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# MODELLING AND STATISTICAL ANALYSIS OF FLANK WEAR DURING TURNING OF Co-Cr-Mo ALLOY

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***Abstract:*** *This paper focuses on modelling the process and evaluating the effects of cutting speed, feed, insert radius and rake angle on flank wear during turning of Co-Cr-Mo alloys. A custom design of experiments based on the D-optimality criterion was used to perform the experimental investigation. Statistical analysis was performed using JMP software and found that all input parameters and their quadratic terms as well as the two-factor interaction between cutting speed and feed had a statistically significant effect on flank wear, while the other interactions between two factors were not statistically significant. Based on the statistical analysis, a regression equation for flank wear was created. The validity of the model was confirmed by confirmatory experiments involving six additional trials that were not included in the original modelling. The results of the confirmation experiments with an error of less than 1% clearly confirm the precision of the model and show the potential of the defined approach for reliable modelling of flank wear in turning of Co-Cr-Mo alloys.*

***Keywords:*** *CNC turning, flank wear, Co-Cr-Mo alloy, design of experiments, statistical analysis*

## 1. INTRODUCTION

The cobalt-chromium-molybdenum (Co-Cr-Mo) alloy is frequently used in biomedical applications, particularly for implants and prostheses, due to its exceptional hardness, wear resistance and biocompatibility [1]. However, machining this alloy poses a major challenge due to its high hardness and wear resistance [2]. Efficient machining of Co-Cr-Mo alloys is not only crucial for maintaining precision and quality, but also for the economic feasibility of the manufacturing process. Tool wear, especially flank wear, is one of the main factors that influence machining performance and affect both the dimensional accuracy and the surface quality of the machined parts. Flank wear, as the predominant mechanism of tool wear, plays a key role in machining efficiency as it directly affects tool longevity and surface quality. Previous research has investigated various aspects of machining Co-Cr-Mo alloys, focusing on turning processes and their effects on tool wear, surface roughness, cutting forces and chip formation.

McParland et al. [1] applied a Bayesian hierarchical Gaussian process model to predict tool wear in turning Co–Cr–Mo alloy. Their findings showed that cutting speed and feed significantly affect tool wear, with lower speeds promoting an adhering layer and higher speeds causing edge chipping. Higher cutting speeds resulted in chipping of large fragments of the cutting edge. Tavares and Hassui [3] investigated the impact of cutting parameters on tool wear and surface roughness during the turning of Co-Cr-Mo alloy using coated carbide tools. Their study revealed that crater wear was the dominant wear type, primarily influenced by feed and the loss of the tool's coating.

Adhesion of workpiece material to the rake surface was identified as a key wear mechanism, alongside abrasive action from embedded carbides. Jagtap et al. [4] investigated the effects of machining parameters on cutting forces during face turning of Co-Cr-Mo alloy in a dry environment. Higher depth of cut, feed and cutting speed increased cutting forces, with radial and tangential forces significantly impacting surface roughness, which rose by 20.75% at maximum parameters. Jagtap and Pawade [5] studied the chip formation mechanism during CNC turning of Co-Cr-Mo alloy under dry conditions. They found that feed significantly influences the chip thickness ratio, with higher feeds increasing chip thickness. Tight coiled chips, formed at optimal feeds, were associated with lower surface roughness, while loose coiled chips led to higher surface roughness. Jagtap and Pawade [6] used acoustic emission signals to monitor surface topography during CNC turning of Co-Cr-Mo biomaterial. They found that cutting speed, feed and depth of cut significantly influenced acoustic emission (AE) root mean square (RMS) voltage and counts. Lower force components and AE RMS voltage were associated with smoother surfaces and lower roughness, while higher roughness corresponded to nonuniform AE signal patterns. Ender et al. [7] investigated the effects of machining parameters on chip morphology and tool wear in turning Co-Cr-Mo alloy using experimental methods and FEM analysis. They found that an increase in feed led to higher force and more pronounced serrated chips. Cracks and adhesions appeared on chip surfaces at higher feeds and the crater wear on the cutting tool increased with feed, though the tool nose radius remained unchanged. The study also showed that the chip height ratio decreased, and the serrated pitch increased as the feed increased. Dijmarescu et al. [8] studied the impact of cutting parameters on the surface roughness of Co-Cr-Mo alloy during dry turning. The results show that roughness increase with the increase in feed and cutting depth, while they decrease with an increase in cutting speed.

A mathematical model was developed to predict the roughness, which indicates that feed has the greatest influence on roughness, followed by cutting depth and cutting speed. Dijmarescu et al. [9] investigated cutting forces during the turning of Co-Cr-Mo alloy using TiAlN PVD-coated inserts. The results showed that the total cutting force increases with the increase in feed and cutting depth, while it decreases with an increase in cutting speed. A mathematical model was developed to predict the cutting forces, which correlated well with the experimental data (average error of 1.18%). The feed had the greatest impact on cutting forces, enabling the application of the model for estimating cutting forces in further experiments. Ince and Asiltürk [10] studied the impact of tool parameters on vibrations during the machining of Co-Cr-Mo alloy on CNC lathes. They found that increasing the tool tip radius reduces vibrations, while decreasing the radius increases vibrations. The lowest vibrations were recorded at 318 rpm, a feed of 0.25 mm/rev, a cutting depth of 0.9 mm, and a radius of 0.8 mm, while the highest were observed at 636 rpm, a feed of 0.1 mm/rev, and a cutting depth of 0.5 mm. Increasing cutting speed reduces vibrations, while feed and cutting depth increase vibrations. Asilturk et al. [11] investigated the optimization of parameters affecting the surface roughness of Co-Cr-Mo alloy during CNC machining, using the Taguchi method and response surface methodology (RSM). Through analysis of variance (ANOVA), they identified the key parameters, and the optimization of parameters to achieve minimal roughness showed that the most significant parameter for Ra was the tool tip radius (38%), while for Rz, the tool radius was dominant with 43%. The best values for minimal roughness were 318 rpm for spindle speed, 0.1 mm/rev for feed, 0.7 mm for cutting depth, and 0.8 mm for the tool tip radius. Asilturk and Alperince [12] developed a fuzzy logic model for predicting surface roughness during CNC turning of Co-Cr-Mo alloy, considering machining parameters such as spindle speed, feed, depth of cut, and tool nose radius. The developed model allows for determining the optimal Ra values depending on material hardness and tool type, contributing to future research and industrial applications, with the potential for comparison with other artificial intelligence methods.

Unlike previous studies that focus on single factors or the use of different methods such as RSM and Bayesian methods, this paper provides a comprehensive analysis of a larger number of input parameters that influence flank wear during turning of Co-Cr-Mo alloys. The aim of this study is to develop a regression model that accurately predicts flank wear and contributes to a better understanding of the tool wear mechanism, thereby improving machining technology and increasing process efficiency.

## 2. METODOLOGY

The research methodology is shown in Figure 1. The input parameters considered in the study are cutting speed (v), feed (f), corner radius (r) and clearance angle (α).

All input parameters were set to three levels. The ranges of the input parameters are: $v$ = 50-90 m/min, $f$ = 0.05-0.15 mm/rev, $r$ = 0.4-1.2 mm, $\alpha$ = 3-7°. All other machining conditions were constant.

The experimental design was defined with the JMP software using the D-optimality criterion within the custom design of experiment.

The experiments were performed on a Gildemeister CTX 310 CNC lathe with controlled machining parameters. The choice of machining parameters was based on the recommendations of the cutting tool manufacturer, the properties of the workpiece material, the workpiece geometry, the clamping, the properties of the equipment and the system stability.

After machining, the flank wear was measured using a LEITZ Orthoplan microscope. Based on the measurement results, a statistical analysis was performed, which enabled the development of a regression model to predict flank wear.

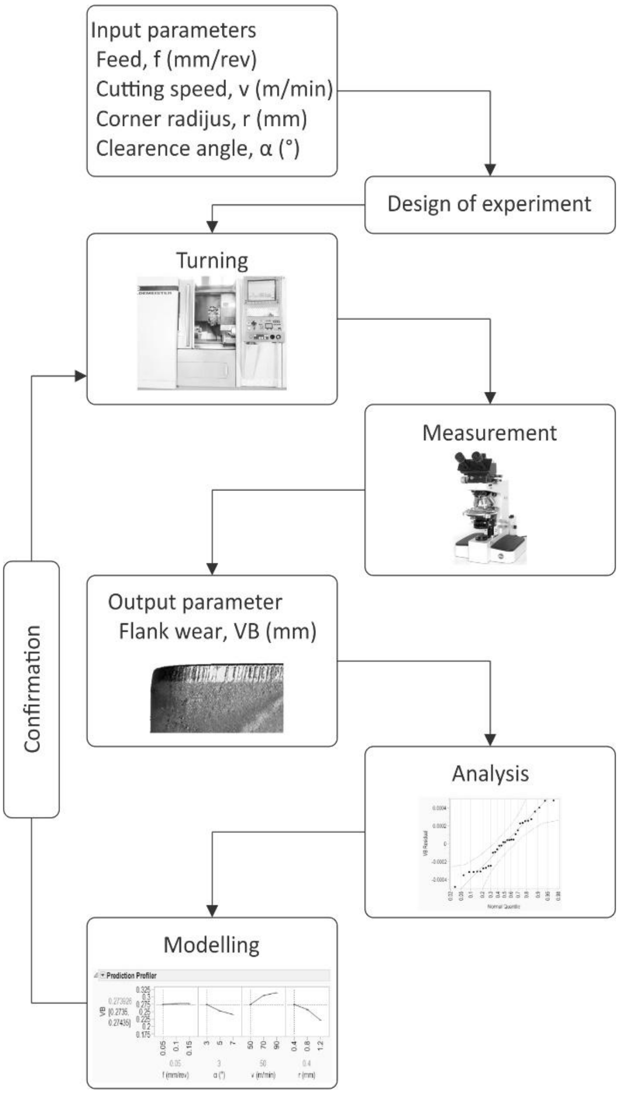


**Figure 1.** Illustration of the research methodology

The accuracy of the developed model was confirmed by six confirmation experiments, ensuring its validity and reliability for application under real conditions.

Experimental investigations were conducted on workpieces with dimensions Ø35 × 400 mm, made of Co-Cr-Mo alloy, the chemical composition of which is shown in Table 1.

**Table 1.** Chemical composition of Co-Cr-Mo alloy

| Element | Percentage |
|---|---|
| Chromium | 27–30% |
| Molybdenum | 5–7% |
| Nickel | <0.5% |
| Iron | <0.75% |
| Carbon | <0.35% |
| Silicone | <1% |
| Manganese | <1% |
| Tungsten | <0.2% |
| Phosphorus | <0.02% |
| Sulphur | <0.01% |
| Nitrogen | <0.25% |
| Aluminium | <0.1% |
| Titanium | <0.1% |
| Bor | <0.01% |
| Cobalt | Balance |

Table 2 shows the properties of the Co-Cr-Mo alloy, which include key mechanical, thermal and physical characteristics.

**Table 2.** Properties of Co-Cr-Mo alloy

| Property | Value |
|---|---|
| Tensile strength (MPa) | 920 |
| Elongation (%) | 16.5 |
| Young's modulus (GPa) | 216 |
| Hardness (HRC) | 34 |
| Thermal conductivity ($W·m^{-1}K^{-1}$) | 13 |
| Specific heat capacity ($J·kg^{-1}K^{-1}$) | 450 |
| Density ($kg·m^{-3}$) | 8300 |

## 3. RESULTS

### 3.1 Experimental research

The experimental investigation was carried out using a custom design of experiment, defined according to predefined input and output parameters. An a priori model was developed that includes main effects, quadratic terms, and two-factor interactions. D-optimal criteria were used in creating the experimental design to ensure accurate estimation of the model coefficients.

The number of experimental points was chosen based on the complexity of the model and the need for an accurate assessment of the effects of input parameters on the output. An evaluation of different experimental plans with varying numbers of points was conducted to determine the optimal number of experimental points. The results of the evaluation showed that 32 experimental points provide sufficient statistical power for reliable identification of real effects input parameters on the output. To eliminate potential systematic bias, the data were randomized. Table 3 presents the randomized experimental design with measured flank wear values.

**Table 3.** Experimental research

| No. | *f* (mm/rev) | *α* (°) | *v* (m/min) | *r* (mm) | *VB* (mm) |
|---|---|---|---|---|---|
| 1. | 0.05 | 7 | 90 | 1.2 | 0.227 |
| 2. | 0.05 | 7 | 50 | 0.4 | 0.24 |
| 3. | 0.15 | 3 | 90 | 0.4 | 0.318 |
| 4. | 0.15 | 3 | 50 | 1.2 | 0.225 |
| 5. | 0.15 | 5 | 50 | 0.4 | 0.256 |
| 6. | 0.1 | 3 | 90 | 1.2 | 0.265 |
| 7. | 0.05 | 3 | 90 | 0.4 | 0.314 |
| 8. | 0.05 | 7 | 90 | 1.2 | 0.227 |
| 9. | 0.05 | 5 | 90 | 0.4 | 0.292 |
| 10. | 0.05 | 3 | 70 | 1.2 | 0.252 |
| 11. | 0.1 | 7 | 50 | 1.2 | 0.19 |
| 12. | 0.15 | 7 | 90 | 0.8 | 0.267 |
| 13. | 0.15 | 7 | 90 | 1.2 | 0.231 |
| 14. | 0.15 | 7 | 90 | 0.4 | 0.284 |
| 15. | 0.15 | 7 | 50 | 1.2 | 0.191 |
| 16. | 0.1 | 5 | 70 | 0.8 | 0.269 |
| 17. | 0.05 | 3 | 90 | 0.8 | 0.297 |
| 18. | 0.15 | 3 | 50 | 0.8 | 0.261 |
| 19. | 0.1 | 3 | 50 | 0.4 | 0.277 |
| 20. | 0.05 | 3 | 50 | 0.4 | 0.274 |
| 21. | 0.15 | 3 | 90 | 0.4 | 0.318 |
| 22. | 0.15 | 5 | 90 | 1.2 | 0.244 |
| 23. | 0.15 | 7 | 50 | 0.4 | 0.243 |
| 24. | 0.05 | 7 | 50 | 0.8 | 0.223 |
| 25. | 0.15 | 3 | 70 | 0.4 | 0.308 |
| 26. | 0.15 | 7 | 70 | 1.2 | 0.222 |
| 27. | 0.05 | 7 | 70 | 0.4 | 0.27 |
| 28. | 0.1 | 7 | 90 | 0.4 | 0.283 |
| 29. | 0.15 | 3 | 90 | 1.2 | 0.266 |
| 30. | 0.05 | 3 | 50 | 1.2 | 0.221 |
| 31. | 0.05 | 5 | 50 | 1.2 | 0.2 |
| 32. | 0.05 | 7 | 90 | 0.4 | 0.28 |

### 3.2 Statistical analysis

The statistical analysis of the experimental results was conducted using JMP software, employing a model that integrates the main effects, their squares and the two-factor interactions of the input parameters. This model enables a detailed analysis of the complex relationships between input and output parameters.

Figure 2 shows the plot of actual by predicted values, which provides a visual assessment of the fit quality of the model. The resulting diagram shows a high correlation between the actual and predicted values, as the points are distributed near to the diagonal line. The diagonal line represents the ideal case where the predicted values are identical to the actual values.

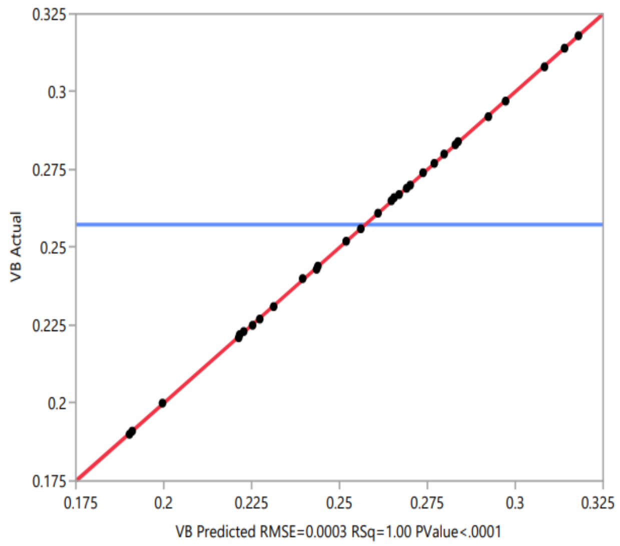


**Figure 2.** Actual by predicted plot

Table 4 shows the sorted parameter estimates for all statistically significant factors.

**Table 4.** Sorted parameter estimates

| Term | Estimate | Std Error | t Ratio | Prob>\|t\| |
|---|---|---|---|---|
| *r* | -0.02623 | 5.872e-5 | -446.7 | <.0001* |
| *v* | 0.0201242 | 5.914e-5 | 340.27 | <.0001* |
| *α* | -0.017127 | 5.872e-5 | -291.7 | <.0001* |
| *v* × *v* | -0.010455 | 0.000149 | -70.27 | <.0001* |
| *r* × *r* | -0.009455 | 0.00.149 | -63.55 | <.0001* |
| *f* | 0.0019799 | 5.872e-5 | 33.72 | <.0001* |
| *α* × *α* | 0.0045447 | 0.000149 | 30.55 | <.0001* |
| *f* × *f* | -0.001205 | 0.000149 | -8.10 | <.0001* |
| *f* × *v* | 0.0001561 | 5.644e-5 | 2.77 | 0.0113* |

The statistical significance of the input parameters was assessed using the p-value (Prob>|t|), whereby parameters with values below 0.05 are considered statistically significant. The strength and direction of the influence of the individual factors, their squares and the two-factor interactions on tool flank wear are represented by positive and negative values of the estimate. Positive values for cutting speed (*v*), feed (*f*) and clearance angle × clearance angle (*α* × *α*) indicate that an increase in these factors leads to an increase in tool flank wear. Conversely, all other effects have a positive influence on flank wear, i.e. tool life.

Information on the quality of the regression model through the summary of the fit is shown in Table 4. The coefficient of determination (RSquare) is almost 1, which means that the model successfully explains the data and covers more than 99% of the variations in the output parameters. The small difference between RSquare and the adjusted RSquare (RSquare Adj) shows that the selected factors are relevant and that the model is not overfitted to the specifics of the data, achieving a good balance between accuracy and model complexity. The low value of the root mean square error (0.000304) indicates that the differences between the actual and predicted values are minimal, which confirms the high precision of the model's results.

**Table 5.** Summary of fit

| Parameter | Value |
|---|---|
| RSquare | 0.999946 |
| RSquare Adj | 0.999927 |
| Root Mean Square Error | 0.000304 |
| Mean of Response | 0.257344 |
| Observations (or Sum Wgts) | 32 |

The results of the analysis of variance for the selected regression model are shown in Table 5. The statistical significance of the effects of the model is confirmed by a p-value of less than 0.0001 (<0.0001), indicating the presence of at least one significant effect in the model. The high F Ratio value of 53038.87 indicates a strong influence of the input parameters on the variability of tool flank wear.

**Table 6.** Summary of fit

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 8 | 0.03925909 | 0.004907 | 53038.87 |
| Error | 23 | 0.00000213 | 9.252e-8 | **Prob > F** |
| C. Total | 31 | 0.03926122 | | <.0001* |

The adequacy of the model was assessed by analysing the studentized residual plot and the residual by predicted plot. Figure 3 shows the studentized residual plot, which illustrates the distribution of the studentized residuals in relation to the predicted values of the model. The even distribution of the points around the horizontal line at zero indicates a stable residual variance and the absence of bias in the model. Additionally, no points significantly deviate from the expected range, confirming that the model has no significant deviations and accurately describes the data.

Figure 4 shows the residual by predicted plot, which illustrates how the residuals are distributed relative to the predicted values of the model. The uniform distribution of points around the horizontal line at zero indicates the absence of systematic errors and a constant residual variance, confirming the validity of the model. The absence of patterns or clustering of points indicates that the model adequately describes the data, while the absence of significant deviations further ensures the reliability of the results.

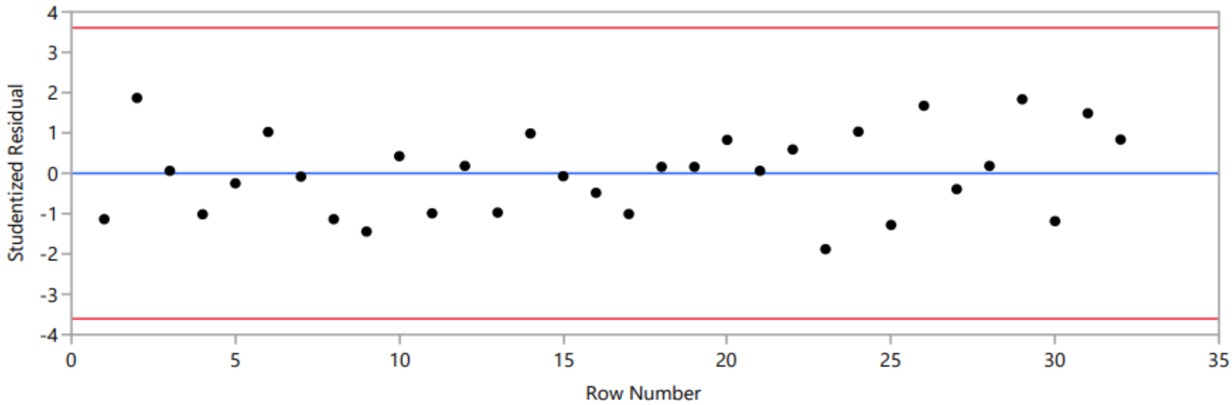


**Figure 3.** Studentized residual plot

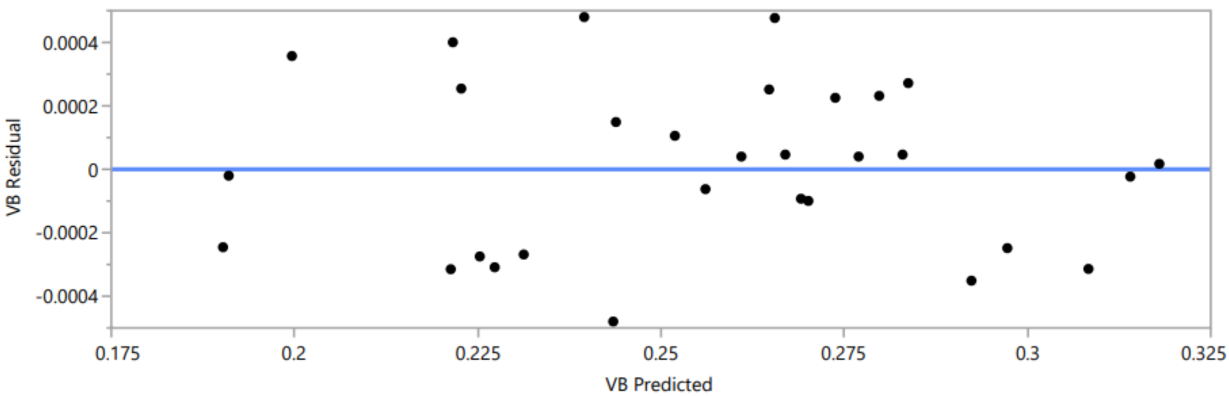


**Figure 4.** Residual by predicted plot

Based on the conducted statistical analysis of the selected model, the following regression equation was obtained, which describes flank wear:

$$VB = 0.148694919911261 + 0.12511563850501 \times f + 0.0290074718536083 \times r + 0.00465124468703994 \times v - 0.0199115286145089 \times \alpha - 0.483869971980812 \times f^2 - 0.0591229683122002 \times r^2 - 0.000261491873248801 \times v^2 + 0.00113508126751199 \times \alpha^2 + 0.000156094172959111 \times f \times v \quad (1)$$

### 3.3 Confirmation experiments

The obtained regression model was validated by conducting additional confirmation experiments to verify its accuracy and reliability. The confirmation of the regression model was carried out through 6 additional experiments for which the initial model generation was not performed. The results of the confirmation experiments, along with the calculated percentage errors indicating the level of agreement between the actual and predicted values, are shown in Table 7.

**Table 7.** Confirmation experiments

| No | *f* (mm/rev) | *α* (°) | *v* (m/min) | *r* (mm) | *VB* (mm) | | *Error* (%) |
|---|---|---|---|---|---|---|---|
| | | | | | Measured | Calculated | |
| 1 | 0.05 | 7 | 50 | 1.2 | 0.187 | 0.187 | 0 |
| 2 | 0.1 | 5 | 90 | 0.8 | 0.279 | 0.278 | 0.36 |
| 3 | 0.15 | 3 | 70 | 0.8 | 0.291 | 0.292 | 0.34 |
| 4 | 0.05 | 5 | 70 | 0.4 | 0.282 | 0.283 | 0.35 |
| 5 | 0.1 | 7 | 90 | 1.2 | 0.23 | 0.230 | 0 |
| 6 | 0.15 | 3 | 50 | 0.4 | 0.274 | 0.277 | 0.73 |

## 4. DISCUSSION

The results of the statistical analysis provided key insights into the flank wear mechanism during the turning of Co-Cr-Mo alloy. The analysis showed that the main factors - cutting speed, feed, cutting insert radius and flank angle, as well as their squares - are statistically significant. Additionally, the analysis revealed that the two-factor interaction between feed and cutting speed also has a statistically significant impact on flank wear. The main effects of cutting speed, radius and clearance angle showed the most pronounced influence on flank wear.

Increasing the cutting speed leads to an increase in tool flank wear. With higher cutting speeds, the temperature in the cutting zone rises, and the result of increased temperature is greater tool flank wear. Increasing the feed causes an increase in tool wear. Higher feeds result in increased cutting forces, which lead to greater flank wear. Reducing the tool tip radius increases flank wear. At smaller tool tip radii, the contact length between the cutting tool and the workpiece is reduced, and the heat generated is dispersed over a smaller surface area, contributing to greater tool wear. Increasing the flank angle reduces friction, and consequently, the abrasive wear on the cutting insert's flank surface.

The results of the statistical analysis also indicate a statistically significant effect of the interaction between feed and cutting speed on flank wear. At higher cutting speeds, an increase in feed has a more pronounced effect on flank wear than at lower cutting speeds. This effect is due to the combined impact of higher cutting forces at higher feeds and elevated temperatures resulting from high cutting speeds.

The results of the confirmation experiments, with percentage errors less than 1%, confirm the high accuracy of the developed regression model in predicting flank wear during the turning of Co-Cr-Mo alloy.

## 5. CONCLUSION

This paper presents a statistical analysis and modelling of flank wear using a custom design of experiments, which allows for the identification of the main input parameters affecting tool life. Based on the statistical analysis, a regression model was developed that allows the estimation of flank wear within a certain range of input parameters. The analysis of the results shows a significant functional dependence between cutting speed, feed, radius and clearance angle on flank wear.

The radius, cutting speed and flank angle have the strongest effects on flank wear, while the feed, the squared effects of cutting speed, radius, flank angle and feed as well as the two-factor interaction between feed and cutting speed have slightly smaller effects. The best tool life or the lowest flank wear is achieved at the lowest values of feed and cutting speed and the highest values of radius and flank angle. The results of the confirmation experiments show that the developed regression model allows an accurate and reliable estimation of flank wear based on the defined parameters under real conditions.

The limitation of this study lies in the limited range of input parameters analysed. The application of the developed regression model is only possible for the conditions under which the experimental investigations were carried out. Future research will focus on expanding the range of input parameters and increasing the number of input parameters to allow application under other conditions.

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