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Posted Date: October 20th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11149076/v1>

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Additional Declarations: No competing interests reported.

Improvement of Biopsy Needle Inner Surface Quality Using Magnetic Abrasive Jet Machining: A CFD-Supported Experimental Study

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Abstract

In aspiration biopsy procedures, resistance caused by the needle inner surface roughness negatively affects the collection of adequate tissue samples. In this study, in order to solve the problem in question, a unique system was designed and manufactured to polish the inner surface of G14 biopsy needles using the Magnetic Abrasive Jet Machining (MAJM) method. The developed system; It consists of abrasive powder transportation with compressed air, adjustable spindle and neodymium magnet components that move back and forth along the axis. The effects of input speed (50, 75 and 100 m/s) and needle rotation speed (300, 500 and 700 rpm) parameters on surface machining performance were examined within the framework of a 3×3 full factorial experimental design using an abrasive mixture consisting of Al₂O₃, SiC and Fe powders. Numerical analyzes were performed in the ANSYS Fluent environment. The erosion model was carried out using the k- ω SST turbulence model and the Discrete Phase Model (DPM). Erosion rate distributions and particle-wall interaction parameters obtained from CFD simulations were evaluated comparatively with SEM surface images and EDS elemental analyses. Frangi filter-based image processing analysis of SEM images allowed the numerical determination of tangential and radial impact indices. The results show that the inflow velocity is the dominant parameter on the erosion rate; In the transition from 50 m/s to 100 m/s, the SEM region reveals that the average erosion speed increases approximately 5.6 times. When the effect of rotation speed is examined, it is seen that the 500 rpm condition produces the highest tangential scratch density in all speed groups and represents the optimum speed level in terms of homogeneous surface processing. This study presents a novel methodology that combines CFD and SEM image processing, demonstrating the feasibility of the MAJM method in processing the biopsy needles inner surface with numerical and experimental evidence.

Keywords: Magnetic abrasive jet processing, biopsy needle, inner surface polishing, CFD.

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1. Introduction

The surface roughness and quality of biopsy needles are of great importance in terms of tissue quality, diagnostic accuracy, and procedural efficiency, especially in delicate applications such as fine needle aspiration biopsy (FNAB). When the surface roughness of the needle increases, it can become difficult for the tissue sample to move freely within the needle and be collected without damage. A smooth and high-quality inner surface allows cells and tissue fragments to be transported within the needle with minimal damage and less compression. This increases the number and integrity of cells in the prepared slides, thus improving the probability of diagnosis. For example, during aspiration biopsy, good needle surface quality helps in the efficient collection of cellular material and obtaining a sufficient quantity and quality of sample for pathological examination [1]. The inner surface quality also reduces friction that may occur in the needle during the aspiration process. This can both increase the patient's comfort during the procedure and, for example, make the needle less damaged, making it more suitable for laboratory analyses. On the other hand, studies exist on the fact that the needle surface should not be excessively smooth, as well as the effect of tip sharpness and surface treatments (e.g., sandblasting) on the cutting and tissue harvesting capacity of the needle. However, some randomized controlled trials have shown no significant difference in results regarding whether excessive roughness leads to pain or tissue damage, meaning the choice may depend on parameters such as clinical preference, ease of procedure, and cost [2]. In summary, the surface roughness and overall quality of biopsy needles offer critical advantages in aspiration biopsy procedures, including: collecting cell and tissue samples without damage, increasing the quantity and quality of samples, improving diagnostic accuracy, and ensuring patient comfort during the procedure. Therefore, optimal surface quality and smoothness of needles used in aspiration biopsy are crucial for early and accurate diagnosis; continuous research is being conducted to improve techniques and materials in this regard. Magnetic etching and air jet etching methods have some significant drawbacks when used individually; therefore, combining these two methods offers significant advantages. Magnetic abrasion is based on the principle of a magnetic field directing abrasive particles with magnetic properties and performing controlled abrasion on the workpiece surface. However, this method has limitations in material, limited accuracy and homogeneity, and process efficiency. For the process to be effective, the workpiece or abrasives must have magnetic properties; therefore, its effectiveness decreases in non-magnetic materials. On the other hand, due to the difficulties in the distribution and control of the magnetic field, the abrasive surface may not be homogeneous; this can reduce surface quality. Magnetic abrasion alone may have difficulty achieving high material removal

rates, especially in solid or hard materials. Air jet abrasion allows abrasive particles entrained by a high-speed air stream to remove material from the workpiece. This method also has limitations in insufficient cutting power, cutting quality problems, and energy efficiency. Magnetic-assisted air jet abrasion opens new horizons, especially in the machining of hard and delicate materials, by improving material removal performance, surface quality, and process efficiency. Furthermore, thanks to parameter optimization and mathematical modeling capabilities, this technology is preferred in advanced manufacturing applications requiring high precision and productivity [3–6].

The combined use of magnetic abrasion and air jet abrasion processes offers an effective and innovative solution for improving the surface quality of hard-to-reach areas such as narrow sections. Thanks to the magnetic field, abrasive particles are directed more controllably and intensely, reducing surface roughness and increasing material removal rate. This leads to increased production efficiency and significantly improved product quality in industrial applications [6–8].

Valens et al [9] investigated the effects of magnetic abrasive finishing (MAF) process parameters on the surface roughness of the AISI 316 Gage 18 biopsy needles (OD:1.27mm and ID: 1.14mm). In the experiments, the amount of magnetic abrasive particles was changed to explore the effect of this factor on average surface roughness, while other parameters were fixed. Both the inner and external surfaces of needles were improved from 0.4–0.5 $\mu\text{m Sa}$, to 0.01 $\mu\text{m Sa}$ in 5 min machining time. Lia et al [10] investigated the friction coefficient and biopsy length between the G 18 biopsy needles and tissue after inner surface polishing AISI 316 material by using MAF process. Average surface roughness of samples were decreased from 0.43 μm to 0.02 μm after smoothly polishing operation. The MAF process significantly reduced the inner friction force and enhanced the biopsy length. Kang et al [11] developed a multiple pole type MAF system using a partially heat-treated magnetic tool for finishing capillary (OD:1.27mm) AISI 304 tubes. In order to further reducing the processing time, a high speed finishing equipment up to 30.000 rpm was developed. It was experimentally found that the magnetic and abrasive powders caused deeper scratches and irregular asperities on the finished surface with unstable machining conditions at high speeds owing to the high centrifugal forces. Optimal revolution speed was observed as 10.000 rpm for a smoothly finishing operation. Comparing to single pole, the developed multi pole system gave 12 times more efficient machining and surface finish of Rz 0.1 μm . Song et al [12] polished the inner wall of Co – Cr alloy cardiovascular stent tube (OD:1.8mm and ID: 1.6mm) using MAF method. They prepared spherical type CBN magnetic abrasive particles (MAPs) by the way of

gas atomisation and rapid solidification technique. A special ultra-long MAF setup was developed for experimentation. The effects of tube rotational speed, feed speed of magnetic pole, MAPs filling quantity and MAPs particle size on the average surface roughness were investigated. The experimental results were optimized using optimization algorithm (WOA) and least squares support vector machine (LSSVM) methods and the average surface roughness R_a was decreases from $0.485\text{ }\mu\text{m}$ to $0.092\text{ }\mu\text{m}$ under optimal machining conditions. Yamaguchi et al [13] proposed a new hybrid tool in another study for internal finishing of G 18 needle inner surface. The developed tool initially works as fixed abrasive but works as loose abrasive once the abrasive binder dissolves into the lubricant. In this technique, the abrasive insertion time saved about 80% and smoother surfaces were achieved than conventional MAF method. Guo et al [14] proposed a new magnetic-assisted chemical abrasive flow polishing (MCAFP) method for inner surface finishing of AISI 316L stainless steel puncture needle with diameters ranging from 0.3 to 0.7 mm (initial S_a 600-1200 nm). A ferromagnetic blockage was positioned in the middle of the tube with 0.7 mm inner diameter to adjust the cross-sectional area of the slurry flow. The abrasive slurry was prepared a composition of $1\text{ }\mu\text{m}$ diameter of Al_2O_3 abrasive particles, Citric acid, Octylphenol ethoxylate, water and Benzotriazole. The blockage profile was mathematically modelled. Under chemical reaction conditions, the surface of workpiece material softened and the material removal rate (MRR) increased due to the easily removing of chips by alumina particles. By using MCAFP method, averaged roughness less than S_a 40 nm was achieved along the axial direction.

Computational Fluid Dynamics (CFD) analysis plays a critical role in understanding and optimizing the underlying mechanisms of magnetic abrasive machining, abrasive air jet machining, and their combined hybrid processes, particularly in terms of improving surface quality in complex geometries. CFD models allow for the visualization of velocity fields, pressure distributions, particle acceleration, and trajectories within nozzles and near workpiece surfaces by estimating them. For example, modeling the movement of abrasive particles in abrasive water jet cutting heads provides information on how particle entry position, feed angle, and focusing tube geometry affect particle velocity and nozzle wear, enabling predictions on how to improve machining efficiency and service life [15,16].

In aspiration biopsy procedures, resistance caused by needle inner surface roughness is a significant problem that prevents the collection of sufficient tissue samples and negatively affects the reliability of clinical diagnosis. To address this problem, a unique MAJM system was designed and manufactured to process the inner surface of G14 biopsy needles. In this study, the effects of entry speed and needle rotation speed parameters on surface processing

performance were experimentally investigated within a 3x3 full factorial experimental design framework on the developed system; the obtained findings were evaluated comparatively with CFD simulations performed using the Oka erosion model, k- ω SST turbulence model, and DPM in the ANSYS Fluent environment. In the interpretation of numerical and experimental results together, tangential and radial wear components were quantified independently using a Frangi filter-based SEM image processing methodology. This study was conducted to demonstrate the applicability of the MAJM method in processing the inner surface of biopsy needles, to determine optimum processing parameters, and to develop a unique methodology that combines CFD with experimental surface characterization.

2. Materials and Methods

2.1. Experimental Setup and Test Procedure

In this study, the inner surface of G14 biopsy needles was processed using the Magnetic Abrasive Jet Machining (MAJM) method. The needles were made of AISI 304 stainless steel, with an inner diameter of 1.6 mm, an outer diameter of 1.8 mm, and a length of 150 mm. Abrasive powder mixture used in experiments; It consists of Fe powder ($d = 43 \mu\text{m}$) as magnetic carrier, Al_2O_3 ($d = 4.5 \mu\text{m}$) and SiC ($d = 4.5 \mu\text{m}$) powders as abrasive. Powders were supplied from Ege Nanotek company and their mass flow rates were determined as $8 \times 10^{-5} \text{ kg/s}$ (Fe), $4 \times 10^{-5} \text{ kg/s}$ (Al_2O_3) and $4 \times 10^{-5} \text{ kg/s}$ (SiC), respectively.

The MAJM system consists of four main components: (i) a pneumatic powder conveying system that delivers abrasive powders into the needle using 2 bar compressed air, (ii) a spindle system that operates the needle at rotational speeds of 300, 500, and 700 rpm, (iii) a neodymium magnet system positioned at a fixed distance of 2 mm from the outer surface of the needle and continuously moving back and forth, scanning the needle axis from one end to the other in 8 seconds, and (iv) a pneumatic powder collection system that collects the powders after processing. The 2 mm distance between the magnet and the needle was determined through preliminary trials using a transparent tube arrangement. In these trials, the distance at which the Fe powders were effectively attracted by the magnet and at the same time prevented clumping to a level that would disrupt the flow continuity was taken as the basis. A photograph of experimental test setup has been given in the Figure 1.

Experimental parameters were determined based on a 3x3 full factorial design, and two independent variables were examined: inlet velocity (50, 75, 100 m/s) and needle rotation speed (300, 500, 700 rpm). Each experimental condition was applied for 25 minutes. The sample groups used in the experiments were coded from S1 to S9 and are summarized in Table 1.

2.2. SEM, EDS and XRD Analysis Reviews

SEM and EDS analysis was performed in the materials laboratory using a Hitachi Su3500 brand SEM instrument (Figure 2). The SEM instrument was used in conjunction with an energy dispersive x-ray spectrometer (EDS, Oxford AZtech). The EDS system performs point, line, and area scanning and selected area X-ray mapping, and qualitative and quantitative elemental analyses are carried out in these regions.

In the XRD Powder Characterization Analysis conducted in this study, qualitative material research, characterization, and quality control were performed using a RIGAKU Miniflex 600 instrument (Figure 3).

2.3. CFD Method

Numerical analyses were performed using ANSYS Fluent 2022 R2 Fluent software. The computational domain was modeled as a single fluid region consisting of the nozzle internal volume and the needle internal volume. The nozzle internal diameter was determined to be 1.4 mm, the needle internal diameter 1.6 mm, and the needle's nozzle exit plane was located 3 mm inside the needle inlet.

The mesh structure was created using the O-Grid method. In this method, a square sub-area is defined at the center of the needle cross-section, and a regular hexahedral (six-sided) element structure is obtained throughout the computational area by slicing the geometry along the diagonals. This approach offers significant advantages in terms of accurately solving the boundary layer near the wall in cylindrical geometries. Mesh independence analysis was performed by testing six different mesh configurations with element numbers ranging from 847,000 to 2,387,901 (Table 2). The area-weighted average erosion rate of the SEM sampling region ($z = 60\text{--}90\text{ mm}$) was used as the comparison metric. The change in this value when transitioning from a mesh structure with 2,025,879 elements to one with 2,387,901 elements was calculated as 0.18%. Since this value is below the 2% threshold, the mesh structure with 2,025,879 elements was used in all calculations. When the network quality metrics are examined, it is seen that the minimum orthogonal quality is 0.529 and the maximum aspect ratio is 96.9.

The steady-phase (air) flow is modeled within the framework of Reynolds-Mean Navier-Stokes (RANS) equations. The $k\text{-}\omega$ SST (Shear Stress Transport) model was preferred for turbulence modeling. This model combines the advantages of both the $k\text{-}\epsilon$ model in the free-flow region and the $k\text{-}\omega$ model near the wall, and its accuracy has been widely validated in the

literature for narrow channel geometries and rotating wall conditions. The continuity and momentum equations are expressed as Eq. 1 and 2 respectively.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad 1$$

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u u) = -\nabla p + \nabla (\tau + \tau_t) + \rho g \quad 2$$

Here, ρ represents the density, u represents the velocity vector, p represents the pressure, τ represents the viscous stress tensor, and τ_t represents the turbulent stress tensor.

The motion of abrasive particles was modeled using the Discrete Phase Model (DPM) within the Lagrangian framework. The particle motion equation is expressed as in Eq. 3.

$$\frac{\partial u_p}{\partial t} = F_D(u - u_p) + \frac{g(\rho_p - \rho)}{\rho_p} + F_{add} \quad 3$$

Here, F_D represents the drag force, u_p represents the particle velocity, ρ_p represents the particle density, and F_{add} represents the additional forces. Turbulent dispersion was modeled using the Stochastic Tracking Model (Discrete Random Walk), with 30 trials per particle. Two-way coupling between the continuous and discrete phases was taken into account.

The Oka et al. model was used to calculate the erosion rate. This model includes material-specific coefficients that depend on both the impact angle and the velocity, and has been extensively validated for the target material, AISI 304 stainless steel. The erosion rate is calculated using the Eq. 4.

$$E_r = K \cdot f(\alpha) \cdot \left(\frac{v_p}{v_{ref}}\right)^{k_1} \cdot \left(\frac{d_p}{d_{ref}}\right)^{k_2} \quad 4$$

Here, K represents the reference erosion rate, $f(\alpha)$ is the function of the impact angle, v_p represents the particle impact velocity, d_p represents the particle diameter, and v_{ref} and d_{ref} represent the reference velocity and diameter. The model coefficients used for AISI 304 stainless steel were determined as follows: $K = 2.0 \times 10^{-4}$, $n_1 = 0.71$, $n_2 = 2.4$, Vickers hardness $H_v = 1.97$ GPa.

The inner surface of the needle is defined as a wall rotating with angular velocities corresponding to the investigated rotational speeds (31,416, 52,360, and 73,304 rad/s). The Pressure-Based Coupled algorithm was used as the solution method, and the Second Order Upwind scheme was applied to all equations in spatial discretization. First, only the continuous phase (air) was converged, then the DPM and erosion calculations were enabled to reach the complete solution. All calculations were performed in double-precision parallel mode using 16 cores.

2.4. Quantitative Analysis of SEM Images via Image Processing

SEM images of the inner surface of the needle were analyzed using image processing methods to numerically characterize the surface morphology. The analyses were performed using the Python programming language and the scikit-image and NumPy libraries. Each SEM image was first converted to grayscale format, and then the experimental label regions located at the corners of the image were excluded from the analysis. The effective image region included in the analysis was consistently defined for each image. The following parameters were calculated in the surface characterization:

Average brightness ($\bar{I}$): The pixel density is the arithmetic mean of the pixel densities in the image and is an indicator of surface reflectivity and overall topographic conditions, expressed as given in Eq. 5.

$$\bar{I} = \frac{1}{N} \sum_{i=1}^N I_i \quad 5$$

Here, I_i represents the grayscale value of each pixel and N represents the total number of pixels.

Dark Pixel Ratio (D): The ratio of pixels with a pixel density below 100 to the total number of pixels. This parameter has been used as an indicator of radial/normal impact, representing craters, deep pits, and localized material rupture zones (Eq. 6).

$$D = \frac{\sum_{i=1}^N 1(I_i < 100)}{N} \cdot 100 \quad 6$$

Gradient Density (G): This is the average magnitude of the gradient, representing the rate of change in pixel density in an image. It has been used as an indirect measure of surface roughness and scratch frequency (Eq. 7)

$$G = \frac{1}{2} \left(\frac{1}{N_x} \sum |\Delta_x I| + \frac{1}{N_y} \sum |\Delta_y I| \right) \quad 7$$

Here, $\Delta_x I$ and $\Delta_y I$ represent the horizontal and vertical pixel difference matrices, respectively.

Surface Roughness Indicator (R): This is the average of the square root of the local pixel variance. It was calculated using a 15×15 pixel floating window (Eq. 8).

$$R = \frac{1}{N} \sum_{i=1}^N \sqrt{Var_{local}(I_i)} \quad 8$$

Scratch Density (S): This refers to the density of scratch/vessel structures calculated using the Frangi vein filter [17]. This filter was applied to the normalized image at pixel scales of $\sigma = 1, 2, 3$. Scratch density was used as the primary indicator of the tangential scratching effect (Eq. 9).

$$S = \overline{F(\sigma, I_n)} \quad 9$$

Here, F represents the Frangi filter response and I_n represents the normalized pixel density. Two composite indices are derived from these parameters. These are the Radial Impact Index (RI) and the Tangential Impact Index (TI).

Radial Impact Index (RI): Defined as the normalized sum of the dark pixel ratio and surface roughness indicator (Eq. 10).

$$RI = \frac{1}{2} \left(\frac{D}{D_{max}} + \frac{R}{R_{max}} \right) \cdot 100 \quad 10$$

The Tangential Scratch Index (TI) is defined as the normalized value of the Frangi filter response (Eq. 11).

$$TI = \frac{S}{S_{max}} \cdot 100 \quad 11$$

Both indices are scaled from 0 to 100, allowing for comparative evaluation across all experimental conditions.

3. Results and Discussion

3.1. Abrasive Powder and Surface Characterization

The magnetic carrier Fe powders and the abrasive powder mixture containing Al_2O_3 and SiC used in the MAF process were comprehensively characterized before and after the process. Additionally, the surfaces subjected to the MAF process were comparatively characterized to evaluate the effects of different process parameters on the machined surfaces. During the characterization analyses, morphological examinations were conducted using an FIB-SEM (Thermo Scientific Scios2) analysis device, and an energy-dispersive X-ray spectrometer (EDS, Oxford AZtech) attached to the instrument was employed to determine the elemental distribution in the examined areas. The abrasive powders were characterized by X-ray diffraction (XRD, Miniflex 600) to determine the chemical changes before and after processing, with XRD measurements were performed in the range of 10° – 90° at a step rate of $0.5^\circ/\text{min}$.

The XRD patterns of the abrasive powder mixture prior to the MAF process and after the MAF process under different operating parameters are shown in Figure 4. In general, no significant differences was observed between the XRD patterns of the powders before and after processing; however, minor differences in peak intensity and width were observed. In addition to the main constituents of the powder mixture, namely Fe, Al_2O_3 , and SiC, the analysis also revealed the formation of Fe_3O_4 . Consistent with the literature, Fe peaks were detected at approximately 45, 65, and 82 (4113928), SiC peaks at approximately 34, 36, 60, and 72 (2310851), Al_2O_3 peaks at 25, 38, 42, 52, 58, and 68 (2101053), and distinct Fe_3O_4 peaks at 30,

36, 43, and 62 (1532800). These results indicate the presence of oxide phases in the magnetic Fe powders, which existed prior to the MAF process and persisted following the process.

The SEM images and EDS analysis results of pure iron powders are presented in Figure 5. The SEM images reveal that the carrier powders exhibit plate-like structures ranging from 50 to 250 μm , and the EDS analysis shows a slight oxidation of the powders prior to processing, evidenced by a low oxygen content. The 5 wt.% oxygen detected in the EDS analysis confirms the oxide content in the powders, consistent with the Fe_3O_4 peaks observed in the XRD analysis. Figure 6 presents the general SEM images of the abrasive powder mixture before and after the MAF process, while Figure 7 shows the EDS analysis results for the mixture before the process, and Figure 8 displays the EDS analysis results after the MAF process (for sample group S1). As expected, before the MAF process, Fe, O, Al, Si, and C were detected in the powders, and EDS analysis revealed that these elements constituted 33.3 wt.%, 17.4 wt.%, 16.3 wt.%, 13 wt.%, and 20.0 wt.%, respectively (Figure 7). After the MAF process, Cr (0.2 wt.%) was detected in the EDS analyses, which was not observed prior to the process (Figure 8). This is believed to be due to contamination from the AISI 304 stainless steel during the MAF process, resulting transfer of Cr to the powders. Additionally, mapping images show that Cr peaks are more pronounced in regions where Fe and Al are present. After the MAF process, a significant decrease in the percentages of Al, Si, O, and C, along with a marked increase in Fe content, were observed. This phenomenon can be explained in two ways: either the abrasive powders mechanically bonded to the AISI 304 stainless steel during the abrasion process, reducing their quantities in the mixture, or the abrasive powders decreased in size during the process, causing them to be overshadowed by the larger Fe particles during EDS analysis. Further characterization analyses of the abraded surfaces after the MAF process would provide clearer insights into this situation.

Figure 9 shows SEM images of the abraded surfaces after the MAF process, while Figure 10 presents the EDS mapping images of the abraded surface of the S5 group sample following the MAF process. The SEM images clearly reveal impurities or contaminations on the abraded surfaces. Additionally, the mapping images presented in Figure 10 confirm the physical adherence of abrasive powders (SiC and Al_2O_3) to the surface during the MAF process. Consequently, all these results indicate that Cr contamination from the alloy to the abrasive powders occurs during the MAF process, and that the abrasive powders become embedded into the abraded surfaces throughout the process.

3.2. Effect of Inlet Velocity and Rotational Speed on Erosion Rate Distribution

Contours of DPM erosion rates on needle surface have been represented in Figure 11 respect to changing needle rotational speeds 300 rpm, 500 rpm and 700 rpm under for constant inlet velocity 50 m/s. Maximum erosion rates are observed between $z=55-70$ mm in all cases and the position of the maximum erosions regions are approximately middle section of the whole needle length in accordance with the position of SEM samples have been collected. Area weighted erosion rate values in SEM region are 2.41×10^{-4} , 2.46×10^{-4} and 2.59×10^{-4} kg/m²s for 300, 500 and 700 rpm needle rotational speed. Erosion rate has been slightly increased with elevated needle rotational speed. The circumferential distribution of erosion rate has been constant. The rotational effects are observed to be remained limited in case of inlet velocity is 50 m/s.

At upper inlet velocity of 75 m/s a significant increase has been observed both for magnitude and spatial extend of erosion rate from the erosion rate contours respect to the case which inlet velocity is 50 ms/s as represented in Figure 12. The peak erosion rate values are seen to be concentrated in the region of $z \approx 60$ mm from the needle inlet, with area weighted average values in SEM region 6.19×10^{-4} , 6.89×10^{-4} and 6.98×10^{-4} respectively for 300, 500 and 700 needle rotational velocities. Effect of rotational speed became more pronounced with increased inlet velocity 75 m/s. Erosion rate enhancement observed as 12.8% with changing needle rotational speed from 300 to 700 rpm at 75 m/s inlet velocity. The combine effect of increased inlet velocity with higher rotational speed is determined to be augmented particle-wall interaction.

Contours of the erosion rate at 100 m/s inlet velocity represented the highest erosion magnitudes in all evaluated cases. The peak erosion rate values are observed to be located at $z \approx 60$ mm from the needle inlet similar with previous cases as represented in Figure 13. Area weighted erosion rates in SEM region are 1.35×10^{-3} , 1.27×10^{-3} , 1.36×10^{-3} for 300, 500 and 700 rpm needle rotating velocity under 100 m/s inlet velocity. The erosion rate values at 100 m/s inlet velocity are approximately 5.6 times the values recorded for 50 m/s inlet velocity. These results have shown that the amount of abrasion becomes more dominant with increasing entry speed again. At this velocity level erosion rates for changing rotational speed of needle slightly diverts from monotonic behavior due to stochastic variations in particle tracking in CFD.

Figure 14 shows the axial distribution of area-weighted average erosion rates calculated at five different axial positions ($z = 60, 70, 75, 80$, and 90 mm) on the inner surface of the needle. In all conditions studied, the maximum erosion velocity was obtained at the $z = 60$ mm position, and a monotonic decrease towards the needle exit was observed. This distribution can

be explained by the fact that the particles entering the needle by acceleration from the nozzle have the highest kinetic energy in the entry region and therefore interact most intensely with the wall in this region. Increasing the entry velocity from 50 m/s to 75 m/s led to an approximately 2.7-fold increase in erosion velocity, while an additional increase of approximately 2.0-fold was observed when transitioning from 75 m/s to 100 m/s. This result reveals the decisive role of entry velocity on erosion. When the effect of rotation speed was examined, increases in erosion rate ranging from 7.6% to 12.8% were calculated when switching from 300 rpm to 700 rpm under the same inlet speed conditions. This result indicates that rotation speed contributes to erosion distribution at a secondary level. The region from which SEM samples were taken ($z \approx 75$ mm) is located within the region where high erosion rates were observed. This allows for comparison of numerical results with experimental surface characterization data and provides a strong basis for validation.

3.3. Particle Wall Interaction Analysis

The wall normal pressure, axial and radial force components, and particle impact angle parameters obtained from CFD simulations were examined to numerically evaluate the interaction characteristics of abrasive particles with the inner surface of the needle in the MAJM process. The results are presented in Figure 14.

As shown in Figure 15 (a), the normal pressure of the wall exhibits a direct proportional increase with the inlet velocity. The average normal pressure, which is $\sim 7.4 \times 10^{-5}$ Pa at 50 m/s, increases to $\sim 1.4 \times 10^{-4}$ Pa at 75 m/s and to $\sim 2.1 \times 10^{-4}$ Pa at 100 m/s. This increase corresponds to approximately 1.9 and 2.8 times, respectively, numerically confirming that the inlet velocity is the dominant parameter determining the particle-wall contact intensity. The effect of rotational speed on the normal pressure remains quite limited compared to the inlet velocity. Similarly, the axial force component F_z also increases with inlet velocity and exhibits a high correlation with the normal pressure. Figure 15 (b) presents the particle impact angle and radial force component F_r values. The calculated impact angles vary between 0.008° and 0.091° under all experimental conditions, indicating that the particles strike the inner surface of the needle almost entirely in the axial direction. This result is consistent with the fundamental flow dynamics of the MAJM process: particles sprayed from the nozzle with compressed air gain high axial momentum, while the magnetic field created by the magnet moving along the axis on the outer surface of the needle has a limited effect on the lateral movement of the particles. The radial force components remain 10^3 – 10^4 times less than the axial force. This ratio indicates that the interaction of the particles with the needle wall occurs largely through axial momentum

transfer. The observed variation in radial force values from condition to condition is due to these values being close to the numerical solution accuracy limit and does not affect the fundamental finding regarding axial motion dominance. When compared with SEM surface images, the calculated axial movement dominance is qualitatively consistent with the line directions observed on the surface. These axially developing wear marks can be considered a reflection of the expected scratching mechanism under low impact angle conditions. However, in the MAJM process, the reciprocating motion of the magnet creates a basis for the particles to perform repeated frictional motion on the surface, and this plays a decisive role in the formation of the observed surface morphology.

3.4. Experimental Surface Characterization

SEM images obtained from the inner surface of the needle were quantitatively evaluated using image processing techniques. Six parameters were calculated from each image: mean brightness, dark pixel ratio, surface roughness index, scratch density (Frangi filter response) [17], gradient density, and surface tone standard deviation. Two composite indices were derived from these parameters: radial effect index (normalized sum of dark pixel ratio and surface roughness) and tangential scratch.

The presented image processing analysis results in Figure 16 show the variation of six parameters quantitatively derived from SEM images with respect to input speed and rotation speed. The radial impact index and dark pixel ratio generally increase with increasing speed; this trend is consistent with the increase in erosion rate obtained from CFD analyses. The tangential scratch index and scratch density show a significant dependence on rotation speed, systematically reaching their highest values at 500 rpm. The surface roughness indicator follows a similar pattern, yielding its highest values at 500 rpm. The average brightness decreases with increasing speed; this reflects the surface acquiring a darker, i.e., more damaged, appearance. These findings demonstrate that the image processing parameters are consistent with both the numerical erosion data obtained from CFD and the visual interpretation of the SEM images.

The radial impact index increases significantly with increasing speed. The highest radial impact was observed under condition S7 (100 m/s, 300 rpm), with a dark pixel ratio of 41.7%, the highest among all conditions. The deep craters and localized rupture zones observed in the SEM image are consistent with this finding. In the 50 m/s group, S3 (700 rpm) has the lowest radial impact indicators. When evaluated in terms of rotational speed, it is seen that the 300 and 500 rpm conditions generate a higher radial impact compared to 700 rpm. This can be

interpreted as the contact time of the particles with the surface shortening at high rotational speeds, and the normal/radial impact energy decreasing. The tangential scratch index yields its highest values under 500 rpm conditions: 79.8 for S2 (50 m/s, 500 rpm), 73.5 for S8 (100 m/s, 500 rpm), and 70.8 for S5 (75 m/s, 500 rpm). This consistent pattern indicates that 500 rpm produces the most intense and regular tangential scratching effect at all speed levels examined. In contrast, 700 rpm conditions (S3, S6, S9) show the lowest values in terms of tangential scratch index. This unexpected finding can be explained by the decrease in the radial pressure time of the magnet on the particles and the irregularity of particle-surface contact at the extreme rotation speeds. Indeed, the irregular crater structures and the prominence of localized material detachments in images S6 and S9 support this interpretation.

CFD analyses reveal that particle motion under all conditions is largely based on axial momentum transfer. It should be noted that radial force components are 10^3 – 10^4 times less than axial force, and magnetic forces are not represented within the scope of the current CFD model. However, SEM image analysis results provide indirect evidence of the magnetic radial imprinting effect that CFD cannot capture: the systematic increase in scratch density at 500 rpm suggests that at this speed level, the magnetic field generated by the magnet optimizes the radial imprinting on Fe particles and most effectively performs the tangential scratching motion of Al_2O_3 and SiC particles. At 700 rpm, the increase in brightness values and decrease in scratch density indicate that the magnetic imprinting effectiveness decreases at this frequency. When image analysis results are evaluated together with CFD erosion rate data, it is seen that the combination of 75–100 m/s inlet velocity and 500 rpm rotation speed (S5 and S8) provides the most balanced conditions in terms of both tangential milling efficiency and controlled surface treatment. In contrast, the S9 condition (100 m/s, 700 rpm) can be considered disadvantageous in terms of homogeneous surface treatment because it shows irregular surface damage in the image analysis despite the high CFD erosion rate.

3.5. Comparison of Experimental and CFD Results

Numerical results obtained from CFD simulations with experimental SEM/EDS analyses and image processing findings are compared and; dominant physical mechanisms in the MAJM process are discussed in this section. CFD analyses numerically reveal the decisive role of inlet velocity on erosion rate. The average erosion rate in the SEM region increases approximately 2.7-fold when transitioning from 50 m/s to 75 m/s, and approximately 2.0-fold when transitioning from 75 m/s to 100 m/s. Experimental image analysis strongly supports this trend: the radial impact index and the ratio of dark pixels systematically increase with increasing

velocity, and a significant increase in surface damage is observed at 100 m/s. This qualitative and quantitative agreement between CFD and experimental data confirms that the erosion model of Oka et al. successfully represents the hydrodynamic abrasion component in the MAJM process.

In CFD simulations, the effect of rotation speed on the erosion rate remained limited compared to the inlet speed; increases ranging from 7% to 13% were calculated when transitioning from 300 to 700 rpm. In contrast, experimental image analysis reveals that rotation speed exhibits a statistically significant and systematic effect on surface morphology. The tangential scratch index reaching its maximum values at 500 rpm in all speed groups, and the decrease in scratch density and increase in irregular surface damage at 700 rpm, indicate the existence of a physical mechanism different from what CFD predicted. This finding can be considered experimental evidence that the magnetic radial imprint specific to the MAJM process modifies the particle-surface interaction depending on the rotation speed. Therefore, while the present study confirms that CFD simulations accurately represent the hydrodynamic component in MAJM, image processing-based SEM analysis independently reveals the effect of the magnetic component, demonstrating that the two methods are complementary.

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EDS analyses show that 0.2% Cr was detected in the abrasive powder mixture after processing. This Cr transfer is direct evidence of material being chipped off the AISI 304 stainless steel needle surface by mechanical abrasion and is consistent with the high erosion rate and normal pressure values obtained from CFD. Furthermore, EDS mapping images confirm that Al_2O_3 and SiC particles are physically embedded in the needle surface. This embedding phenomenon is explained by the magnetic radial pressure applied through Fe

particles during the reciprocating motion of the magnet along its axis, pressing Al_2O_3 and SiC particles onto the surface. The high axial momentum and low impact angle values calculated in CFD analyses reveal that the particles are in prolonged tangential contact with the surface; this provides a physical basis supporting both the embedding mechanism and Cr transfer.

4. Conclusions

In this study, the MAJM system, developed to improve the inner surface quality of G14 biopsy needles, and its performance were comprehensively investigated using CFD simulations and experimental surface characterization methods. The findings are summarized below:

1. Inlet velocity is the dominant parameter determining the erosion rate on the inner surface of the needle. In the SEM sampling region ($z = 60\text{--}90\text{ mm}$), the area-weighted average erosion rate increased approximately 2.7 times when transitioning from 50 m/s to 75 m/s, and approximately 2.0 times when transitioning from 75 m/s to 100 m/s.
2. CFD analyses reveal that the maximum erosion rate is concentrated in the needle entry region ($z \approx 60\text{ mm}$). This region coincides with the region from which SEM samples were taken, confirming the spatial agreement between experimental and numerical findings.
3. Particle-wall interaction analysis shows that the axial force component is $10^3\text{--}10^4$ times larger than the radial force component. This result indicates that axial momentum generated by the jet stream under high inlet velocity conditions is the dominant mechanism and exhibits qualitative agreement with the axially oriented wear tracks observed in SEM images.
4. The effect of rotational speed on erosion rate has remained limited (7–13%) in CFD analyses. However, Frangi filter-based SEM image processing analysis reveals that the 500 rpm condition produces the highest tangential scratch density and the most homogeneous surface morphology across all speed groups. At 700 rpm, a decrease in scratch density and an increase in irregular surface damage were observed. This finding provides experimental proof of the rotational speed-dependent effect of magnetic forces beyond the CFD model.
5. EDS analyses show that 0.2% Cr was detected in the abrasive powder mixture after processing. This is evidence that mechanical abrasion caused material transfer from the needle surface and is consistent with CFD erosion rate data. Furthermore, the physical embedding of Al_2O_3 and SiC particles into the surface was confirmed by EDS mapping images.

6. This study demonstrates that combining CFD simulations with Frangi filter-based SEM image processing allows for the elucidation of the effects of both the hydrodynamic and magnetic components in the MAJM process. This methodological approach offers a unique framework for the numerical and experimental investigation of magnetic etching processes.
7. Among the parameters examined, the combination of an entry speed of 75–100 m/s and a rotation speed of 500 rpm stands out as the optimum conditions in terms of both sufficient erosion rate and homogeneous surface treatment. This finding supports the idea that the MAJM method can be applied in a manner consistent with clinical requirements for processing the inner surface of biopsy needles.

Funding

This work was supported by TÜBİTAK (The Scientific and Technological Research Council of Türkiye) under Project No. 223M594 within the scope of the 1001 Scientific and Technological Research Projects Funding Program.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Authors' Contributions

Alparsan Ulaş Çaydaş conceived and supervised the study. The experimental work, data collection, and data analysis were performed by the authors. All authors contributed to the interpretation of the results, reviewed the manuscript, and approved the final version of the manuscript.

Availability of Data and Materials

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

References

- [1] E. Kim, E. Acosta, L. Hilborne, J. Phillipson, F. DeGregorio, P. Liu, et al., “Modified technique for fine needle aspiration biopsy that eliminates needle manipulation,” *Acta Cytologica*, vol. 40, no. 1, pp. 174–176, 1996, doi: 10.1159/000333684.

- [2] M. Pezeshki Rad, M. Ghandhari, A. Doostparast, M. Emadzadeh, A. H. Khosronejad, and A. Khazen, "Randomized trial of biopsy needle sandblasting in coaxial core-needle liver biopsy: No significant improvement in ultrasound visibility, pain, or tissue yield," *Abdominal Radiology*, vol. 50, pp. 3156–3164, 2025, doi: 10.1007/s00261-025-05214-1.
- [3] X. Fan, Q. Li, W. Zhang, and H. Yin, "Multi-objective process parameter optimization for abrasive air jet machining using artificial bee colony algorithm," *Machines*, vol. 13, no. 10, Art. no. 964, 2025, doi: 10.3390/machines13100964.
- [4] Y. He, T. Chen, X. Man, and T. Su, "Towards ultra-precision manufacturing: Advancements and future trends in energy field-assisted jet machining," *Micromachines*, vol. 17, no. 4, 2026, doi: 10.3390/mi17040415.
- [5] H. S. Farwaha, D. Deepak, and G. S. Brar, "Process parameter optimization of ultrasonic assisted electrochemical magnetic abrasive finishing of 316L stainless steel," *Journal of Physics: Conference Series*, vol. 1240, 2019, doi: 10.1088/1742-6596/1240/1/012041.
- [6] Y. C. Lin and H. S. Lee, "Optimization of machining parameters using magnetic-force-assisted EDM based on gray relational analysis," *International Journal of Advanced Manufacturing Technology*, vol. 42, pp. 1052–1064, 2009, doi: 10.1007/s00170-008-1662-7.
- [7] S. Singh, A. P. Singh, Y. R. Gautam, D. Singh, and S. Khalid, "An experimental investigation of abrasive jet machining parameters for optimized surface finish of mild steel components," *ARPJ Journal of Engineering and Applied Sciences*, vol. 19, pp. 797–803, 2024, doi: 10.59018/072410.
- [8] C. T. Lin, L. D. Yang, and H. M. Chow, "Study of magnetic abrasive finishing in free-form surface operations using the Taguchi method," *International Journal of Advanced Manufacturing Technology*, vol. 34, pp. 122–130, 2007, doi: 10.1007/s00170-006-0573-8.
- [9] N. Valens, Y. Wang, W. Li, A. Shih, and H. Yamaguchi, "Surface finishing of needles for high-performance biopsy," *Procedia CIRP*, vol. 14, pp. 48–53, 2014.
- [10] W. Li, P. Zhou, W. C. Lin, V. Nteziyaremye, H. Yamaguchi, D. Guo, and A. Shih, "Effects of needle inner surface topography on friction and biopsy length," *International Journal of Mechanical Sciences*, vol. 119, pp. 412–418, 2016.
- [11] J. Kang, A. George, and H. Yamaguchi, "High-speed internal finishing of capillary tubes by magnetic abrasive finishing," *Procedia CIRP*, vol. 1, pp. 414–418, 2012.

- [12] Z. Song, Y. Zhao, G. Liu, C. Cao, Y. Gao, X. Zhang, Z. Li, D. Dai, and Y. Pu, "Study on finishing inner wall of CoCr alloy cardiovascular stent tube via novel atomized CBN/metal spherical magnetic abrasive powders," *Journal of Manufacturing Processes*, vol. 92, pp. 206–225, 2023.
- [13] H. Yamaguchi, V. Nteziyaremye, M. Stein, and W. Li, "Hybrid tool with both fixed-abrasive and loose-abrasive phases," *CIRP Annals – Manufacturing Technology*, vol. 64, no. 1, pp. 337–340, 2015.
- [14] J. Guo, Q. Li, Z. Tong, W. Zhao, and L. Li, "A new internal surface polishing method for sub-millimeter slender tube with varying diameters," *CIRP Annals – Manufacturing Technology*, vol. 73, no. 1, pp. 265–268, 2024.
- [15] X. Zhang, C. Zhou, L. Jiang, and R. Guo, "Influence of process parameters on abrasive particle motion characteristics in abrasive water jet descaling," *International Journal of Advanced Manufacturing Technology*, vol. 90, pp. 2741–2749, 2017, doi: 10.1007/s00170-016-9564-6.
- [16] D. Feng, Y. Cheng, J. Xiao, G. Hu, and Z. Cao, "Material removal characteristics and particle motions in abrasive water jet quantitative machining," *Applied Optics*, vol. 62, pp. 196–205, 2023, doi: 10.1364/AO.475659.
- [17] A. F. Frangi, W. J. Niessen, K. L. Vincken, and M. A. Viergever, "Multiscale vessel enhancement filtering," in *Medical Image Computing and Computer-Assisted Intervention — MICCAI'98*, W. M. Wells, A. Colchester, and S. Delp, Eds. Berlin, Heidelberg: Springer, 1998, pp. 130–137.

Figures

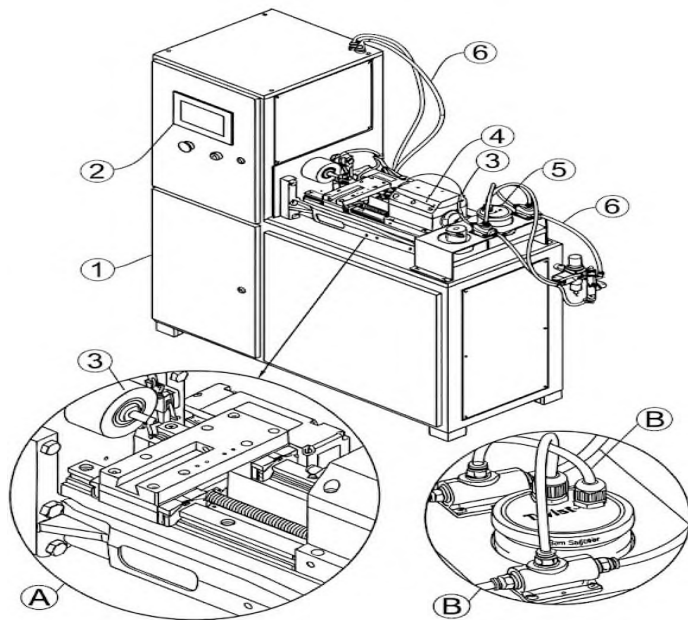


Figure 1. Experimental test setup (1- Housing, 2- Panel Screen, 3- Fixed bed, 4- Nozzle, 5- Powder tank, 6- Powder supply line)



Figure 2. SEM and EDS analysis device

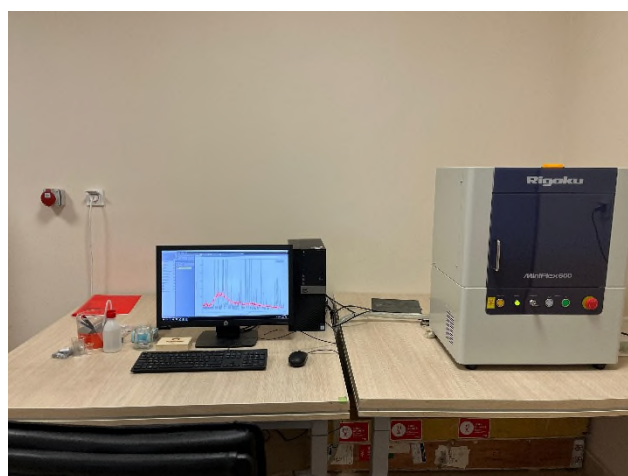


Figure 3. XRD and powder characterization analyser

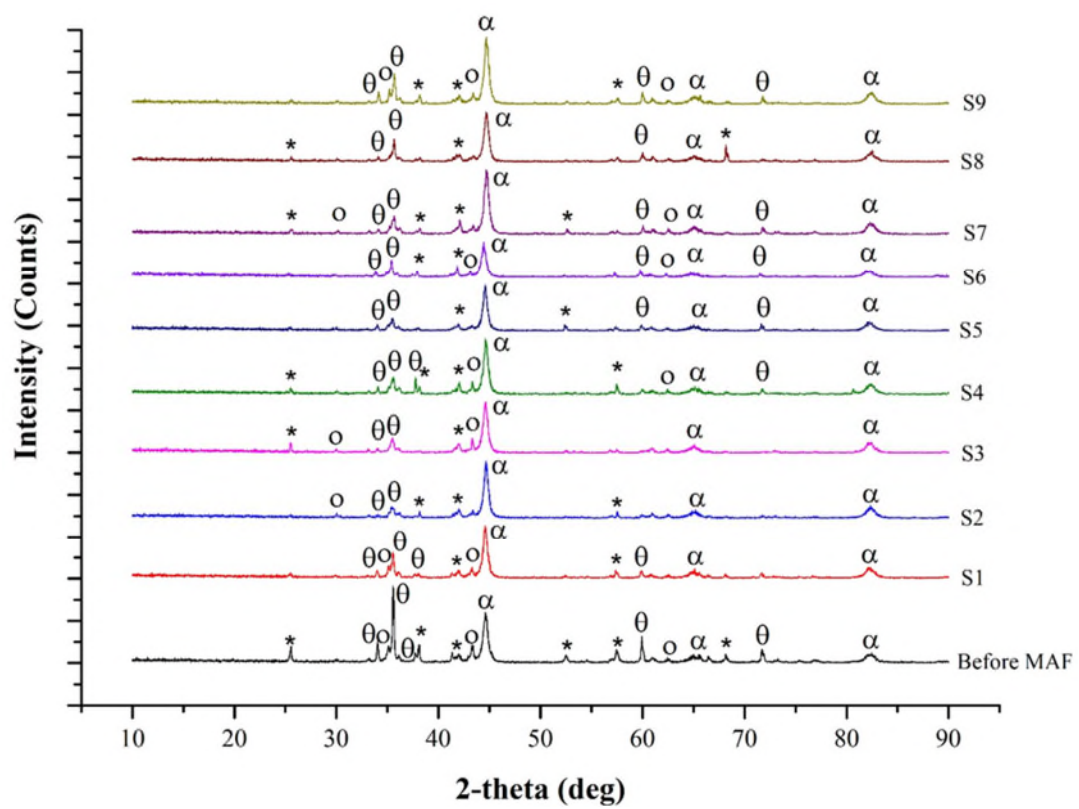


Figure 4. The XRD patterns of abrasive powders before and after the MAF process

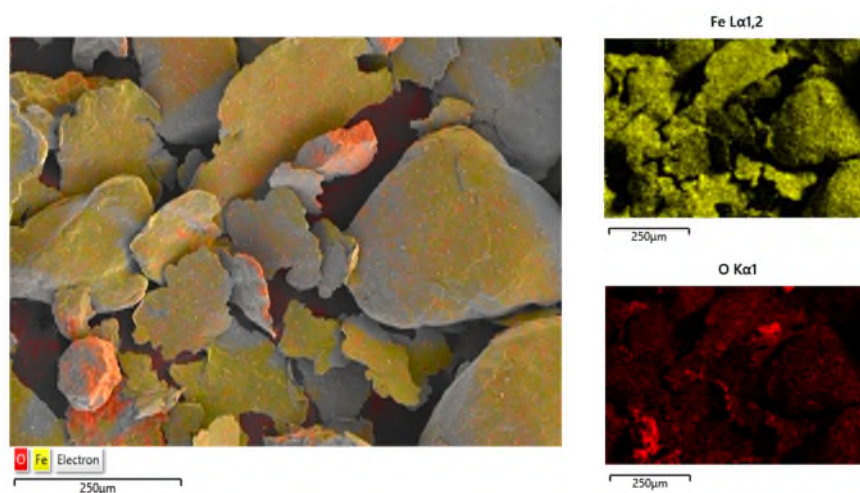


Figure 5. The SEM image and EDS mapping of Fe powders

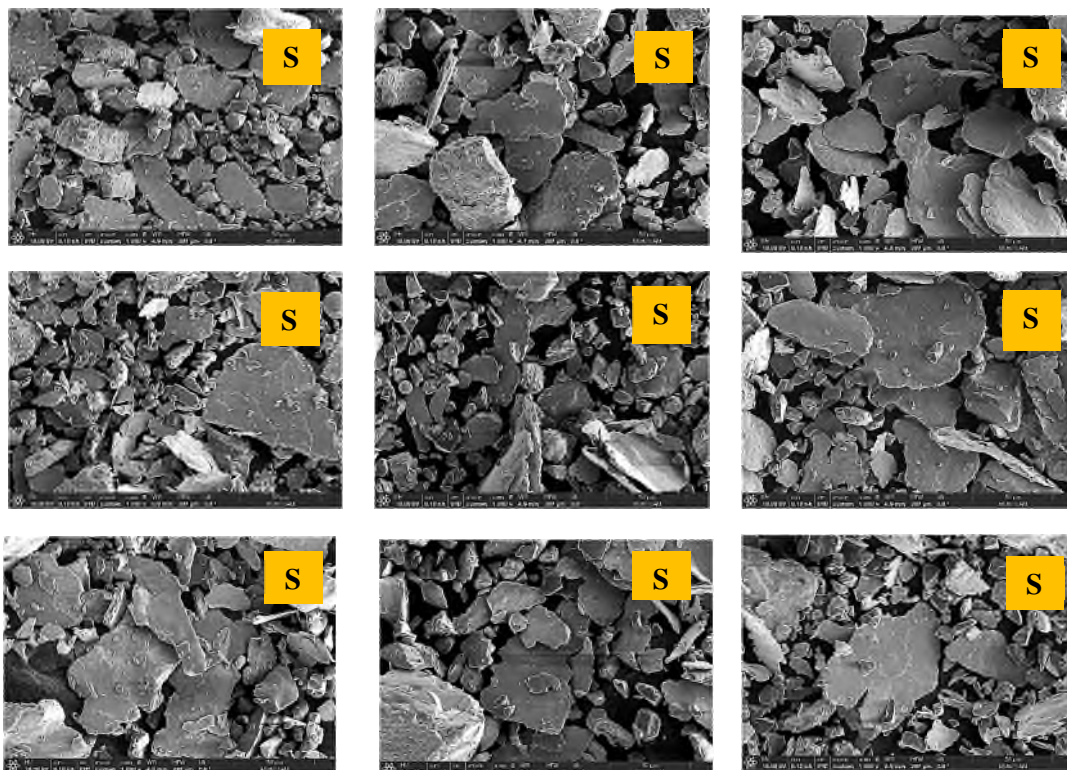
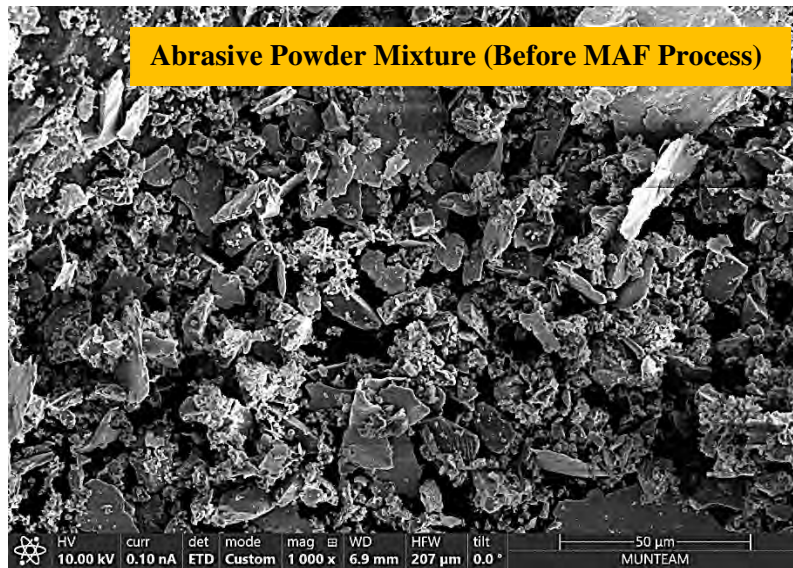
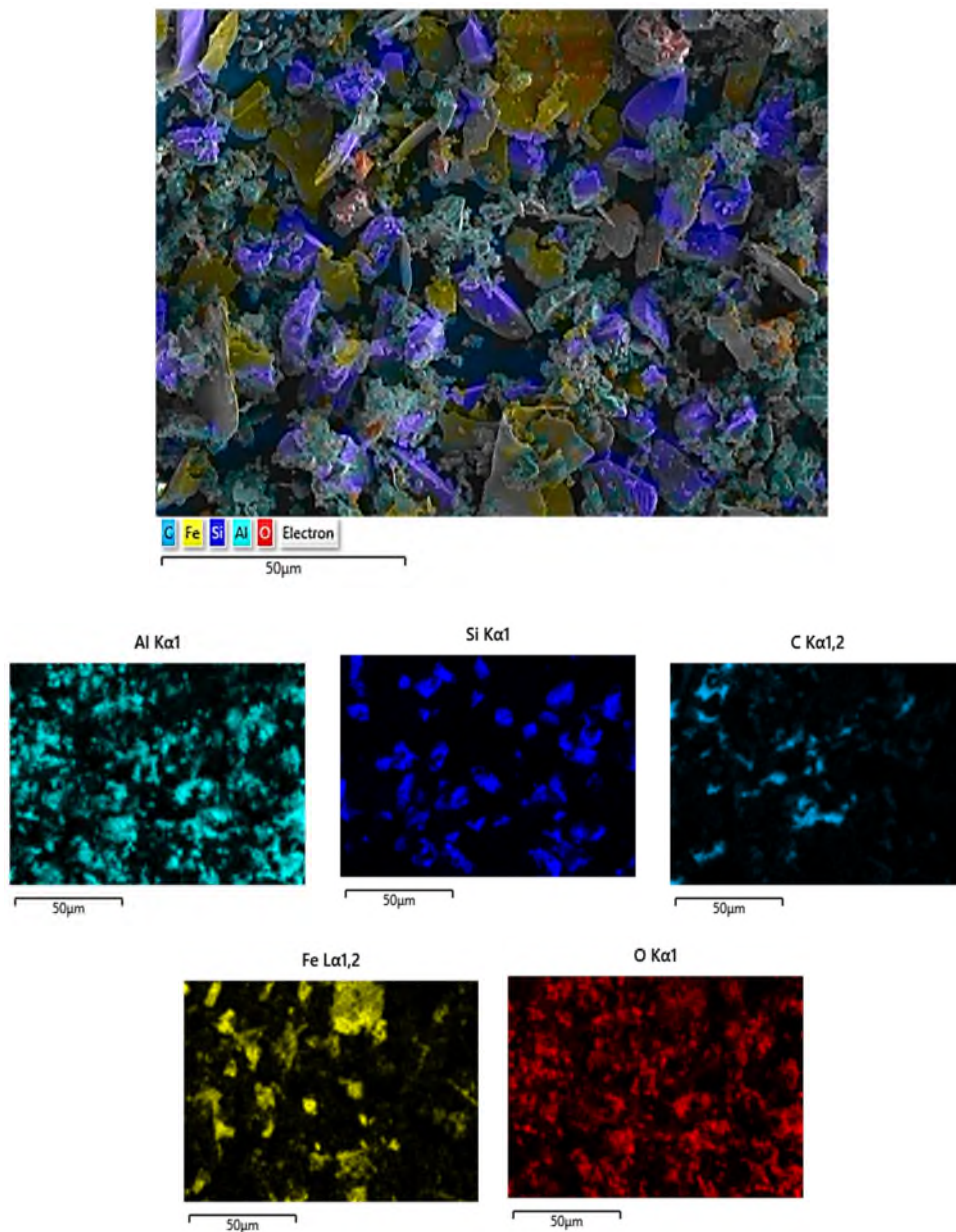
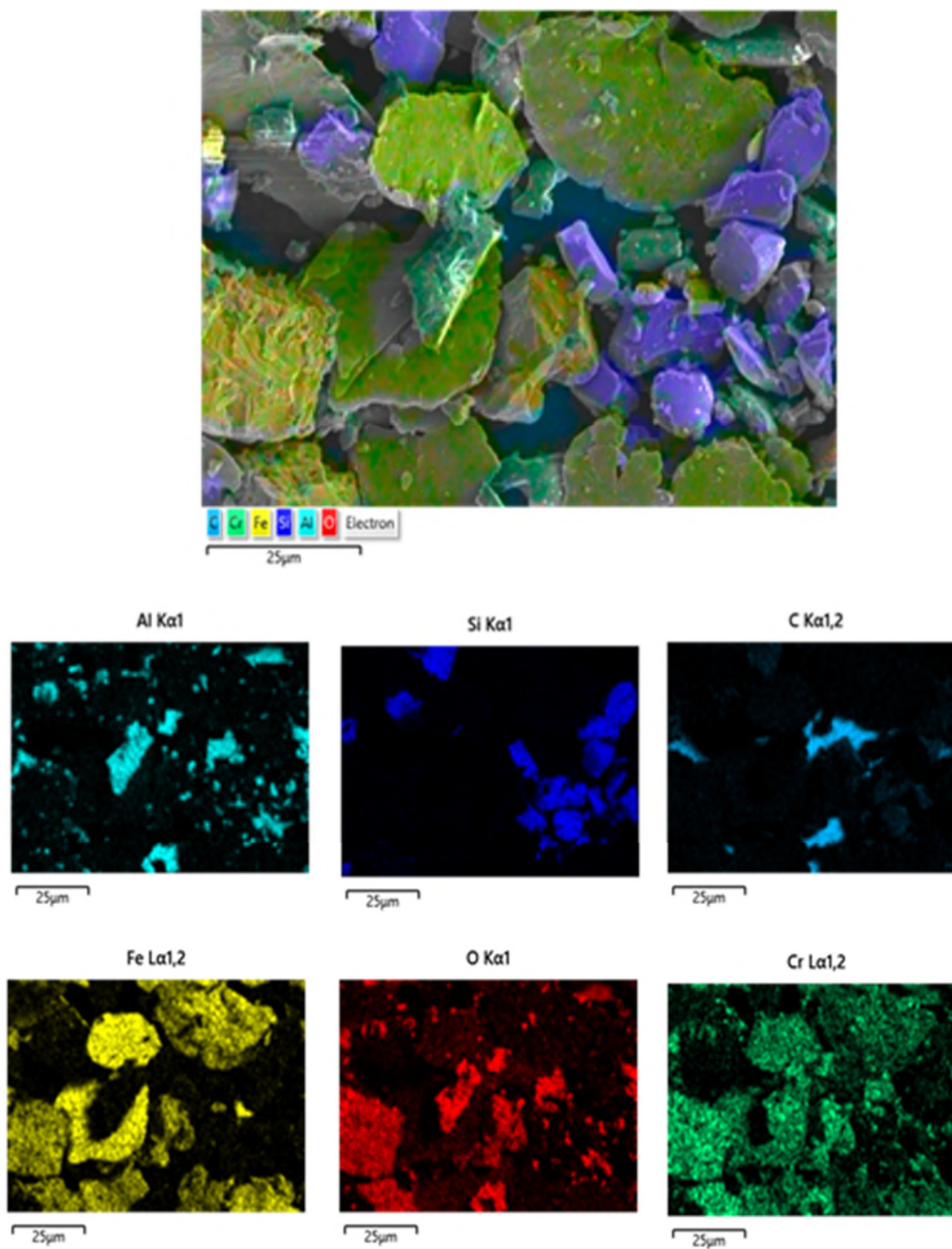


Figure 6. SEM images of abrasive powders before and after MAF process



Spectrums	EDS Spectra (wt. %)				
Mapping	Fe	O	Al	Si	C
	33,3	17,4	16,3	13,0	20,0

Figure 7. The EDS mapping images and EDS spectrum of the powder mixture before MAF process



Spectrums	EDS Spectra (wt. %)					
Mapping	Fe	O	Al	Si	C	Cr
	59,1	10,7	7,5	10,0	12,5	0,2

Figure 8. The EDS mapping images and spectrum of the powder mixture after processing (S1)

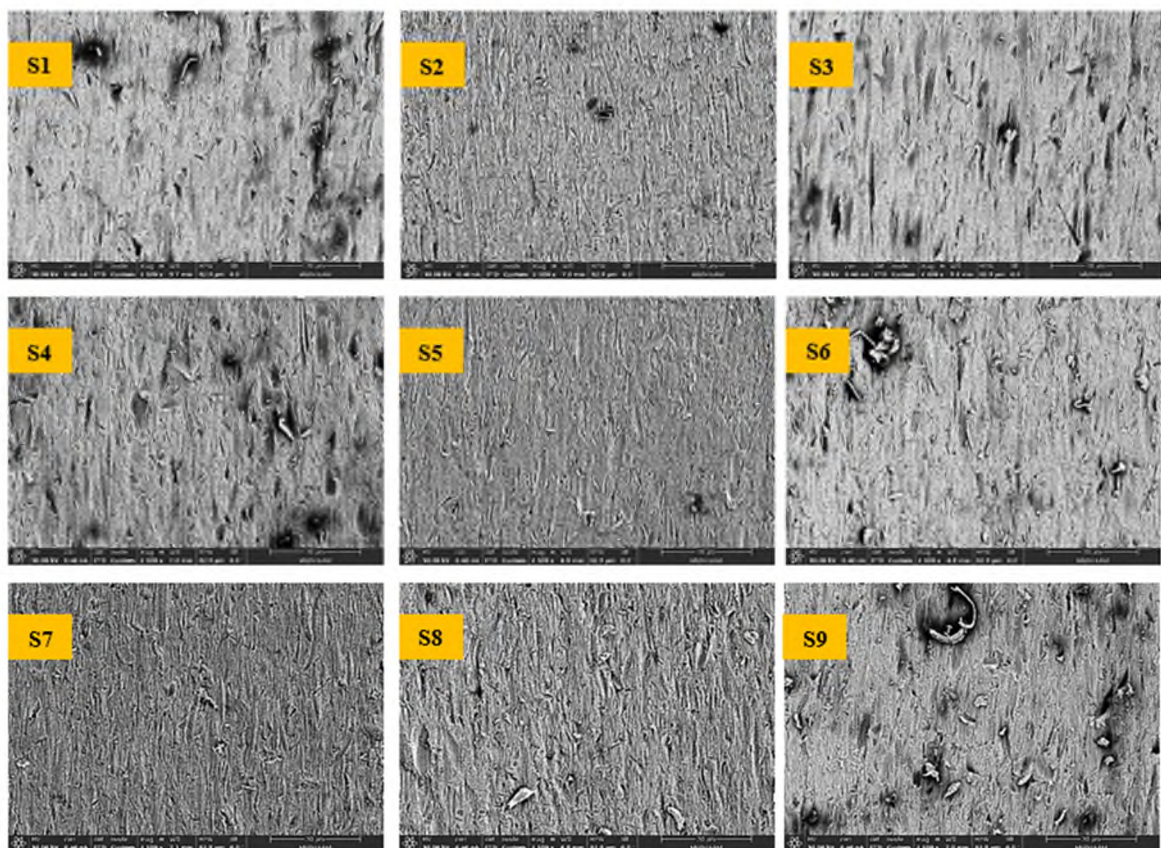


Figure 9. SEM images of surfaces after MAF processing

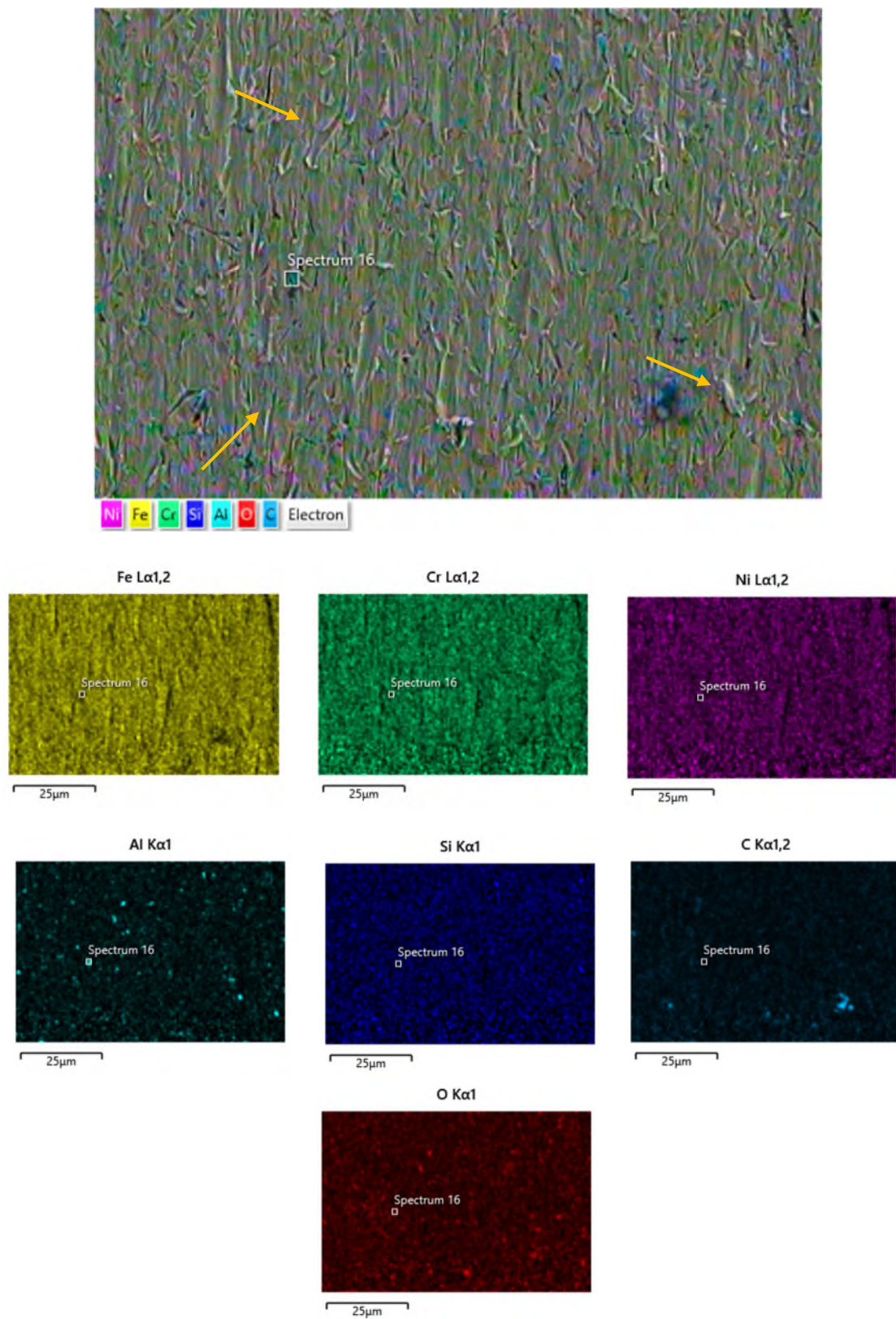


Figure 10. The EDS mapping image of the surface after MAF processing (S5)

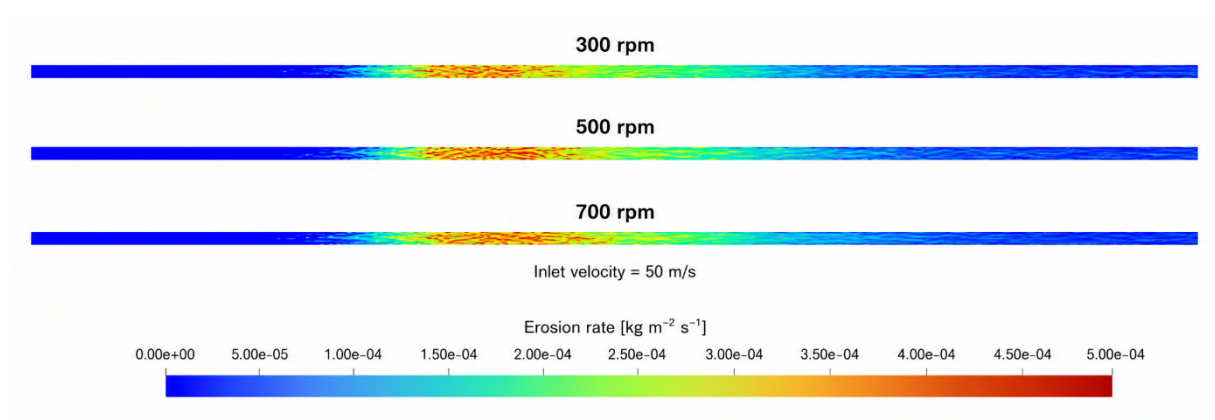


Figure 11. CFD results of erosion rates on needle inner surface for 50 m/s inlet velocity and 300 rpm, 500 rpm and 700 rpm needle rotational speed

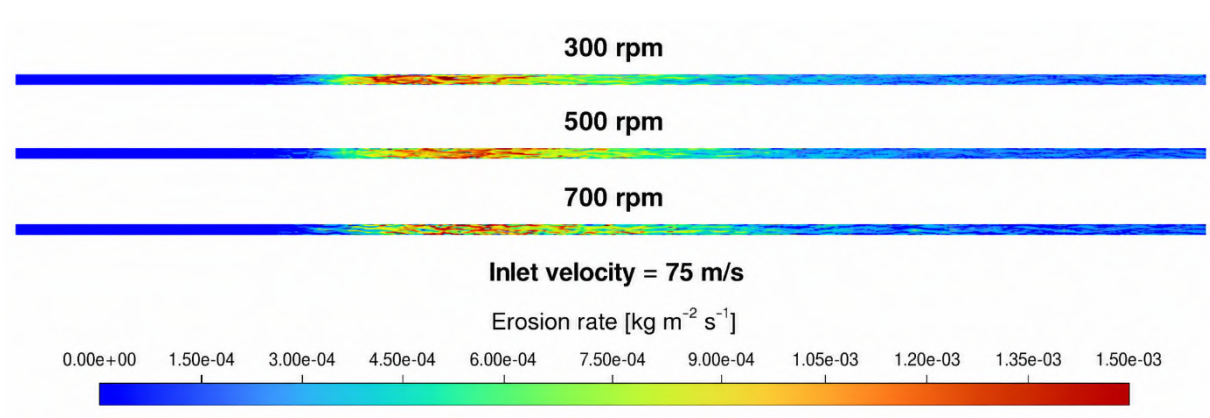


Figure 12. CFD results of erosion rates on needle inner surface for 75 m/s inlet velocity and 300 rpm, 500 rpm and 700 rpm needle rotational speed

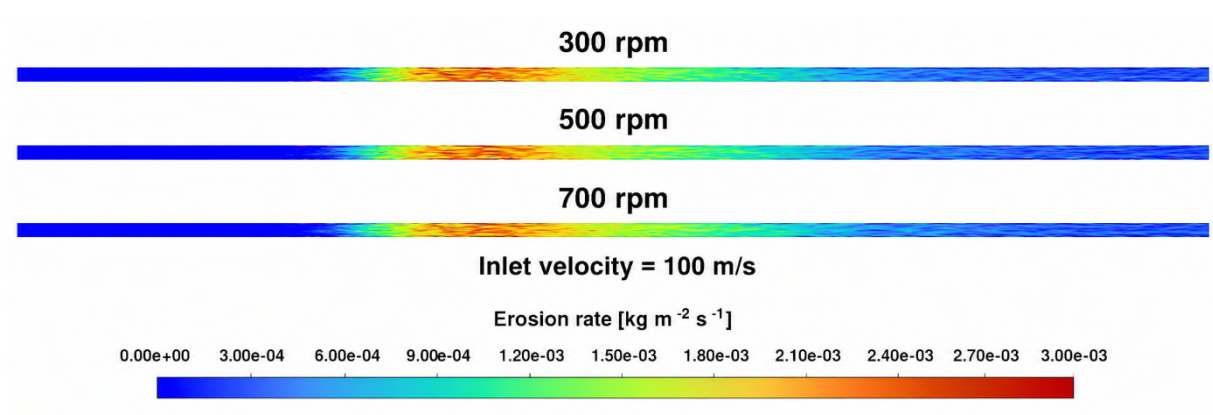


Figure 13. CFD results of erosion rates on needle inner surface for 100 m/s inlet velocity and 300 rpm, 500 rpm and 700 rpm needle rotational speed

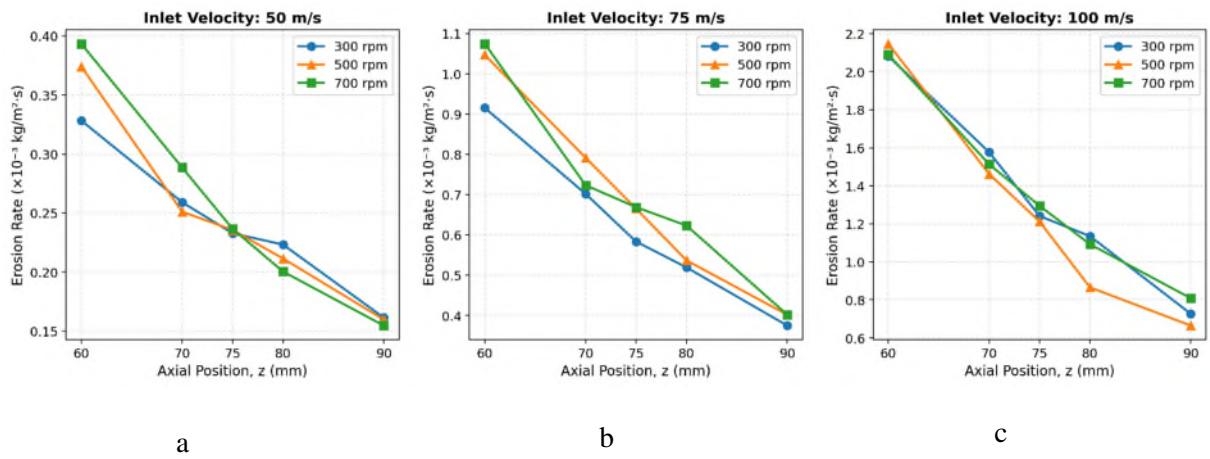


Figure 14. Axial erosion velocity distribution on the needle inner surface at different entry and needle rotational velocities: (a) 50 m/s, (b) 75 m/s, (c) 100 m/s (Oka model, $z = 60\text{--}90$ mm, SEM sampling region)

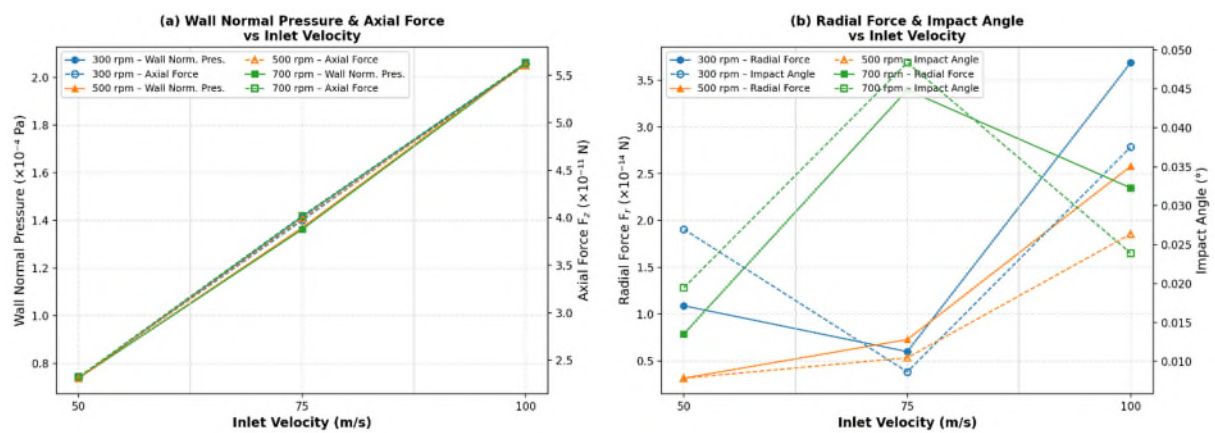


Figure 15. The variation of particle-wall interaction parameters with inlet velocity in the MAJM process is: (a) wall normal pressure and axial force component F_z , (b) radial force component F_r and particle impact angle θ

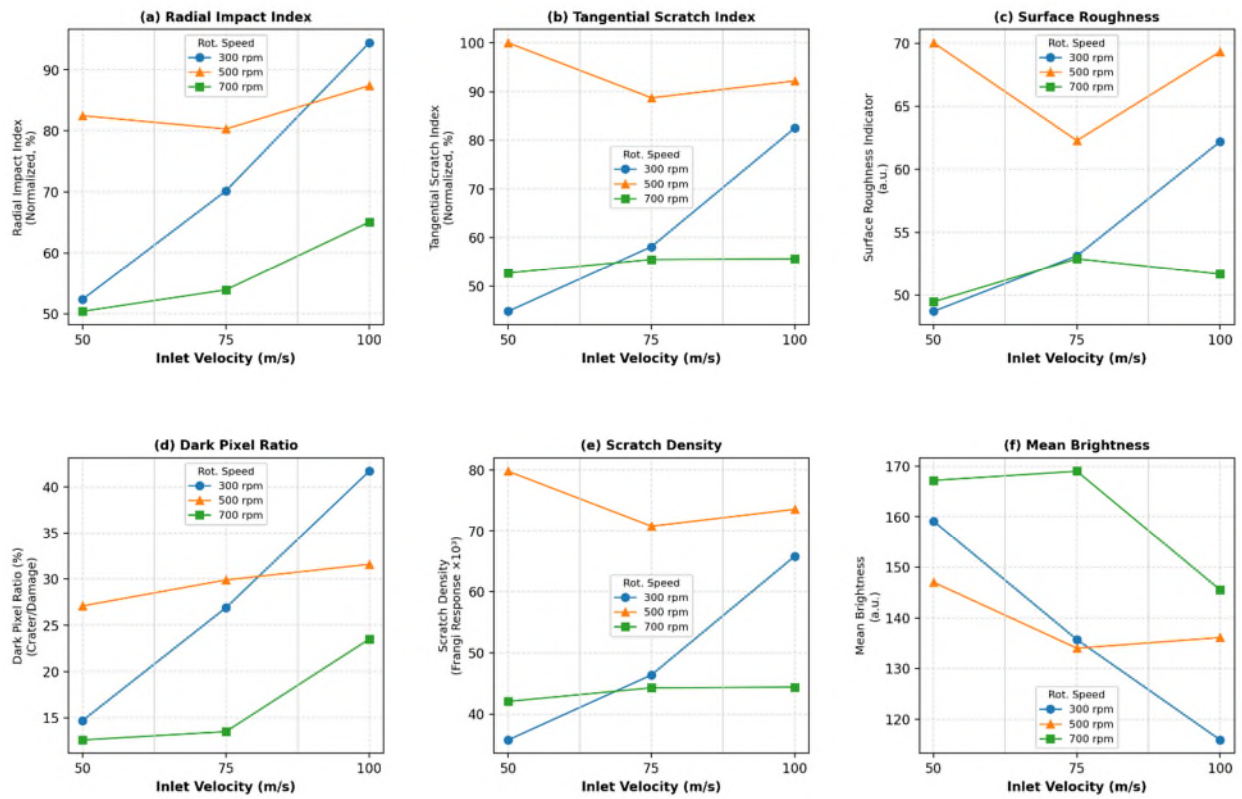


Figure 16. Comparative analysis of image processing parameters obtained from SEM images of the needle inner surface under different input and rotation speed conditions in the MAJM process: (a) radial impact index, (b) tangential scratch index, (c) surface roughness indicator, (d) dark pixel ratio, (e) scratch density, (f) average brightness

Figures Captions

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Tables

Table 1. Experimental test matrix

Specimen Group	Inlet Velocity (m/s)	Needle Rotational Velocity (rpm)
S1	50	300
S2	50	500
S3	50	700
S4	75	300
S5	75	500
S6	75	700
S7	100	300
S8	100	500
S9	100	700

Table 2. Mesh independency table

Mesh No	Number of Elements	SEM Region Avg. Erosion Rate ($\times 10^{-4}$ kg/m ² .s)	Change from previous (%)
1	847000	1.882	-
2	1001250	2.012	10.43
3	1527322	2.255	12.08
4	1887456	2.379	5.49
5*	2025879	2.410	1.30
6	2387901	2.414	0.18

*Selected Mesh (change<2%)

Tables Captions

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