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Roughness Parameters with Statistical Analysis and Modelling Using Artificial Neural Networks After Finish Milling of Magnesium Alloys with Different Edge Helix Angle Tools

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The paper presents the results of a study investigating the roughness parameters Rq, Rt, Rv, and Rp of finished-milled magnesium alloys AZ91D and AZ31B. Carbide end mills with varying edge helix angles were used in the study. Statistical analysis was additionally performed for selected machining conditions. In addition, modelling of selected roughness parameters on the end face for the AZ91D alloy was carried out using artificial neural networks. Results have shown that the tool with λ_s *= 20° is more suitable for the finish milling of magnesium alloys because its use leads to a significant reduction in surface roughness parameters with increased cutting speed. Increased feed per tooth leads to increased surface roughness parameters. Both radial and axial depth of cut has an insignificant effect on surface roughness parameters. It has been proven that finish milling is an effective finishing treatment for magnesium alloys. In addition, it was shown that artificial neural networks are a good tool for the prediction of selected surface roughness parameters after finishing milling of the magnesium alloy AZ91D.*

Keywords: magnesium alloys, finish milling, roughness, surface quality, statistical analysis, artificial neural networks

Highlights

- *Finish milling of magnesium alloys AZ31B and AZ91D is an effective kind of machining method.*
- *The surface roughness (Rq, Rt, Rv, and Rp) depends on the geometry of the different edge helix angles.*
- *The tool with* λ_s *= 20° is more suitable for the finish milling of magnesium alloys.*
- *The change of cutting speed vc and feed per tooth fz has a significant influence on the surface roughness parameters during finish milling.*
- *Both the radial and axial depths of cut (ae and ap) have an insignificant effect on surface roughness parameters.*
- *Artificial neural networks are a good tool for the prediction of selected surface roughness parameters after finishing milling of the magnesium alloy AZ91D.*

0 INTRODUCTION

The machinability of a material is described by machinability indices, one of which is surface quality. Geometric structure is defined as the general surface condition, and it is the end result of the technological process for a given workpiece. The geometric structure consists of all surface texture irregularities that are formed due to material wear and machining. The evaluation of the condition of this structure includes considering shape deviations, waviness, and surface roughness.

To compare and verify surface roughness requirements for constructional materials after machining, studies use parameters describing surface conditions in quantitative terms. These include two-dimensional (2D) and 3D surface roughness parameters, where 2D measurements are made on the profile, i.e., in the cross-section of a given workpiece, and 3D measurements, known as stereometric, are made on the surface.

The fundamental and most widely analysed surface roughness parameter is *Ra*; however, surface roughness evaluation that is based on this parameter only is far from being exhaustive. The *Ra* parameter is widely used in industry even though it does not provide data about many significant roughness profile features. Therefore, additional parameters must be considered, such as *Rq*, *Rt*, *Rv*, and *Rp*. The *Rq* parameter is usually considered together with *Ra*, with the value of *Rq* being greater than the value of *Ra* (by approx. 25 % for random profiles). This relationship for random profiles can be expressed as $Rq \approx 1.25\ Ra$ [1].

Another common parameter used for surface quality evaluation is the maximum height of the profile, *Rz*. Given the fact that single profile peaks and valleys are partly taken into account, this parameter should primarily be analysed for bearing or sliding surfaces and measurement areas [1] and [2]. The *Rz* parameter is often analysed together with another surface roughness parameter, *Rt*. These two parameters should also be analysed in combination with other parameters such as *Rp* (maximum profile peak height) and *Rv* (maximum profile valley depth). The *Rt* parameter (total height of profile) may affect

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the so-called functional properties of a given surface (e.g., fatigue strength, wear and tear, lubrication etc.) [3]. This parameter is the vertical distance between the maximum profile peak height and the maximum profile valley depth along the evaluation length between (it belongs to the group of so-called amplitude parameters).

The *Rp* parameter provides information about, e.g., profile shape. Moreover (by analysing the *Rp* parameter), it is possible to assess the surface in terms of abrasion resistance. A surface with poor abrasion resistance is characterized by high values of *Rp* compared to *Rv*. Depending on the values of *Rp* and Rz and their ratio, it is possible to obtain data about profile shape and, thus the abrasion resistance of the analysed surface. If the *Rp*/*Rz* ratio considerably exceeds a value of 0.5, this means that the profile has sharp peaks and the surface is less abrasion-resistant. The use of the above parameters is recommended for evaluating sliding surfaces, bearings, and pre-coated surfaces, as well as for analysing close fits in terms of shrink behaviour [1] and [3].

Measurements and research of surface roughness parameters are important due to such surface features as friction and wear, lubrication, assembly tolerances, contact deformations, load capacity, contact stresses and other surface features related to the physical or functional properties of a given surface.

Previous studies on the machinability of materials by milling have predominantly investigated the surface roughness parameter *Ra*. A comparison of machining methods and evaluated roughness parameters used in previous studies is given in Table 1.

Table 1. *Comparison of machining methods and roughness parameters under evaluation in milling of magnesium alloys*

Machining method	Roughness parameters	Material / Alloy grade	Year	Reference
milling	*Ra, Rq, Rz, RzDIN, Rt, Ry, RSm*	AZ91D/HP	2016	[4]
milling	*Ra*	Mg-SiC/B4C	2017	[5]
high-speed dry face milling	*Ra*	Mg-Ca0.8	2010	[6]
dry milling and low plasticity burnishing	*Ra*	Mg-Ca0.8	2011	[7]
milling	*Ra*	Mg-Ca0.8	2018	[8]
milling	*Ra*	Mg-Ca1.0	2017	[9]
dry end milling	*Ra*	AM60	2017	[10]
dry milling and low plasticity burnishing		Mg-Ca0.8	2011	[11]
milling	*Ra, Rt, Rv, Rp Rku, Rsk, RSm, Sa, Sv, Sp, St, Ssk, Sku*	AZ91D	2019	[12]
dry face milling	*Ra*	ZE41	2018	[13]
milling	*Ra, Sa, RSm, Ssk, Sku*	AZ91D	2021	[14]
milling	*Ra*	AZ61	2017	[15]
face milling (DRY, MQL)	*Sa*	AZ61	2019	[16]
high speed milling	*Ra*	AZ91D	2016	[17]
dry milling by air pressure coolant	*Ra*	AZ31B	2010	[18]
milling	*Ra*	AZ91D	2016	[19]
precision milling	*Ra, Rv, Rp, Rt, Rvk, Rk, Rpk*	AZ91D	2023	[20]

Summing up, surface roughness analysis is particularly important in terms of the quality of finished components of machines and devices. Light alloys, including magnesium and aluminium alloys [21] and [22], occupy a special place among construction materials. Surface quality and roughness are even more important when it comes to finishing treatments and operations. Therefore, it seems that the finish milling of light alloys (aluminium and magnesium) is significant not only from the practical and implementation-related points of view but also due to knowledge-related reasons, as there is a lack of comprehensive studies devoted to this problem.

1 METHODS

The objective of this study was to evaluate the surface roughness of two magnesium alloys, AZ91D and AZ31, after milling depending on the value of the technological parameters and tools with variable helix angle. The employed research scheme is shown in Fig. 1. Milling was conducted on the vertical machining centre AVIA VMC800HS with Heidenhain iTNC 530 control and maximum spindle speed of 24000 [rev/min]. In the study, we used two carbide 3-edge end mills with a diameter of 16 mm and a variable helix angle λ_s (λ_s = 20°, λ_s = 50°). Using the ISG 2200 shrink-fit machine from H. Diebold GmbH & CO (Jungingen, Germany), the end mills were mounted in the CELSIO HSK-A63 ϕ16 × 95 tool holder from SCHUNK (Lauffen am Neckar, Germany). According to the ISO 21940–11:2016 standard [23], the tool with the tool holder was balanced to G2.5 (residual unbalance was 0.25 g mm) with a CIMAT RT 610 balancing machine (Bydgoszcz, Poland).

The milling process was conducted using the following ranges of technological parameters: cutting speed v_c = 400 m/min to 1200 m/min, feed per tooth f_z = 0.05 mm/tooth to 0.3 mm/tooth, axial depth of cut a_p = 0.1 mm to 0.5 mm, radial depth of cut a_e = 0.5 mm to 3.5 mm. The following surface roughness parameters were analysed: *Rq*, *Rt*, *Rv*, and *Rp*. Surface roughness measurements were made on both lateral and end faces with the use of a contact-type roughness tester, HOMMEL TESTER T1000, from ITA-K. Pollak, M. Wieczorowski Sp. J. (Poznań, Poland). The measurement parameters were as follows: total measuring length *lt* = 4.8 mm, sampling length *lr* = 0.8 mm,

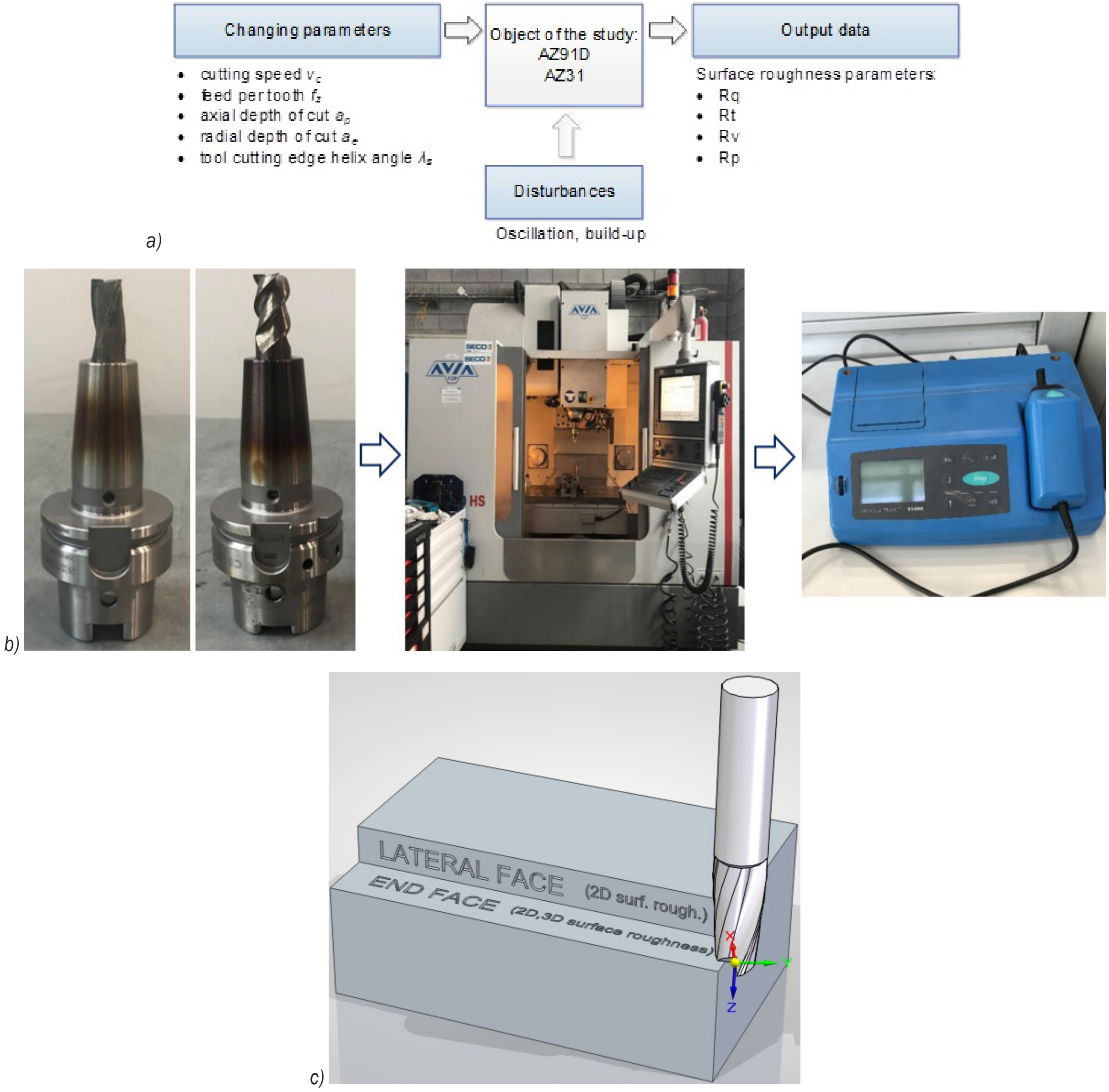


Fig. 1. *Research scheme: a) the test set-up, b) the measurement equipment (end mill, milling machine and 2D profilographometer), and c) milling visualization with the roughness measurement model with end face and lateral face on the workpiece surfaces*

scanning speed v_t = 0.5 mm/s and measuring range/resolution M = ±320 µm (range) / 0.04 µm (resolution). Every measurement was repeated five times per each surface.

Data from surface roughness measurements were subjected to statistical verification. The assumed level of significance was α = 0.05. There exist several criteria that must be taken into account when selecting a statistical test. In this study, output data were treated as independent quantitative variables. As shown in the scheme, results of the Shapiro-Wilk test for checking the normality of distribution were used to decide whether further tests had to performed. If the normal distribution was not confirmed, the non-parametric Mann-Whitney U test was performed. If the zero hypothesis saying that "the distributions are not different from the normal distribution in a statistically significant way" was accepted, the significance of differences had to be assessed by one of two parametric tests: Student's t-test or Cochran's Q test. The test type was selected by assessing the equality of variances, which was made based on the results of Levene's test and the Brown and Forsythe test. It should be noted that the selected test type and the end result depended on the p-value. All statistical tests were conducted using Statistica 13 [24] and [25].

Next, the modelling of selected roughness parameters (Rq and Rt) on the face of the magnesium alloy AZ91D after finishing milling was carried out with variable helix angle λ_s (λ_s = 20°, λ_s = 50°) using Matlab software. The input parameters for network learning were machining parameters such as cutting speed v_c = 400 m/min to 1200 m/min, feed per tooth f_z = 0.05 mm/tooth to 0.3 mm/tooth and axial depth of cut a_p = 0.1 mm to 0.5 mm. At the output from network learning, the appropriate roughness parameter (Rq, Rt) was obtained for the specified tool (λ_s = 20°, λ_s = 50°).

A shallow neural network with one hidden layer was used for modelling. The learning algorithm Levenberg-Marquardt was used. The number of neurons was selected experimentally in the range of 5 to 10. The dataset was split in a proportion of 80 % : 20 % (for training and validation data, respectively) putting aside the test set due to the small amount of data. Network quality was assessed based on the value of the correlation coefficient R, Mean Squared Error (MSE) and root mean square error ($RMSE$). The correlation coefficient R that was calculated in accordance with the Eq. (1):

$$R\left(y', y^*\right) = \frac{cov\left(y', y^*\right)}{\sigma_{y'}\sigma_{y^*}}, \tag{1}$$

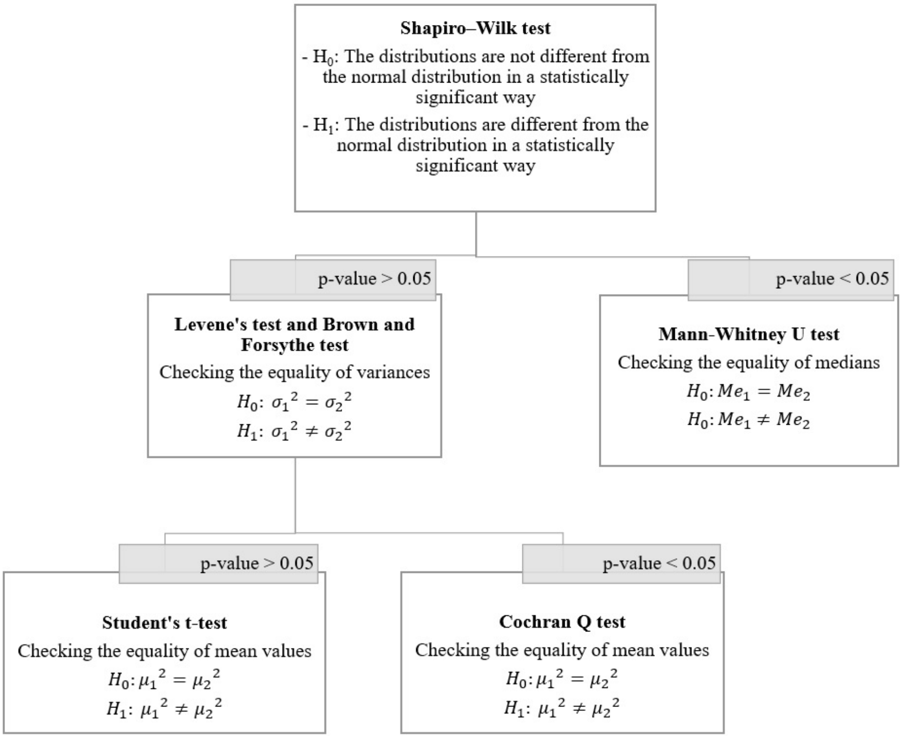


Fig. 2. *Statistical test selection scheme* [20]

where $\sigma_{y'}$ is the standard deviation of values of the analysed roughness parameter obtained as a result of experimental tests, σ_{y*} standard deviation of values obtained as a result of the model predicting the value of the analysed roughness parameter. R is a real number in the interval between 0 and 1.

In addition, the value of the MSE, calculated according to Eq. (2), was taken into account:

$$MSE = \frac{1}{n}\sum_{n=1}^{n}\left(\hat{y}_i - y_i\right)^2, \qquad (2)$$

as well as RMSE, calculated according to the Eq. (3):

$$RMSE = \sqrt{\frac{1}{n}\sum_{n=1}^{n}\left(\hat{y}_i - y_i\right)^2}, \qquad (3)$$

where y_i is value of the analysed roughness parameter obtained as a result of experimental tests and $\hat{y}_i$ is values obtained as a result of the model predicting the value of the analysed roughness parameter.

2 EXPERIMENTAL RESULTS AND DISCUSSIONS

This section of the paper presents experimental results of surface roughness evaluation for two magnesium alloys: AZ91D and AZ31, obtained with the use of tools with varying helix angles (λ_s = 20°, λ_s = 50°). The surface roughness of AZ31 was evaluated for the extreme values of the technological parameters.

Fig. 3 shows the relationship between cutting speed v_c and surface roughness parameters. It can be

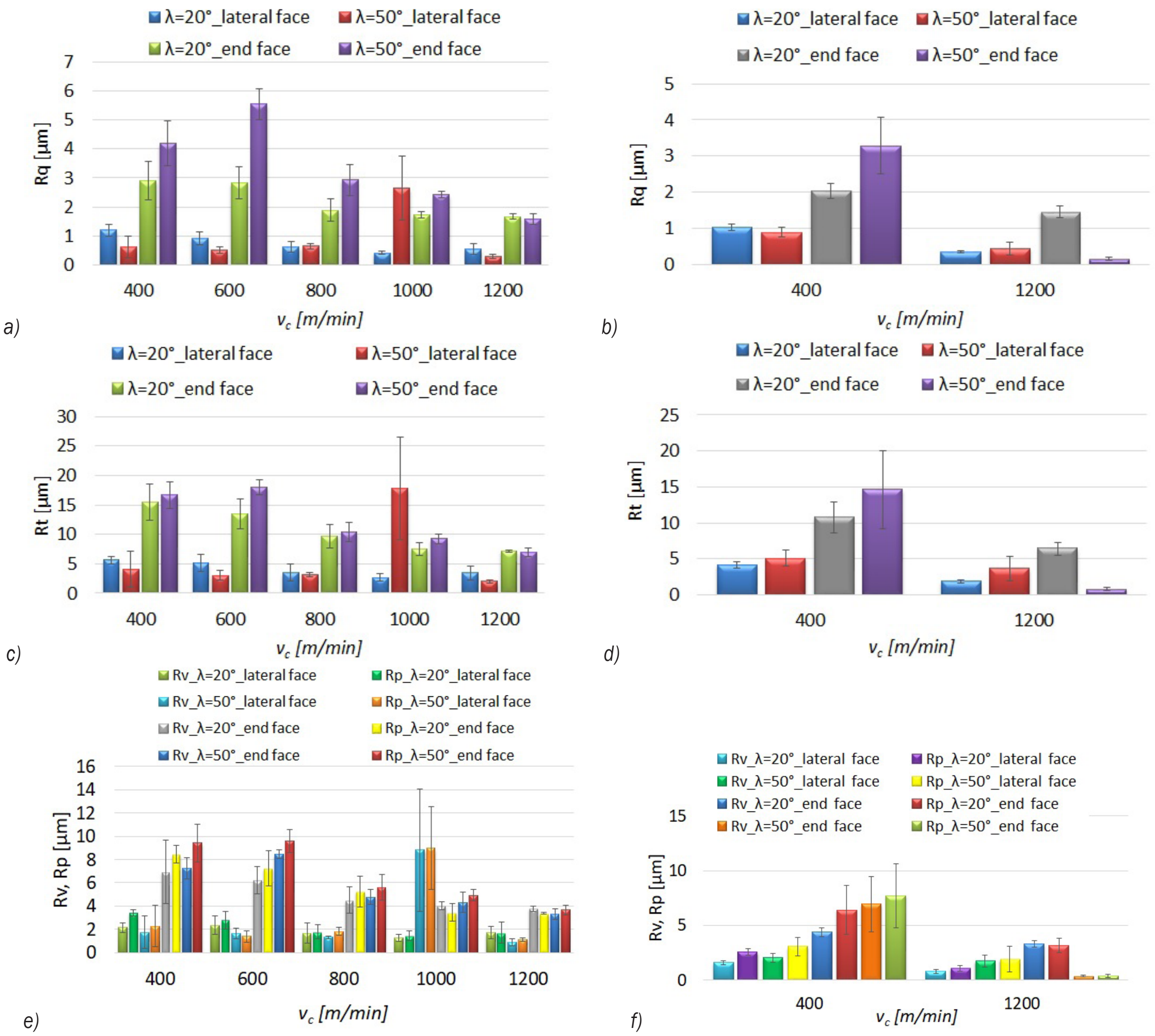


Fig. 3. *Cutting speed versus surface roughness parameters: a) Rq of AZ91D, b) Rq of AZ31 c) Rt of AZ91D, d) Rt of AZ31, e) Rv, Rp of AZ91D, f) Rv, Rp of AZ31; f_z = 0.15 mm/tooth, lateral face: a_e = 2 mm, a_p = 8 mm, end face: a_e = 14 mm, a_p = 0.3 mm*

observed that the milling process for AZ91D alloy conducted with the cutting speed v_c ranging from 600 m/min to 1200 m/min results in a clear decrease in the values of *Rq* and *Rt* with increasing the cutting speed. The surface roughness parameters only increased on the lateral face after milling with the λ_s = 50° tool and increasing the cutting speed value from v_c = 800 m/min to 1000 m/min. It should be stressed that the surface roughness parameters are lower on the lateral face. The lowest values of these parameters were obtained with λ_s = 50° at v_c = 1200 m/min (*Rq* = 0.29 µm, *Rt* = 2.02 µm). The lowest values of the parameters were obtained with λ_s = 50° on the end face for the milling process conducted with v_c = 600 m/min (*Rq* = 5.54 µm, *Rt* = 18.04 µm). The values of *Rv* and *Rp* on the lateral face are similar for all tested cutting speeds and range from 0.89 µm to 3.44 µm. On the end face the parameters *Rv* and *Rp* clearly decreased with increasing the cutting speed and their values range 3.29 µm to 9.61 µm.

An increase in cutting speed leads to decreased values of the surface roughness parameters *Rq*, *Rt*, *Rv* and *Rp* for both AZ91D and AZ31. The greatest differences between these surface parameters can be observed on the end face for the λ_s = 50° tool. The parameter *Rq* value decreased by 3.14 µm and that of *Rt* by 13.87 µm. Regarding the parameters *Rv* and *Rp*, increasing the cutting speed from 400 m/min to 1200 m/min had the greatest impact on these parameter

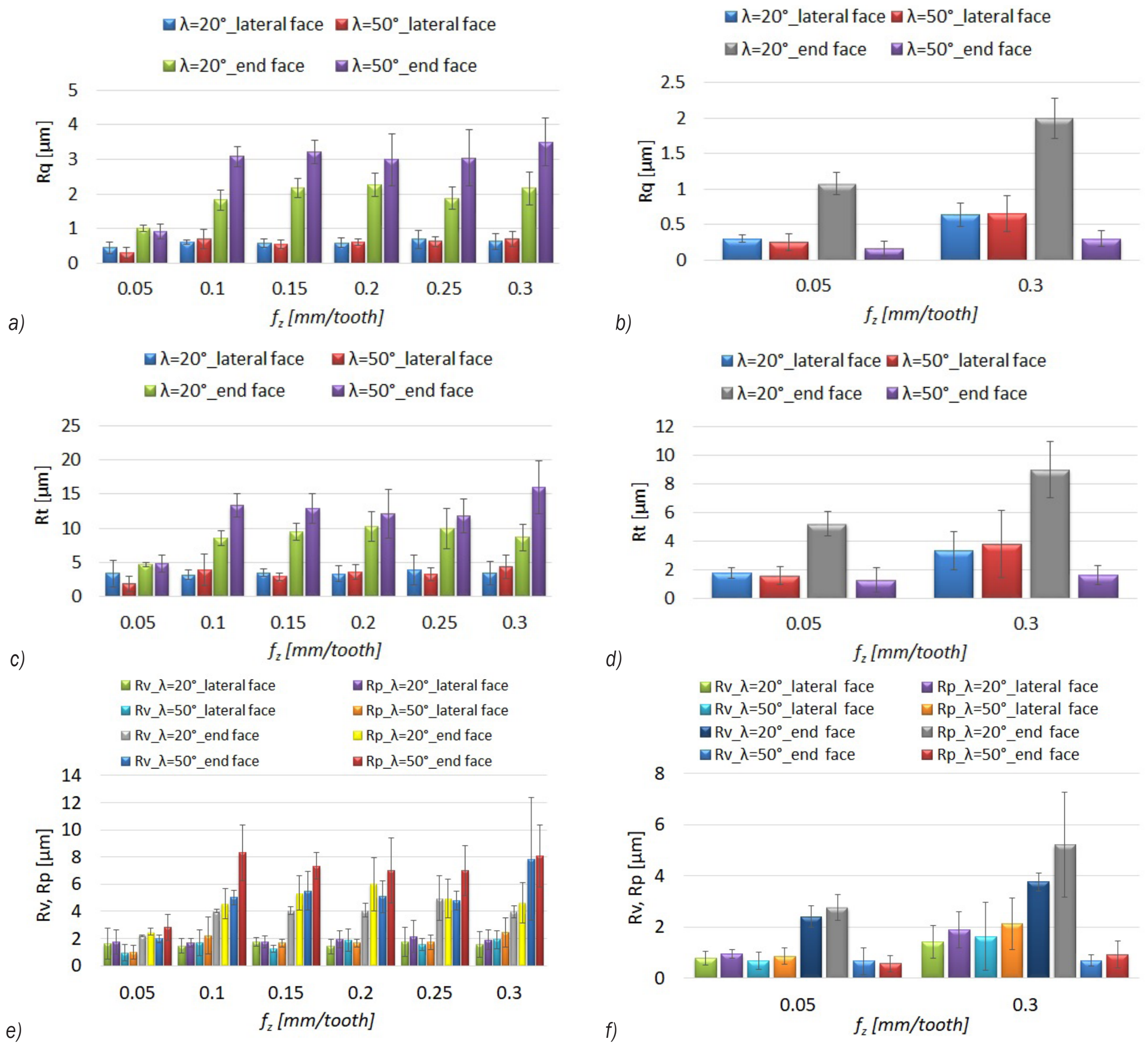


Fig. 4. *Feed per tooth f_z versus surface roughness parameters: a) Rq of AZ91D, b) Rq of AZ31, c) Rt of AZ91D, d) Rt of AZ31, e) Rv, Rp of AZ91D, f) Rv, Rp of AZ31; v_c = 800 m/min, lateral face: a_e = 2 mm, a_p = 8 mm, end face: a_e = 14 mm, a_p = 0.3 mm*

values on the end face for the λ_s = 50° tool, the value of *Rv* decreased by 6.57 µm and that of *Rp* by 7.3 µm.

Comparing, for example, the machinability of both magnesium alloys for the highest cutting speed value, it can be seen that for the *Rq* parameter, a lower value roughness was obtained on the end face for the AZ31B alloy (*Rq* = 1.45 µm), while for the AZ91D alloy (*Rq* = 1.67 µm).

Fig. 4 shows the relationship between feed per tooth f_z and surface roughness parameters. Regardless of the tool used, increased feed per tooth has no significant effect on the surface roughness parameters on the lateral face of magnesium alloy AZ91D, and the values of these parameters range as follows: *Rq* 0.32 µm to 0.72 µm, *Rt* 1.95 µm to 4.28 µm, *Rv* 0.96 µm to 1.94 µm, *Rp* 0.99 µm to 2.45 µm. However, the roughness parameters show a sudden increase on the end face with increasing the feed per tooth value from f_z = 0.05 mm/tooth to f_z = 0.1 mm/tooth. In the range f_z = 0.1 mm/tooth to –0.3 mm/tooth, the feed per tooth increases. The highest values of the surface roughness parameters were observed for f_z = 0.3 mm/tooth. The highest values of *Rq* = 3.5 µm and *Rt* = 15.91 µm are obtained on the end face for λ_s = 50° at f_z = 0.3 mm/tooth. Moreover, for the feed per tooth range f_z = 0.1 mm/tooth to 0.25 mm/tooth (λ_s = 50, end face), the values of *Rp* are higher than those of *Rv*, which means that the surface has poor abrasion resistance [1].

Regarding magnesium alloy AZ31, increased feed per tooth results in a slight increase in the values of *Rq* and *Rt*. The values of *Rq* and *Rt* range: Rq 0.17 µm to 0.65 µm and *Rt* 1.25 µm to 3.77 µm. For λ_s = 20°, the values of the parameters *Rq* and *Rt* are higher on the end face, both at v_c = 400 m/min (*Rq* = 1.08 µm, *Rt* = 5.18 µm) and at v_c = 1200 m/min (*Rq* = 1.99 µm, *Rt* = 8.96 µm). Increasing the feed per tooth value from 0.05 mm/tooth to 0.3 mm/tooth also causes an increase in the values of *Rv* and *Rp*. The highest values are obtained on the end face with the λ_s = 20° tool, both at f_z = 0.05 mm/tooth (*Rv* = 2.41 µm, *Rp* = 2.76 µm) and at f_z = 0.3 mm/tooth (*Rv* = 3.58 µm, *Rp* = 5.21 µm).

Comparing both magnesium alloys on the example of the results for the *Rq* parameter, it can be seen that at f_z = 0.3 mm/tooth (similarly to the cutting speed analysis) a lower value of the *Rq* parameter was recorded on the end face for the AZ31B alloy (*Rq* = 1.99 µm), than for AZ91D alloy (*Rq* = 2.17 µm).

Fig. 5 illustrates the relationship between axial depth of cut and surface roughness parameters. For alloy AZ91D, no significant changes in the parameters *Rq*, *Rt*, *Rv*, *Rp* are observed in the entire tested axial depth of cut range. The values of the surface roughness parameters are similar and range as follows: for λ_s = 20°: *Rq* (1.8 µm to 2.13 µm), *Rt* (8.43 µm to 10.99 µm), *Rv* (3.97 µm to 4.66 µm), *Rp* (4.47 µm to 6.53 µm), and for λ_s = 50°: *Rq* (1.69 µm to 3.36 µm), *Rt* (8.56 µm to 12.9 µm) *Rv* (3.96 µm to 5.57 µm), *Rp* (4.71 µm to 7.33 µm). However, it should be noted that the differences between the values of the above parameters depending on the tool can particularly be observed for a_p = 0.2 mm to 0.5 mm. The results demonstrate that the above axial depth of cut range leads to higher values of *Rp* compared to *Rv*.

The increased axial depth of cut has no significant effect on the surface roughness parameters of both AZ91D and AZ31. It is noteworthy that the roughness parameters obtained with the λ_s = 50° tool are smaller than the values of these parameters obtained after milling with the λ_s = 20° tool (AZ31).

An inverse relationship can be observed by analysing the change in the axial depth of cut on the end face, the value of the *Rq* parameter in the conditions when a_p = 0.5 mm, for the AZ31B alloy is higher (*Rq* = 1.99 µm), than for the AZ91D alloy (*Rq* = 1.81 µm).

Fig. 6 shows the relationship between the radial depth of cut a_e and surface roughness parameters. The results demonstrate that the radial depth of cut has no significant effect on the roughness parameters *Rq*, *Rt*, *Rv*, *Rp* of both AZ91D (λ_s = 20°) and AZ31 (λ_s = 20° and λ_s = 50°). The obtained values are similar and range as follows: *Rq* (0.53 µm to 0.73 µm), *Rt* (2.4 µm to 4.24 µm), *Rv* (1.08 µm to 2.07 µm), *Rp* (1.53 µm to 2.17 µm). In contrast, for the tool with λ_s = 50° one can observe a sharp increase in the values of *Rq* (by 2.56 µm) and *Rt* (by 13.39 µm), *Rv* (by 6.59 µm), *Rp* (by 6.8 µm) when the radial depth of cut value is changed from a_e = 1.5 mm to 2.5 mm.

Similarly, analysing the radial depth of cut on the end face, it can be seen that for a_e = 3.5 mm, the machining results are better (lower value of the *Rq* parameter) for the AZ91D alloy (*Rq* = 0.56 µm), while for the AZ31B alloy (*Rq* = 0.70 µm).

Thus, comparing the results obtained using carbide cutters for roughing and the analysis of the surface of the end face of the workpiece AZ91HP/D [4] and [12], the following conclusions can be drawn:

- when employing a carbide cutter coated with titanium aluminium nitride (TiAlN), higher values of the parameters *Rq*, *Rp*, and *Rv* were recorded, specifically:

1. for the variable parameter v_c, the parameters *Rv* and *Rp* range between 6.8 µm to 8.32 µm, while the parameter *Rt* spans from 14.24 µm to 17.72 µm;

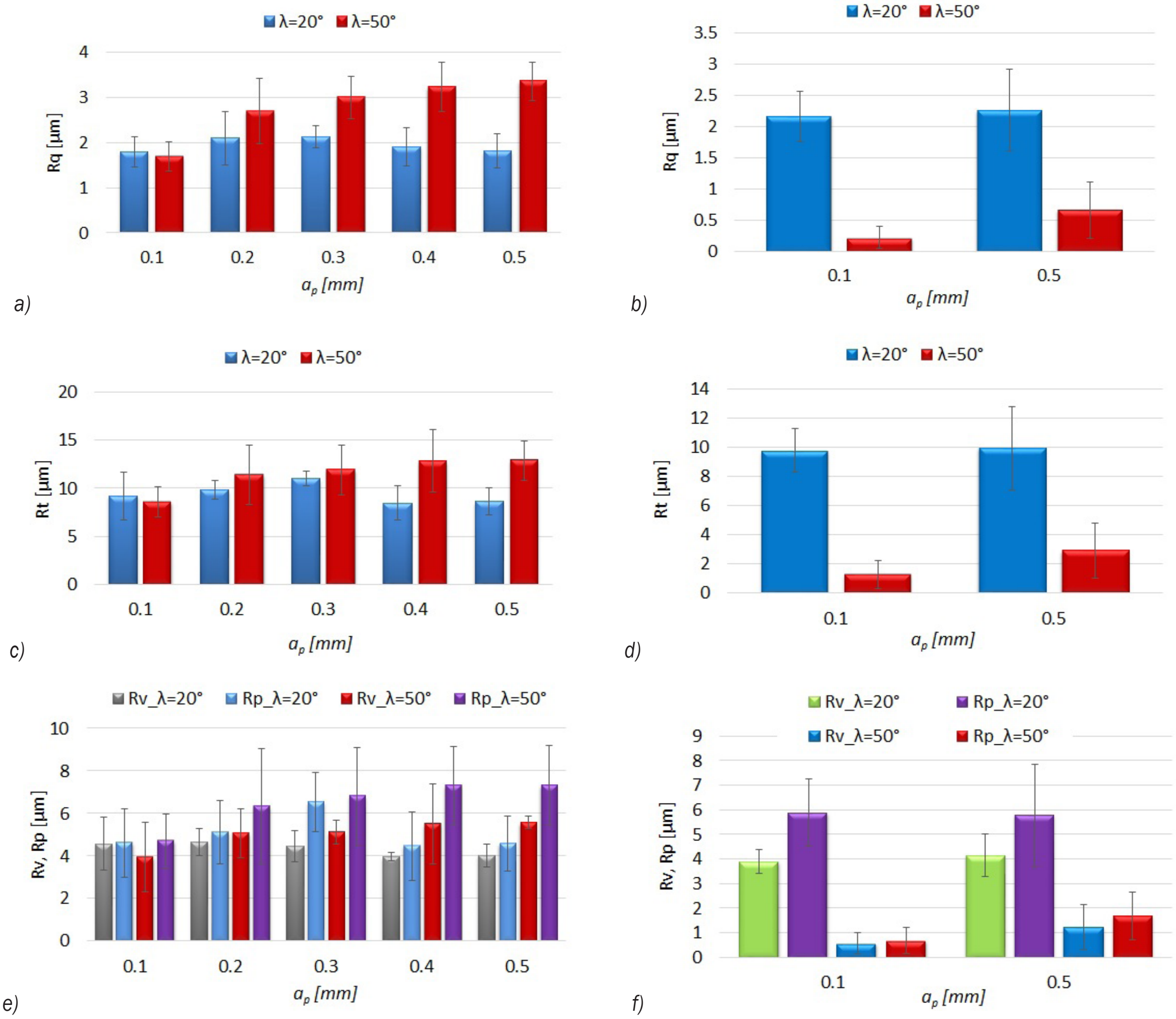


Fig. 5. *Axial depth of cut ap versus surface roughness parameters: a) Rq of AZ91D, b) Rq of AZ31 c) Rt of AZ91D, d) Rt of AZ31, e) Rv, Rp of AZ91D f) Rv, Rp of AZ31; v_c = 800 m/min, f_z = 0.15 mm/tooth, a_e = 14 mm*

2. considering the variable parameter f_z, the parameters Rv and Rp lie within the spectrum of 1.94 µm to 15.84 µm, with the parameter Rt standing at 4 µm to 31.04 µm;
3. for the variable parameter a_p, the values of Rv and Rp present remarkable similarity, recorded within the interval of 5.26 µm to 7.78 µm, and for Rt the values range from 12.02 µm to 24.82 µm;

- in instances of machining with cutters of diverse blade geometry (different rake angles γ), the parameters Rq and Rt were investigated:

1. for the variable parameter v_c, the parameter Rq did not surpass 4 µm, with Rt recorded within the range of 10 µm to 15 µm,
2. in relation to the variable parameter f_z, the Rq parameter ascends to a maximum value of approximately 3 µm, with the Rt parameter spanning from 10 µm to 15 µm,
3. concerning the variable parameter a_p, the Rq parameter consistently approximates 3 µm, while the value of Rt does not exceed approximately 15 µm.

Therefore, these values are much higher than those observed in the present experiment. This is due to the larger cross-sections of the cutting layer obtained during roughing. However, as the literature lacks a broader analysis of surface roughness parameters, especially after finishing machining while roughing mainly analyses the basic surface roughness parameters (usually mainly Ra), it seems advisable to extend the state of knowledge in this area.

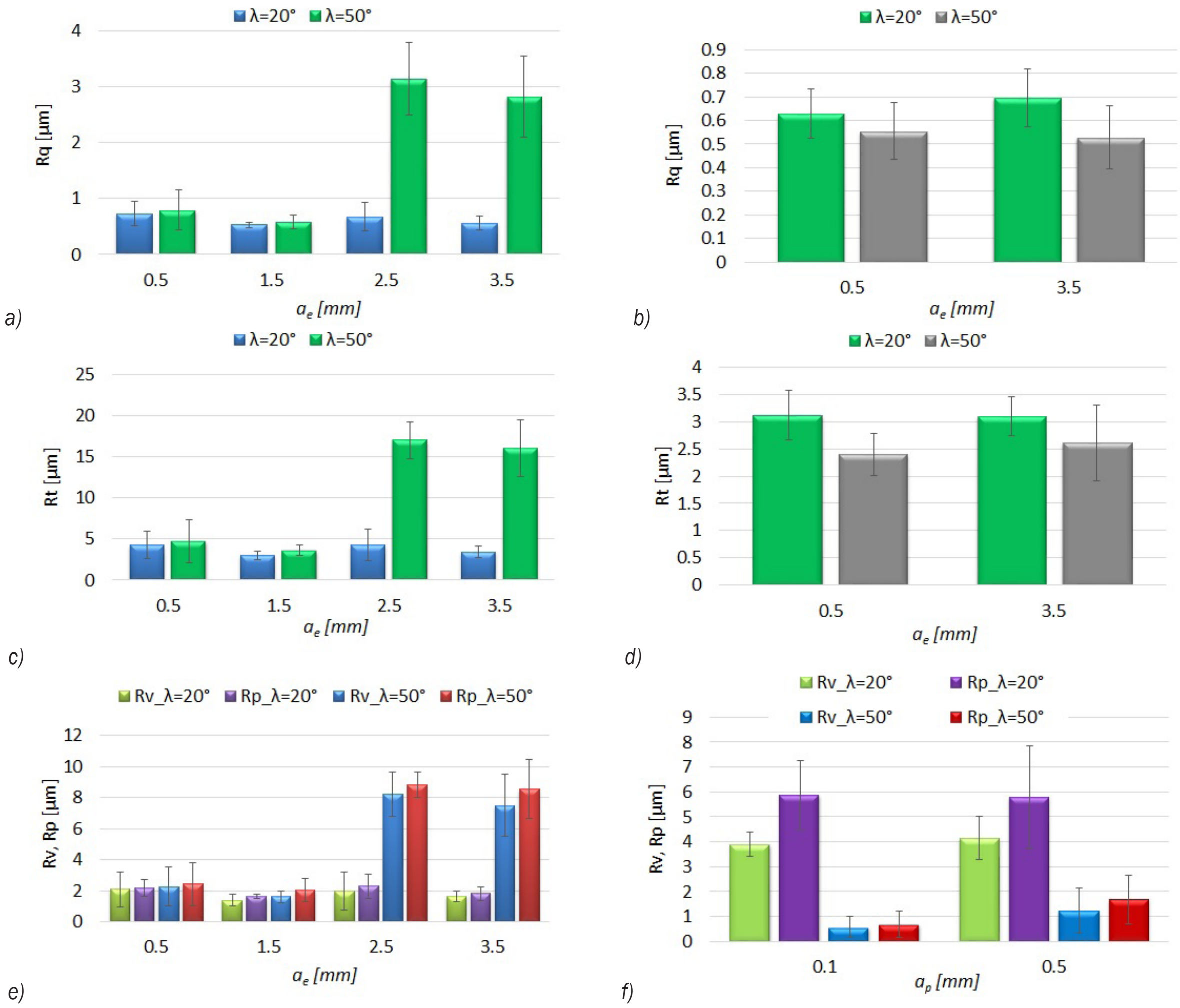


Fig. 6. *Radial depth of cut ae versus surface roughness parameters: a) Rq of AZ91D, b) Rq of AZ31, c) Rt of AZ91D, d) Rt of AZ31, e) Rv, Rp of AZ91D, f) Rv, Rp of AZ31; v_c = 800 m/min, f_z = 0.15 mm/tooth, a_p = 8 mm*

3 STATISTICAL ANALYSIS

The experiments were followed by statistical analysis. Significance tests were performed to determine if the following technological parameters: cutting speed v_c, feed per tooth f_z, axial depth of cut a_p and radial depth of cut a_e affected the mean values of surface roughness parameters. The statistical analysis made it possible to determine whether the differences were statistically significant for the assumed level of confidence.

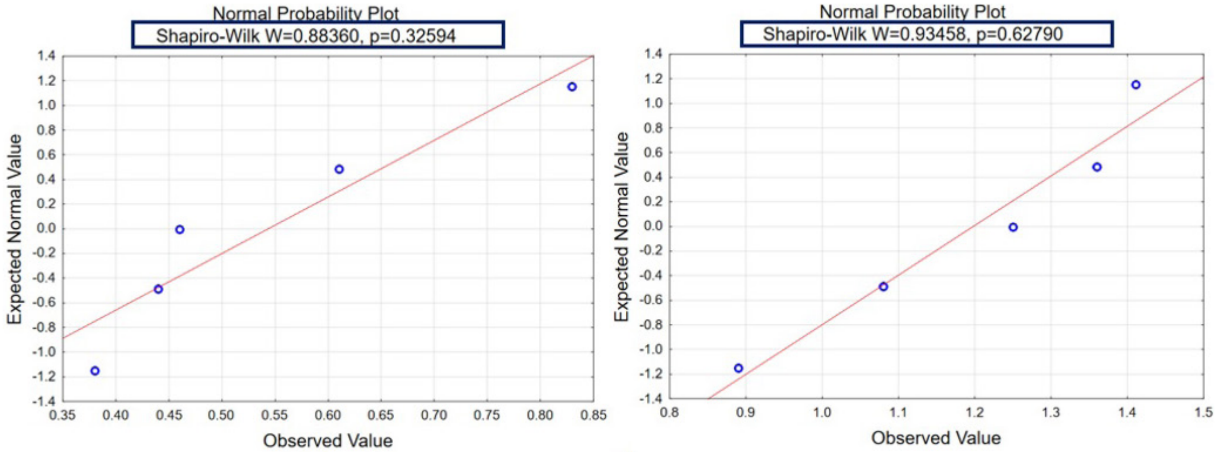
Hypotheses were tested taking account of the extreme values of the technological parameters, i.e., cutting speed v_c = 400 m/min, and 1200 m/min, feed per tooth f_z = 0.05 mm/tooth, and, 0.3 mm/tooth, axial depth of cut a_p = 0.1 mm, and 0.5 mm, radial depth of cut a_e = 0.5 mm, and 3.5 mm. In this paper, we report the final test results, i.e. the median and mean values from the tests.

Fig. 7 shows an example of results obtained by the Student's t-test for the zero hypothesis of normal distribution and the equality of variance hypothesis.

Tables 2 and 3 give the results of the Mann-Whitney U test, Student's t-test, and Cochran's Q test. The results make it possible to statistically assess the significance of differences between the mean and median values obtained for the compared groups.

The statistical analysis results demonstrate that, irrespective of the magnesium alloy grade, for the tool with λ_s = 20° increased cutting speed has, in most cases, the greatest impact on the mean and median values of the surface roughness parameters.

Feed per tooth also has a significant impact on the surface roughness parameters for the tool with



	Levene'a F(1,df)	df Levene'a	p Levene'a	Brn-Fors F(1,df)	df Brn-Fors	p Brn-Fors
Rq 400 vs. Rq 1200	0.252875	8	0.628607	0.164551	8	0.695634

Student's t-test

	t	df	p
Rq 400 vs. Rq 1200	5.222816	8	0.000800

Fig. 7. *Student's t-test results*

Table 2. *Results of Mann-Whitney U test, Student's t-test, Cochran's Q test for the roughness parameters of magnesium alloy AZ91D after milling*

	$\lambda_s = 20°$		$\lambda_s = 50°$	
	Lateral face	End face	Lateral face	End face
	p-value	p-value	p-value	p-value
v_c [m/min] 400 vs. 1200				
Rq	0.0008	0.01354	0.09172	0.00124
Rt	0.00794*	0.00384	0.18904	0.00794*
Rv	0.15079*	0.06089	0.22089	0.00794*
Rp	0.01587*	0.00009	0.21357	0.00794*
f_s [mm/tooth] 0.05 vs. 0.3				
Rq	0.22222*	0.00466	0.03175*	0.00004
Rt	1*	0.00902	0.06349*	0.00028
Rv	0.84127*	0.0007	0.06349*	0.00794*
Rp	0.78555	0.03114	0.03175*	0.00422
	a_e [mm] 0.5 vs. 3.5	a_e [mm] 0.1 vs. 0.5	a_e [mm] 0.5 vs. 3.5	a_e [mm] 0.1 vs. 0.5
Rq	0.17048	0.95209	0.00149	0.0001
Rt	0.35526	0.69048*	0.00103	0.00536
Rv	0.43513	0.40148	0.00282	0.150794*
Rp	0.27617	0.97658	0.01587*	0.03102

* Mann-Whitney U test for checking the equality of the medians

Table 3. *Results of Mann-Whitney U test, Student's t-test, Cochran's Q test for the roughness parameters of magnesium alloy AZ31 after milling*

	$\lambda_s = 20°$		$\lambda_s = 50°$	
	Lateral face	End face	Lateral face	End face
	p-value	p-value	p-value	p-value
v_c [m/min] 400 vs. 1200				
Rq	0.00794*	0.00093	0.00362	0.00088
Rt	0.000004	0.00287	0.159	0.00443
Rv	0.00018	0.00126	0.35012	0.00435
Rp	0.00003	0.02907	0.19048*	0.00507
f_s [mm/tooth] 0.05 vs. 0.3				
Rq	0.00813	0.00022	0.01372	0.13088
Rt	0.01587*	0.00953	0.07128	0.51158
Rv	0.05556*	0.00052	0.15926	0.966295
Rp	0.00794*	0.054187	0.02645	0.278767
	a_e [mm] 0.5 vs. 3.5	a_e [mm] 0.1 vs. 0.5	a_e [mm] 0.5 vs. 3.5	a_e [mm] 0.1 vs. 0.5
Rq	0.3862	0.77097	0.76164	0.06349*
Rt	0.84127*	0.42063*	0.61483	0.12539
Rv	0.38109	0.55077	0.94354	0.195110
Rp	0.12928	0.92479	0.42396	0.087671

* Mann-Whitney U test for checking the equality of the medians

λ_s = 20°. The only exception are the results obtained for the lateral end of AZ91D, as they show that changing the feed per tooth value from 0.05 mm/tooth to 0.3 mm/tooth does not result in statistically significant differences between the values of the surface roughness parameters. The opposite can be observed for the tool with λ_s = 50°, where the p-values are either smaller than the assumed confidence level or verge on the statistically significant limit.

For alloy AZ91D, the differences in the mean and median values of the surface roughness parameters are affected by the radial and axial depth of cut, and depend on the tool.

For alloy AZ31, irrespective of the tool used, the radial and axial depth of cut has no effect on the mean and median values of the surface roughness parameters *Rq*, *Rt*, *Rv*, *Rp* (on the statistical level).

4 MODELLING OF ARTIFICIAL NEURAL NETWORKS

Artificial neural networks were trained for the magnesium alloy AZ91D in order to build four models showing the relationship between the technological parameters (cutting speed v_c, feed per tooth f_z and axial depth of cut a_p) and the predicted roughness on the face surface of the *Rq* and *Rt* parameters, respectively, after machining with the tool with variable helix angle (λ_s = 20°, λ_s = 50°). Approximately 100 networks were trained for each model.

The quality of the obtained models was assessed on the correlation coefficient *R*, value of *MSE* and *RMSE*. Table 4 presents four different models obtained from an artificial neuron network (ANN.)

The best modelling results for the *Rq* and *Rt* parameters after machining with a tool with a helix

Table 4. *Network parameters*

Model No.	Roughness parameter	Helix angle λ_s	*MSE*	*RMSE*	R training data set	R validation data set	R all data set
1	*Rq*	20	0.0022	0.0467	0.99999	0.99029	0.99563
2	*Rt*		0.1058	0.3252	0.99999	0.9989	0.99358
3	*Rv*	50	0.0193	0.1391	0.99999	0.96648	0.99263
4	*Rp*		0.3424	0.5851	0.99999	0.95309	0.98741

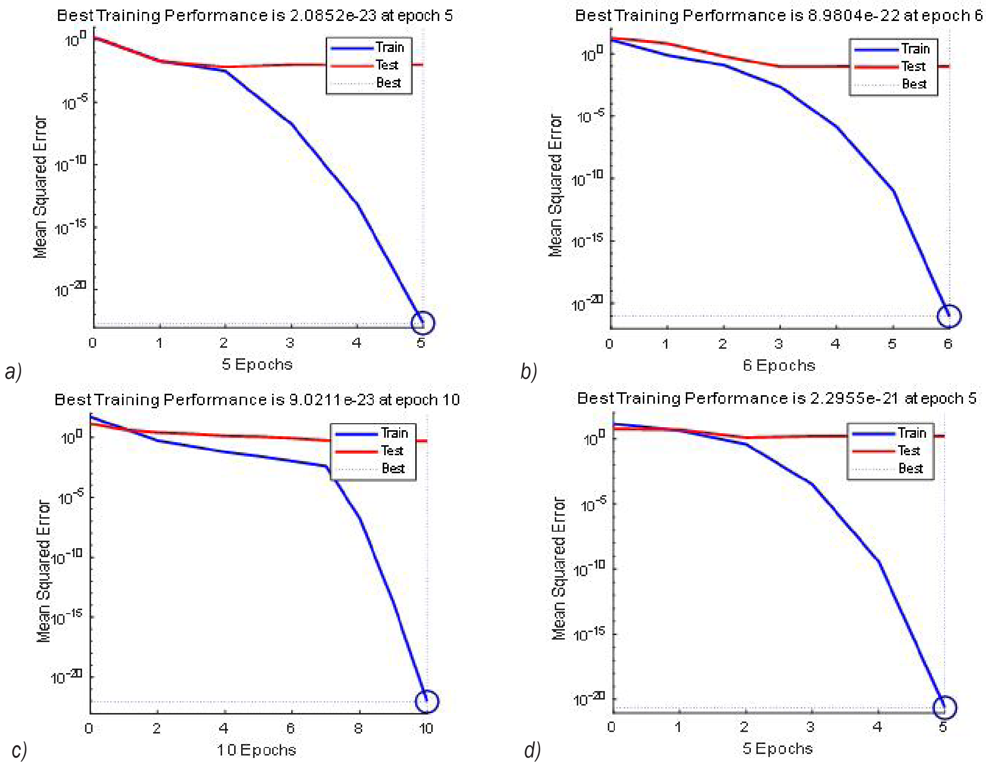


Fig. 8. *ANN best training performance for a) parameter Rq, λ_s = 20°, b) parameter Rt, λ_s = 20°, c) parameter Rq, λ_s = 50°, d) parameter Rt, λ_s = 50°*

angle λ_s = 20° were obtained for the network with 10 neurons in the hidden layer. The network for the *Rq* parameter was obtained in five iterations, and for the *Rt* parameter in ten iterations. In the case of the tool with the helix angle λ_s = 50°, for the *Rq* parameter, it was also a network with 10 neurons (obtained in 6 iterations), and for the *Rt* parameter a network with eight neurons in the hidden layer (obtained in 5 iterations). The best validation performance was obtained respectively for iteration 5 (for *Rq* parameter when machined with helix angle λ_s = 20°), which is shown in Fig. 8a, for iteration 6 (for *Rt* parameter when machined with helix angle λ_s = 20°); Fig. 8b, for iteration 10 (for the *Rq* parameter when machining with a helix angle λ_s = 50°); Fig. 8c and for iteration 5 (for the *Rt* parameter when machining with a helix angle λ_s = 50°); Fig. 8d.

ANN regression statistics for individual sets and the total set was presented in Fig. 9. Respectively for parameter *Rq* when machining with tool with helix angle λ_s = 20°; Fig. 9a, for parameter *Rt* when machining with tool with helix angle λ_s = 20°; Fig. 9b, for parameter *Rq* when machining with tool with helix angle λ_s = 50°; Fig. 9c and for parameter *Rt* when machining with tool with helix angle λ_s = 50°; Fig. 9d.

Taking into account the quality of the presented models measured by the level of *MSE*, *RMSE* and the *R* value (*R* in each case is a value greater than 0.95),

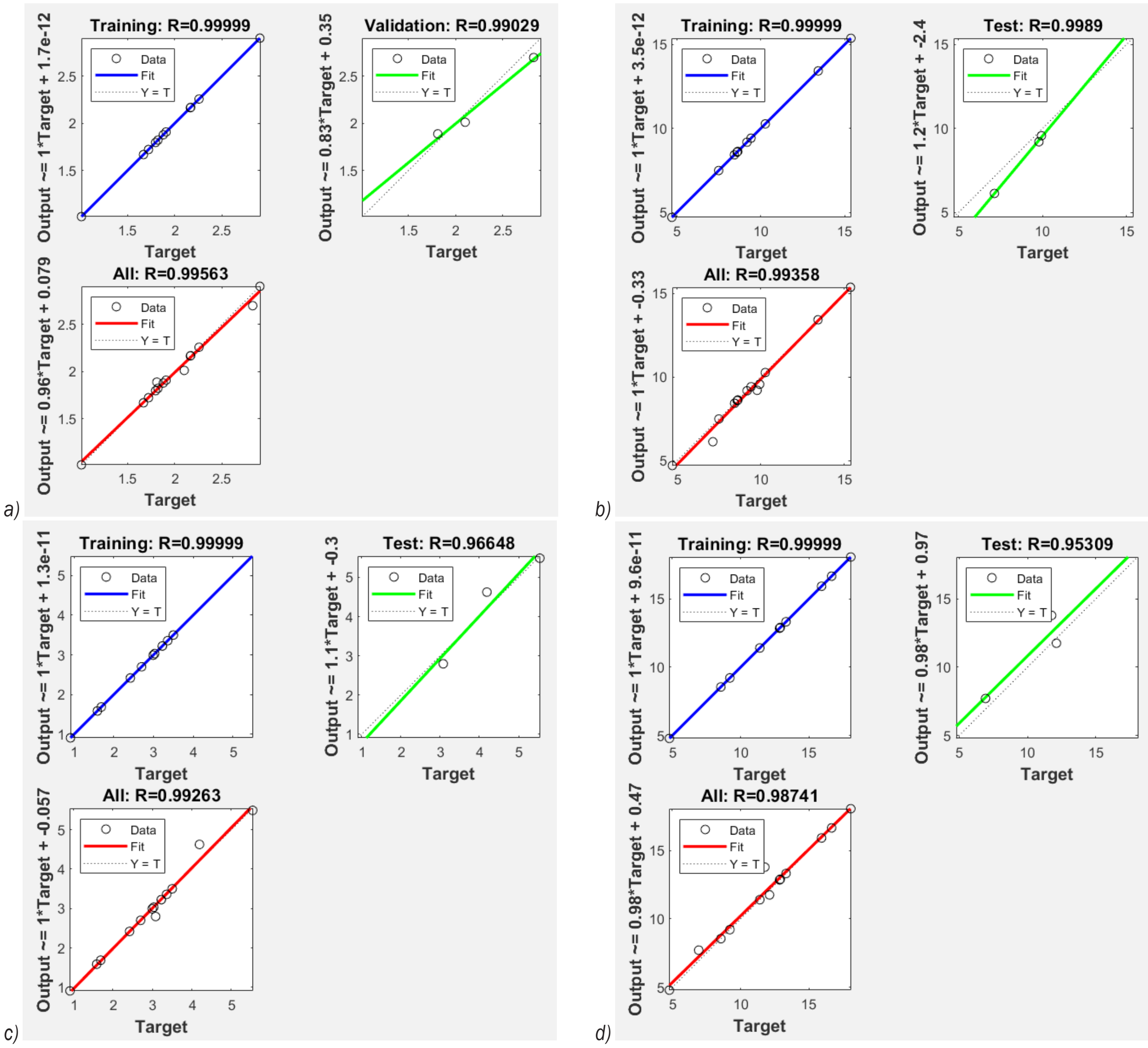


Fig. 9. *ANN regression statistics for individual sets and the total set: a) parameter Rq, λ_s = 20°, b) parameter Rt, λ_s = 20°, c) parameter Rq, λ_s = 50°, c) parameter Rt, λ_s = 50°*

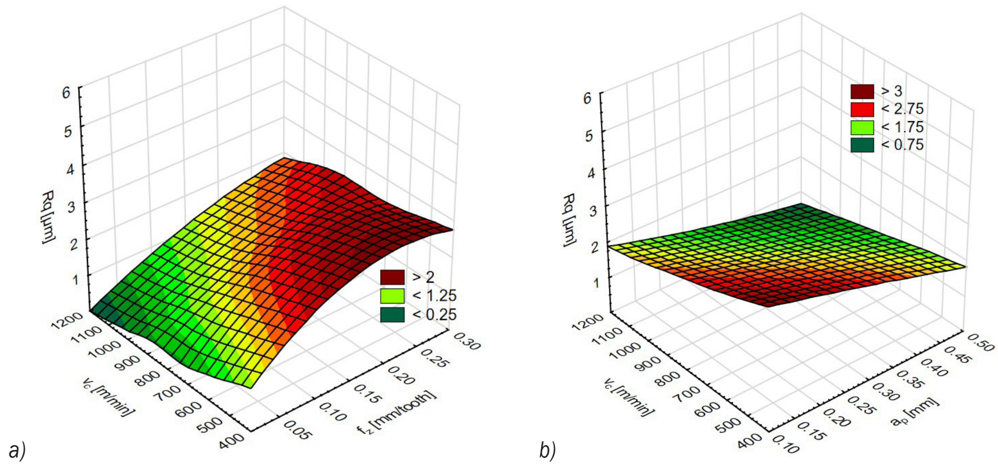


Fig. 10. *Simulation results of the* Rq *surface roughness parameter after machining with tool with helix angle* λ_s *= 20°*
a) for the v_c *and* f_z*, and b) for the* v_c *and* a_p

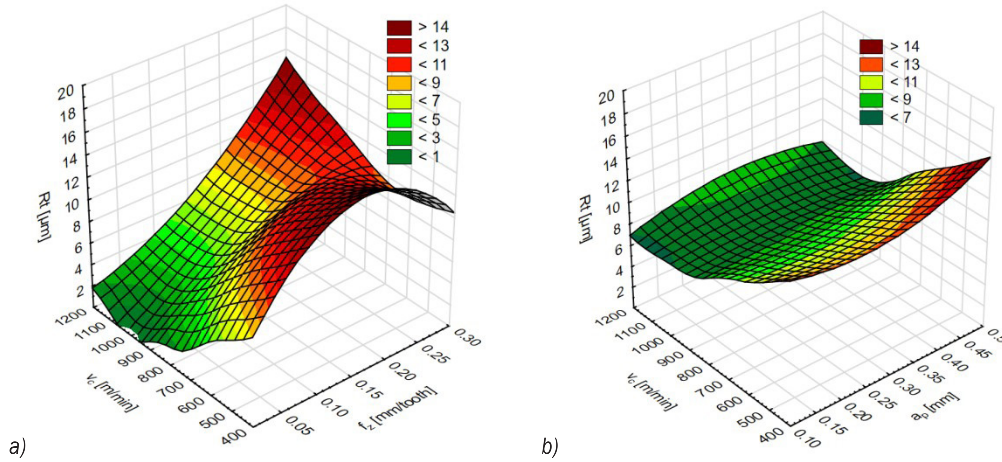


Fig. 11. *Simulation results of the* Rt *surface roughness parameter after machining with tool with helix angle* λ_s *= 20°*
a) for the v_c *and* f_z*, and b) for the* v_c *and* a_p

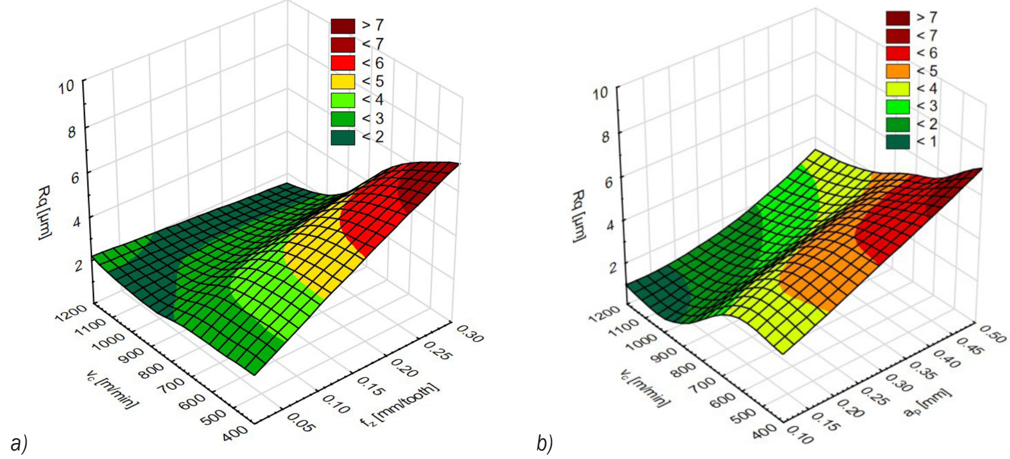


Fig. 12. *Simulation results of the* Rq *surface roughness parameter after machining with tool with helix angle* λ_s *= 50°*
a) for the v_c *and* f_z*, and b) for the* v_c *and* a_p

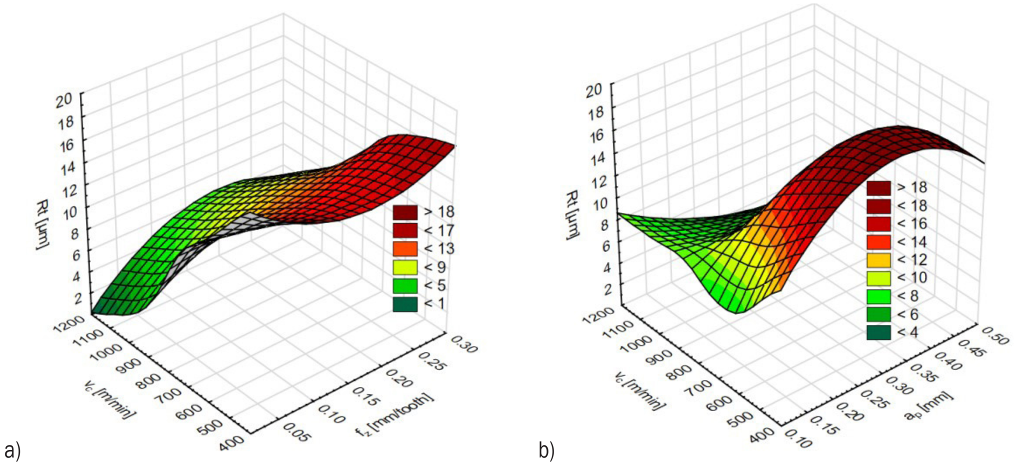


Fig. 13. *Simulation results of the Rt surface roughness parameter after machining with tool with helix angle λ_s = 50° a) for the v_c and f_z, and b) for the v_c and a_p*

it can be concluded that the presented ANN models show an acceptable level of error and can be used to predict approximate values of roughness parameters.

The simulation results of the appropriate roughness parameters Rq/Rt of the AZ91D alloy for the appropriate tool with helix angle λ_s = 20°, and 50°, for the assumed range of cutting speed v_c, feed per tooth f_z and axial depth of cut a_p parameters are shown in Figs. 10 to 13. The simulation results for each model are presented in two graphs, depending on cutting speed v_c and feed per tooth f_z or cutting speed v_c and axial depth of cut a_p.

5 CONCLUSIONS

The experimental and statistical analysis results of the study leads to the following conclusions:

- for the λ_s = 20° tool increased cutting speed leads to a considerable decrease in surface roughness parameters, whereas for the tool with λ_s = 50° increased cutting speed has no significant effect on lateral face surface roughness parameters;
- increased feed per tooth leads to increased surface roughness, which was particularly visible when the feed per tooth f_z = 0.05 mm/tooth was changed to f_z = 0.1 mm/tooth for AZ91D alloy;
- irrespective of the magnesium alloy grade, for the tool with λ_s = 20° both axial and radial depth of cut has an insignificant effect on surface roughness parameters;
- the statistical analysis results show that for the tool with λ_s = 20° increased cutting speed has, in most cases, the greatest effect on the mean and median values of the roughness parameters for both AZ91D and AZ31;
- the statistical analysis results for the tool with λ_s = 50° show that the roughness parameters of magnesium alloy AZ91D are most affected by varying feed per tooth as well as axial and radial depth of cut;
- as a result of modelling the Rq and Rt parameters after machining with a variable helix angle λ_s tool (λ_s = 20°, λ_s = 50°), the best models were obtained primarily for the network with 10 neurons in the hidden layer, only in the case of the Rt parameter with helix angle λ_s = 50° the best model had 8 neurons in the hidden layer;
- networks obtained as a result of modelling surface roughness parameters show a satisfactory predictive ability, as evidenced by the obtained regression values R: $Rq_{(\lambda s=20°)}$ = 0.99563, $Rt_{(\lambda s=20°)}$ = 0.99358, $Rq_{(\lambda s=50°)}$ = 0.99263 and $Rt_{(\lambda s=50°)}$ = 0.98741;
- as a result of the conducted modelling of neural networks, it can be concluded that they are an effective tool that can be used to predict surface roughness parameters.

6 ACKNOWLEDGEMENTS

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