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Modelling and optimization of dimensional accuracy and surface roughness in dry turning of Inconel 625 alloy

Vukelic, D.[a,*], Milosevic, A.[a], Ivanov, V.[b], Kocovic, V.[c], Santosi, Z.[a], Sokac, M.[a], Simunovic, G.[d]

[a]University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia
[b]Sumy State University, Faculty of Technical Systems and Energy Efficient Technologies, Sumy, Ukraine
[c]University of Kragujevac, Faculty of Engineering, Kragujevac, Serbia
[d]University of Slavonski Brod, Mechanical Engineering Faculty in Slavonski Brod, Slavonski Brod, Croatia

ABSTRACT

The CNC dry turning of Inconel 625 alloy was investigated in this study. Turning was performed using different feeds, corner radii, and insert types. The dimensions and the arithmetic mean surface roughness were measured before and after turning. The influence of the input parameters and the process modelling were evaluated using a full factorial design of experiments. Prediction models were developed, and process optimization was carried out to simultaneously maximize dimensional accuracy and surface quality. The optimal values of the input parameters were identified for the wiper insert, a feed rate of 0.1 mm/rev, and a corner radius of 0.8 mm. Under these conditions, the optimal deviation from the specified dimension was 0.2 mm, while the surface roughness was 0.297 µm. During the confirmation phase, the mean percentage errors were 0.9 % for surface roughness and 3.45 % for dimensional deviation. The percentage errors observed in the confirmation experiments, all of which were below 5 %, demonstrate the feasibility of using the proposed approach for modelling and optimizing the turning of Inconel 625 alloy.

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**Corresponding author:*
vukelic@uns.ac.rs
(Vukelic, D.)

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1. Introduction

Turning is one of the machining processes most frequently used for machining cylindrical workpieces. It can often be used as a finish operation without the need for further machining. In this case, it is crucial to perform the machining within the tolerance limits and the required surface roughness [1,2]. In other words, it is crucial to solve the problem of dimensional accuracy and the surface quality [3]. Considering all variables is very difficult due to their large number. Therefore, it is necessary to identify and evaluate the most influential input parameters. Different materials can be machined by finish turning using different machine tools, cutting tools and fixtures [4,5]. The problem of achieving the required dimension and surface roughness becomes much more complicated when machining Inconel alloys, especially under dry conditions. Inconel alloys are difficult-to- cut materials because turning is associated with high temperatures and many accompanying effects such as poor surface finish, intense tool wear, microstructural changes in the material, etc. [6].

In previous research, the turning of Inconel 625 alloy was studied under different aspects and conditions.

Kushwaha and Singh [7] investigated the influence of cutting speed, feed and depth of cut on surface roughness during dry and wet turning using the Taguchi method. The lowest surface roughness was achieved when all input parameters were at the lowest level during wet turning. Kosaraju *et al.* [8] investigated the influence of cutting speed, feed and depth of cut on cutting force and surface roughness using the Taguchi method. Jeykrishnan *et al.* [9] evaluated the influence of cutting speed, feed, and depth of cut on surface roughness using the Taguchi method. The results showed a dominant influence of feed on surface roughness, with increasing feed the surface roughness deteriorated. Dhananchezian [10] investigated the influence of cutting speed and type of cooling on surface roughness and tool wear. The surface roughness decreased with the increased speed and the used of cryogenic cooling. Liquid nitrogen had a significant effect on reduced tool wear. Magri *et al.* [11] investigated the influence of coolant direction on surface roughness and tool life. The coolant directed to the flank face contributed to the improvement of surface roughness, while directing the coolant to the flank and rake faces simultaneously did not contributed to the increase in tool life. Singh and Padhy [12] investigated the effects of cooling and lubrication conditions, cutting speed, feed and depth of cut on surface roughness, tool wear, cutting forces and temperature. Dry turning showed the worst results and wet or minimum quantity lubrication (MQL) turning showed the best results. Yildirim [13] investigated the influence of lubrication and cooling conditions on tool wear, temperature and surface roughness. The hexagonal boron nitride (hBN) liquid nitrogen cooling method showed the best performance. Yildirim *et al.* [14] investigated the effect of hBN nanoparticles at MQL on surface roughness, tool wear and temperature. The use of hBN nanofluid effectively reduced both tool wear and surface roughness in machining processes. Singh and Padhy [15] investigated the effect of lubrication method, cutting speed, feed and depth of cut on temperature. The regression model showed that the temperature increased with the increased machining parameters and that the feed had the greatest influence. Nano MQL lubrication conditions also showed better results in terms of temperature, tool wear and chip morphology. Yagmur [16] presented the dependence of tool life, temperature and surface roughness in relation to cutting conditions, cutting speed and feed. MQL provided the best results compared to dry and vortex cooling methods. Padhy and Singh [17] presented a finite element analysis (FEA) of the influence of the type of lubrication (dry, MQL, NMQL) on cutting force, temperature and tool wear. The NMQL conditions showed the best results in all aspects. Rakesh and Chakradhar [18] investigated the influence of cutting speed, feed, depth of cut and cooling conditions on surface roughness, tool wear and cutting force. Cryogenic cooling (LN_2 air) produced the best parameters. With increased feed and depth of cut, surface roughness, cutting forces and tool wear increased. With increased speed, surface roughness and cutting forces decreased, while tool wear increased. Surface roughness improved with increasing cutting speed and decreasing feed and depth of cut. Makhesana *et al.* [19] investigated the influence of different lubrication and cooling conditions on surface roughness, tool wear, chip morphology, hardness and power consumption. The most favourable results were obtained with nMQL with graphite and MoS_2.

As can be seen, the turning of Inconel 625 alloy has been intensively studied using near-dry turning methods. The results obtained indicate the efficiency of these methods, as the results are very close to wet turning. However, a lower amount of coolant and lubricant results in less contamination, which is still present to a lesser extent. In addition, equipment, fluid, fluid treatment requirements and the like incur additional costs. Therefore, dry turning should not be eliminated and replaced by near-dry turning.

Several studies were carried out exclusively under the conditions of dry turning of the Inconel 625 alloy. Marimuthu and Baskaran [20] evaluated the effect of cutting speed, feed and depth of cut on surface roughness and material removal rate (MRR) using the Taguchi method. Feed and cutting speed had a significant effect on surface roughness, and feed and depth of cut had a significant effect on MRR. Venkatesan *et al.* [21] investigated the influence of cutting speed, feed and depth of cut on cutting force and surface roughness using the Taguchi method. Feed and cutting speed had the greatest influence on surface roughness, and feed had the greatest influence on cutting force components. Ramanujam *et al.* [22] investigated the influence of cutting speed, feed and depth of cut on surface roughness, power consumption and MRR using the Taguchi method and fuzzy logic. The greatest influence on the output parameters had feed. Jain *et al.* [23] presented the influence of spindle speed, feed and depth of cut on MRR. Spindle speed and feed had the greatest influence on MRR. Prokes *et al.* [24] presented the dependence of surface roughness on cutting speed, feed and depth of cut. Only the feed showed a significant influence on the surface roughness. Lotfi *et al.* [25] presented a FEA to predict tool wear as a function of cutting speed, feed and depth of cut for two types of cutting tools (coated carbide and ceramic). The depth of cut had a significant effect, and the feed had no effect on tool wear. Cutting speed had an effect on tool flank wear, but only for coated carbide tools. Hemakumar and Kuppan [26] presented the effects of cutting speed and feed on cutting force, surface roughness and flank wear using a full factorial experimental design. They found that feed had the greatest effect on cutting force and surface roughness, and that cutting speed had the greatest effect on flank wear. Vasudevan *et al.* [27] presented the influence of cutting speed, feed and depth of cut on surface roughness and MRR. Feed was the most influential factor on both output parameters. Waghmode and Dabade [28] investigated the dependence of cutting speed, feed and depth of cut on cutting forces and surface roughness. The cutting forces increased with increased depth of cut and feed. The increased in feed also had an effect on the increased in surface roughness. Padhy and Singh [29] investigated the effects of cutting speed, feed and depth of cut on surface roughness, cutting force and MRR using Taguchi method. Depth of cut and feed had the greatest effect on forces, cutting speed and feed had the greatest effect on surface roughness, and cutting speed had the greatest effect on MRR. Narkhede *et al.* [30] investigated the influence of cutting speed, feed and depth of cut on surface roughness during dry turning and under cryogenic coolant conditions. The lowest surface roughness was found at the lowest feed and the smallest depth of cut as well as the highest cutting speed. Cutting forces and temperature were measured under the most favourable turning conditions. It was proved that the performance parameters are improved by using cryogenic coolant. Padhy and Singh [31] applied the Taguchi method to analyse the influence of cutting speed, feed and depth of cut on cutting force, surface roughness and MRR. The most influential parameter for surface roughness and MRR was cutting speed, and the most important parameter for cutting force was feed. Sim *et al.* [32] investigated the effects of cutting speed, feed and depth of cut on cutting force and temperature, using fuzzy logic to optimize the process. The depth of cut had the greatest effect on cutting forces and temperature.

Compared to alternative techniques such as minimum quantity lubrication, minimum quantity cooling lubrication or cryogenic cooling, dry turning of the alloy Inconel 625 is the most environmentally friendly and the chips are the easiest to recycle. With dry turning, there are no problems associated with the cutting fluid (disposal, recycling, reuse), the costs of which can be considerable. The disadvantages of dry turning are the occurrence of higher temperatures in the cutting zone, which leads to higher tool wear and shorter tool life. Dry turning also causes higher energy consumption due to the higher cutting forces. Finally, surface roughness and dimensional accuracy can deteriorate due to the above-mentioned phenomena. These negative effects of dry turning do not occur if the machining parameters (cutting speed, feed and depth of cut) have lower values, and the machining time is not long. For sustainable production, however, it is necessary to find a balance between the required characteristics of accuracy and quality, productivity and also the environmental requirements of modern production systems. To eliminate the previous problems in dry turning, high-precision machine tools and rigid fixtures must be used to ensure reliable locating and secure clamping. In addition, coated cutting tools with suitable geometry should be used to improve tribological effects, i.e. to keep cutting temperatures and energy consumption as low as possible. Finally, it is necessary to optimize the turning parameters to minimize temperature and reduce wear, especially during prolonged dry turning.

It can be noted that in previous research in the field of dry turning, various methods (Taguchi, RSM, fuzzy logic, etc.) have been used to analyse and optimise the output parameters of turning (surface roughness, cutting force, temperature) based on the input parameters. All the research carried out so far in the field of dry turning of Inconel 625 alloy has its advantages and disadvantages. It should be noted that there has been no research to date in which dimensional accuracy and surface roughness have been integrally investigated. The interactions between the input parameters and their influence on the output parameters have also not been investigated, nor has the fact that the input parameters are usually turning modes (cutting speed, feed and depth of cut).

In contrast to the previous work, the main contribution of this study is the evaluation of the influence of the dominant factors and their interactions on dimensional accuracy and surface roughness. Feed, corner radius and insert type were selected as input parameters. The output parameters, which were evaluated, estimated, modelled and then optimised, were the dimensional deviation and the arithmetic mean of the surface roughness. First, the influence of feed, corner radius and insert type on dimensional accuracy and surface roughness was evaluated. Then the effects were evaluated, and the most important factors and their interactions were selected. The turning process was then modelled and optimised. The validity of the modelling and optimization was evaluated by confirmatory tests. In view of the increasing environmental protection requirements and legal obligations in many countries, research was carried out under dry conditions.

2. Materials and methods

The flowchart according to which the investigation was carried out is shown in Fig. 1.

The investigations were carried out on workpieces made of Inconel 625 alloy, whose chemical composition is as follows: 58-71 % Ni, 21-23 % Cr, 8-10 % Mo, 5 % Fe, 3.2-3.8 % Nb + Ta, ≤ 1 % Co, ≤ 1 % Mn and ≤ 0.40 % Al. The properties of the Inconel 625 alloy are: modulus of elasticity $2.1\ 10^5$ MPa, density 7.8 g/cm^3, tensile strength 990 MPa, yield strength 516 MPa, hardness 160 HB, thermal expansion 15.8 µm/m°C, and thermal conductivity 8.5 W/mK. The dimensions of the workpieces are Ø 44 × 420 mm.

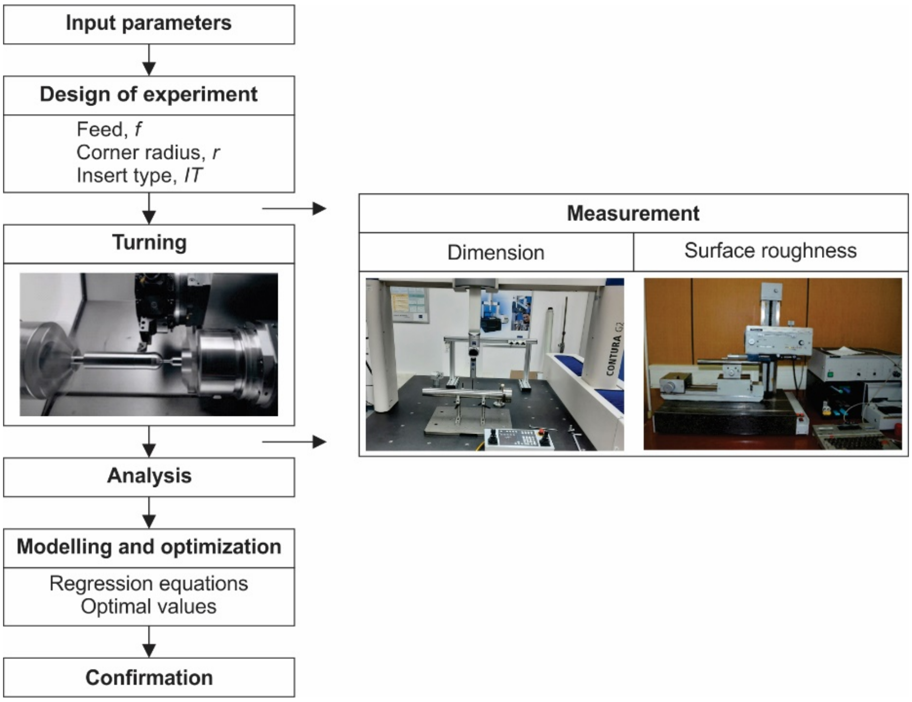

Fig. 1 Flowchart of the methodology

The finish longitudinal turning is carried out on a CNC lathe. The workpiece is locating and clamped using a chuck and a turning centre. The turning parameters and the inserts were selected in accordance with the recommendations of the insert manufacturer and based on the properties of the workpiece material, the workpiece geometry, the type of process, the properties of the technological equipment and the process stability. The cutting speed and feed were selected at lower but recommended levels in order to minimise the effects of tool wear on the results obtained. The cutting speed is 60 m/min. The insert size was selected to achieve the required depth of cut and the mutual relationship between cutting edge length and effective cutting edge length was considered. The assumed depth of cut a_p = 1.5 mm is greater than the corner radius of any insert. A new PVD TiAlN+TiAlN insert was used for each experiment. The common characteristics of the inserts are: square shape, thickness 4.8 mm, cutting edge length 12.3 mm, fixing hole diameter 5.2 mm and inscribed circle diameter 12.7 mm.

Three input parameters were varied during the experimental research. The feed (*f*) was treated as a continuous factor, the corner radius (*r*) as a categorical numerical factor and the insert type (*IT*) as a categorical attributive factor. The input parameters used in this study are as follows: *f* = 0.1, 0.15, 0.2, 0.25, 0.3 mm/rev, *r* = 0.2, 0.4, 0.8, 1.2 mm and *IT* = standard, wiper.

The dimensional accuracy is quantified by the deviation of the theoretical dimension in relation to the realized dimension. Since the diameters of the workpieces differ by small values defined by the width of the tolerance field, the measurement deviation for each experiment is calculated as follows:

$$\Delta D_i = D_{2ti} - D_{2mi} \qquad i=1, 2, \ldots, 40 \tag{1}$$

where D_{2t} is the theoretical value of the diameter after turning (required nominal dimension) and D_{2m} is the measured (real) value of the diameter after turning. The theoretical value of the diameter before turning is calculated as follows:

$$\Delta D_{2ti} = D_{1i} - 2 \cdot a_p \qquad i=1, 2, \ldots, 40 \tag{2}$$

where D_{1i} is the measured diameter value before turning and a_p is the depth of cut.

The measurements of dimensions and surface roughness were carried out under controlled microclimatic conditions at a temperature of 20 °C ± 1 °C.

The surface roughness was measured with a Talysurf measuring device. The measurements were carried out in the feed direction with a sampling length of 0.8 mm and an evaluation length of 4 mm using a Gaussian filter. Five measurements were taken to reduce the relative measurement error. The surface roughness is quantified by the arithmetic mean surface roughness (*Ra*).

The dimensions were measured on a Carl Zeiss Contura G2 CMM. The accuracy of the CMM is 1.9 + $L/300$ µm (L – measuring length). A measuring probe with a length of 75 mm was used. The diameter of the ball was 5 mm. The measurement strategy used is point by point. By measuring five reference diameters, the relative error of the diameter change is reduced.

A randomized experimental design is used to modelling the turning process. During modelling, an evaluation of the main effects and interactions is first carried out. This makes it possible to exclude the main factors and interactions from the regression due to their lack of significance and to create the conditions for conducting the experiment with minimal prediction error. An analysis of variance and an analysis of model adequacy are then carried out, as well as the creation of regression equations for dimensional accuracy (dimensional deviation, ΔD) and the quality of the treated surface (surface roughness, *Ra*).

The turning process is optimized using D-optimal design of experiments, which enables a systematic investigation of the input parameters and their interactions to determine the optimal setting of the input parameters to achieve the specified objective function – simultaneous maximization of accuracy and quality (minimization of dimensional deviation and surface roughness).

3. Results

3.1 Experiments

The experimental investigations were carried out according to the full factorial experimental design, which allows the investigation of all combinations of levels of the input parameters. Considering the fact that 5 levels were assumed for the feed, 4 levels for the corner radius and 2 levels for the insert type, a total of 5 × 4 × 2 = 40 tests were carried out. The measurement results for different combinations of input parameters performed according to the randomized experimental design are shown in Table 1.

Table 1 Experimental results

No.	f (mm/rev)	r (mm)	*Insert*	Ra (μm)	ΔD (mm)
1	0.1	0.2	Wiper	1.316	0.101
2	0.1	0.4	Standard	1.251	0.048
3	0.25	0.4	Wiper	3.908	0.312
4	0.15	0.2	Wiper	2.961	0.225
5	0.25	0.2	Wiper	8.224	0.617
6	0.25	0.2	Standard	15.625	0.586
7	0.15	0.2	Standard	5.625	0.213
8	0.15	0.4	Wiper	1.406	0.112
9	0.3	1.2	Wiper	2.814	0.367
10	0.15	0.8	Wiper	0.669	0.056
11	0.1	1.2	Standard	0.665	0.035
12	0.15	0.8	Standard	1.406	0.052
13	0.1	0.2	Standard	2.503	0.095
14	0.2	0.8	Standard	2.502	0.091
15	0.3	0.2	Standard	22.503	0.859
16	0.2	1.2	Standard	2.664	0.148
17	0.25	0.8	Standard	3.906	0.141
18	0.15	0.4	Standard	2.812	0.104
19	0.25	1.2	Wiper	1.953	0.252
20	0.1	0.4	Wiper	0.625	0.052
21	0.3	0.4	Wiper	5.622	0.452
22	0.2	0.2	Wiper	5.263	0.401
23	0.3	0.2	Wiper	11.844	0.905
24	0.2	0.8	Wiper	1.192	0.101
25	0.2	0.4	Standard	5.004	0.187
26	0.3	0.8	Wiper	2.678	0.227
27	0.1	1.2	Wiper	0.314	0.039
28	0.1	0.8	Standard	0.627	0.022
29	0.15	1.2	Wiper	0.705	0.091
30	0.25	0.8	Wiper	1.861	0.157
31	0.2	0.2	Standard	10.008	0.382
32	0.25	0.4	Standard	7.813	0.292
33	0.2	1.2	Wiper	1.254	0.161
34	0.2	0.4	Wiper	2.503	0.202
35	0.15	1.2	Standard	1.502	0.083
36	0.3	1.2	Standard	6.004	0.336
37	0.25	1.2	Standard	4.163	0.231
38	0.1	0.8	Wiper	0.297	0.025
39	0.3	0.8	Standard	5.626	0.204
40	0.3	0.4	Standard	11.252	0.421

3.2 Process analysis and modelling

The statistical analysis of the measurement results was carried out using the JMP software, whereby a model with main effects and two-factor interactions was selected. In this way, a model is obtained that allows the modelling of complex relationships between input and output parameters. Given the irregular distribution of the data and the excessive variation between values, a logarithmic transformation of Ra was performed to allow interpretation and statistical analysis. The estimated input parameters of the model, sorted by statistical significance, are shown in Table 2. As can be seen, all input parameters and the interaction of feed and corner radius are statistically significant. Other two-factor interactions are not significant.

Table 2 Effect summary

Source	Log Worth	P Value
f (0.1,0.3)	25.304	0.00000
r	20.530	0.00000
Insert	15.528	0.00000
$f \times r$	14.713	0.00000

Table 3 shows the summary of fit of the selected factor models of surface roughness and dimensional deviation. The predictions of the coefficient of determination (RSquare, RSquare Adj) are close to 1, which means that the model fits the data very well. In both cases, RSquare values (0.985099, 0.984298) are close to the RSquare Adj values (0.981253, 0.980246). The coefficients of determination show that more than 98 % of the variability in surface roughness and dimensional deviation is determined by the feed, corner radius, insert type and the interaction of feed and corner radius. The root mean square error is small compared to the mean of the response, indicating a good fit and accuracy of the prediction model, i.e. that the model fits the measured data well.

Table 4 shows the analysis of variance for the selected regression models. A high model F-value of 256.1723 for surface roughness and 242.9135 for dimensional deviation with a low p-value (< 0.0001) indicates that the model effects are statistically significant.

Table 5 shows the estimated regression coefficients of the parameters. The parameters provide an estimate of the effects of the model input parameters on the dimensional deviation and the logarithmically transformed value of the surface roughness. P-values (Prob > |t|) of less than 0.05 indicate that the model factors are significant (marked with * in Table 4).

Table 3 Summary of fit

Parameter	$\log Ra$	ΔD
RSquare	0.985099	0.984298
RSquare Adj	0.981253	0.980246
Root Mean Square Error	0.143263	0.029879
Mean of Response	0.957479	0.234625

Table 4 Analysis of variance

Source	DF	$\log Ra$			ΔD		
		Sum of Squares	Mean Square	F Ratio	Sum of Squares	Mean Square	F Ratio
Model	8	42.061990	5.25775	256.1723	1.7348960	0.216862	242.9135
Error	31	0.636252	0.02052	Prob > F	0.0276754	0.000893	Prob > F
C. Total	39	42.698242		<.0001*	1.7625714		<.0001*

Table 5 Parameter estimates

Term	$\log Ra$				ΔD			
	Parameter Estimate	Std. Error	t Ratio	Prob>|t|	Parameter Estimate	Std. Error	t Ratio	Prob>|t|
Intercept	0.9574789	0.022652	42.27	<.0001*	0.234625	0.004724	49.66	<.0001*
f(0.1,0.3)	1.0829312	0.032035	33.81	<.0001*	0.209	0.006681	31.28	<.0001*
r [0.2]	0.883553	0.039234	22.52	<.0001*	0.203775	0.008183	24.90	<.0001*
r [0.4]	0.1647571	0.039234	4.20	0.0002*	-0.016425	0.008183	-2.01	0.0535
r [0.8]	-0.552802	0.039234	-14.09	<.0001*	-0.127025	0.008183	-15.52	<.0001*
r [1.2]	-0.495508	0.039234	-12.63	<.0001*	-0.060325	0.008183	-7.37	<.0001*
Insert [Standard]	0.3541856	0.022652	15.64	<.0001*	-0.008125	0.004724	-1.72	0.0954
Insert [Wiper]	-0.354186	0.022652	-15.64	<.0001*	0.008125	0.004724	1.72	0.0954
$f \times r$ [0.2]	6.3579e-5	0.055485	0.00	0.9991	0.1811	0.011572	15.65	<.0001*
$f \times r$ [0.4]	0.0001446	0.055485	0.00	0.9979	-0.0156	0.011572	-1.35	0.1874
$f \times r$ [0.8]	0.000214	0.055485	0.00	0.9969	-0.1132	0.011572	-9.78	<.0001*
$f \times r$ [1.2]	-0.000422	0.055485	-0.01	0.9940	-0.0523	0.011572	-4.52	<.0001*

Feed, corner radius and insert type have statistical significance for surface roughness. Feed has the highest statistical significance, followed by corner radius and then insert type. The interactions between the factors have no statistical significance for surface roughness.

Feed, three levels of corner radius (0.2, 0.4 and 1.2) and their interactions have statistical significance for the dimensional deviation. A corner radius of 0.4 mm is neither statistically significant independently nor in interaction with any other parameter. The insert type has no statistical significance either independently or in interaction with other parameters.

Fig. 2 illustrates the relationship between the actual and predicted values. The resulting plots demonstrate that the data points closely align with the line, indicating a strong fit of the model. This suggests that the predicted values are accurate and closely match the actual values for both surface roughness and dimensional deviation. The narrow range of the confidence interval further supports the precision of the predicted values.

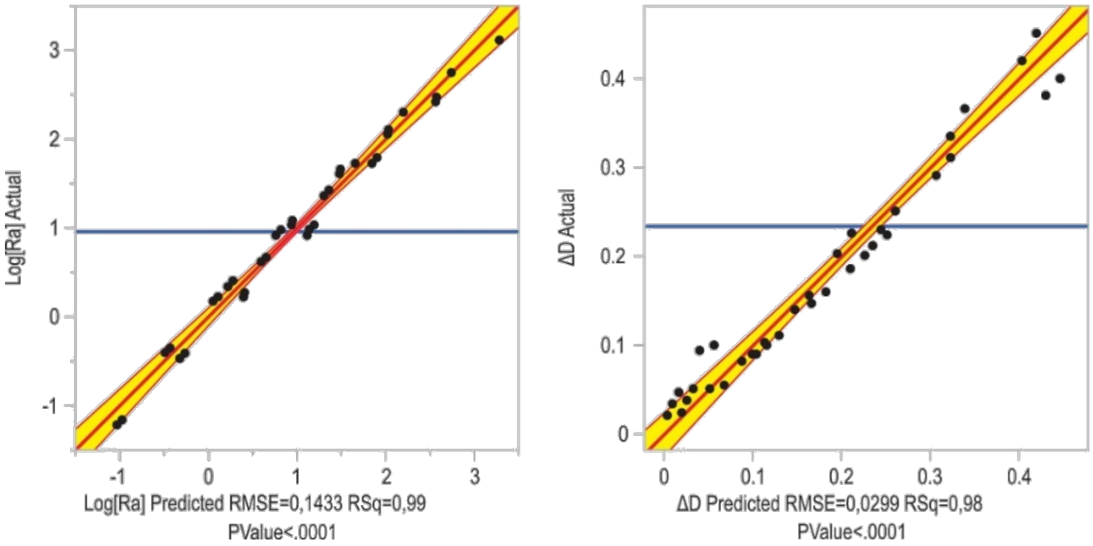

Fig. 2 Actual by predicted plot

Fig. 3 shows the dependence of the residuals on the predicted value. It can be seen that the residuals are independent in both cases, i.e. they do not correlate with a parameter, which indicates that there was no systematic increase or decrease in the residuals during the experiment.

Fig. 4 shows that the studentized residuals are not outside the interval and are randomly distributed around the value zero, which not only confirms the normal distribution, but also means that there are no significantly deviating values, i.e. no potential outliers.

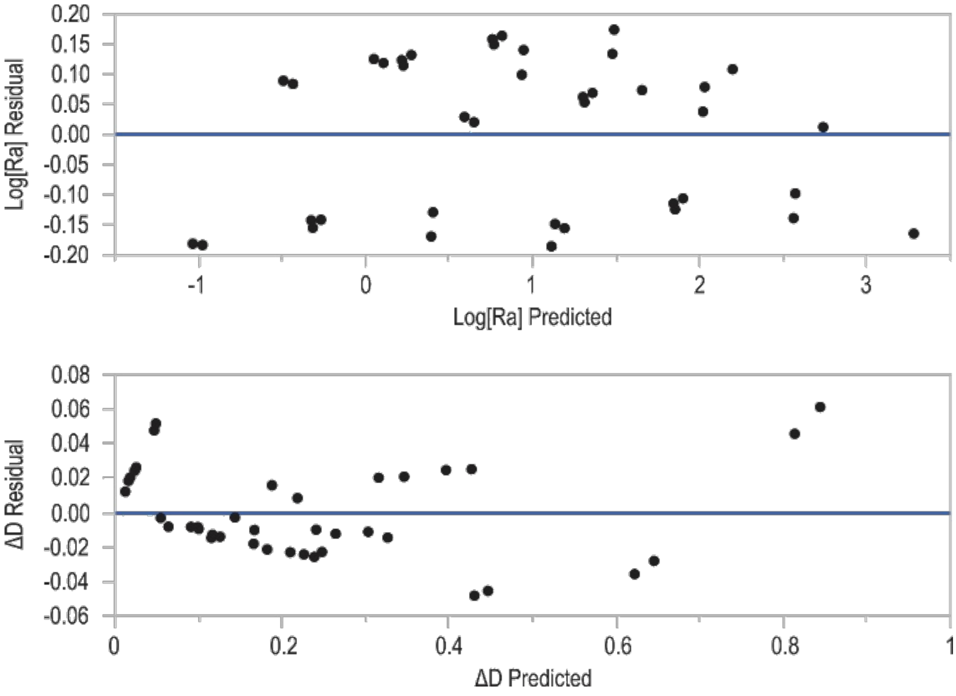

Fig. 3 Residual by predicted plot

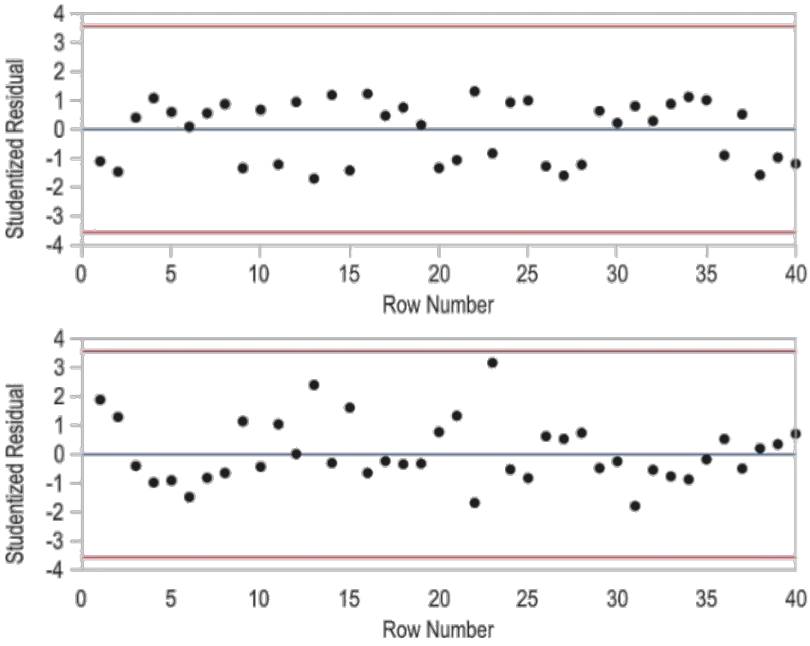

Fig. 4 Studentized residuals

For the selected models, the statistical analysis of the measured data yields the following regression equations for roughness and dimensional deviation:

$$\log Ra = 0.9574789383 + 1.0829311516 \cdot \left(\frac{f-0.2}{0.1}\right) + Match(r)\begin{pmatrix} "0.2" & \Rightarrow & 0.8835530387 \\ "0.4" & \Rightarrow & 0.1647570702 \\ "0.8" & \Rightarrow & -0.552802394 \\ "1.2" & \Rightarrow & -0.495507715 \\ else & \Rightarrow & . \end{pmatrix} + \left(\frac{f-0.2}{0.1}\right) \cdot Match(r)\begin{pmatrix} "0.2" & \Rightarrow & 0.0000635788 \\ "0.4" & \Rightarrow & 0.0001445986 \\ "0.8" & \Rightarrow & 0.0002140391 \\ "1.2" & \Rightarrow & -0.000422217 \\ else & \Rightarrow & . \end{pmatrix} + Match(Insert)\begin{pmatrix} "Standard" & \Rightarrow & 0.3541856229 \\ "Wiper" & \Rightarrow & -0.3541856229 \\ else & \Rightarrow & . \end{pmatrix} \tag{3}$$

$$\Delta D = 0.234625 + 0.209 \cdot \left(\frac{f-0.2}{0.1}\right) + Match(r)\begin{pmatrix} "0.2" & \Rightarrow & 0.203775 \\ "0.4" & \Rightarrow & -0.015425 \\ "0.8" & \Rightarrow & -0.127025 \\ "1.2" & \Rightarrow & -0.060325 \\ else & \Rightarrow & . \end{pmatrix} + \left(\frac{f-0.2}{0.1}\right) \cdot Match(r)\begin{pmatrix} "0.2" & \Rightarrow & 0.1811 \\ "0.4" & \Rightarrow & -0.0156 \\ "0.8" & \Rightarrow & -0.1132 \\ "1.2" & \Rightarrow & -0.0523 \\ else & \Rightarrow & . \end{pmatrix} + Match(Insert)\begin{pmatrix} "Standard" & \Rightarrow & -0.008125 \\ "Wiper" & \Rightarrow & 0.008125 \\ else & \Rightarrow & . \end{pmatrix} \tag{4}$$

The graphical interpretation of the influence of the input parameters on the output parameters is illustrated by surface plots in Fig. 5.

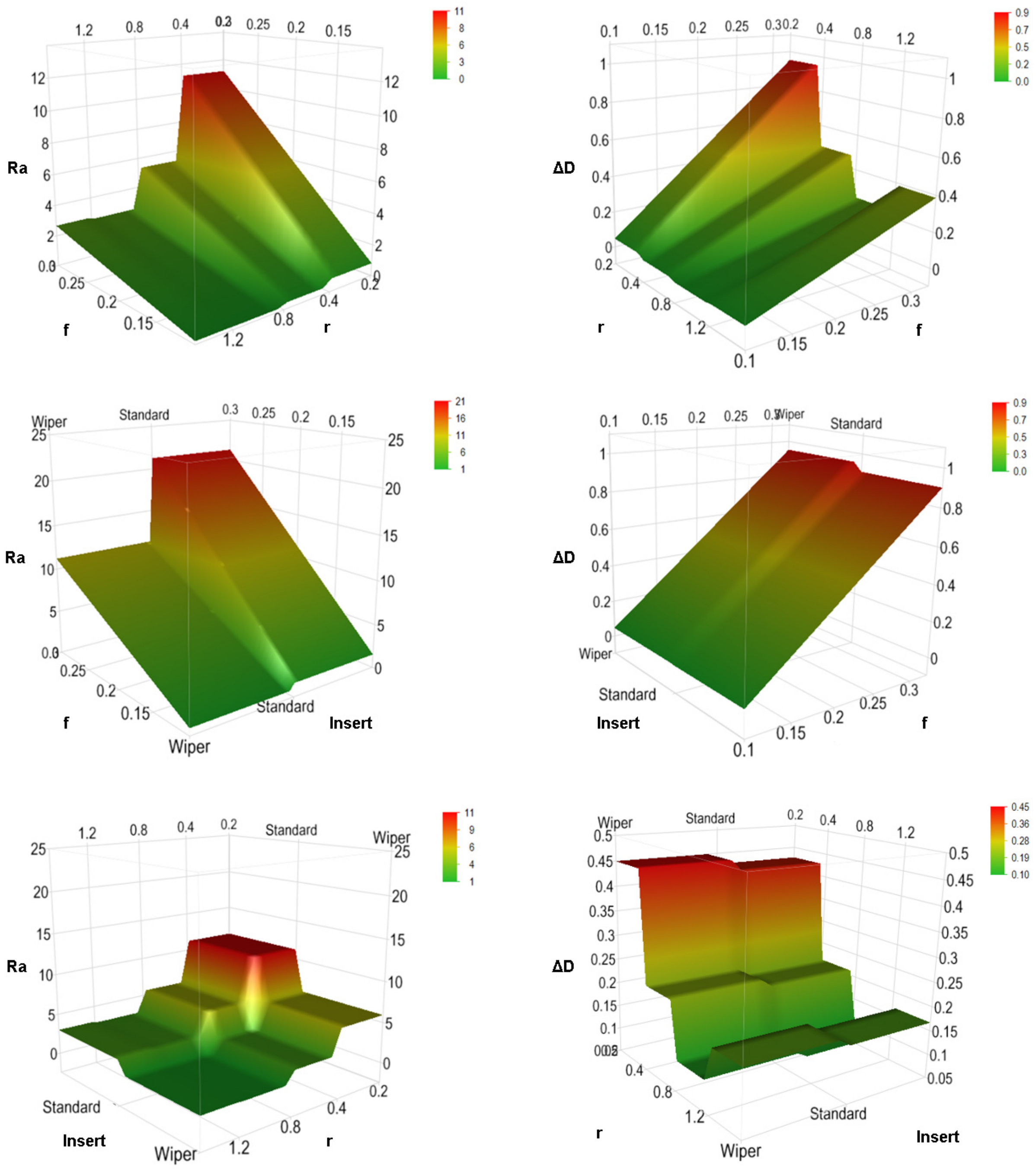

Fig. 5 Surface plot

3.3. Process optimization

After modelling, an optimization is carried out. The optimization problem was solved using the Wolfe reduced-gradient approach in the JMP software. The constraints are set in accordance with the conditions of the experimental research. The objective function is the simultaneous minimization of the surface roughness and the dimensional deviation. Since these two requirements must be met together in practice, both output parameters are given the same importance (same weighting coefficients).

The quantification of the optimization can be illustrated most easily with the profile plot of the prediction profiles (Fig. 6). The profiler plot shows the prediction of the optimal input variables. The optimal predicted value of the surface roughness is log *Ra* = -1.03265 µm, i.e. *Ra* ≈ 0.356 µm. The optimal predicted value of the measurement deviation is *ΔD* ≈ 0.02 mm. The optimum predicted values can be determined with a confidence interval of 95 % for the following optimum input parameters f = 0.1 mm/rev, r = 0.8 and wiper insert. The desirability function shows how the desirability value changes when the input parameters change, allowing quick (visual) identification of the combination of input parameters that best meet the set optimization goal. The desirability index provides a comprehensive assessment of the effectiveness of the solution obtained, taking into account the optimization goal and its importance. A high value of the overall desirability measure (close to 1) indicates that the optimal values of the parameters were achieved in accordance with the set optimization goals. This means that the values achieved are satisfactory in terms of product or process quality.

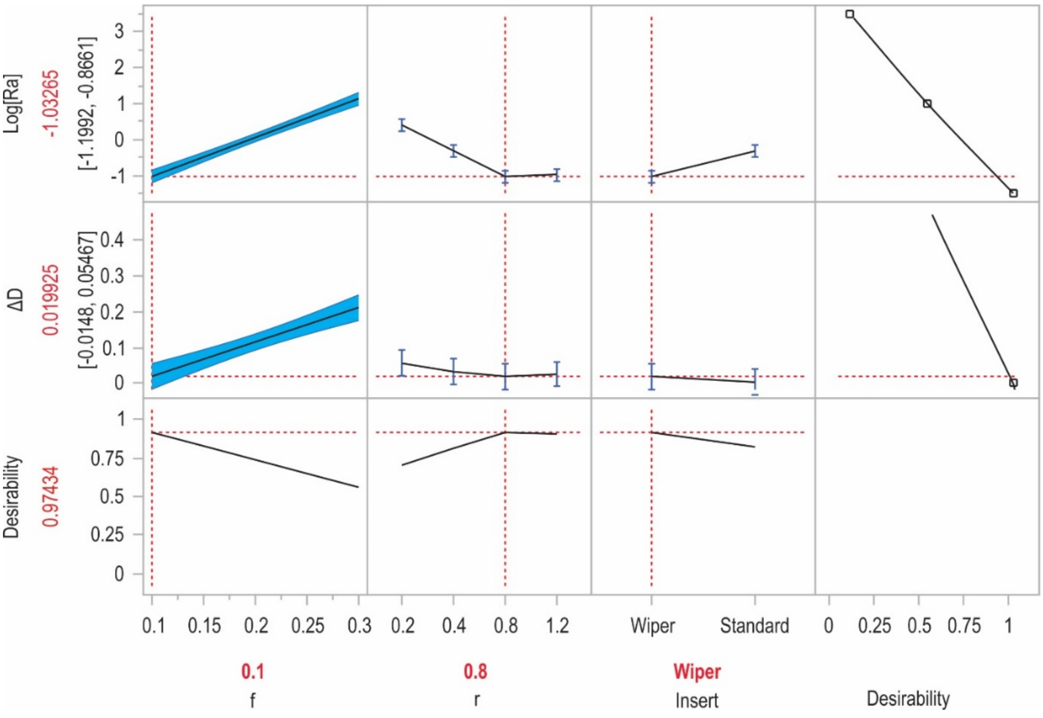

Fig. 6 Prediction profiler

3.4. Confirmation experiments

The regression models obtained and the optimum values for surface roughness and dimensional deviation were confirmed by a further 9 tests.

The confirmation of the regression models obtained was carried out with unknown combinations of input parameters in 8 trials. Since corner radius and insert type are categorical values, they were not varied. The feed was varied in 4 levels (0.125, 0.175, 0.225, 0.275 mm/rev).

The optimum values for surface roughness and dimensional deviation were confirmed at the theoretical optimum for the parameters f = 0.1 mm/rev, r = 0.8 and wiper insert. The results obtained together with the calculated percentage errors are shown in Table 6.

Table 6 The results of the confirmation experiments

No.	f (mm/rev)	r (mm)	*Insert*	Measurement		Prediction		Percentage error	
				Ra (μm)	ΔD (mm)	Ra (μm)	ΔD (mm)	PE_{Ra} (%)	$PE_{\Delta D}$ (%)
1	0.125	0.2	Standard	3.994	0.143	3.971	0.138	0.58	3.50
2	0.125	0.4	Wiper	0.969	0.086	0.956	0.082	1.34	4.65
3	0.175	0.2	Wiper	3.389	0.354	3.374	0.349	0.44	1.41
4	0.175	0.4	Standard	3.358	0.170	3.339	0.162	0.57	4.71
5	0.225	0.8	Wiper	1.395	0.148	1.379	0.141	1.15	4.73
6	0.225	1.2	Standard	2.976	0.211	2.965	0.205	0.37	2.84
7	0.275	0.8	Standard	4.824	0.177	4.811	0.172	0.27	2.82
8	0.275	1.2	Wiper	2.533	0.306	2.509	0.301	0.95	1.63
9	0.1	0.8	Wiper	0.365	0.021	0.356	0.020	2.47	4.76

4. Discussion

The results of experimental research show that the obtained output parameters achieved within very wide range. For surface roughness, the results vary in a range of 0.297-22.503 µm and with a ratio between the maximum and minimum values of 75.77 (7577 %). For dimensional deviation, the results vary in a range of 0.022-0.905 mm and a ratio between the maximum and minimum values of 41.14 (4134 %). High ratio values indicate the possibility of controlling the output parameters within very wide limits depending on the combination of input parameters. In addition, the minimum values of surface roughness and dimensional deviation show that it is possible to achieve high surface quality and high dimensional accuracy in dry turning if the machining parameters are optimized.

The results of the statistical analysis of the experimental results show that the regression models are appropriate and significant, which means that they describe the process of dry turning of Inconel 625 alloy well. The statistical analysis made it possible to identify significant factors and their interactions on the output parameters of the process.

Based on the estimated factors, the regression equations and the surface plots, it can be observed that the value of surface roughness increases with increasing feed and decreasing corner radius. The reverse is also true. At higher feeds and smaller corner radii, the peaks and valleys formed on the workpiece are deeper and wider. The theoretical geometric surface roughness is a function of the feed for a specific corner radius. Smaller corner radii lead to a poorer quality of the machined surface at the same feed. This is due to the different values of the approach angle along the cutting edge. Increasing the corner radius at the same feed improves the quality of the machined surface (up to the limit value of 0.8). A further increase in the corner radius (after the value of 0.8 mm) of the cutting insert affected the likely occurrence of chatter and vibration [33], leading to a deterioration in surface roughness and dimensional accuracy (at a radius of 1.2 mm). This conclusion is also confirmed by the flank wear, which is close to the smallest and largest value of the dimensional deviation, which was to be expected considering the short cutting time and the identically smaller value of the cutting speed, which in previous studies proved to be the most influential parameter for intensifying the wear mechanisms of the cutting insert.

Larger values of the feed and smaller values of the corner radius, individually or in interaction, form an uneven surface, resulting in a significant deviation from the circularity and cylindricity, and the waviness of the surface increases, worsening the dimensional accuracy. Similar to the surface roughness, after reaching the critical value of the corner radius of 0.8 mm, there is a slight deterioration in dimensional accuracy due to the likely occurrence of vibration. In addition to the deterioration in surface roughness, the induced vibrations also influenced the deterioration in dimensional accuracy.

Furthermore, the results showed that there is a significant interaction between feed and corner radius on dimensional deviation (Fig. 7). When the feed increases, the dimensional accuracy deteriorates. With an increase in the corner radius, the dimensional accuracy initially improves significantly and then deteriorates slightly. The smallest dimensional deviations are achieved with a corner radius of 0.8 mm. For each combination of feed and corner radius, the standard insert achieves a slightly better dimensional accuracy. The interaction of feed and corner radius follows the trends for feed and corner radius. The influence of the interaction is more pronounced for larger values of the feed and smaller values of the corner radius. This means that a smaller corner radius (0.2 mm) in combination with an increase in the feed has a linear (worse) effect on the dimensional accuracy. The smallest effect of this interaction on the dimensional accuracy is given at the smallest feed (0.1 mm/rev) and at a corner radius of 0.8 mm.

The insert type showed a significant effect on the surface roughness. Wiper inserts are designed to improve the quality of the machined surface. Therefore, for the same feed and corner radius, wiper inserts always produce a better quality turned surface, i.e. a lower surface roughness value. The insert type had no significant influence on the realisation of the dimension, i.e. on the dimensional deviation, therefore in machining operations where a certain surface roughness is not required, it is more rational to use standard inserts as they are cheaper.

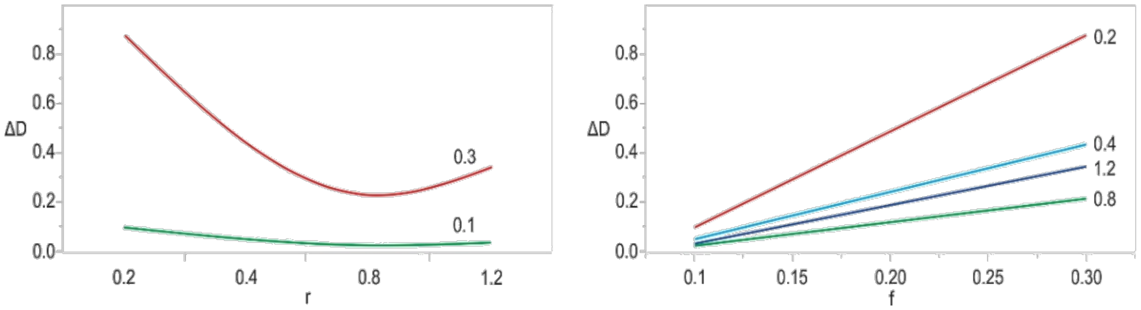

Fig. 7 Interaction profiles

The results of the confirmation experiments have shown that dry turning of Inconel 625 alloy is modelled sufficiently accurately for the given input and output parameters, as the percentage errors are in the range of 0.27-2.47 % for the surface roughness, i.e. in the range of 1.41-4.76 % for the measurement deviation.

5. Conclusion

The results of the experimental investigations and the statistical analysis of the measurement results have shown that there is a mutual functional dependency between the feed, the corner radius and the insert type on the one hand and the dimensional deviation and surface roughness on the other.

The prediction and validation of the created regression models demonstrated that it is possible to model both surface roughness and dimensional deviation.

The optimization results further confirmed that it is possible to optimize the turning process by considering the combined influence of feed, corner radius, and insert type on both surface roughness and dimensional deviation.

As the corner radius increases up to a certain value, both dimensional deviation and surface roughness improve, but after reaching a threshold, they begin to deteriorate slightly. As the feed increases, both dimensional deviation and surface roughness increase. The type of cutting insert affects surface roughness but does not influence dimensional deviation.

The percentage errors achieved, which are less than 5 % in the worst case, show that the process is correctly modelled and that the regression models created can be practically applied in a real production environment.

For future research, it is planned to include further input and output parameters in the prediction and optimization model.

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