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Impact of Surface Modification Techniques for Replaceable Cutting Inserts on Cutting Forces and Surface Finish in Machining Operations

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Abstract. This study investigates the impact of surface modification techniques, specifically microblasting and Magnetorheological Finishing (MRF), on the performance of uncoated sintered carbide replaceable cutting inserts (RCIs) during machining operations. The primary focus is on the relationship between surface roughness modifications and two key performance metrics: the quality of the workpiece surface finish and the cutting forces generated during turning operations. The study involved controlled experiments using RCIs that were untreated, sandblasted, or MRF-treated. Microblasting was found to increase surface roughness, leading to higher cutting forces and poorer workpiece surface quality. Conversely, MRF treatment reduced surface roughness, resulting in lower cutting forces and improved workpiece surface finishes.

1. Introduction

In the realm of precision machining, the quality of cutting tools significantly impacts manufacturing efficiency and outcomes. Among various factors, the quality of replaceable cutting inserts (RCIs) plays a pivotal role in determining both the quality of the workpiece and the dynamics of the cutting forces encountered during turning operations. Uncoated RCIs are extensively utilized across multiple industrial sectors due to their cost-effectiveness and versatility. However, as these tools undergo repeated use, their surface conditions deteriorate, leading to increased roughness that can adversely affect machining performance [1]. The degradation of surface quality in RCIs is a critical concern, as it influences friction, heat generation, and tool wear, all of which can degrade the surface finish of the workpiece and increase the cutting forces required [2, 3].

Observing the surface quality of RCIs in the turning process is crucial for several reasons. Research has shown that different types of cutting inserts, such as wiper inserts and cubic boron nitride (CBN) inserts, can significantly impact surface quality during turning operations [4, 5]. For instance, wiper inserts have been found to offer superior surface quality at higher feed rates compared to conventional inserts, although factors like process parameters and cutting tool geometry can influence the surface quality when using wiper inserts [4]. Similarly, CBN inserts have been noted for producing good surface quality and minimal flank wear when turning hardened steel [5]. Moreover, the choice of cutting parameters, such as insert radius, feed rate, and depth of cut, can play a vital role in determining surface roughness during turning operations [6, 7]. These studies have recommended using specific combinations of these parameters to achieve better surface roughness when using different types of inserts. Additionally, the type of coating on inserts, such as CVD or PVD coatings, can also impact surface roughness, with experiments showing varying effects on surface finish based on the coating method used [8, 9]. Furthermore, the optimization of cutting conditions, including cutting speed, depth of cut, and feed, is essential for achieving high-quality surface finishes during turning processes [10, 11]. Additionally, factors like tool geometry, cutting edge angles, and rake angles can influence tool wear and surface roughness during hard turning operations [12].

The quality and roughness of the rake face itself of cutting inserts significantly influence the turning process, needles to highlight low number of scientific contributions. Relevant research has shown that the rake face surface condition affects various machining aspects, such as cutting forces, tool-chip interface temperature, tool wear, surface roughness, and chip formation. For example, Yang et al. [13] demonstrated that micro-texture on the rake face of the tool improves milling behavior and surface quality. Additionally, Haddag et al. [14] found that grooved rake faces with chip breakers can decrease the tool-chip contact area and enhance chip fragmentation. Furthermore, Lotfi and Amini [15] compared cutting tools with different rake face and flank face structures, showing that the rake face structure influences cutting performance. Fatima investigated the effect of various rake face surfaces on tool crater wear, emphasizing the significance of rake face quality in tool performance.

Magnetorheological Finishing (MRF) is an advanced surface finishing process that utilizes magnetorheological fluids to achieve high-quality surface finishes without disturbing the polished surface topography [16]. This innovative technique offers several advantages, including good polishing effects, the absence of subsurface damage, and suitability for processing complex surfaces [17]. MRF is particularly valuable for achieving the surface precision of difficult-to-cut materials and can be used as a deterministic procedure for producing complex optics with high figure accuracy and low surface roughness [13, 18]. The application of MRF in surface finishing has been recognized as a method to achieve desired surface finish and shape accuracy without introducing surface or subsurface damage also by [19, 20]. This technique enables the production of ultra-smooth optical surfaces with surface accuracy on the order of 10 nm peak-to-valley and surface micro-roughness less than 10 Å [21]. MRF is known for its ability to provide extremely low finishing normal loads, facilitating the attainment of ultrasmooth surfaces on optics through a highly stable finishing tool [22]. Moreover, MRF has been utilized in various applications, such as improving surface quality and optimizing finishing force control in the machining of titanium alloys [23]. The technique has also been employed for deterministic polishing of optical components made of brittle materials, offering a promising solution for achieving high-quality surface finishes [24]. MRF has been used to polish optics with little to no surface or subsurface fractures, aiming to enhance their high fluence ultraviolet laser damage resistance [25]. Additionally, Yan [13] and Chen [26] proposed a magnetorheological finishing process for small concave surfaces, demonstrating the fabrication of optical surfaces with surface roughness below 1 nm and minimal surface damage. Chen [26] and Thiyagu [18] studied the machinability of Super Duplex Stainless Steel S32750 with MRF-assisted nano-finished cutting tool inserts to enhance tribological properties in the tool-chip contact zone [18, 15] investigated surface roughness tuning at sub-nanometer levels in MRF, highlighting the mechanisms for achieving ultra-smooth optical surfaces [15]. In summary, MRF is a versatile and effective technique for achieving high-precision surface finishes, particularly in the optics and materials processing industries, thus can be applied for RCIs in achieving high-precision surface finishes and improving tribological properties in the tool-chip contact zone.

On the other hand, microblasting is a surface treatment method that involves using compressed air to propel abrasive grits at high speed onto an object's surface. This process is known to alter surface properties by changing surface roughness, promoting the formation of a porous layer, and potentially decreasing corrosion resistance [27]. Microblasting has been recommended as a preferred surface treatment method for densely sintered oxide ceramics, with studies highlighting its effectiveness in improving bond strength and enhancing the surface properties of materials [28, 29]. The application of microblasting has been investigated in various fields, such as dental ceramics, where it is used to improve bond strength between framework and veneer materials [30]. Additionally, microblasting has been studied for its impact on the mechanical properties of materials, such as ASTM A516 grade 70, where it was found to influence mechanical properties [31]. Microblasting treatments, while known to enhance mechanical properties and improve surface quality, can also adversely affect surface characteristics by causing excessive roughness that leads to poor adhesion of subsequent coatings [32, 33]. Moreover, prolonged microblasting processes may compromise surface integrity and decrease coating adhesion strength, indicating a potential deterioration in surface quality [34]. However, it is important to note that while microblasting can alter surface roughness and promote bonding strength in certain applications, it may also introduce micro-cracks and potentially decrease the strength and longevity of materials like zirconia ceramics. In the context of RCIs treatment, while there is no specific reference directly addressing the use of microblasting for cutting inserts, the general understanding of microblasting's ability to modify surface properties, increase surface roughness, and improve bonding strength suggests that it could potentially be beneficial for treating cutting inserts.

This study aims to systematically examine the relationship between the surface roughness of uncoated sintered carbide RCIs and two key performance metrics: the quality of the workpiece surface finish and the cutting forces generated during turning operations. Specifically, this research will focus on the modification of the rake face of RCIs using MRF and microblasting techniques and compare the machining performance of these modified inserts against reference RCIs with unaltered surface conditions. By conducting controlled experiments and rigorous analyses, this research seeks to provide valuable insights that can inform tool maintenance practices and replacement strategies, ultimately enhancing machining efficiency and product quality in industrial applications.

2. Methodology

The RCIs used in this study were SNMA120416 TK0501, manufactured by SECO Tools. These uncoated sintered carbide inserts are known for their hardness and wear resistance, making them suitable for general machining operations of various materials, particularly K-type materials such as grey cast iron. The SNMA120416 TK0501 inserts have specific parameters that contribute to their performance. These inserts feature a corner radius of 1.60 mm, a cutting edge length of 12.70 mm, and an insert thickness of 4.76 mm. The insert shape code is S, indicating a square shape, and they possess an included angle of 90 degrees. Notably, these inserts are uncoated, which makes them an ideal candidate for studying the effects of surface modifications on machining performance.

Microblasting was used to deteriorate surface roughness, which can influence friction parameters and potentially machining performance. For this study, a standard industrial microblasting machine Sinterit Sandblaster was utilized, with aluminum oxide particles serving as the abrasive medium. The characteristics of the abrasive particles are as follows: the material used is corundum with a grit size of 180, a brown color, and an angular grain shape. The grain size ranged from 90 to 75 μm, with a hardness of 9 on the Mohs scale and a typical hardness of 2000 kg/mm² according to the Knoop hardness scale.

The microblasting machine operated at a pressure of 0.6 MPa, and the nozzle was maintained at a distance of 100 mm from the RCI surface to ensure uniform application. Handling the manual microblasting equipment presented certain challenges in achieving uniform roughness across all inserts. The varying degree of roughness on the inserts was compensated for by adjusting subsequent processes in the further integration stages. The choice of 180-grit corundum was appropriate as it provided an ideal balance between abrasion efficiency and protection of the insert surface. The final microblasting process was conducted with precision and care to achieve consistency in the final surface texture.

Initially, the inserts had an average roughness parameter (Ra) of approximately 0.35 μm. Through the manual microblasting process, this value was increased to a range of 1–1.4 μm. Despite the incomplete uniformity of roughness across the RCIs, the desired increase in roughness parameter Ra was achieved, preparing the inserts for the subsequent experimental machining. However, as previously noted, microblasting in such cases can lead to a deterioration of surface quality [32-34], in this case desired. The graph in figure 1 depicts the observed relationship between microblasting duration and relative surface quality, calculated as the ratio of the measured Ra value to the initial Ra-ref value of the RCI.

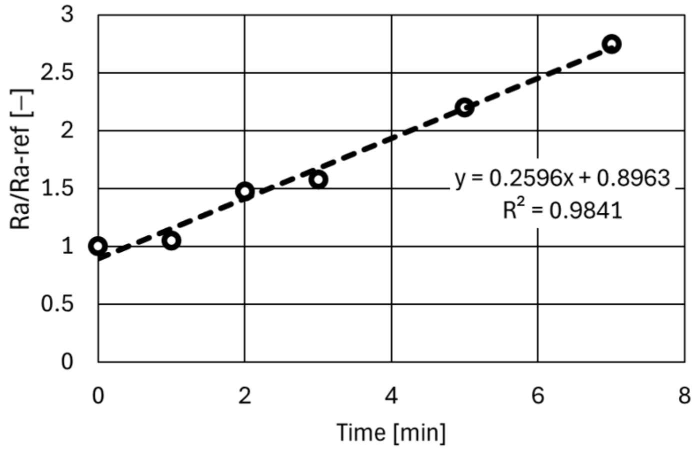

Figure 1. Relative roughness Ra as a function of time, illustrating the impact of microblasting.

Magnetorheological Finishing (MRF) was vice-versa used to improve surface quality of rake face of RCIs. The MRF equipment used in the figure 2 (left) can handle samples with a circular cross-section of 20 mm diameter or a square cross-section with a side length of 20 mm, with a maximum spindle speed of 3,000 rpm. The RCIs were fixed in a specially machined fixture within the MRF device, and a polishing mixture was applied. The mixture consisted of 6 % Al_2O_3 with a grit size of K 180, 36 % CICN magnetic particles, and WD-40 as the carrier fluid. The total weight of the mixture was 10 grams.

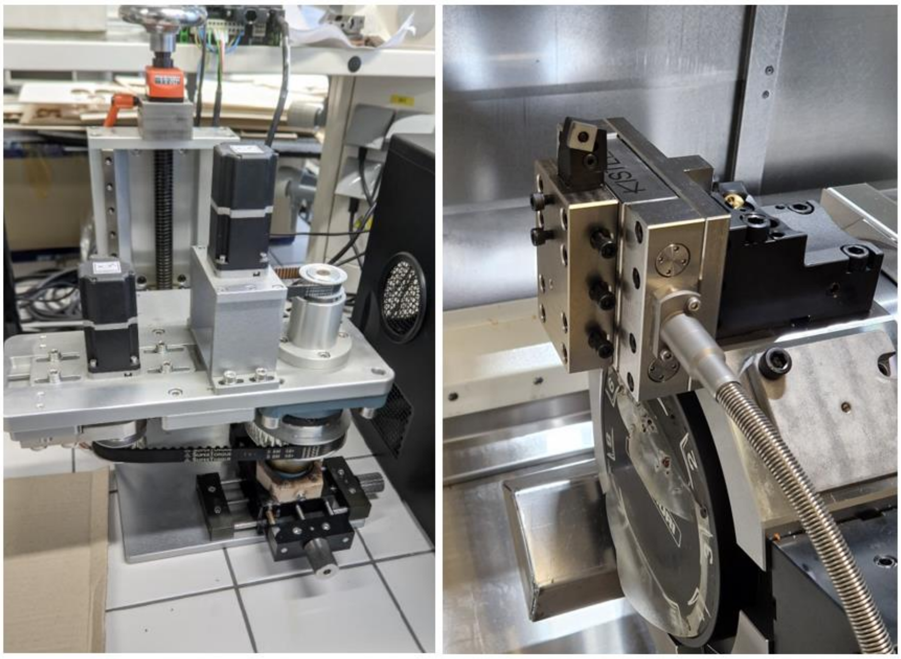

Figure 2. Magnetorheological Finishing (MRF) device setup used in the experiment (left), setup on the NTX 1000 machine tool for machining experiments (right).

The process conditions included a gap size of 1 mm, a rotational speed of 300 rpm, and a magnetic field intensity of 420 kA/m. These conditions provided an optimal environment for polishing. Initial average roughness of the inserts was 0.35 μm, which was reduced to 0.2 μm after 40 minutes of finishing as can be seen in relative roughness in figure 3. Measurements were conducted using a Mitutoyo Surftest SJ-410, and the results indicated a significant improvement in surface quality.

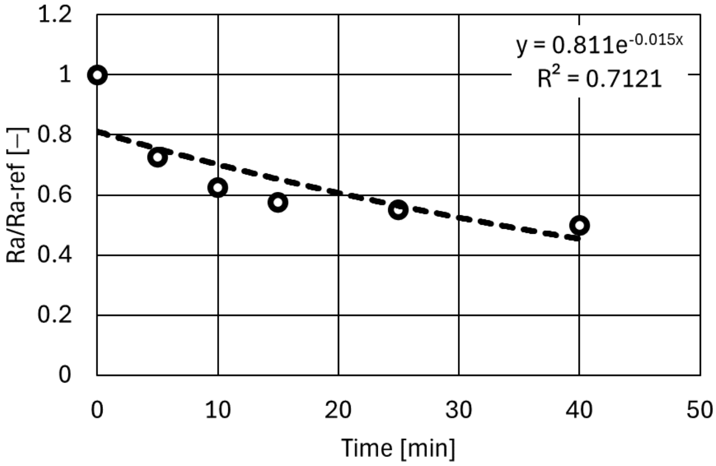

Figure 3. Relative roughness Ra as a function of time, illustrating the impact of MRF.

The turning experiments were conducted on an NTX 1000 turn-mill center by DMG Mori. Cutting forces were measured using a Kistler 9129AA dynamometer, which is known for its high accuracy and sensitivity. Surface roughness of the machined workpieces was measured using a Mitutoyo Surftest SJ-410, a portable roughness tester, that is capable of high-precision measurements, providing detailed surface roughness profiles. A test bar made of unalloyed structural steel (designation E335, 1.0060), with a diameter of 50 mm and a length of 500 mm, was clamped in the chuck of NTX 1000 for the machining experiments.

The machining experiments were conducted under specific conditions. The cutting speed was set to 250 m/min, feed rate was maintained at 0.5 mm/rev, and the depth of cut was held at 1 millimeter.

Each RCI, whether untreated, sandblasted, or MRF-treated, was securely mounted on the tool holder PSBNR2020K12 visible in the figure 2 (right) of the NTX 1000 turn-mill center. The workpiece material used was AISI 1045 steel, commonly in the form of hot-rolled steel bars.

The turning operations were performed under dry conditions to isolate the effects of surface roughness modifications without interference from cooling or lubricating fluids. Each experiment involved a single pass with the length of 50 mm of the cutting tool along the workpiece, repeated on each workpiece 6 times. During the turning operations, cutting forces were continuously recorded using the Kistler 9129AA dynamometer. The dynamometer captured real-time data on tangential, radial, and axial forces. After each machining pass, the surface roughness of the machined workpieces was measured using the Mitutoyo Surftest SJ-410. Multiple measurements were taken at different points along the machined surface to ensure consistency and accuracy in the data.

The data collected from the experiments were thoroughly analyzed to assess the impact of surface roughness modifications on the performance of uncoated RCIs (RCIs). Cutting force components, including cutting force *Fc*, feed force *Ff* and passive force *Fp*, were recorded using the Kistler 9129AA dynamometer and analyzed using Dynoware software between untreated, sandblasted, and MRF-treated inserts.

Surface roughness measurements were conducted using the Mitutoyo Surftest SJ-410 at multiple points along the machined surface to ensure consistency and accuracy. The average surface roughness (Ra) values were calculated and compared across different RCI treatments. Statistical analysis, including mean and standard deviation calculations, was performed to evaluate the significance of the differences observed in cutting forces and surface roughness. To ensure the reliability and validity of the experimental results, each measurement was repeated ten times. Any anomalies or outliers in the data were thoroughly investigated and addressed, ensuring the robustness and accuracy of the experimental conclusions.

3. Results and Discussion

3.1. Roughness Measurement

The following section presents the surface roughness analysis of the cutting inserts (RCIs), which were measured using the Zygo 8000 optical profilometer before and after testing, and measured by surface profilometer Mitutoyo Surftest SJ-410. The Zygo 8000 is a highly precise instrument that allows for detailed and accurate measurement of surface properties, capturing microscopic surface details and providing critical information about the geometry and quality of the RCIs.

Figure 4 captures the optical comparison of the RCIs before and after a series of cuts. It is important to note the scale on the right side of each image, which shows the height deviations in micrometers; the maximum values differ in each case, reflecting the variations in surface topography. The differences in material structure are evident, with the sandblasted RCI showing the most pronounced peaks, while the MRF-treated RCI exhibited the most stable structure. The initial roughness texture was measured using the Zygo 8000 profilometer near the tool tip. The Zygo instrument also provides the parameter Sa, which is the extension of Ra to a surface area. For the original RCI, the Sa value was 0.205 µm; for the microblasted RCI, it was 1.085 µm; and for the MRF-treated RCI, it was 0.162 µm. These quantitative measurements confirm the visual observations of surface roughness variations among the different RCIs.

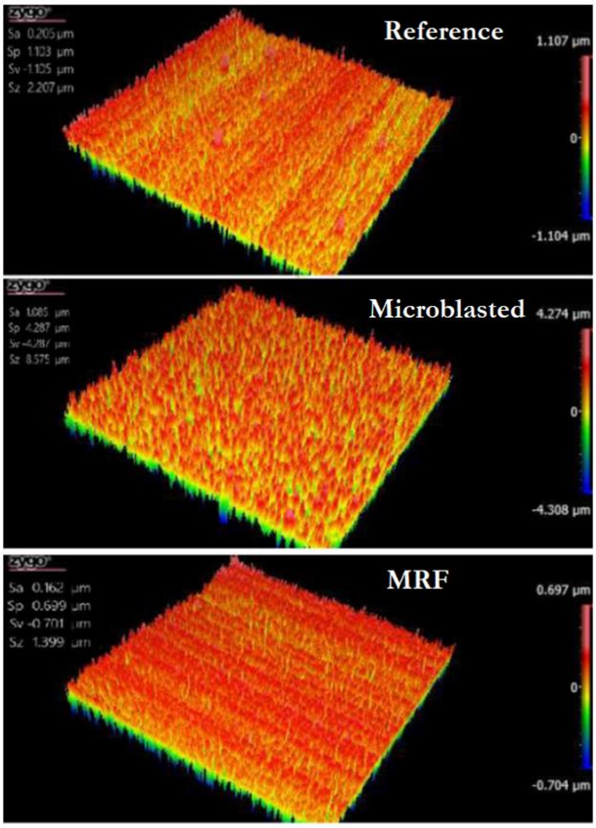

Figure 4. Surface roughness of the rake face of RCIs before machining.

After machining, significant wear was observed on the reference RCI, particularly on the tool's rake face, indicating mechanical wear. This wear can also be attributed to thermal stress at the cutting edge during the machining process, as can be observed in figure 5. In these cases, due to the accompanying effects during machining, the values of the Sa parameter changed: the reference RCI had a Sa value of 0.649 μm, the microblasted RCI had 2.162 μm, and the MRF-treated RCI had 0.308 μm. The increase in Sa is understandable as a result of the cutting process, with more pronounced increases observed in inserts that originally had low variability in height irregularities. The sandblasted RCI showed no significant damage to the rake face after machining. This can be attributed to the prior roughening of the insert by microblasting, which optimized material removal and minimized debris entrapment. The observed groove indicates the trajectory of the cutting tool and corresponds to mechanical wear of the insert. However, the wear rate was not alarming since the insert had been previously roughened by microblasting. Thermal stress marks on the insert surface suggest localized temperature increases during machining.For the MRF-treated RCI, a pronounced groove and signs of thermal stress were observed after machining. The groove indicates the chip movement direction and signifies wear on the insert. Thermal stress marks suggest a localized temperature increase during the machining.

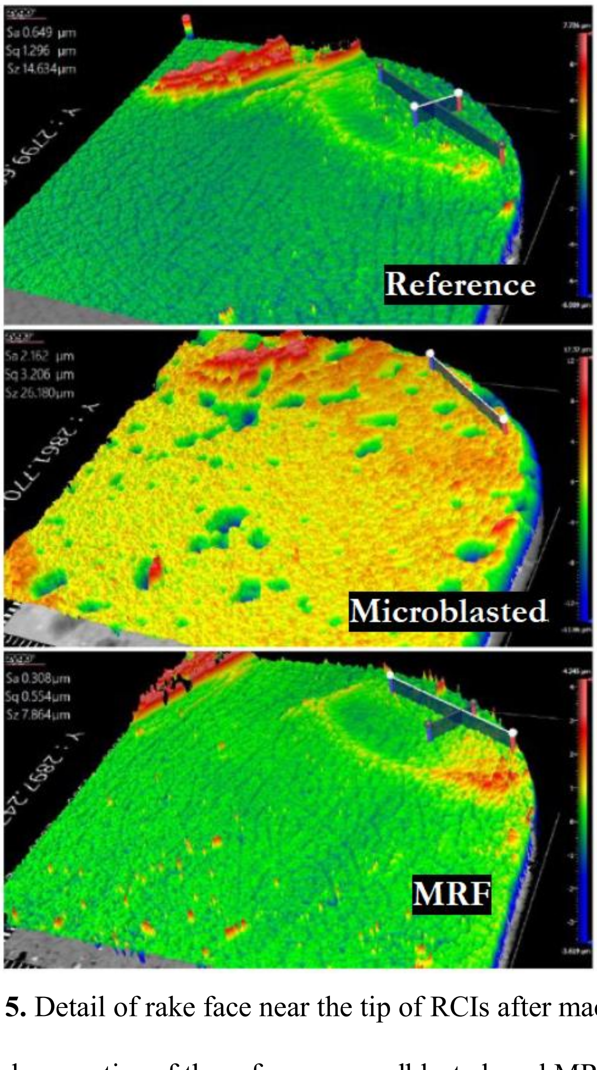

Figure 5. Detail of rake face near the tip of RCIs after machining.

The comparative optical properties of the reference, sandblasted, and MRF-treated RCIs reveal that the reference and MRF-treated inserts exhibited noticeable chip and crater formations during the separation process. An analysis of the surface roughness measured by Mitutoyo Surftest SJ-410 of the reference insert in the material removal area showed that the Ra value increased almost threefold compared to the sandblasted and MRF-treated inserts. The sandblasted and MRF-treated RCIs doubled their Ra value. The absence of pronounced grooves on the sandblasted RCI is likely due to the non-uniform chip removal. The experiment suggests the importance of a smooth surface on the reference RCI for smooth chip removal and minimal groove and crater formation. Sandblasted and reference RCIs likely lead to surface property modifications, resulting in roughening and poorer chip removal.

Figure 6 describes the progression of Ra on the workpiece after machining with inserts of varying roughness. Measurements were conducted using the Mitutoyo Surftest SJ-410. The analysis of the polynomial function for the reference RCI indicates a steeper wear tendency, suggesting a potentially shorter lifespan compared to the sandblasted and MRF-treated RCIs.

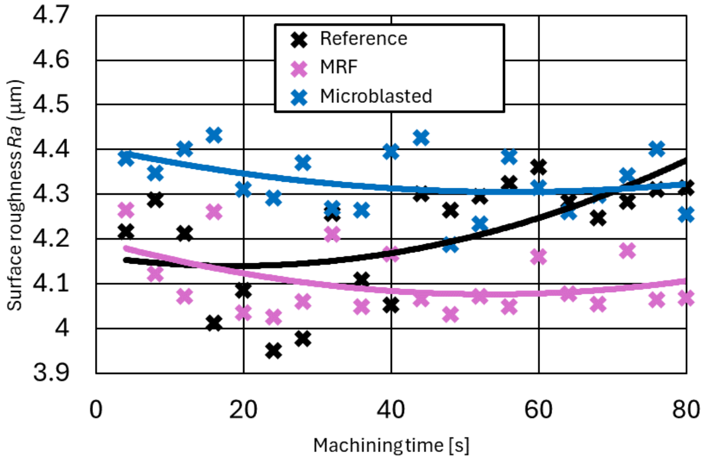

Figure 6. Workpiece surface roughness Ra after machining.

The impact of RCI roughness on the final workpiece roughness is overall to be: the MRF-treated RCI achieved the best results in terms of final roughness, while the sandblasted RCI had the worst effect on surface Ra value. This indicates that the roughness of the RCI plays a crucial role in achieving the desired workpiece roughness. For optimal results, the RCI should ideally have the lowest possible roughness. However, this optimum must be considered in the context of other factors, such as polishing time and overall RCI lifespan. Excessive polishing to achieve the lowest roughness might be costly in terms of polishing time.

3.2. Cutting Forces

This section presents the analysis of cutting forces measured during the machining tests of the RCIs. The cutting force data for the RCIs were visualized in DynoWare, recording 25,000 data points per second. For detailed evaluation, only the segments where the cutting insert was fully engaged with the workpiece were considered. The average values for each force component were calculated from this segment.

Figure 7 illustrate time dependent force component for machining with reference untreated RCI. The highest force measured was F_c, with relatively consistent characteristics across all axes, indicating stable measurements however indicating significant radial resistance. The average F_p values are shown over time, demonstrating stable characteristics throughout the test. F_f values were consistently lower than F_p and F_c.

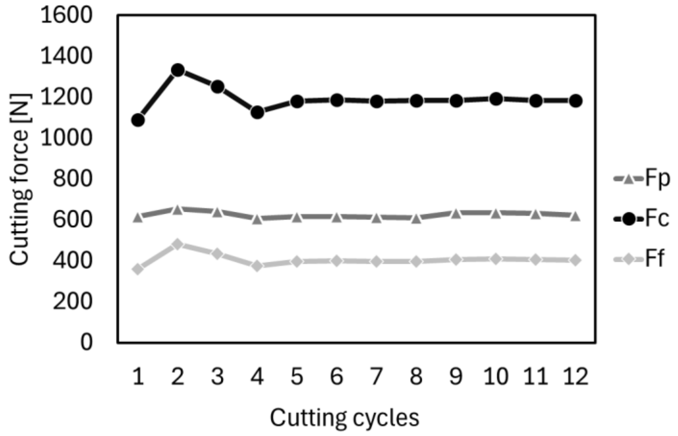

Figure 7. Time dependent force components of reference RCI.

For the sandblasted RCI, the cutting force components were measured and analyzed similarly to the reference RCI. The average *Fp* values over time showed an increase compared to the reference RCI. *Fc* remained the highest component, but showed a slight decrease compared to the reference RCI. *Ff* values also showed a reduction compared to the reference RCI.

Figure 8 shows the time-dependent force components for the sandblasted RCI. The data indicate that microblasting reduced the cutting forces slightly, but *Fc* remained the dominant force.

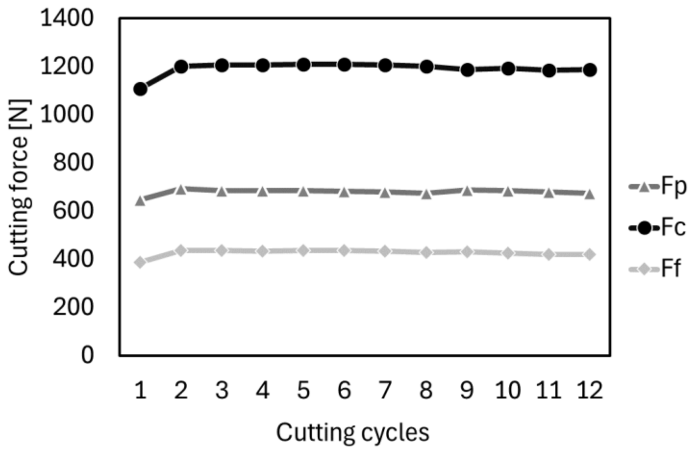

Figure 8. Time dependent force components of sandblasted RCI.

The MRF-treated RCI showed the lowest cutting forces among the tested inserts. *Fp* values were the lowest, indicating reduced tangential resistance. *Fc* values were significantly lower than both the reference and sandblasted RCIs. *Ff* values were also the lowest, reflecting the least axial resistance.

Figure 9 shows the time-dependent force components for the MRF-treated RCI, and figure 10 presents the average values with error bars. The data highlight that MRF treatment effectively reduced all components of the cutting forces, particularly *Fc*.

Comparing the cutting forces across different RCIs presented in figure 10: The highest *Fp* was observed in the sandblasted RCI. The difference in *Fp* between the reference and MRF-treated RCIs was minimal, with both showing similar values. The reference RCI exhibited a higher variance in *Fp*, as indicated by the standard deviation. Analysis showed that the MRF-treated RCI had the lowest *Fc*, implying the highest efficiency in cutting. *Fc* is the most critical component, influencing tool stress, machine power requirements, and overall machining efficiency.

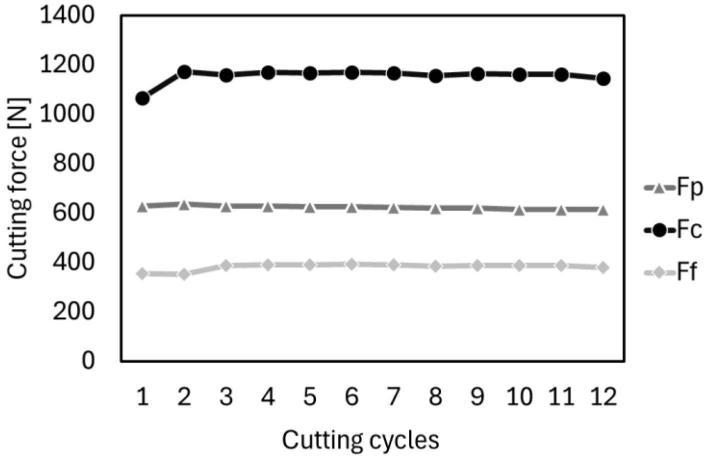

Figure 9. Time dependent force components of MRF treated RCI.

The MRF-treated RCI also had the lowest *Ff*, whereas the sandblasted RCI had the highest. Lower *Ff* values indicate less stress on the machine's feed mechanisms, allowing for simpler designs and reduced maintenance.

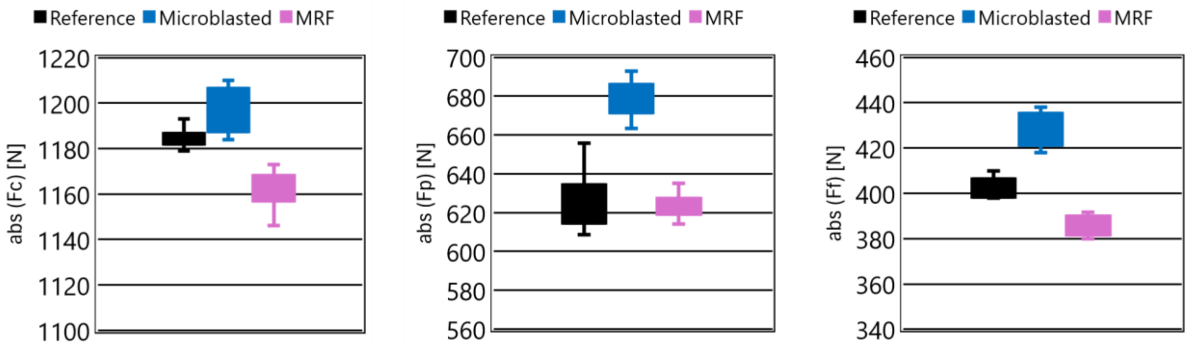

Figure 10. Analysis of cutting force components.

The analysis reveals that surface roughness significantly influences cutting forces during turning operations. RCIs with smoother surfaces, such as the MRF-treated RCI, generated the lowest forces, while the sandblasted RCI, with the highest roughness, produced the highest forces. These findings demonstrate a direct correlation between RCI roughness, and the forces experienced during machining. Smoother RCI surfaces reduce resistance, lowering the required cutting forces. Conversely, rougher surfaces increase friction and material deformation, leading to higher forces.

Optimizing the surface roughness of RCIs is crucial for efficient and energy-saving turning operations. Practically, selecting RCIs with appropriate roughness ensures the desired workpiece surface quality while minimizing cutting forces and mechanical loads.

4. Conclusion

The study focused on evaluating the effects of surface roughness modifications on the performance of uncoated RCIs during turning operations. Various surface treatments, including microblasting and MRF, were applied to the RCIs, and their impacts on cutting forces and surface roughness were analyzed. The following key conclusions were drawn from the experimental results:

- The study underscores the critical role of surface roughness in determining the performance of RCIs during turning operations.

- RCIs with smoother surfaces, such as those treated with MRF, generate lower cutting forces and produce better surface finishes on the workpiece.
- Optimizing the surface roughness of RCIs can lead to more efficient and energy-saving machining operations, reducing tool wear and extending tool life.
- Practically, selecting RCIs with appropriate surface treatments can enhance the overall quality of the machined product while minimizing mechanical loads and operational costs.
- The implementation of MRF-treated RCIs in industrial machining processes offers a practical solution for manufacturers aiming to improve machining efficiency, reduce energy consumption, and enhance product quality, thereby providing a competitive advantage in high-precision manufacturing sectors.

Future research could explore the long-term effects of these surface treatments on tool life and performance across different machining conditions and materials. Additionally, investigating the economic aspects of these treatments, including cost-benefit analyses and the scalability of surface modification techniques, could provide valuable insights for industrial applications such as those that require high-precision machining and superior surface finishes.

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