
16	0.6	170	0.05	485	81	0.354	–53.71	–38.17	9.02
17	0.6	170	0.08	525	67	0.406	–54.40	–36.52	7.83
18	0.6	170	0.12	480	69	0.643	–53.62	–36.78	3.84

Overall mean of T_{CTI} = 446.11 °C, *S/N* ratio of T_{CTI} = –52.95 dB
Overall mean of T_{T} = 70.78 °C, *S/N* ratio of T_{CTI} = –36.95 dB
Overall mean of R_{a} = 0.578 µm, *S/N* ratio of R_{a} = 5.24 dB

The variation of the tool temperature and the tool-chip interface temperature with the cutting parameters are shown in **Figures 4a** and **4b**. Obviously, it is clear that the tool-chip interface temperature and the tool temperature increase with an increase in the cutting speed (**Figure 4a**). The influence of the tool temperature and the feed rate on the surface roughness is shown in **Figure 5a**. It was observed that the lowest feed rate produced a better surface quality. The experiments showed that the cutting speed and the feed rate are the main factors affecting the surface roughness (**Figure 5b**).

4.1 Analysis of the control factors for the temperature and surface roughness

The responses for the *S/N* ratios (smaller is better) of T_{CTI}, T_{T} and R_{a} are presented in **Table 5** and the responses for the means in **Table 6**. While the signal value represents the real desired value that the system gives and which is to be measured, the noise factor represents the portion of the undesired factors in the measured value. The *S/N* ratio analysis provided significant information about the nature of the process of turning hardened AISI 4140 steel with coated carbide cutting tools under selected conditions. The fact that the differences between the highest and the lowest *S/N* ratio values of each control factor calculated at different levels

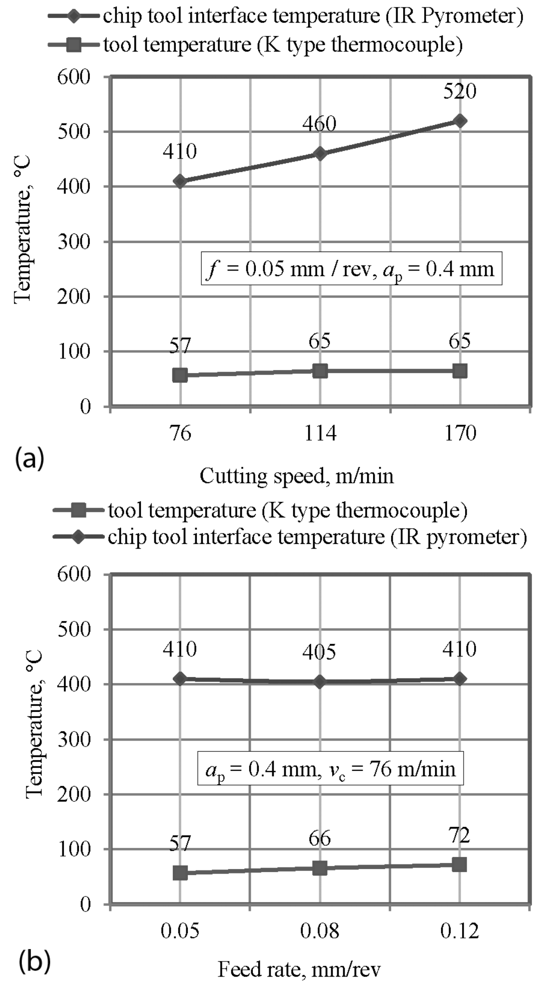

Figure 4: The influence of cutting speed and feed rate on the temperature: a) cutting speed, b) feed rate
Slika 4: Vpliv hitrosti rezanja in hitrosti podajanja na temperaturah: a) hitrost rezanja, b) hitrost podajanja

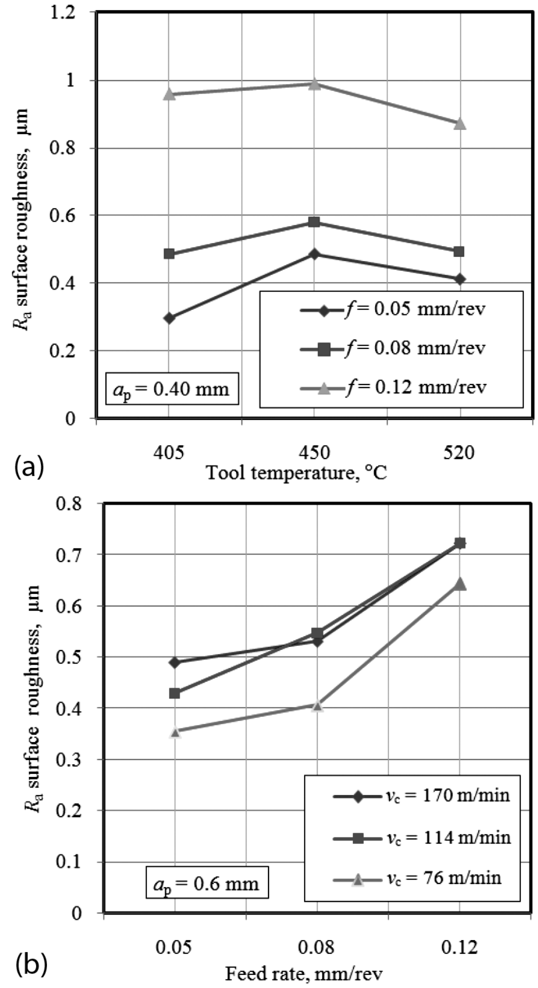

Figure 5: Influence of tool temperature and feed rate on surface roughness: a) tool temperature, b) feed rate
Slika 5: Vpliv temperature orodja in hitrosti podajanja na hrapavost površine: a) temperatura orodja, b) hitrost podajanja

Table 5: Response table for *S/N* ratios (smaller is better) of T_{CTI}, T_T and R_a
Tabela 5: Razpredelnica odgovorov za *S/N* razmerja (manjše je boljše) za T_{CTI}, T_T in R_a

Level	Tool-chip interface temperature, T_{CTI} (dB)			Tool temperature, T_T (dB)			Surface roughness, R_a (dB)		
	a_p	v_c	f	a_p	v_c	f	a_p	v_c	f
1	–53.07	–52.08	–53.04	–36.33	–36.91	–36.84	4.838	5.313	7.873
2	–52.83	–52.85	–53.08	–37.58	–37.07	–36.78	5.632	4.429	5.969
3	–	–53.93	–52.73	–	–36.88	–37.24	–	5.963	1.864
Δ	0.25	1.85	0.35	1.25	0.19	0.46	0.793	1.534	6.008
Rank	3	1	2	1	3	2	3	2	1

Table 6: Response table for means of T_{CTI}, T_T and R_a
Tabela 6: Tabela odgovorov za pomen T_{CTI}, T_T in R_a

Level	Tool-chip interface temperature, T_{CTI} (°C)			Tool temperature, T_T (°C)			Surface roughness, R_a (µm)		
	a_p	v_c	f	a_p	v_c	f	a_p	v_c	f
1	452.2	401.7	450.8	65.67	70.50	70.00	0.6179	0.5792	0.4102
2	440.09	439.2	453.3	75.89	71.83	69.33	0.5378	0.6248	0.5062
3	–	497.5	434.2	–	70.00	73.00	–	0.5295	0.8172
Δ	12.2	95.8	19.2	10.22	1.83	3.67	0.0801	0.0953	0.4070
Rank	3	1	2	1	3	2	3	2	1

are higher or lower was used in the determination of the factors effective on T_{CTI}, T_T and R_a. The most effective parameters on T_{CTI} were the cutting speed, the feed rate and the depth of cut because there were (1.85, 0.35 and 0.25) dB differences between their levels (**Table 5**). The most effective parameters on T_T were determined to be the depth of cut, the feed rate and the cutting speed, with differences of (1.25, 0.46 and 0.19) dB, respectively (**Table 5**). The most effective parameters on R_a were determined to be the feed rate, the cutting speed and the depth of cut, with differences of (6.008, 1.534 and 0.793) dB, respectively (**Table 5**). The optimum values for the surface roughness and the dimensional accuracy were reported to be $a_2v_1f_3$, $a_1v_3f_2$ and $a_2v_3f_1$, respectively (**Table 6**).

The main effects of the control factors on the performance characteristics during the turning of the quenched and tempered AISI 4140 steel with coated carbide cutting tools were demonstrated using the "Graphical Representation of Factor Effects" and evaluated.[8–11] The main effect graphs showing the effects of the control factors on T_{CTI}, T_T and R_a are given in **Figures 6** and **7**, respectively.

In **Figure 6**, the optimum levels of the control factors for the tool-chip interface temperature are a_2 (a_p = 0.6 mm), v_1 (v_c = 76 m/min) and f_3 (f = 0.12 mm/rev), respectively. T_{CTI} increases depending on the increase of the cutting speed and the decrease of the depth of cut and the feed rate. From the same graphic it is clear that the most effective control factor on T_{CTI} is the cutting speed. In **Figure 7**, the optimum levels of the control factors for the tool temperature are a_1 (a_p = 0.4 mm), v_2 (v_c = 114 m/min) and f_2 (f = 0.08 mm/rev), respectively.

In **Figure 7**, when the effects of the control factors on tool temperature were examined, a significant increase was observed on T_T, depending on the increase in the depth of cut. With an increase of the cutting speed from 76 m/min to 114 m/min and an increase of the feed rate from 0.08 mm/rev to 0.12 mm/rev the tool temperature was increased (**Figure 7**). Similarly, the optimum levels for the minimum R_a surface roughness were observed to be a_2 (a_p = 0.6 mm), v_3 (v_c = 170 m/min) and f_1 (f = 0.05 mm/rev), respectively (**Figure 5**). The most effective parameter on R_a was the feed rate (**Figure 7**). With a further increase in the feed rate value the R_a surface roughness value increased.

ANOVA is a statistically based, objective, decision-making tool used for determining any difference in the average performance of a group of items being tested.[15–18] In the case when the F value of a process parameter is greater than the tabulated F ratio, it shows that the control factor has a significant effect on the performance characteristic. An analysis of variance (ANOVA) with a 95 % confidence interval was carried out for each experiment using the L_{18} orthogonal array in order to determine the effects of the control factors and their interactions on selected performance/quality characteristics. The results of the ANOVA carried out for T_{CTI}, T_T and R_a are presented in **Tables 7**, **8** and **9**. The cutting speed became the most effective factor for the tool-chip interface temperature, with a contribution of 86.57 % followed by the feed rate with 4.03 % (**Table 7**). The effects of other control factors and their interactions on T_{CTI} became insignificant with a smaller 5 % contribution (**Table 7**). The results of the ANOVA for the tool

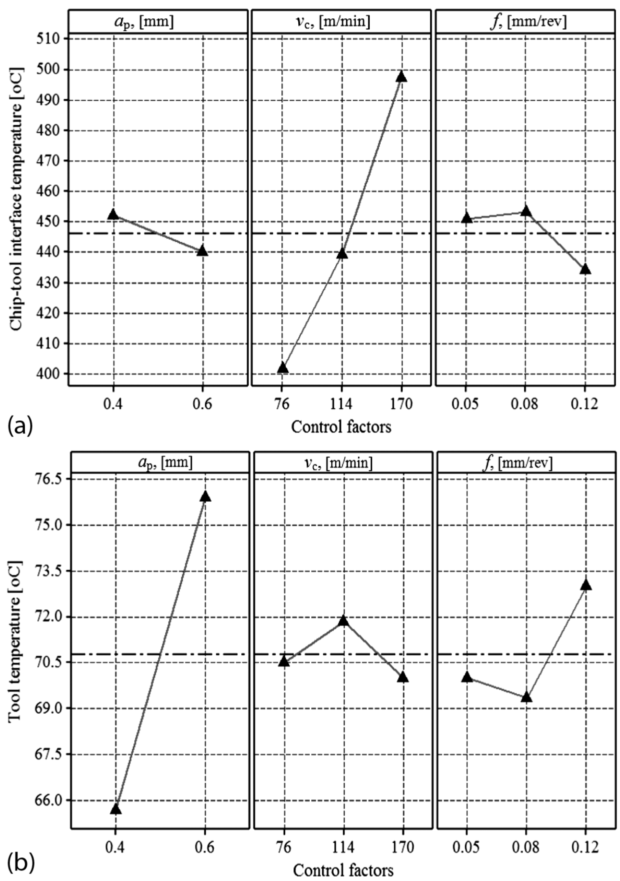

Figure 6: Mean effect plots for temperatures: a) tool-chip interface temperature, b) tool temperature

Slika 6: Diagram srednjega vpliva na temperature: a) temperatura stika orodje-ostružek, b) temperatura orodja

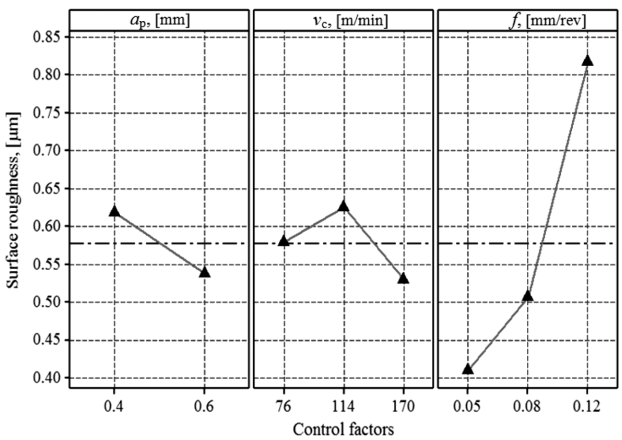

Figure 7: Mean effect plots for R_a surface roughness

Slika 7: Diagrami srednjega vpliva na hrapavost površine R_a

temperature (T_T) indicate that the depth of cut (a_p) has more influence on the tool temperature, with a contribution of 52.65 % and a cutting speed–feed rate (*v*x*f*) 16.75 %, depth of cut–cutting speed (*a*x*v*) 9.12 %, depth of cut–feed rate (*a*x*f*) 7.51 %, feed rate (*f*) 5.13 % and cutting speed (v_c) 1.21 % followed by a contribution %, respectively (**Table 8**). Finally, from **Table 9**, it is concluded that the feed rate with a contribution of 76.63 % has more influence on the surface roughness (R_a) followed by the depth of cut–feed rate (*a*x*f*), the depth of cut (a_p) and the cutting speed (v_c) to obtain the minimum surface roughness (**Table 9**).

Table 7: Results of ANOVA for tool-chip interface temperature (T_{CTI})
Tabela 7: Rezultati ANOVA za temperaturo stika orodje-ostružek (T_{CTI})

Source	DoF	SS	V	*F*-Ratio	Prob.>*F*	Contr. (%)
a_p	1	672.3	672.2	3.44	0.137	2.08
v_c	2	27986.1	13993.1	71.71	0.001	86.57
f	2	1302.8	651.4	3.34	0.140	4.03
*a*x*v*	2	302.8	151.4	0.78	0.519	0.94
*a*x*f*	2	369.4	184.7	0.95	0.461	1.14
*v*x*f*	4	913.9	228.5	1.17	0.441	2.83
Res.Err.	4	780.6	195.1			2.41
Total	17	32327.8				100.00

R^2 = 97.6, R^2 (adj) = 89.7 (significant at 95 % confidence level)

Table 8: Results of ANOVA for tool temperature (T_t)
Tabela 8: Rezultati ANOVA za temperaturo orodja (T_t)

Source	DoF	SS	V	*F*-Ratio	Prob.>*F*	Contr. (%)
a_p	1	470.22	470.22	27.57	0.006	52.65
v_c	2	10.78	5.389	0.32	0.746	1.21
f	2	45.78	22.889	1.34	0.358	5.13
*a*x*v*	2	81.44	40.722	2.39	0.208	9.12
*a*x*f*	2	67.11	33.556	1.97	0.254	7.51
*v*x*f*	4	149.56	37.389	2.19	0.233	16.75
Res.Err.	4	68.22	17.056			7.64
Total	17	893.11				100.00

R^2 = 92.4, R^2 (adj) = 67.5 (significant at 95 % confidence level)

Table 9: Results of ANOVA for surface roughness (R_a)
Tabela 9: Rezultati ANOVA za hrapavost površine (R_a)

Source	DoF	SS	V	*F*-Ratio	Prob.>*F*	Contr. (%)
a_p	1	0.028880	0.028880	10.73	0.031	4.18
v_c	2	0.027281	0.013641	5.07	0.080	3.95
f	2	0.543172	0.271586	100.89	0.000	78.63
*a*x*V*	2	0.014830	0.007415	2.75	0.177	2.15
*a*x*f*	2	0.062656	0.031328	11.64	0.022	9.07
*V*x*f*	4	0.003192	0.000798	0.30	0.867	0.46
Res.Err.	4	0.010767	0.002692	–	–	1.56
Total	17	0.690779	–	–	–	100.00

R^2 = 98.4, R^2 (adj) = 93.4 (significant at 95 % confidence level)

4.2 Developed second-order predictive equations for the temperature and surface roughness

The equations that were developed with multiple linear regression analysis to predict T_{CTI}, T_T and R_a in the turning of quenched and tempered AISI 4140 steel with coated carbide cutting tools and the equations that contain the main effects of the control factors and their interaction effects are presented in Equations (3) to (5), respectively.

$$T_{CTI} = 382 - 146a + 0.966v + 179f + 0.708av - 3.58vf \quad (4)$$

$$T_T = 2.0 - 96.8a + 0.328v + 255f - 0.381av - 1.74vf \quad (5)$$

$$R_a = -0.114 - 0.34a + 0.00332v + 7.15f - -0.00617av - 0.0102vf \quad (6)$$

These equations were developed according to the un-coded values of the control factors (*i.e.,* 0.4, 0.6 mm, *etc.* for a_p; *i.e.,* 76, 114, 170 m/min, *etc.* for v_c; *i.e.,* 0.05, 0.08, 0.012 mm/rev, *etc.* for *f*). *af* is highly correlated with other variables, so *af* has been removed from all of the equations. The correlation coefficients (R^2) and the adjusted correlation coefficients (R^2(adj)) of the second-order equations developed for the predictive tool-chip interface temperature (T_{CTI}) measured with an IR pyrometer, the tool temperature (T_T) measured with a thermocouple and the surface roughness (R_a) were calculated as R^2 = 92.8 %, R^2(adj) = 89.8 %, R^2 = 68.1 %, R^2(adj) = 54.8 % and R^2 = 82.6 % R^2(adj) = 75.3 %, respectively. R^2(adj) determines the amount of deviation about the mean that is described by the model. The predicted R^2 value and the R^2(adj) value were found to be in good agreement. These values show that the equations developed are sufficient to determine all the response values at a confidence interval of 95 %. The regression models can be successfully adopted for estimating T_{CTI}, T_T and R_a. Moreover, as seen in these equations, v_c and *f* have additive effects, while a_p has a negative effect on T_{CTI}, T_T and R_a.

The comparisons of the results of T_{CTI}, T_T and R_a measured experimentally (**Table 4**) with the fits for T_{CTI}, T_T and R_a estimated via the Taguchi method and fits for T_{CTI}, T_T and R_a estimated via the Regression model (Equation (3) to (5)) are given in **Table 8**. As can be seen from this table, the T_{CTI} results obtained from the Taguchi method and the linear regression analysis were found to be very close. The mean of the % error ratios of the estimated results obtained by the Taguchi method and the predictive equations were less than 14 %. This reflects the reliability of the statistical analyses (**Tables 10** and **11**).

5 CONCLUSIONS

In this study, the Taguchi design was selected to determine the effects of the control factors. The effects of the depth of cut, the cutting speed and the feed rate on the tool-chip interface temperature (T_{CTI}), the tool

Table 10: The comparisons of measured of T_{CTI}, and T_t experimentally with fits estimated via the Taguchi method and regression models
Tabela 10: Primerjava izmerjenih T_{CTI} in eksperimentalnih T_t, z ujemanji, določenimi po Taguchi metodi in z regresijskimi modeli

Exp. no	Tool-chip interface temperature, T_{CTI} (°C)					Tool temperature, T_t (°C)				
	Meas-ured T_{CTI}	Fits for T_{CTI} estimated via Taguchi method	Error %	Fits for T_{CTI} estimated via Regression model	Error %	Meas-ured T_t	Fits for T_t estimated via Taguchi method	Error %	Fits for T_t estimated via Regression model	Error %
1	410	418	2.0	414	0.9	57	56	1.0	60	5.7
2	405	401	0.9	411	1.4	66	68	2.9	64	3.2
3	410	406	1.1	407	0.7	72	71	1.9	69	4.5
4	460	462	0.5	454	1.3	65	62	3.9	64	2.1
5	465	458	1.5	447	3.8	61	61	0.1	65	7.0
6	425	430	1.1	438	3.1	67	70	3.9	68	0.8
7	520	510	2.0	514	1.1	65	68	4.8	69	5.5
8	500	511	2.1	501	0.2	67	65	2.8	67	0.5
9	475	475	0.1	484	1.9	71	70	1.7	66	7.5
10	400	392	2.0	395	1.2	72	73	0.8	74	2.5
11	390	394	0.9	392	0.6	80	78	2.4	77	3.1
12	395	399	1.1	389	1.6	76	77	1.8	82	8.4
13	430	428	0.5	441	2.6	80	83	3.2	74	7.1
14	435	442	1.6	434	0.2	75	75	0.1	76	1.3
15	420	415	1.1	425	1.2	83	80	3.1	78	5.8
16	485	495	2.1	509	4.9	81	78	3.8	75	7.4
17	525	514	2.0	496	5.5	67	69	2.8	74	10.1
18	480	480	0.1	479	0.2	69	70	1.8	72	4.5
Min	390	392	0.1	389	0.2	57	56	0.1	60	0.5
Max	525	514	2.1	514	5.5	83	83	4.8	82	10.1
Mean	446	–	1.3	–	1.8	71	–	2.4	–	4.8

Table 11: The comparisons of the measured R_a with fits estimated via the Taguchi method and the regression models
Tabela 11: Primerjava izmerjene R_a z ujemanji, določenimi po Taguchi metodi in z regresijskimi modeli

Exp.no	Measured R_a	Fits for R_a estimated via Taguchi method	Error %	Fits for R_a estimated via Regression model	Error %
1	0.295	0.338	14.4	0.406	37.5
2	0.483	0.478	1.1	0.597	23.5
3	0.958	0.921	3.9	0.851	11.1
4	0.484	0.461	4.7	0.418	13.5
5	0.579	0.594	2.5	0.598	3.3
6	0.988	0.996	0.8	0.837	15.3
7	0.410	0.390	4.9	0.438	6.7
8	0.492	0.483	1.9	0.600	21.9
9	0.872	0.901	3.4	0.816	6.4
10	0.489	0.446	8.7	0.380	22.3
11	0.530	0.535	1.0	0.571	7.7
12	0.720	0.757	5.2	0.826	14.7
13	0.429	0.452	5.3	0.346	19.4
14	0.547	0.532	2.7	0.525	4.0
15	0.722	0.714	1.1	0.765	5.9
16	0.354	0.374	5.7	0.296	16.5
17	0.406	0.415	2.3	0.458	12.8
18	0.643	0.614	4.6	0.674	4.9
Min	0.295	0.338	0.8	0.296	3.3
Max	0.988	0.996	14.4	0.851	37.5
Mean	0.578	–	4.1	–	13.7

temperature (T_T) and the surface roughness (R_a) were investigated in the turning of the quenched and normalized AISI 4140 steel workpieces that were machined using TiAlN-TiN, PVD-coated, carbide tools and the obtained results are as follows:

The most effective parameter on the tool-chip interface temperature was the cutting speed with a contribution ratio of 86.57 %. The effective parameters for tool temperature were the depth of cut, the cutting speed-feed rate, the depth of cut–cutting speed, the depth of cut-feed rate, the feed rate and the cutting speed with contributions of 52.65 %, 16.75 %, 9.12 %, 7.51 %, 5.13 % and 1.21 %.

The feed rate with a contribution of 76.63 % has more influence on the surface roughness (R_a) followed by the depth of cut–feed rate (*axf*), the depth of cut (a_p) and the cutting speed (v_c) to obtain the minimum surface roughness.

The optimum levels of the control factors were a_p = 0.6 mm, v_c = 76 m/min and f = 0.12 mm/rev for the minimum tool-chip interface temperature; a_p = 0.4 mm, v_c = 114 m/min and f = 0.08 mm/rev for the minimum tool temperature, and a_p = 0.6 mm, v_c = 170 m/min and f = 0.05 mm/rev for the minimum R_a surface roughness.

The tool-chip interface temperature increased significantly depending on the increase of the cutting speed. The depths of cut and feed rate do not have a significant effect on the tool-chip interface temperature.

The tool temperature increased significantly depending on the increase of the depth of cut.

The surface roughness increased depending on the increase of the feed rate, while the same tendency was not observed for the depth of cut and the cutting speed.

The correlation coefficients of the predictive equations developed for the estimation of the minimum tool-chip interface temperature, the tool temperature and the surface roughness by multiple linear regression analysis were calculated as 0.928, 0.681 and 0.826, respectively. Higher correlation coefficients reflect the reliability of the developed equations.

The mean of the % error ratios of the estimated results obtained by Taguchi method and the predictive equations were less than 14 %. This reflects the reliability of the statistical analyses.

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