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Abrasive particle study on magnetorheological immersed tumbling for cutting edge preparation

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Abstract
Immersed tumbling is a well-established post-processing technique for cutting edge preparation of milling tools, ensuring uniform edge microgeometry and mitigating edge chipping and tool wear. Previously, we introduced magnetorheological fluids as lapping media for immersed tumbling, achieving controllable material removal rates influenced by the applied magnetic field. In this study, the effect of abrasive particle type on material removal rate and edge chipping of high-speed steel workpieces is systematically investigated. For this purpose, lapping media are prepared using polyalphaolefin oil as a carrier liquid, carbonyl iron powder as magnetic particles and various abrasive particles (FRD-A, FRD-G018, Al_2O_3 and tungsten carbide). A test bench, incorporating a magnetic excitation system surrounding and enforcing the lapping container by a magnetic field, is employed to evaluate the abrasive effect on square bar workpieces from high-speed steel. Key parameters, including the volume fractions of magnetic and abrasive particles, magnetic flux density, and the relative speed between the lapping medium and the workpiece, are held constant, referring to optimized parameter studies in previous work. A CNC milling machine is used to enable precise kinematic trajectories for the workpieces when driving through the lapping medium. Edge microgeometry, including edge radii and maximum edge chipping, is measured before and after testing using a focus variation microscope. These measurements, coupled with optical microscopy observations of the workpiece edges, enable evaluation of surface quality and material removal rates for each abrasive particle type. Additionally, the interactions between abrasive particles and the magnetizable carrier medium under magnetic excitation and translational motion is examined. The results indicate a significant influence of abrasive particle type on the material removal rates, underscoring the crucial role of abrasive selection for the optimization of the magnetorheological immersed tumbling process.

Immersed tumbling, abrasive magnetorheological fluids, cutting edge preparation, milling tools

1. Introduction

Surface defects and grain chipping often occur on the primary and secondary cutting edges of milling tools during manufacturing [1, 2]. Post-processing methods for cutting-edge preparation such as brushing, blasting, electrochemical machining, laser ablation, immersed tumbling, and magnetic finishing are therefore established to reduce tool wear and to ensure reliable machining, as depicted in **Figure 1** [3, 4].

Among these methods, immersed tumbling is widely adopted due to its straightforward equipment design and high machining efficiency [2]. Adressing the challenge of uniform lapping media flow and large processing times in immersed tumbling, we previously introduced magnetorheological fluids (MRF) as lapping media for immersed tumbling, achieving controllable material removal rates influenced by the applied magnetic field [5, 6, 7]. In **Figure 2**, the fundamental concept of the MRF immersed tumbling process is depicted. In this process, a lapping medium, consisting of magnetizable carbonyl-iron particles, abrasive particles (AP) and a carrier liquid is introduced into an MRF container. Upon applying a magnetic field, the carbonyl-iron particles (CIP) become magnetized and align along the magnetic flux lines, forming solid-state bridges that significantly increase the overall viscosity of the fluid. Workpieces moved through the container along defined trajectories experience a grinding effect due to the AP held within or inbetween the solid-state bridges.

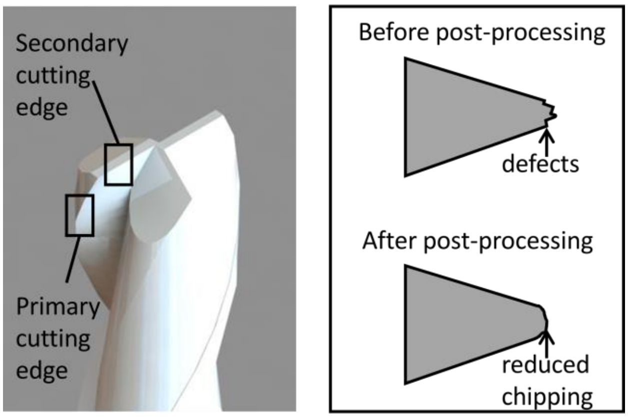

Figure 1. Typical micro-milling tool geometry and schematic diagram of cutting edge preparation [6]

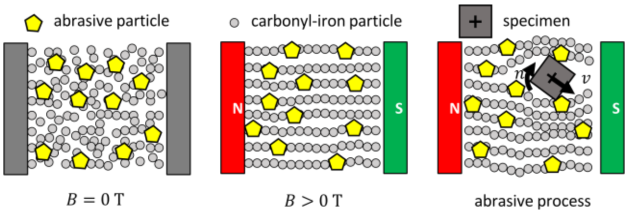

Figure 2. Scheme of the MRF immersed tumbling process [7]

Previous work on MRF immersed tumbling processes primarily focused on studying abrasive and rheological properties of MRF, including variations in the composition of the abrasive MRF as lapping medium and in the abrasive particle sizes [5, 6, 7]. For general polishing applications using abrasive MRF, the influence of particle size variations on surface quality and rheological behavior has been investigated in [8]. Additionally, studies have utilized abrasives such as diamond or Al_2O_3 for MRF-based finishing applications [9]. However, no systematic investigation has been conducted addressing the effect of varying AP types under identical experimental conditions.

This study aims to systematically examine the influence of AP type on the material removal rate, edge chipping, and surface roughness of high-speed steel (HSS) workpieces during MRF immersed tumbling. The investigated abrasive particles include diamond particles FRD-A and FRD-G018, aluminium oxide Al_2O_3 and tungsten carbide WC-Co. To isolate the effect of abrasive particle type, other experimental parameters, including the volume fractions of magnetic and abrasive particles, magnetic flux density and the relative speed between the lapping medium and the workpiece, are held constant, based on optimized parameter studies from previous research [5, 6].

Using the test bench for MRF immersed tumbling introduced in [5], the abrasive effect of the selected particles on square bar workpieces from high-speed steel (HSS) is investigated. The edge radii, maximum edge chipping, and surface roughness of each workpiece are evaluated before and after testing to provide a comprehensive analysis of the influence of AP type on cutting-edge preparation outcomes.

2. Materials and methods

2.1. Abrasive MRF preparation

Four distinct abrasive MRF compositions are prepared by varying the AP types. **Figure 3** illustrates the geometry of the utilized abrasives. Common non-magnetizable abrasives, such as monocrystalline diamond particles FRD-A and polycrystalline diamond particles FRD-G018, are utilized with diameters of $d_{\mathrm{FRD-A}} = d_{\mathrm{FRD-G018}} \approx 252\ \mu\mathrm{m}$. Additionally, aluminium oxide Al_2O_3-type abrasives, which are widely used, were employed with a larger diameter of $d_{\mathrm{Al2O3}} \approx 500\ \mu\mathrm{m}$. Finally, tungsten carbide WC-Co is investigated as a magnetizable abrasive with a comparatively small diameter of $d_{\mathrm{WC-Co}} \approx 20\ \mu\mathrm{m}$.

Carbonyl-iron particles CIP of type BASF CEP-OF with a diameter of $d_{\mathrm{cip}} \approx 6.6\ \mu\mathrm{m}$ are utilized in the composition. Further components as carrier liquid and additives are selected according to the MRF composition described in [6].

The volume fraction of CIP and AP is maintained constant at $\varphi_{\mathrm{cip}} = 45\%$ and $\varphi_{\mathrm{ap}} = 15\%$ respectively, based on the optimized abrasive MRF composition outlined in [5, 6].

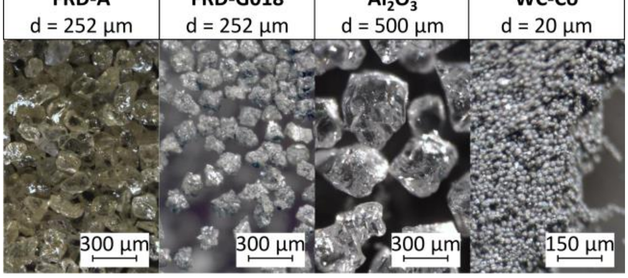

Figure 3. Abrasive particles FRD-A, FRD-G018, Al_2O_3 and WC-Co

2.2. Macroscopic particle interactions in abrasive MRF

In **Figure 4**, the interactions of AP and MRF under magnetic excitation are illustrated. For that, a typical Couette flow in a shear gap is observed using an Olympus SZX12 optical microscope. The magnetic excitation, applied perpendicular to the flow, is generated using permanent magnets.

The diagrams in **Figure 4** show the progression of the shear gap under different conditions. In the left diagram, the shear gap is depicted in its initial state. In the middle diagram, the moving boundary plate is shifted after time t_1 by Δx_1. In the right diagram, the critical shear strain is reached after t_2 at Δx_2, causing the solid-state bridges to break and form new chain structures. These obeservations aling with findings reported in [10].

The diagrams reveal the highly macroscopic nature of the solid-state bridges. Instead of forming single chains, macroscopic bands approximately $100\ \mu\mathrm{m}$ in width are observed. Furthermore, it is evident that abrasive particles are predominantly located between these macroscopic solid-state bridges rather than embedded within them, as previously anticipated. This phenomenon is likely attributable to the significant disparity in diameter between CIP and AP.

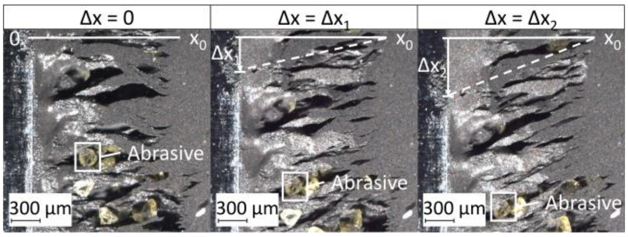

Figure 4. Interactions between abrasive particles and magnetizable MRF under magnetic excitation and translational motion

2.3. Experimental setup for MRF immersed tumbling

The abrasive experiments are conducted using an MRF immersed tumbling test bench, as described in [5]. **Figure 5** provides an illustration of the test bench. During each experiment, the selected abrasive MRF is introduced into the MRF container, serving as the lapping medium. The test bench was interfaced with a PFM 24 MediMill CNC milling machine from PRIMACON GMBH, Peissenberg, Germany, with the HSS specimen securely mounted in the tool holder.

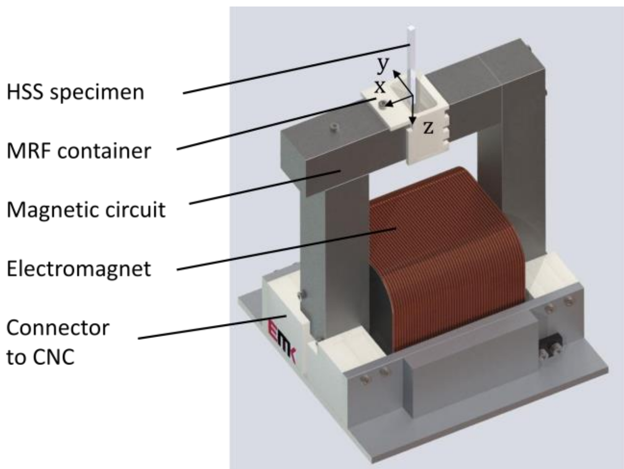

Figure 5. CAD of test bench established in [5]

When activating the power supply of the electromagnet a constant magnetic flux density of approximately $B = 0.3\ \mathrm{T}$ is generated within the MRF container. The HSS specimen is then subjected to a rotational motion at a speed of $n = 10{,}000\ \mathrm{U}/min$ and is simultaneously translated along a circular path with a diameter $d_{\mathrm{CNC}} = 10\ \mathrm{mm}$. This translational motion is performed at a feed rate of $v_{\mathrm{f}} = 5\ \mathrm{mm/s}$. Each experiment has a duration of $30\ \mathrm{min}$.

2.4. Design of experiment

This study aims to investigate the impact of varying abrasive particle types on the microgeometry of high-speed steel (HSS) specimens, while keeping all other experimental conditions constant. To achieve this, the edge and surface microgeometry of HSS square bar workpieces is determined before and after each individual experiment. The edge radius r_β and maximum edge chipping $R_{\mathrm{s,max}}$ is measured using the infiniteFocus G4 focus variation microscope from Alicona Imaging GmbH, Graz, Austria. The arithmetic mean and average surface roughness R_{a} and R_{z} are determined using the nanoscan 855 opto-mechanical measuring system from Jenoptik AG, Jena, Germany.

The overall material removal rate Q in each experiment can be calculated from the edge radii before and after the abrasive test $r_{\beta 1}$ and $r_{\beta 2}$ using the relationship

$$Q = \frac{4 \cdot \Delta A \cdot h_{\mathrm{CNC}}}{t}, \qquad (1)$$

where t is the processing time, h_{CNC} is the immersion depth, and ΔA is the change in the cross-sectional area of the edge, expressed as

$$\Delta A = {r_{\beta 2}}^2 \left(1 - \frac{\pi}{4}\right) - {r_{\beta 1}}^2 \left(1 - \frac{\pi}{4}\right). \qquad (2)$$

The change in maximum edge chipping is determined as $\Delta R_{\mathrm{Smax}} = R_{\mathrm{Smax2}} - R_{\mathrm{Smax1}}$. Similarly, the changes in arithmetic mean roughness ΔR_{a} and average surface roughness ΔR_{z} are calculated as $\Delta R_{\mathrm{a}} = R_{\mathrm{a2}} - R_{\mathrm{a1}}$ and $\Delta R_{\mathrm{z}} = R_{\mathrm{z2}} - R_{\mathrm{z1}}$. These parameters provide a comprehensive assessment of the effect of abrasive particle type on the material removal and surface quality of HSS specimens

3. Results

In order to evaluate the effect of various abrasive particles on the microgeometry of HSS specimens, a series of experiments was conducted using the MRF immersed tumbling test bench. Four distinct abrasive MRF compositions were prepared, incorporating FRD-A, FRD-G018, Al_2O_3 and WC-Co abrasive particles. To account for statistical variability, the experiments were repeated, and for each abrasive particle type, six distinct edges were analyzed to assess maximum edge chipping R_{Smax} and edge radii r_β. Additionally, four distinct lateral surfaces were examined to evaluate the arithmetic mean roughness R_{a} and average surface roughness R_{z}.

Qualitative analysis, illustrated in **Figure 6**, highlights the edge microgeometry for each abrasive particle type before and after the abrasive tests. Consistent with previous studies [5, 6], monocrystalline diamond particles FRD-A yield relatively large and uniform edge rounding. Polycrystalline diamond particles FRD-G018 produce even more pronounced edge rounding. In contrast, Al_2O_3 particles exhibit uneven edge rounding, while WC-Co abrasives have a limited effect on edge rounding but achieve smooth edge chipping.

These qualitative observations agree with quantitative analysis of edge geometry and surface roughness. In **Figure 7**, the mean and standart deviation for Material removal rate Q, change in maximum edge chipping ΔR_{Smax}, arithmetic mean roughness ΔR_{a} and average surface roughness ΔR_{z} are depicted corresponding to abrasive particle type.

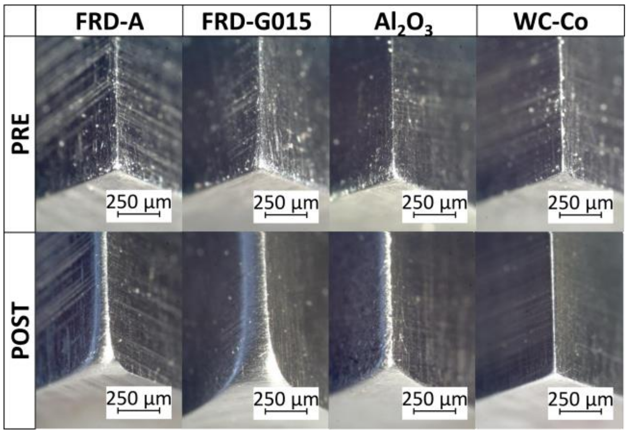

Figure 6. Edges of HSS-specimens before (PRE) and after (POST) abrasive tests using varying abrasives (FRD-A, FRD-G018, Al_2O_3 and WC-Co)

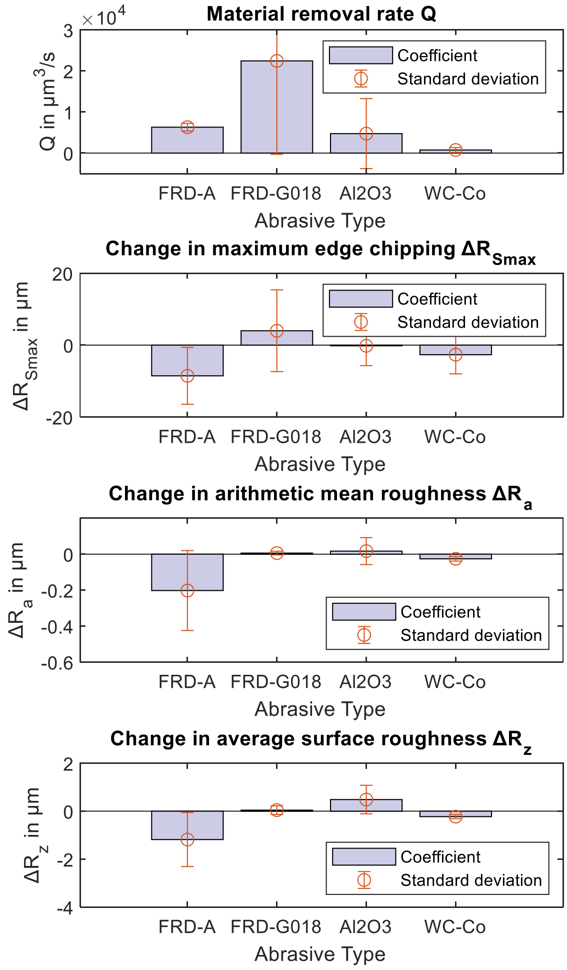

Figure 7. Material removal rate Q, change in maximum edge chipping ΔR_{Smax} , arithmetic mean roughness ΔR_{a} and average surface roughness ΔR_{z} corresponding to abrasive particle type (FRD-A, FRD-G018, Al_2O_3 and WC-Co)

The results show that polycrystalline diamond particles FRD-G018 achieve the highest material removal rate Q during MRF immersed tumbling, followed by monocrystalline diamond particles FRD-A and Al_2O_3. WC-Co abrasives, however, demonstrate negligible material removal rates Q. Regarding the change in maximum edge chipping ΔR_{Smax}, arithmetic mean roughness ΔR_{a}, and average surface roughness ΔR_{z}, monocrystalline diamond particles FRD-A significantly enhance surface quality, followed by WC-Co abrasives. Conversely, the use of Al_2O_3 particles result in diminished surface quality, while FRD-G018 particles increased edge chipping.

In summary, FRD-A particles exhibit a favorable balance between moderate material removal rates and superior surface smoothing capabilities, making them the optimal choice among the tested abrasives.

4. Conclusion and outlook

This study systematically investigates the impact of various abrasive particles on material removal rates and surface smoothing performance in the context of cutting-edge preparation using magnetorheological fluids. Abrasive tests were conducted on high-speed steel square bar specimens using an established MRF immersed tumbling test bench. The types of abrasive particles examined included monocrystalline diamond (FRD-A), polycrystalline diamond (FRD-G018), aluminum oxide (Al_2O_3), and tungsten carbide (WC-Co), while key process parameters—such as the volume fraction of lapping medium components and magnetic flux density—were kept constant throughout the study.

This research emphasizes the decisive role of abrasive particle type in determining the efficiency and effectiveness of MRF-based immersed tumbling processes. The primary findings of this investigation are as follows:

- Monocrystalline diamond particles FRD-A exhibit a well-balanced performance, combining moderate material removal rates with superior surface smoothing properties.
- Polycrystalline diamond particles FRD-G018 deliver the highest material removal rates but are associated with significant edge chipping.
- Aluminum oxide Al_2O_3 particles achieve satisfactory material removal rates but are limited in their ability to enhance surface smoothness.
- Tungsten carbide WC-Co particles demonstrate relatively low material removal rates but are effective in surface smoothing and reducing edge chipping.
- Larger abrasive particles are predominantly positioned between the macroscopic solid-state bridges formed by carbonyl-iron particles under magnetic excitation. This behavior differs notably from MRFs containing abrasives with particle sizes comparable to those of the carbonyl-iron particles.

These findings emphasize the role of abrasive particle selection in optimizing cutting-edge preparation via MRF technology. Future research should explore the interplay of abrasive particle size and magnetic field parameters to further enhance process efficiency. Additionally, the findings on the post-processing of HSS square bar workpieces will be extended to the post-processing of RSE230-type double-edged end mills.

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