CUTTING TOOLS CONFERENCE 2024
RESEARCH, INNOVATIONS AND PRACTICAL APPLICATION

MM Science Journal | www.mmscience.eu
ISSN 1803-1269 (Print) | ISSN 1805-0476 (On-line)
Special Issue | CUTTING TOOLS 2024
1st International Conference on Cutting Tools
November 20-22, 2024, Trnava, Slovakia
DOI: 10.17973/MMSJ.2025_03_2025011

MM SCIENCE JOURNAL

CUTTINGTOOLS2024-00001

STATISTICAL EVALUATION OF CUTTING FORCE COMPONENTS AS A FUNCTION OF CUTTING EDGE RADIUS SIZE FOR MILLING OF AUSTENITIC STAINLESS STEEL AISI 316L

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Abstract

This study investigates the impact of cutting edge radius on cutting forces during machining of AISI 316L with uncoated cemented carbide tools. Four cutting edge radii were tested, each with three tools. Milling was conducted with different parameters for roughing and finishing. Cutting forces were measured and analyzed into tangential and radial components. Statistical evaluation using linear regression and analysis of variance assessed the influence of edge radius, machining conditions, and interactions. Results showed that both edge radius and machining conditions significantly affect cutting forces, providing insights for optimizing tool selection and improving tool life under various conditions.

Keywords:
Milling, Cutting forces, Cutting edge radius, Cemented carbide tools, Statistical analysis

1 INTRODUCTION

The influence of cutting tool microgeometry, specifically cutting edge radius, on machining performance has been widely recognized [Zhuang 2021, Denkena 2014], yet the statistical relationships between cutting edge geometry and the resulting cutting forces remain complex and not completely examined [Zyłka 2023, Wimmer 2023]. Cutting edge radius can affect cutting forces, tool life, and surface finish, with smaller radii often reducing cutting forces but potentially increasing tool wear, while larger radii can enhance tool stability but may lead to higher cutting forces [Denkena 2020]. Understanding these interactions is critical, especially when machining challenging materials like austenitic stainless steel AISI 316L, known for its work-hardening and high strength properties [Lv 2020].

While previous studies have investigated the effects of cutting edge radius on cutting forces, most of these studies have focused on qualitative observations or specific experimental conditions [Edem 2018, Padmakumar 2020]. There has been a lack of detailed quantitative analysis of how cutting edge radius interacts with machining parameters (e.g., cutting speed, feed rate, and depth of cut) and how these interactions influence the two primary components of cutting forces—tangential and radial forces. Some experimental work has been carried out for the turning [Aslan 2020, Yang 2019] but studies of cutting forces for milling are not commonly found. Moreover, statistical methods for determining the relative importance of these factors and their interactions have not been comprehensively applied across different cutting conditions, particularly in the context of uncoated cemented carbide tools and austenitic stainless steel.

The goal of the experiments described in the paper is to provide a more in-depth, data-driven understanding of how cutting edge geometry influences cutting forces components. The statistical insights derived from this study will contribute to the optimization of cutting tool microgeometry design improving machining performance, particularly when working with materials like AISI 316L.

2 MATERIALS AND METHODS

This study aims to apply statistical methods to quantify the effects of cutting edge radius on cutting forces during milling of AISI 316L. Four cutting edge radius sizes - 5, 15, 30, and 45 µm - were tested under two distinct machining conditions: roughing and finishing. The cutting forces generated during these operations were measured and analyzed, with particular focus on the tangential and radial components of cutting forces.

For each machining operation, three milling tools were tested, each set with four different cutting edge radius rounding size. Uncoated tools with macrogeometry design for milling stainless steel were manufactured to conduct long-term wear tests with the objective of examining modified edge microgeometry. Because it was necessary to obtain cutting tools with a sharp cutting edge, the mills had to be grinded from cemented carbide blanks before they could be processed by drag finishing. Tool parameters can be found in Tab. 1. The machine used for manufacturing the cutting tools for the experiment was 5-

axis tool grinder Reinecker WZS 60 and tool geometry was designed in Numrotoplus software.

Tab. 1: Tool parameters specification

Tool parameter	Value
Maximum depth of cut	20 mm
Cutting diameter	10 mm
Shank diameter	10 mm
Cutting edge count	4
Flute helix angle	48°
Main cutting edge setting angle	89°
Secondary cutting edge setting angle	4.15°
Corner chamfer length/radius size	0.125×45° mm

As a method for edge preparation, drag finishing process was used to achieve edge rounding and enhance surface quality after grinding. Due to its effectiveness and ease of use, drag finishing was selected as the preferred technique for preparing the tools in this experiment. This method offers advantages such as high repeatability and short processing time. By using different finishing media, various edge dimensions and surface finishes can be achieved. The OTEC DF-3 machine was used to modify the microgeometry, with SIX 70/16 granulate as the process medium. The process duration varied from 10 to 45 minutes, depending on the extent of the cutting edge rounding. The machine operator set the parameters for the drag finishing process, as outlined in Tab. 2. To attain the desired cutting edge radii and tool surface finish, two finishing media with different grain composition and size were employed.

Tab. 2: Drag finishing parameters

Parameter / Medium	QZ			HSC		
r_n[μm]	15	30	45	15	30	45
Tool holder [rev/min]	20	45	50	65	65	65
Rotor speed [rev/min]	20	30	50	40	40	40
Immersion depth [mm]	400					
Process time [min]	4	6	30	5	7.5	12
Rotation direction	Clockwise/Counterclockwise					
Tilt angle	0°					

Machined material for the experiments was austenitic stainless steel AISI 316L, mechanical properties of which are listed in Tab. 3.

Tab. 3: Mechanical properties of AISI 316L material

Property	Designation	Value
Yield strength	$R_{p\,0.2\%}$ [MPa]	268
Yield strength	$R_{p\,1.0\%}$ [MPa]	308
Tensile strength	R_m [MPa]	568
Elongation	A [%]	56.8

Long-term wear tests were conducted on a DMG DMU 85 5-axis machining center, with the tools clamped in a CoroChuck 930 hydraulic chuck. The experiments were designed to constitute a side milling operation, with tool paths created using the Autodesk PowerMill CAM software based on the specified parameters. The tool wear criterion was set to VB_k = 0.3 mm based on the dimensions of the flank face. The complete machining setup is shown in Fig. 1, and the final cutting conditions used in the experiments are detailed in Tab. 4.

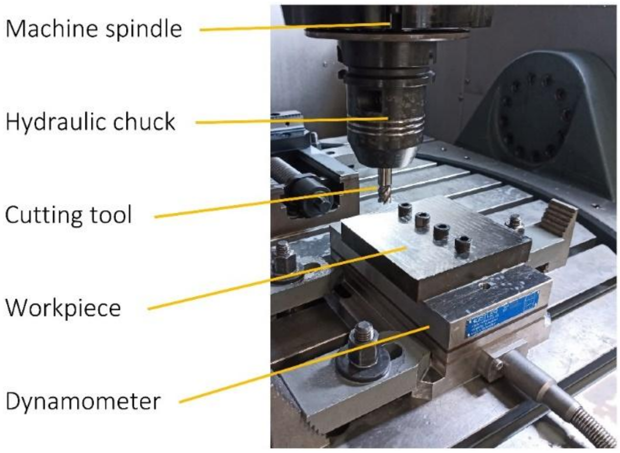

Fig. 1: Experimental setup

Tab. 4: Machining parameters of the experiment

Parameter/Operation	Roughing	Finishing
Axial depth of cut [mm]	3	3
Radial depth of cut [mm]	3	0,4
Feed per tooth [mm]	0,09	0,03
Cutting speed [m/min]	190	300

Austenitic stainless steels are considered difficult-to-cut materials due to low thermal conductivity, leading to poor heat dissipation from the cutting zone. Heat accumulates and increases load on the cutting edge. To prevent a hardened surface layer during machining, proper cooling is essential. Thus, a water-based coolant with 5% Blaser EcoCut MD25 was used as the cutting fluid in the experiments. Kistler 5070A workpiece dynamometer was used to measure cutting forces during the machining process. It was firmly attached to the machine tool table using clamps, and the workpiece was secured by four screws. Special care was taken to minimize the rotation of the dynamometer relative to the machine tool's coordinate system, ensuring that the axes of both coordinate systems remained parallel, as shown in Fig. 2.

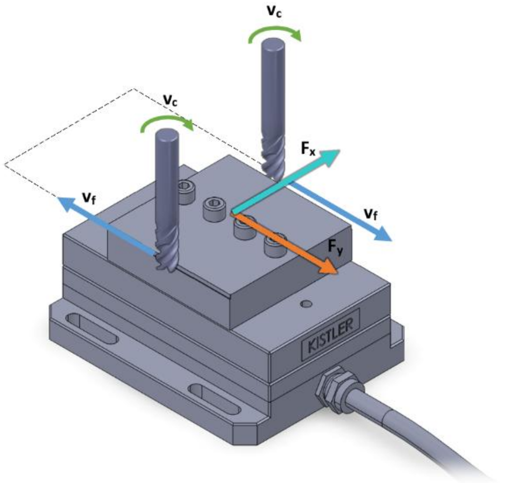

Fig. 2: Cutting force components measurement setup scheme

Cutting force data were recorded at the beginning of each toolpath for every machined segment of the workpiece. Data collection was managed using DynoWare software, which also facilitated preliminary data processing, including basic statistical analysis, due to its ability to handle large datasets. The processed values were then transferred to MS Excel.

To assess the significance of the cutting edge radius and other machining parameters, regression analysis and analysis of variance (ANOVA) were employed. These techniques enable an evaluation of the relative influence of cutting edge radius, machining conditions, and their interactions on the cutting force components. By using these statistical approaches, the study not only establishes the individual and combined effects of these factors but also quantifies their statistical significance, allowing for the identification of optimal cutting edge radii under varying operational conditions.

3 RESULTS AND DISCUSSION

Matlab R2024b software was used to further examine the acquired data and to carry out statistical evaluation. First, a two-way analysis of variance was calculated to observe the effect of the cutting edge rounding on the cutting forces. Mean values of measured cutting force were used for the analysis. Based on the results of ANOVA p-values of each cutting force component were plotted to determine the significance of influence of cutting edge rounding size (r_n) and machining operation (MO). Tab. 5 contains results of the ANOVA for the tangential cutting force component *Fx* at the beginning of the long term wear tests.

Tab. 5: Results for the initial *Fx* component of cutting forces

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
MO	262296.3	1	262296.3	6659.1	2.1E-22	4.5
r_n	24519.5	3	8173.2	207.5	5.1E-13	3.2
Interaction	8613.9	3	2871.3	72.9	1.5E-09	3.2
Within groups	630.2	16	39.4			
Total	296059.9	23				

The ANOVA results for the initial values of the tangential cutting force components indicate that machining operation, cutting edge rounding size, and their interaction all have a statistically significant effect at a significance level of 0.05. The machining operation factor shows a strong influence, meaning different machining operations lead to notable variations in the initial tangential cutting force. Cutting edge rounding size also has a meaningful impact, suggesting that changes in rounding size contribute to differences in the force component. Additionally, the interaction between these two factors is significant, indicating that the effect of one factor depends on the level of the other. This suggests that both individual factors and their interaction play a role in determining the initial values of the tangential cutting force components.

Tab. 6: Results for the final Fx component of cutting forces

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
MO	580291.8	1	580291.8	558.6	7.2E-14	4.5
r_n	49551.9	3	16517.3	15.9	4.7E-05	3.2
Interaction	11822.7	3	3940.9	3.8	0.1	3.2
Within groups	16621.9	16	1038.9			
Total	658288.3	23				

The results for the final values of the tangential cutting force components show that machining operation, cutting edge rounding size, and their interaction contribute to variations in the response variable, similar to initial cutting forces. At a significance level of 0.05, the machining operation factor has a statistically significant effect, indicating that different machining operations lead to noticeable differences in the final tangential cutting force. The cutting edge rounding size factor also influences the response, though to a lesser extent, as its *P-value* remains below the significance threshold. The interaction between machining operation and cutting edge rounding size, however, does not show statistical significance at $\alpha = 0.05$, suggesting that the combined effect of these two factors is not substantial in determining the final force values. These results imply that while machining operation and cutting edge rounding size individually affect the final tangential cutting force, their interaction does not play a major role in influencing the outcome.

Tab. 7: Results for the initial Fy component of cutting forces

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
MO	26798.8	1	26798.8	328.2	4.7E-12	4.5
r_n	119.3	3	39.8	0.5	0.7	3.2
Interaction	659.1	3	219.7	2.7	0.1	3.2
Within groups	1306.5	16	81.7			
Total	28883.7	23				

The results for the initial values of the radial cutting force components indicate that machining operation has a statistically significant effect at a significance level of 0.05, meaning different machining operations lead to clear variations in the initial radial force. The cutting edge rounding size factor, however, does not show a significant impact, as its *P-value* is well above the threshold, suggesting that changes in rounding size do not substantially influence the initial radial force. The interaction between machining operation and cutting edge rounding size also does not reach statistical significance, indicating that their combined effect is not strong enough to produce notable variations in the response. These results suggest that, for the initial radial cutting force component, machining operation is the primary influencing factor, while cutting edge rounding size and its interaction with machining operation do not play a significant role.

Tab. 8: Results for the final Fx component of cutting forces

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
MO	26366.9	1	26366.9	2403.8	7.2E-19	4.5
r_n	341.6	3	113.9	10.4	4,9E-4	3.2
Interaction	1383.1	3	461.0	42.0	8.2E-08	3.2
Within groups	175.5	16	11.0			
Total	28267.0	23				

The results of ANOVA for the final values of the radial cutting force components indicate that machining operation, cutting edge rounding size, and their interaction all have statistically significant effects at a significance level of 0.05. The machining operation factor has a strong influence, suggesting that different machining operations lead to noticeable variations in the final radial force. Cutting edge rounding size also shows a significant impact, meaning that changes in rounding size contribute to differences in the force component. Additionally, the interaction between these two factors is significant, indicating that the effect of one factor depends on the level of the other. These results suggest that both individual factors and their interaction play an important role in determining the final values of the radial cutting force component.

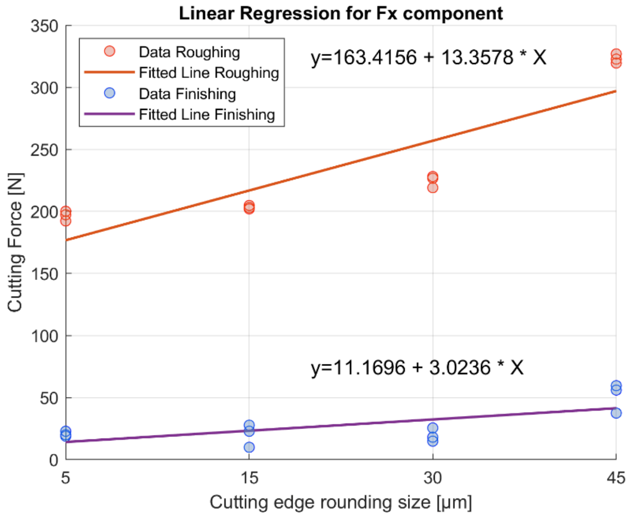

Fig. 3: Results of linear regression for Fx component of cutting forces

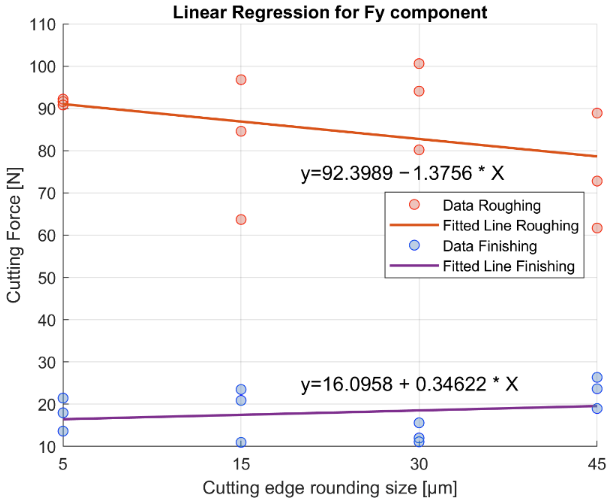

Fig. 4: Results of linear regression for Fy component of cutting forces

The Fig. 3 presents the results of a linear regression analysis for the tangential component *Fx* of cutting forces, with the measured data points plotted alongside the fitted regression lines. The figure compares the relationship between cutting edge radius size and the *Fx* component for two distinct machining operations: roughing and finishing.

For the roughing operation, the fitted line exhibits a much steeper slope, indicating a stronger positive correlation between cutting edge radius size and *Fx* component of cutting forces. The data points for this operation are consistently higher, suggesting that as the cutting edge radius size increases, the *Fx* cutting forces increase significantly. In contrast, for the finishing operation, the regression line is much less steep, indicating a weaker correlation, with the data points being generally lower. This suggests that the increase in *Fx* cutting forces with increasing cutting edge radius size is less pronounced in finishing compared to roughing.

The considerable difference between the roughing and finishing operations can be attributed to the distinct characteristics of these two machining operations. During roughing, the cutting process is generally more volatile, involving higher material removal rates, larger depths of cut, and greater tool engagement with the workpiece. As the cutting edge radius increases, the cutting forces tend to rise more substantially due to increased contact area, greater resistance to cutting, and higher friction. In contrast, the finishing operation is typically characterized by lower cutting speeds, lower material removal rates, resulting in reduced cutting force values. The influence of cutting edge radius size is impacting the finishing operation less significantly, as the process is more stable and the tool's microgeometry plays a smaller role in generating high cutting forces.

The linear regression model for the tangential cutting force component during roughing resulted in a Root Mean Squared Error (RMSE) of 26.5, indicating the average deviation between predicted and actual values. In comparison, the RMSE for the finishing phase is 12, which suggests that the model performs better for finishing, with predictions being closer to the actual values. The difference in RMSE values highlights that the roughing conidtions show more variability or complexity that the model does not fully capture, while the finishing operation appears to follow a more predictable pattern.

The Fig. 4 presents the results of a linear regression analysis for the radial component of cutting forces *Fy*, with measured data points plotted alongside the fitted regression lines. Similar to the previous figure, the relationship between cutting edge radius size and cutting forces is examined for both roughing and finishing operations.

For the finishing operation, the regression line shows a positive correlation between cutting edge radius size and cutting forces, consistent with the expected increase in cutting forces as the cutting edge radius grows. This suggests that as the cutting edge radius increases, the *Fy* component of the cutting forces also increases in a similar manner to the *Fx* component shown above.

In contrast, for the roughing operation, the regression line shows a descending character, indicating an inverse relationship between cutting edge radius size and cutting forces. The data points for roughing show a decrease in the *Fy* component as the cutting edge radius increases. This inverse correlation is unexpected compared to the positive correlation seen in the *Fx* component and the finishing operation.

The difference in the development of radial component Fy for roughing operation can be attributed to the specific dynamics of the cutting process during roughing. Unlike the *Fx* component, which primarily reflects resistance to cutting in the direction of material removal, the *Fy* component represents forces acting perpendicular to this direction, often influenced by factors such as tool vibration, deflection, and the interaction of the tool with the workpiece surface. During roughing, larger cutting edge radii may reduce the concentration of force in a small area, leading to a more distributed force across the cutting edge. This redistribution may reduce the *Fy* component, especially in demanding cutting operations, as larger radii may lead to reduced frictional forces in the perpendicular direction.

Additionally, the roughing operation typically involves higher depths of cut and greater tool engagement, which may alter the interaction between the tool and the workpiece in a way that results in a decrease in the *Fy* component. As the cutting edge radius increases, the cutting forces may become more evenly distributed, reducing the forces acting perpendicular to the cutting direction. The linear regression model for the radial cutting force component during roughing resulted in a Root Mean Squared Error (RMSE) of 12.3, indicating some deviation between the predicted and actual values. For the finishing phase, the RMSE was 5.43, suggesting that the model performs more accurately during finishing, with predictions being closer to the observed values. This difference in RMSE values suggests that the roughing opertation has more variability or complexity, while the finishing operation is more predictable and easier to model.

4 SUMMARY

This study presents a statistical evaluation of cutting force components during the machining of austenitic stainless steel AISI 316L using uncoated cemented carbide tools with varying cutting edge radii sizes. Two machining conditions, roughing and finishing, were analyzed, with long-term wear tests conducted across three tools per radius size for repeatability. Cutting force components, tangential force (*Fx*) and radial force (*Fy*), were examined using two-way ANOVA and linear regression in Matlab.

Two-way ANOVA revealed that cutting edge radius significantly influenced both initial and final cutting forces, especially at tool life's end. However, machining operation did not significantly affect initial cutting forces (*p-value* > 0.05), indicating other factors, such as material properties and tool geometry, are more influential at early wear stages. Linear regression showed that *Fx* increased with cutting edge radius size for both operations, due to larger tool-workpiece contact area, increasing friction and cutting resistance. In contrast, *Fy* decreased with larger radii in roughing operations, likely due to more even force distribution along the tool's edge and higher material removal rates.

The results of cutting forces analysis confirm the importance of cutting edge radius in shaping cutting forces, particularly as tool wear accumulates. It suggests that tool microgeometry should be carefully considered for machining austenitic stainless steel, influencing both tangential and radial force components. Different effects between roughing and finishing highlight the need for optimized tool design and process strategies in demanding cutting conditions like roughing.

In conclusion, this study provides insights into tool microgeometry's impact on cutting forces when machining AISI 316L material, emphasizing the importance of cutting edge radius on tangential forces and the unique radial force component behavior in roughing. Future work could explore the mechanisms causing observed results, expanding the analysis to other materials and tool geometries to further optimize machining performance and tool lifespan in various industrial applications.

5 ACKNOWLEDGMENTS

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-21-0071. This work was supported by the Science Grant Agency - project VEGA 1/0266/23.

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