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The effects of sharpened tools on tool flank wear–surface roughness and optimization of cutting parameters in milling Vanadis 4E powder metallurgic tool steel

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Abstract. Vanadis 4E is a powder metallurgic tool steel that provides an excellent combination of wear resistance and ductility for high-performance tools, and it is more machinable than AISI D2 tool steel. This study applied grooving on Vanadis 4E powder metallurgic tool steel with the dimensions of 80 × 105 × 35 mm, and during the milling process, investigated the effects of cutting parameters on surface roughness and tool flank wear. Using the Taguchi L9 (34) array, 9 experiments were carried out. In the experiments, uniform carbide end mills with diameters of 12 mm were used as new and sharpened (first usage, first sharpening, second sharpening), and the experiments were performed with three cutting depths (1, 1.5 and 2 mm), three cutting speeds (60, 80 and 100 m/min) and three feed rates (0.02, 0.04 and 0.06 mm/tooth). During the experiments, temperature measurements were made with a thermal camera from the cutting area, and surface roughness and tool wear measurements were made after every one experiment. The cutting parameters were optimized by using the obtained roughness and flank wear values, and the results were analyzed by signal-to-noise ratios, analysis of variance (ANOVA), three-dimensional graphs and thermal images. After optimization, three confirmation experiments were conducted by using the optimum parameters, and the values that were estimated with the Taguchi method and the results of the verification experiments were compared.

Keywords. Vanadis 4E; surface roughness; tool flank wear; thermal measurement; re-sharpening; Taguchi method.

1. Introduction

Vanadis 4E is a patented product, and it has much better machinability and grindability properties in comparison to other high-alloy powder metallurgic tool steels. It is also a chromium, molybdenum and vanadium allow powder metallurgic (PM) tool steel that is utilized to cut and shape advanced high-strength steels. It has excellent ductility, high wear resistance, high pressure strength, good dimensional stability during thermal treatment, excellent hardening properties and good tempering resistance. One of the greatest advantages of Vanadis 4E is that its dimensional stability after hardening and tempering is better than those of all known high-performance cold-work tool steels [1]. Although Vanadis 4E has good machinability properties according to the manufacturer's catalogue information, there is only one study in the literature on wire electric discharge machining in this material [2]. The Vanadis series steels are not limited to 4E, while they include different series such as Vanadis 4, Vanadis 6 and Vanadis 8. In the literature review, many studies on material behaviors were observed to have been carried out for purposes such as investigating the changes in mechanical properties with different types of reinforcements added to these materials, examining corrosion behaviors, phase composition and stress situations with nitriding, examination of the changes in the material's structure by deep cryogenic treatment, wear resistance and coating applications on the material [3–8].

Surface quality plays an important role in determining the machinability qualities of parts that are produced. A good surface roughness value provides important developments in the tribological properties of the material, its fatigue strength, corrosion resistance and aesthetical appearance. Additionally, surface roughness influences such properties of machined parts as friction, wear and thermal conductivity [9, 10]. Another issue that has a significant role in machining is tool wear. This is because surface roughness is dependent on tool wear. Surface roughness and tool wear are affected by several parameters such as tool material, type of tool coating, cutting speed, feed rate and the type of the material that is being machined. Achieving the minimum surface roughness and tool wear by optimizing these parameters is highly

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important to reduce machining costs [9]. The Taguchi method offers a statistical experiment design that is commonly used in many machinability studies today [11–13]. This way, by optimizing the parameters that affect the values that are measured in experiments with the experimental design it offers, it provides a statistical result in a short time and compares the accuracy of the optimization process to verification experiments. Thus, the Taguchi-based optimization technique provides optimization that is different to conventional practices, unique and strong [14].

End milling is a type of surface milling, and it is used for profiling and slotting operations. In studies on end milling, methods such as the Taguchi method, RSM (response surface methodology) and artificial networks are used in estimation of target values and optimization of the parameters that affect the target values. Zain *et al* [15] estimated surface roughness in an end milling operation by using the method of Artificial Neural Networks. Zhang *et al* [16] used the Taguchi method to optimize surface quality in a grooving process. In their study, they conducted a total of 9 experiments by determining three parameters as spindle speed, feed rate and depth of cut. As a result, they showed that spindle speed and feed rate were more influential on surface roughness than depth of cut. Ghani *et al* [17] utilized the Taguchi method in optimization of end milling parameters. By applying an end milling procedure with a P10 carbide cutting tool coated with TiN on an AISI H13 material, they optimized the cutting forces and surface roughness values that obtained by the experimental study they conducted with the cutting speed, feed rate and depth of cut values they determined. They analyzed the results by the S/N ratio and ANOVA. Pillai *et al* [18] aimed to put together a set of combinations of optimal operational parameters for milling the Al 6005 A alloy. Additionally, they examined the effects of parameters like tool part strategy, spindle speed and feed rate on performance characteristics such as machining time and surface roughness by using the Taguchi-Gray relational optimization method. Mersni *et al* [19] optimized the factors effective on surface roughness by applying ball end milling on the Ti-6Al-4V titanium alloy. They conducted 9 experiments by using a fitted carbide cutter tool and different cutting speeds, feed rates and depths of cut. The literature review did not reveal any milling study on the material that was used in this study.

This study applied end milling on Vanadis 4E powder metallurgic steel by using three different types of the same cutter (new, first sharpening, second sharpening), three different cutting rates, three different feed rates and three different depths of cut. 9 experiments were carried out by using the Taguchi method in the experimental design. At the end of each experiment, surface roughness and tool flank wear were measured. The results were analyzed with signal-to-noise ratios, ANOVA and three-dimensional diagrams. Additionally, using thermal images that were taken during each experiment, the temperatures in the cutting region were examined. At the end of the study, the accuracy of the optimization process was tested with verification tests.

2. Experimental details

2.1 *End milling experiments*

The grooving processes used a Delta Seiki 1050A (Fanuc Oimate MC, maximum speed of cutting tool 8000 rpm, operational pressure 5.5 bar, motor power 12 kW) three-axis vertical milling machine. WIDIA brand 4-flute solid carbide end mills with 12 mm of diameter were used as the cutting tools (figure 1). According to the catalogue information, this tool may be used for roughing and finishing operations [20].

2.2 *Material selection*

As the workpiece, Vanadis 4 Extra powder metallurgic tool steel from the firm Uddeholm with the dimensions of 80x105x35 mm was used. The mechanical properties and component element properties of the material that was used are shown in table 1.

2.3 *Sharpening cutting tools*

For the sharpening process, a Vertex VEG-13A end mill sharpening machine with a sharpening diameter of Ø4 ~ Ø 13 mm, power of 450 W and speed of 6000 rpm was utilized. The same type of cutting tools that was used in the experiments was used in three different forms as new, sharpened once and sharpened twice. The new cutting tools that were used for the first time were sharpened in the end mill sharpening machine (figure 2) after the first three experiments, and three additional experiments were carried out with these tools that were sharpened. These cutting tools were then sharpened for a second time, and the last three experiments were conducted this way.

2.4 *Surface roughness and flank wear measurements*

The surface roughness measurements were made by a Marsurf PS10 device. The measurements were made from the start and the finish points of the surface that was grooved perpendicularly to the side of the piece with a sampling length of 4 mm. The flank wear images of the cutting tools were taken by using a Dino-Lite Pro2 polarized microscope. The images were taken with a magnification of 50 times, and the measurements were obtained by using the Dino Capture 2.0 software.

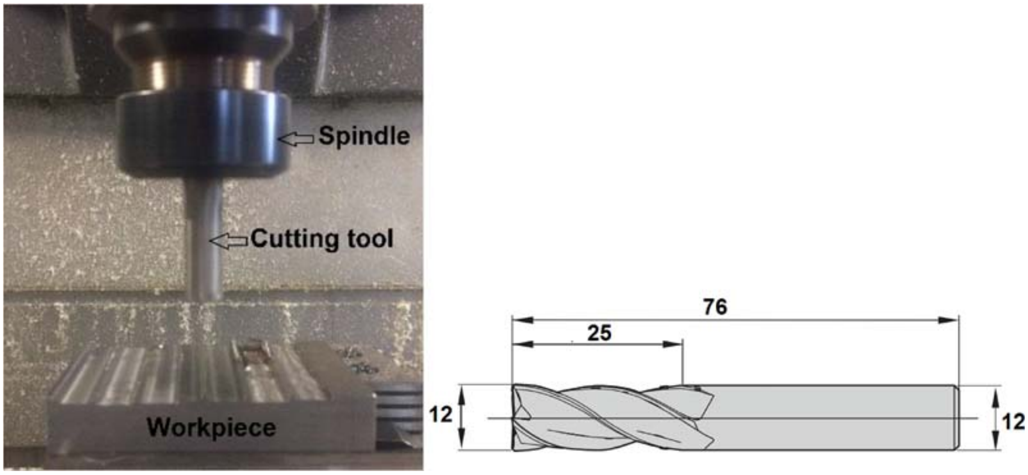

Figure 1. Experimental set-up and cutting tool dimensions.

Table 1. Mechanical and component element properties of the Vanadis 4E material.

Mechanical properties			
Density	Modulus of elasticity (GPa)	Hardness Brinell	Thermal conductivity
7.70 gr/cc	205	230	30 W/m-K

Component elements properties (%)						
C	Cr	Fe	Mn	Mo	Si	V
1.4	4.7	85.9	0.40	3.5	0.40	3.7

2.5 *Thermal measurements*

For each experiment, 3 sec after the cutting tool started removing material, temperature measurements were made from the cutting region by using a Fluke TiS20 model thermal camera. The thermal camera that was used was able to make measurements between −20 °C and 350 °C with a sensor resolution of 120x90, a field of view of 35.7° × 26.8° and a frame rate of 9 Hz.

3. Conducted tests and optimization

3.1 *Experimental design and tests*

The Taguchi L_9 orthogonal array was used for the experimental design, and 9 experiments were carried out. In the analyses and examinations that are performed with the Taguchi method, it is possible to reduce the number of experiments to a substantial extent. The Taguchi method uses some functions in determining quality characteristics. These functions transform the obtained data into signal-to-noise (S/N) ratios. Three different equations are used for transformation of S/N ratios as "nominal the best", "larger the better" and "smaller the better". AS the minimum values of surface roughness and tool flank wear were the desired values in this study, the "smaller the better" function was utilized (1).

$$\text{Smaller the better} \quad S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad (1)$$

Here, n is the number of observed values, and is the data observed [21, 22]. Selection of an orthogonal array in the Taguchi method is dependent on the factors that are selected, interactions of these factors, number of levels for each factor and the objective of the experiment. So, firstly experimental parameters and levels are determined for selection of the correct orthogonal array. Table 2 shows the selected cutting parameters and the levels of these parameters. The material and cutting tool catalogue was taken as the reference while determining the cutting parameters [20, 23].

In Taguchi method, firstly the appropriate orthogonal array is selected considering the cutting parameters. To determine the optimum cutting parameters and analyze the effects of these determined parameters, the most

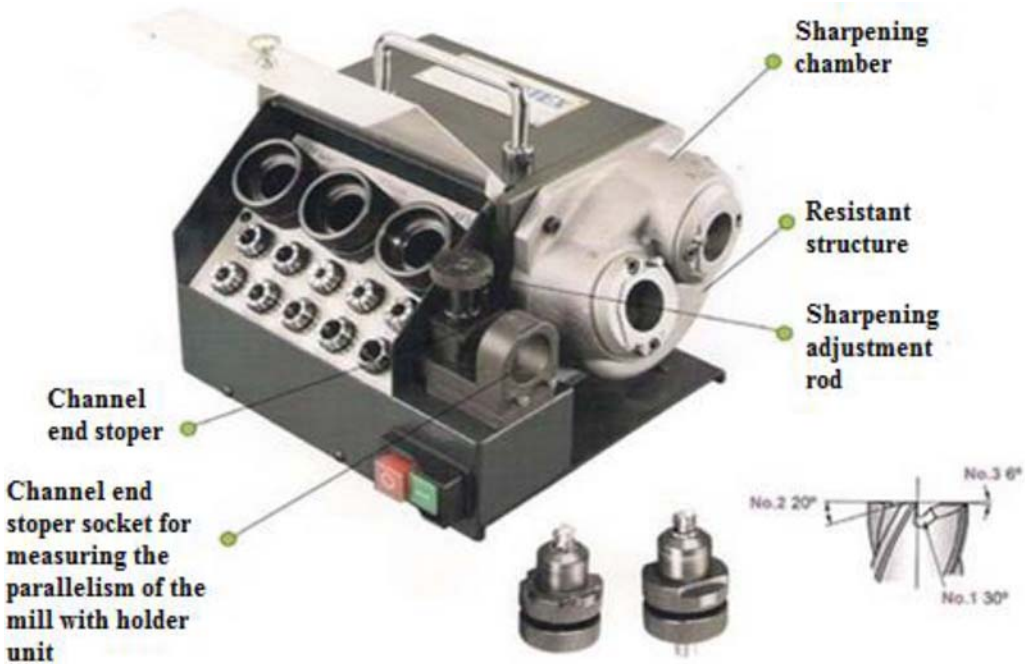

Figure 2. End mill sharpening machine.

Table 2. Cutting parameters selected as cutting parameters and their levels.

Symbol	Parameters	Level 1	Level 2	Level 3
A	Cutting tool (Ct)	New	1st sharpening	2nd sharpening
B	Cutting depth (a, mm)	1	1.5	2
C	Cutting speed (V, m/min)	60	80	100
D	Feed rate (f, mm/tooth)	0.02	0.04	0.06

Table 3. Surface roughness and tool flank wear values obtained from experiments and S/N ratios.

	Control factors				Surface roughness (Ra)		Flank Wear (V_f)	
Test no.	A Cutting tool (Ct)	B Cutting depth (a)	C Cutting speed (V)	D Feed rate (f)	Ra (μm)	S/N_{Ra} (dB)	V_f (mm)	S/N_{Vf} (dB)
1	New	1	60	0.02	0.49	6.169	0.089	21.012
2	New	1.5	80	0.04	1.16	−1.259	0.101	19.913
3	New	2	100	0.06	0.99	0.131	0.205	13.764
4	1st sharpening	1	80	0.06	1.48	−3.431	0.086	21.310
5	1st sharpening	1.5	100	0.02	0.50	6.046	0.073	22.733
6	1st sharpening	2	60	0.04	3.09	−9.799	0.785	2.102
7	2nd sharpening	1	100	0.04	2.17	−6.715	0.111	19.093
8	2nd sharpening	1.5	60	0.06	1.64	−4.286	0.148	16.594
9	2nd sharpening	2	80	0.02	1.54	−3.764	0.17	15.391

suitable array [L_9 (3^4)] was selected. As a result of the experiments that were conducted, optimization of the roughness and tool wear values on the measured surface was achieved by S/N ratios. Table 3 shows the surface roughness and tool wear values that were measured as a result of the experiments that were carried out based on the

L_9 Taguchi experimental design and the S/N ratios that were calculated by using equation (1).

After the 9 experiments that were carried out, the mean surface value was found as 1.45 µm, while the mean S/N ratio was calculated as −1.88 dB. Moreover, after 9 experiments, the mean wear value was 0.20 mm, and the mean S/N ratio for the wear values was 16.88 dB.

3.2 *Determining optimum parameters*

In table 4, the cutting parameters that were denoted as the control factors were identified by considering different levels and probable effects for the selected orthogonal array. These levels represent the signal to noise ratios and the mean values for each level of the roughness and wear values calculated for the analysis of surface roughness and tool wear. These values were used to calculate estimation values for the optimum parameters that were determined.

Another requirement for calculating the optimum values is determining the optimum levels. The optimum levels may be determined by assessing different levels of the cutting parameters based on the results of combinations that are produced by the L9 orthogonal array. These values are used to draw main effect graphs (figure 3).

The S/N ratios and mean surface roughness distributions that were calculated based on the control factors and their levels are shown in figure 3. As the "smaller the better" characteristic was selected in the study, the minimum mean values were considered for all levels to determine the optimal combination of the cutting parameters. Accordingly, the optimum combination of the cutting parameters for surface roughness was determined as $A_1B_2C_3D_1$ (A_1 = new cutting tool, B_2 = 1.5 mm cutting depth, C_3 = 100 m/min cutting speed and D_1 = 0.02 mm/tooth feed rate). Furthermore, the optimum combination of the cutting parameters for tool wear was determined as $A_1B_1C_2D_1$ (A_1 = new cutting tool, B_1 = 1 mm cutting depth, C_2 = 100 m/min cutting speed and D_1 = 0.02 mm/tooth feed rate).

3.3 *Effects of cutting parameters on roughness*

Figure 4 shows the graphs on surface roughness. By using variations of the cutting parameters, four graphs were obtained (figure 4). Figure 4(a) shows the effects of type of cutting tool and depth of cut on surface roughness. Here, there was a decrease in surface roughness at 1.5 mm of cutting depth and 1st sharpening, but a large increase in surface roughness was observed when the depth of cut was increased to 2 mm with 1st sharpening. During the experiments at 2 mm of cutting depth, there was heating of up to 200 °C in the tool tip and accumulation of chippings on the tool. This situation was caused by the hardness of the material, and it is recommended to use coated carbide cutters for better cutting. In the same graph, it may be seen that there was a decrease in the roughness values with the new cutting tool at 1 mm of cutting depth. Figure 4(b) shows the effects of feed rate and type of cutting tool on roughness. Here, likewise, there was a decrease in the roughness values at a feed rate of 0.02 mm/tooth with 1st sharpening. However, when the feed rate increased, the roughness values increased substantially with 1st sharpening and 2nd sharpening. Due to the decrease in the roughness values with 1st sharpening as seen in figure 4(a) and (b), 1st sharpening and low feed rate constitute a desirable combination for this material.

Figure 4(c) © shows the effects of feed rate and cutting speed on roughness. Here, there was an increase in roughness at a cutting speed of 60 m/min and a feed rate of 0.04 mm/tooth. As seen in the graph, roughness decreased as the cutting rate increased, but an increase, yet a small one, was observed at 80 m/min. Figure 4(d) shows the effects of cutting speed and cutting tools on surface roughness. Here, it is observed that the roughness values

Table 4. S/N ratios (dB), mean surface roughness and wear values.

	Surface roughness (Ra)				Flank wear (V_f)			
	A	B	C	D	A	B	C	D
Control factors	S/N ratios (dB)				S/N ratios (dB)			
Level 1	1.6805	−1.3257	−2.6386	2.8172	18.23	20.47	13.24	19.71
Level 2	−2.3947	0.1671	−2.8184	−5.9245	15.38	19.75	18.87	13.70
Level 3	−4.9220	−4.4775	−0.1791	−2.5289	17.03	10.42	18.53	17.22
Delta	6.6025	4.6446	2.6394	8.7417	2.85	10.05	5.64	6.01
	Means (µm)				Means (mm)			
Level 1	0.8775	1.3808	1.7398	0.8442	0.1316	0.0953	0.3406	0.1106
Level 2	1.6910	1.0975	1.3943	2.1375	0.3146	0.1073	0.1190	0.3323
Level 3	1.7823	1.8725	1.2167	1.3692	0.1430	0.3866	0.1296	0.1463
Delta	0.9048	0.7750	0.5232	1.2933	0.1830	0.2913	0.2216	0.2216

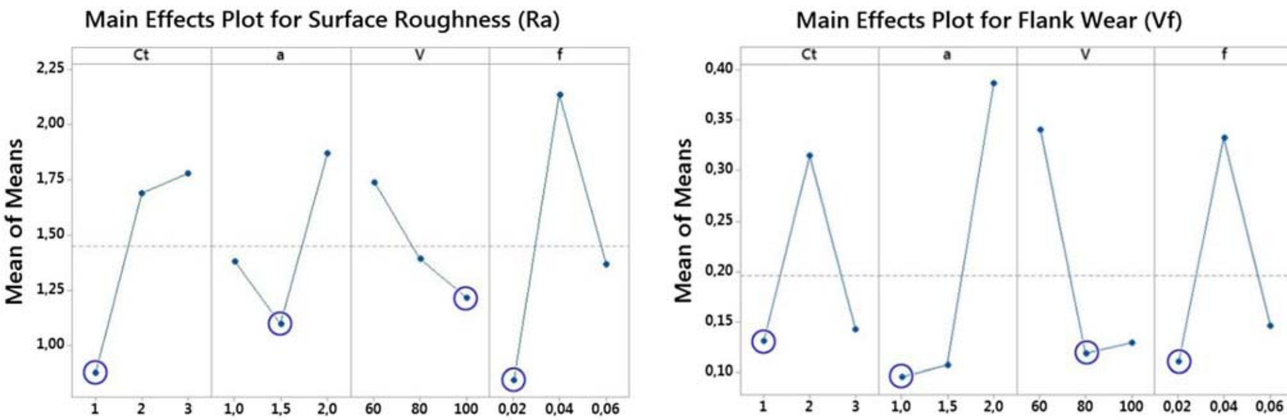

Figure 3. Effect plots of cutting parameters for surface roughness and wear.

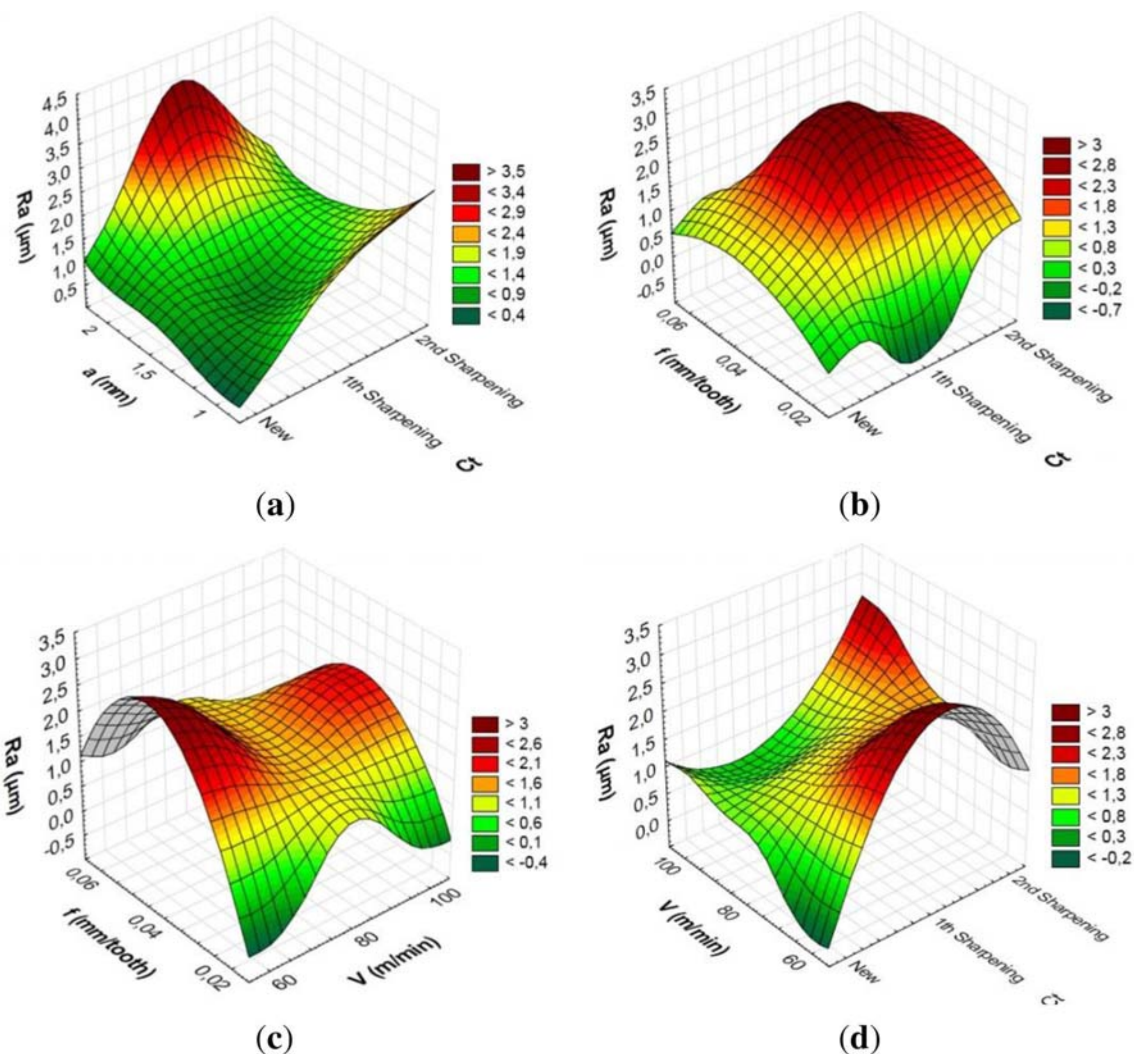

Figure 4. Cutting parameters and surface roughness graphs.

increased for 2nd sharpening, but at a cutting speed of 100 m/min, roughness decreased both for the new tool and with 1st sharpening. Roughness also decreased at a cutting speed of 60 m/min and for the new tool.

3.4 *Effects of cutting parameters on wear*

Figure 5 shows the effects of cutting parameters on wear. Figure 5(a) displays the effects of cutting depth and cutting tools on wear. Here, as the cutting depth increased, wear also increased, and the wear values peaked especially at a cutting depth of 2 mm. During the experiments at 2 mm of cutting depth, the cutting tool overheated, and there was chipping build-up on the tool. Figure 5(b) shows the effects of feed rate and cutting tools on wear. Accordingly, it is seen that the new cutting tool did not show a difference in wear in comparison to feed rate, but there was a sudden increase in wear at a feed rate of 0.04 mm/tooth with 2nd sharpening. On the other hand, at a feed rate of 0.02 mm/tooth and with 1st sharpening, there was a decrease. Figure 5(c) shows the effects of feed rate and cutting speed on wear. Here, the wear values increased at a cutting speed of 60 m/min and a feed rate of 0.05 mm/tooth, but they decreased at cutting speeds of 80 and 100 m/min. Here, it may be seen that wear increased at a cutting speed of 60 m/min with 1st and 2nd sharpening, while the wear values were low with the new tool. Figure 5(d) shows that there was an increase, though a small one, in the wear values as the cutting speed increased. Considering these graphs in general, it is recommended to sharpen a new tool once. However, a second procedure of sharpening is not recommended.

3.5 *Analysis of temperature measurements*

Figure 6 shows the images obtained with the thermal camera for all experiments and table 5 shows the values that were recorded. It was observed that the temperatures increased as

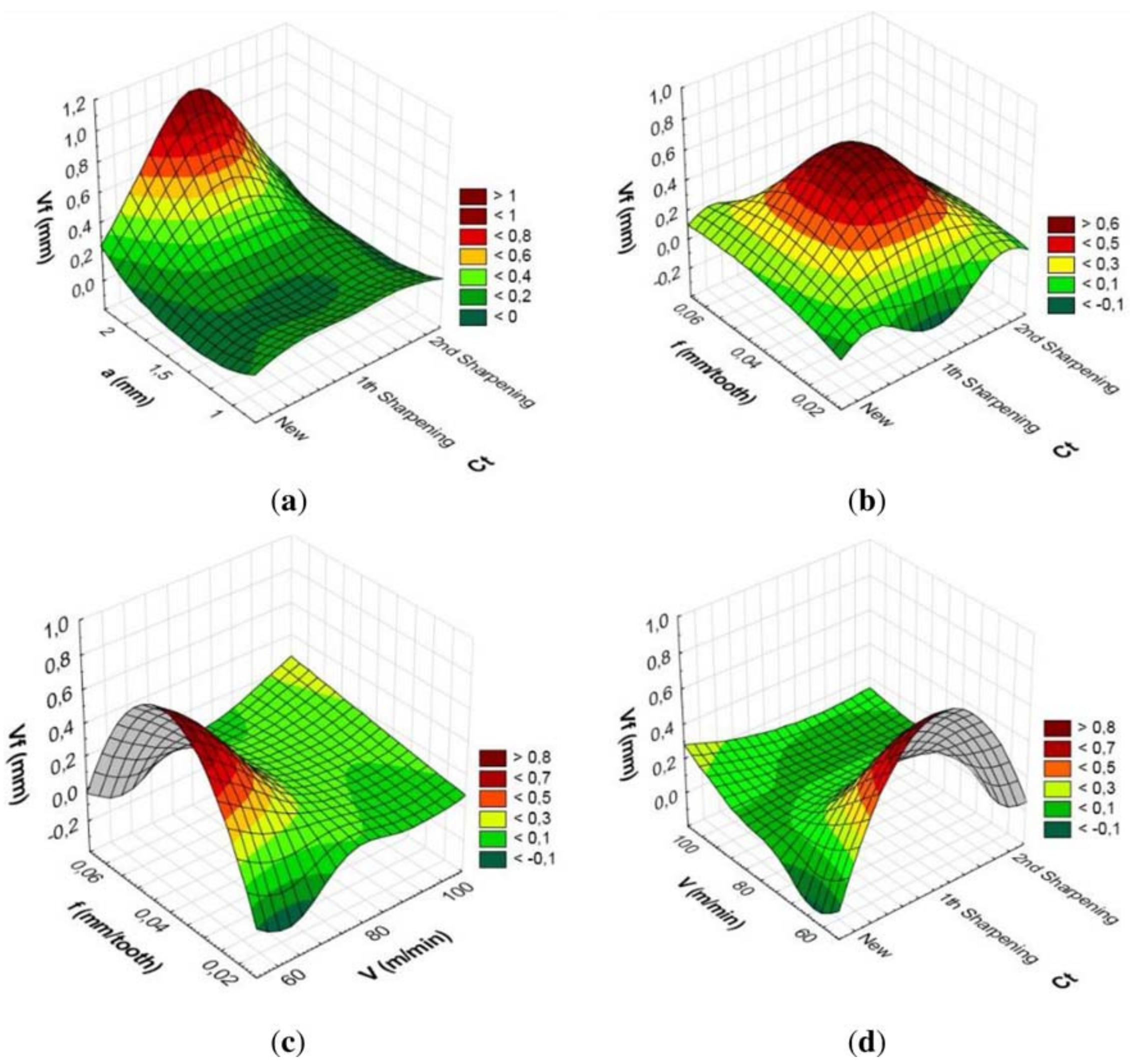

Figure 5. Cutting parameters and tool wear graphs.

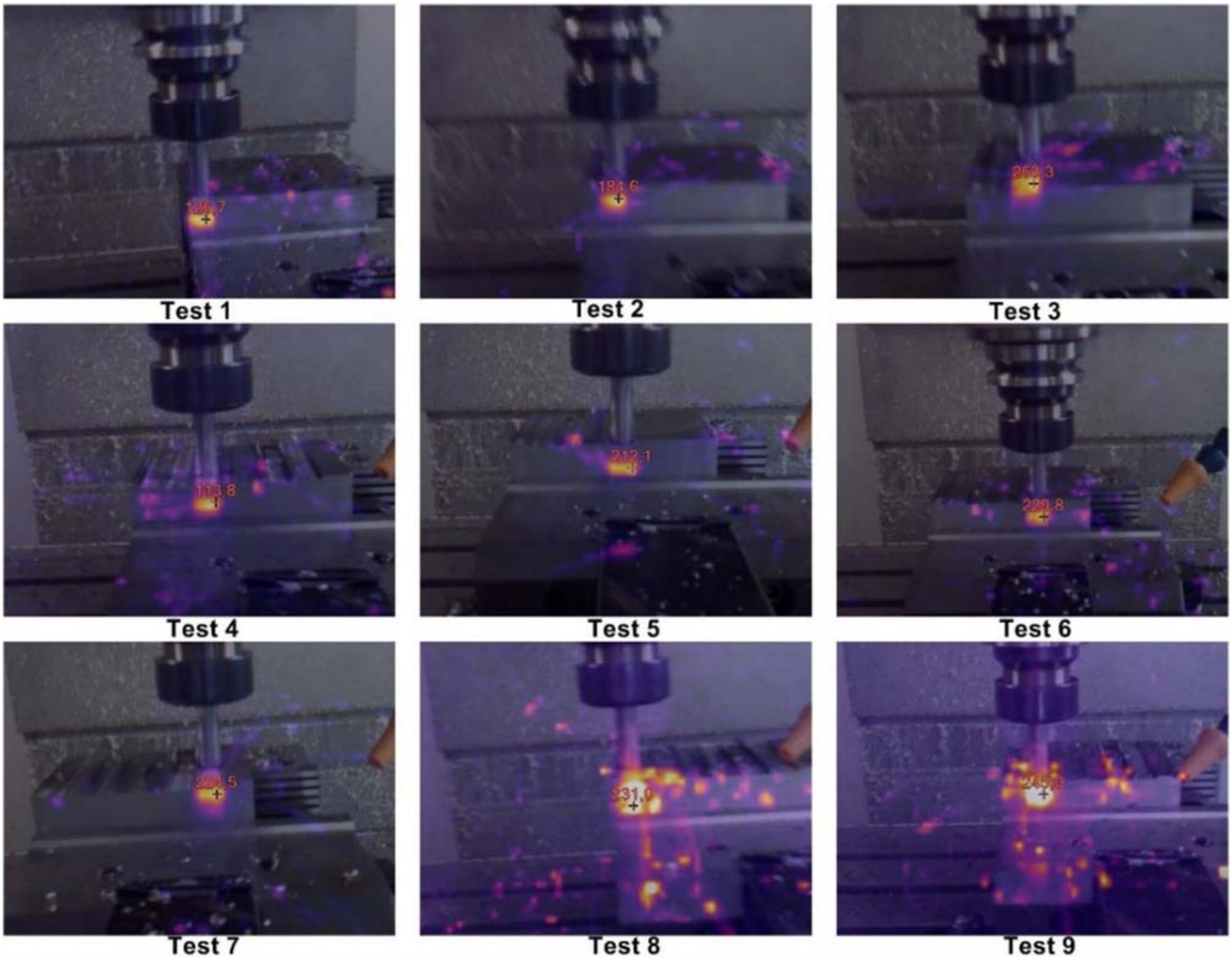

Figure 6. Images on temperatures measured in experiments.

Table 5. Temperatures recorded with the thermal camera.

	Cutting parameters				
Test no.	Cutting tool (Ct)	Cutting depth (*a*)	Cutting speed (*V*)	Feed rate (*f*)	Temperature (°C)
1	New	1	60	0.02	126.7
2	New	1.5	80	0.04	184.6
3	New	2	100	0.06	263.3
4	1st sharpening	1	80	0.06	113.8
5	1st sharpening	1.5	100	0.02	212.1
6	1st sharpening	2	60	0.04	229.8
7	2nd sharpening	1	100	0.04	224.5
8	2nd sharpening	1.5	60	0.06	231.5
9	2nd sharpening	2	80	0.02	245

the depth of cut increased, and the highest temperature was obtained with the new cutting tool at a cutting depth of 2 mm. The fourth experiment with the lowest cutting temperature was carried out at a cutting depth of 1 mm, a cutting speed of 80 m/min and a feed rate of 0.06 mm/tooth with a cutting tool that was sharpened once. For this experiment, the roughness and wear values were found respectively as 1.48 μm and 0.086. Low temperatures are caused by low friction, and this shows that sharpening once would be suitable for this tool. It was seen in the experiments that the temperatures were higher after the second sharpening process (tests 7, 8 and 9), and there were also increases in the roughness and wear values. Therefore, a second sharpening procedure is not recommended for this tool.

3.6 *Evaluation of wears*

The wear images were taken by using a digital microscope with 50X magnification. Figure 7 shows the wear images of the 9 experiments. The lowest wear value obtained from the test results was in the 5th test (0.073 mm). This was attributed to the low cutting depth and low progression rate. The same situation was observed in the 1st and 4th tests. The wear value was 0.089 mm in Test 1 and 0.086 mm in Test 4. The cutting depth in these tests was 1 mm. As seen in figure 7, there were local burns on the cutting tool in Test 3. This was attributed to the high cutting depth and high progression rate. When the tests with the cutting depth of 2 mm in figure 7 (Test 3, Test 6 and Test 9) and table 3 are examined, it is seen that the wear values were high. The highest wear value occurred in Test 6, where the cutting depth was 2 mm. When the optimum parameters that were obtained for the wear values with the Taguchi method are examined, the optimum parameter for cutting depth is 1 mm. This situation was in parallel with the wear values in the 9 experiments.

3.7 *Evaluation of experimental results using ANOVA*

ANOVA is used to determine how all control factors used in the experimental design affect each other, what type of effect this has on the performance variables and what kind of changes occur in the performance variables on different levels of the parameters [13]. The effects of cutting tools,

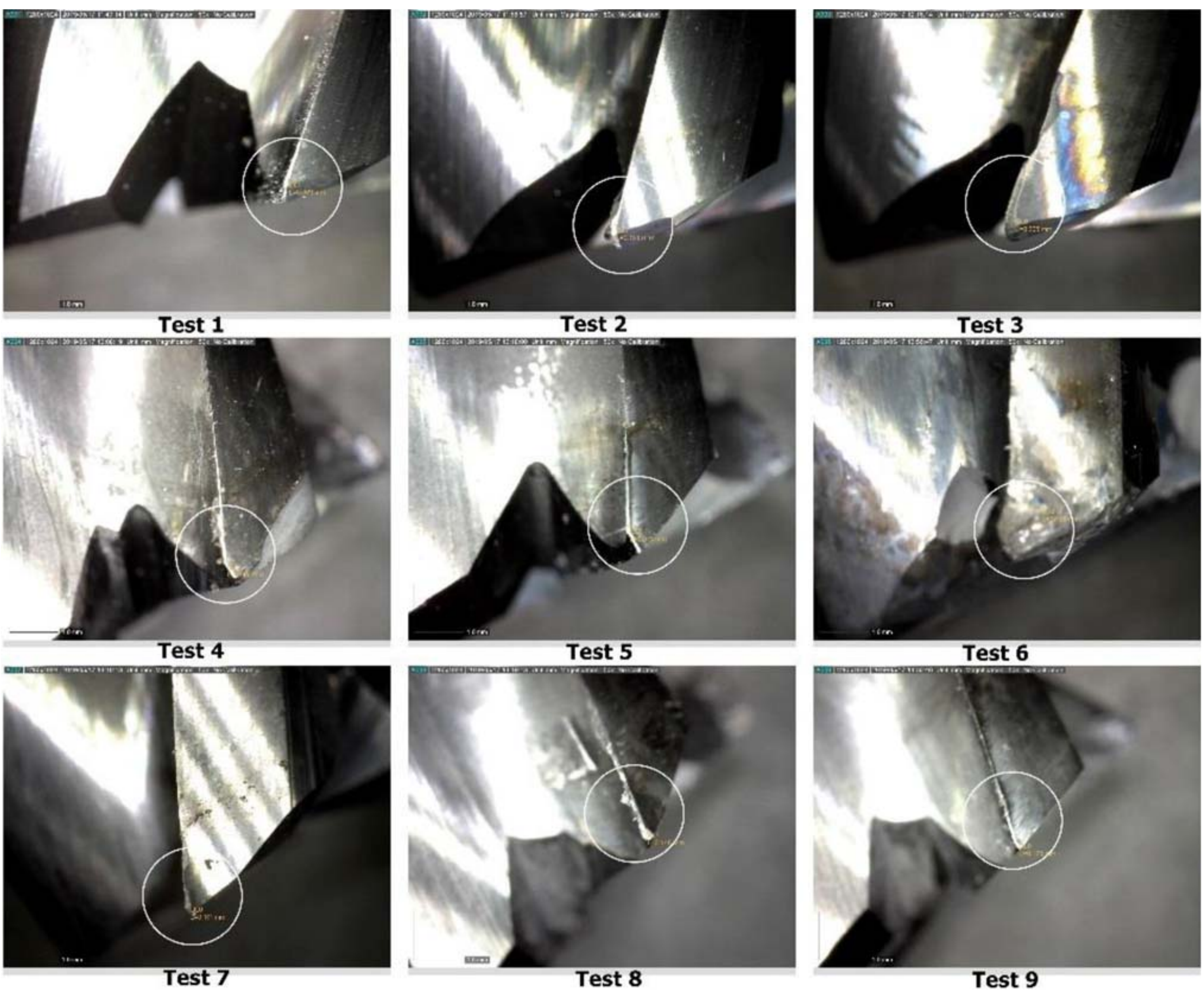

Figure 7. Wear images obtained from digital microscope.

Table 6. ANOVA results for surface roughness and wear.

Variance source	Degrees of freedom (DoF)	Sum of squares (SS)	Mean squares (MS)	F-value	P-value	Contribution rate (%)
Surface roughness (Ra_m-µm)						
Ct	1	0.8667	0.8667	2.68	0.177	28.44
a	1	0.1975	0.1975	0.61	0.478	6.48
V	1	0.1203	0.1203	0.37	0.575	3.95
f	1	0.5682	0.5682	1.76	0.256	18.65
Error (*e*)	4	1.2945	0.3236			42.48
Total	8	3.0473				100
Wear (Vf, mm)						
Ct	1	0.0288	0.0288	0.08	0.793	0.69
a	1	2.0091	2.0091	5.49	0.079	48.05
V	1	0.5572	0.5572	1.52	0.285	13.33
f	1	0.1231	0.1231	0.34	0.593	2.95
Error (*e*)	4	1.4627	0.3656			34.98
Total	8	4.1810				100

cutting speed, feed rate and depth of cut on surface roughness and wear values were analyzed by ANOVA, and the results were examined in a 95% confidence interval. The results of this analysis are shown in table 6.

As seen in table 6, the factor that affected roughness the most was the cutting tool with 28.44% contribution. This factor was followed by feed rate with 18.65%, while the contribution rates of the depth of cut and cutting speed factors were respectively 6.48% and 3.95%. Moreover, the factor that affected wear the most was depth of cut with 48.05% contribution. This factor was followed by cutting speed with 13.33%, while the contribution rates of the cutting tool and feed rate were respectively 0.69% and 2.95%. In the experiments, it was observed that the temperature in the medium increased as cutting depth increased. Therefore, especially at a cutting depth of 2 mm, chippings accumulated on the tool, and this situation increased the rates of wear. The ANOVA results verified this outcome.

3.8 *Regression analysis and mathematical models*

Regression analyses are used to model and analyze different variables in cases of one dependent variable and one or more independent variables [24]. In this study, two different quadratic mathematical models were obtained for surface roughness and tool wear, and the R^2 value of these two models was found as 100. The models that were obtained are shown in equations (2) and (3).

$$\begin{aligned} \mathrm{Ra} \ = \ & 1.386 + 1.897\ \mathrm{Ct} - 5.858\ \mathrm{a} - 0.04665\ \mathrm{V} \\ & + 219.3\ \mathrm{f} - 0.3611\ \mathrm{Ct}^2 + 2.117\ \mathrm{a}^2 \\ & + 0.000210\ \mathrm{V}^2 - 2577\ \mathrm{f}^2 \end{aligned} \tag{2}$$

$$\begin{aligned} \mathrm{Vf} \ = \ & 1.759 + 0.7150\ \mathrm{Ct} - 1.313\ \mathrm{a} - 0.05174\ \mathrm{V} \\ & + 41.66\ \mathrm{f} - 0.1773\ \mathrm{C}t^2 + 0.5347\ \mathrm{a}^2 \\ & + 0.000290\ \mathrm{V}^2 - 509.6\ \mathrm{f}^2 \end{aligned} \tag{3}$$

3.9 *Verification experiments*

The purpose of verification experiments, which is the last stage of the Taguchi method, is to analyze the quality characteristics. Verification experiments are also used to test the accuracy of the optimization process. In other words, these experiments are utilized to test the optimum combination of cutting parameters and levels that is determined. According to the optimum combination that was obtained for surface roughness by considering the individual effects of the cutting parameters (A_1 = new cutting tool, B_2 = 1.5 mm cutting depth, C_3 = 100 m/min cutting speed and D_1 = 0.02 mm/tooth feed rate), estimated surface roughness (Ra_p), and according to the optimum combination that was obtained for tool wear by considering the individual effects of the cutting parameters (A_1 = new cutting tool, B_1 = 1 mm cutting depth, C_2 = 100 m/min cutting speed and D_1 = 0.02 mm/tooth feed rate), estimated tool wear (Vf_p) were calculated by using the equations given below [13].

$$\eta_{gRa} = A_1 + B_2 + C_3 + D_1 - 3\eta_{\frac{S}{N}-Ra} \tag{4}$$

$$Ra_p = 10^{-\eta_g Ra/20} \tag{5}$$

$$\eta_{gVf} = A_1 + B_1 + C_2 + D_1 - 3\eta_{\frac{S}{N}-Vf} \tag{6}$$

$$Vf_p = 10^{-\eta_{gVf}/20} \tag{7}$$

In the equations, $A_1B_2C_3D_1$ and $A_1B_1C_2D_1$ are the signal to noise ratios for the optimum levels of the factors. η_{gRa} is the S/N ratio calculated for the optimum surface roughness levels, η_{gVf} is the S/N ratio calculated for the optimum wear levels, Ra_p is the estimated value of surface roughness, and Vf_p is the estimated value of tool wear. The estimated surface roughness value that was calculated by using equations (4) and (5) (Ra_p) was 0.311 µm, while the estimated tool wear value that was calculated by using equations (6) and (7) (Vf_p) was 0.046 mm. A confidence interval (CI) is used to compare the results of verification experiments and estimated values and verify the quality characteristics. A CI consists of a maximum value and a minimum value, while the accuracy of the verification experiments is tested by comparing the empirically calculated value to the estimated value. CI is calculated by using the equation given below [22].

$$CI = \sqrt{F_{\alpha:1,Ve} x V_{ep} x \left(\frac{1}{n_{eff}} + \frac{1}{r}\right)} \tag{8}$$

In equation (8), $F_{\alpha:1,V_e}$ is the ratio of the significance level α to F, α is the significance level, 1-α is the confidence interval, V_e is the error's degrees of freedom, V_{ep} is the error's variance, r is the number of verification experiments, and n_{eff} is the number of effectively measured results [22].

$$n_{eff} = \frac{N}{1 + V_t} \tag{9}$$

In equation (9), N is the total number of experiments (9), and V_t is the total degrees of freedom for the cutting parameters for which mean values were calculated based on table 6 (4). In this study, 3 verification experiments were carried out by considering the optimum combinations that were determined for surface roughness and tool wear. Considering these values, for surface roughness and tool wear, the n_{eff} value was calculated as 1.8. When the experimental results were analyzed in a 95% CI, and equations (8) and (9) were considered, the CI for surface roughness (CI_{Ra}) was found as 1.23, while the CI for tool wear (CI_{Vf}) was found as 1.31. The average of the 3 verification experiments on surface roughness was 0.32 µm. In this case, the interval of (0.311–1.23) $<$ 0.32 $<$ (0.311 + 1.23) = 0 $<$ 0.32 $<$ 1.541 was obtained, and the verification experiments resulted within the CI. The average of the 3 verification experiments on tool wear was 0.048 mm. In this case, the interval of (0.046–1.31 $<$ 0.047 $<$ (0.046 + 1.31) = 0 $<$ 0.047 $<$ 1.356 was obtained, and the verification experiments resulted within the CI. The optimization processes that were carried out for both sets of measurements were found to be successful. Table 7 shows the comparison of the results of the experiments and the projected results obtained by using the Taguchi method. The estimated values and the experimental values were very close to each other. For a reliable statistical analysis, error values should be lower than 20% [13].

Table 7. Comparison of surface roughness and tool wear combinations to estimated values.

	Taguchi method		
Levels	Exp.	Pred.	Error (%)
Ra (µm)			
$A_1B_2C_3D_1$ (optimum)	0.32	0.31	3.13
$A_2B_2C_3D_1$ (random)	0.50	0.50	0
Vf (mm)			
$A_1B_1C_2D_1$ (optimum)	0.047	0.046	2.12
$A_3B_1C_3D_2$ (random)	0.111	0.111	0

Table 7 shows the comparison of the surface roughness and tool wear values. It may be seen that the difference between the results of the verification experiments and the results obtained with the Taguchi method was minimal. Additionally, the error rate was found to be 0 in the randomly selected variables. In this case, the results obtained in the verification experiments show that the optimization process was successful.

4. Conclusion

In this study, the Taguchi method was used to optimize the cutting parameters in the process of grooving on the Vanadis 4E powder metallurgic steel material under dry milling conditions by using carbide end mills that in three forms as new, sharpened once and sharpened twice and to reduce the number of experiments. The results that were obtained in the study may be listed as the following.

- In the optimization process carried out for minimizing the surface roughness and tool wear values, the optimum combination of the cutting parameters for surface roughness was determined as A1B2C3D1 (A1 = new cutting tool, B2 = 1.5 mm cutting depth, C3 = 100 m/min cutting speed and D1 = 0.02 mm/tooth feed rate), whereas the optimum combination of the cutting parameters for tool wear was determined as A1B1C2D1 (A1 = new cutting tool, B1 = 1 mm cutting depth, C2 = 100 m/min cutting speed and D1 = 0.02 mm/tooth feed rate).
- As a result of the statistical analysis, the most effective factors were the cutting tools for surface roughness by 28.44% and the depth of cut tool wear by 48.05%.
- For both equations obtained for the quadratic regression models for surface roughness and tool wear, the correlation coefficients (R^2) 1.00.
- The error rate between the results obtained with the verification experiments and the estimated results was very low, and these values were within the confines of a 95% confidence interval. Additionally, there was no

error for the experimental and estimated results obtained for the randomly selected parameters, and the results overlapped each other.
- In the experiments at a cutting depth of 2 mm (Tests 3, 6 and 9), spinning formed on the tool due to high temperatures.
- In comparison not the cutting tools that were sharpened once or twice, the new cutting tools showed an expected performance, while the surface roughness and tool wear values for the tools that were sharpened once were close to those in the new tools.
- According to the experimental results, the surface roughness and wear values turned out to be higher after the second sharpening process, so, it is not recommended to sharpen this particular tool a second time.
- In the experiments after the second sharpening process, temperatures of 224.5 °C, 231.5 °C and 245 °C were recorded, and these temperatures affected the surface roughness and tool wear values negatively.
- As seen in the three-dimensional graphs, the best results for the surface roughness and tool wear values were obtained at cutting depths of 1 and 1.5 mm.
- According to the information shown in the aforementioned three-dimensional graphs, the lowest roughness and wear values were obtained by sharpening once and at a feed rate of 0.02 mm/tooth.
- In the verification experiments that were carried out with the optimum combinations that were obtained with the Taguchi method, the lowest surface roughness and tool wear values were measured.

All these results showed that the Taguchi method is a reliable methodology in milling Vanadis 4E powder metallurgic steel and minimizing production costs and manufacturing times. In finish milling operations to be carried out with carbide end mills for this material, it is recommended to choose the maximum depth of cut value of 1.5 mm based on the experimental results. Additionally, in finish milling operations to be applied in these conditions on this material, usage of cooling fluids is recommended against high temperatures. Furthermore, based on the experimental results of this study, it is recommended to sharpen carbide end mills once. This material, on which there is no machinability study in the literature, may be subjected to different milling operations in future studies to test the performances of cutting parameters. Moreover, the machinability performance for this material may be investigated by using coated carbide end mills, chip breakers, nose Radius and different types of cooling.

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