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INVESTIGATION OF ABRASIVE MEDIA WEAR AND ITS INFLUENCE ON PERFORMANCE IN VIBRATORY MASS FINISHING TREATMENT

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Abstract

This study investigates the wear behavior of abrasive media used in Vibratory Mass Finishing Treatment (VMFT) and its impact on process performance. The primary objective is to establish the relationship between the evolving characteristics of Abrasive Media Mass Finishing (AMMF) and the efficiency of the finishing process. Particular attention is given to the mechanisms of media wear and their effect on cutting capacity and surface quality. Experimental analysis was conducted to evaluate how variations in AMMF properties, such as size, shape, and load volume, affect wear rates and finishing performance across different engineering materials. The results demonstrate that AMMF wear significantly influences process stability, material removal efficiency, and surface finish quality. Key wear mechanisms, including grain blunting, particle detachment, and self-sharpening effects, were identified as critical factors governing performance. The findings highlight that optimizing AMMF characteristics and monitoring their wear state are essential for maintaining consistent finishing quality. Furthermore, the study provides insights into selecting suitable media and operating conditions to improve process reliability and extend media life. This work contributes to a better understanding of wear evolution in VMFT and supports the development of more stable and efficient finishing operations.

Keywords: Abrasives Medias Mass Finishing (AMMF), Vibratory Mass Finishing Treatment (VMFT), workpiece materials, cutting capacity, wear analysis

1. INTRODUCTION

For accurate and high-precision manufacturing, machining, and finishing of hard materials and hardened surfaces, abrasive machining techniques, also known as machining with geometrically unclear cutting edges, are the clear choice. Usually performed as postmachining or finishing machining procedures for precision, high-precision, and ultraprecision components with tight dimensional and form tolerances and good surface finishes are abrasive machining processes. Conversely, general exceptions to the abrasive machining techniques used to create precision components are abrasive blasting methods like abrasive water-jet machining. Abrasive blasting is used in situations where high precision or good surface quality are not usually necessary [1]. Recent studies collectively examine different aspects of vibratory and abrasive finishing processes, with each contributing from a distinct perspective experimental, analytical, and simulation-based. The study by Stańczyk and Figlus [2] focuses on vibro-abrasive processing of 6082 aluminium alloy, emphasizing the influence of process parameters such as time and media type on surface roughness. Their findings highlight a significant improvement in surface quality, achieving up to a 75.5% reduction in roughness, demonstrating the effectiveness of controlled finishing conditions in mass production environments. Similarly, Nezarati et al. [3] investigate vibratory surface finishing but extend the analysis to additively manufactured stainless steel parts. Their work not only confirms substantial reductions in surface roughness (around 75%) but also introduces additional considerations such as dimensional deviation and microhardness, showing that while surface quality improves, there are trade-

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offs in dimensional accuracy and subsurface properties. In contrast, Liu et al. [4] adopt a simulation-based approach to understand the motion characteristics of abrasive media within vibratory finishing systems. Rather than focusing directly on surface outcomes, their study explains the underlying mechanics of media movement—describing it as annular spiral motion, which is essential for optimizing process design and predicting finishing behavior. Meanwhile, Tarasov et al. [5] provide an analytical perspective on vibration behavior, specifically examining horizontal oscillations in vibratory rollers. Although their work is not directly centered on finishing processes, it contributes foundational knowledge about vibration dynamics, which is critical for improving machine design and operational efficiency.The processing capability of Vibratory Mass Finishing Treatment (VMFT) was extensive, as it functioned as a mechanical-chemical process used for cleaning, deburring, burnishing, radiusing, smoothing, polishing, stress stabilization, and degreasing both individual and mass-produced parts, while also improving surface finish. Mobark et al. [6] studied the vibration behavior of Al_2O_3-reinforced nano-composite cantilever beams with structural defects. They demonstrated that higher nanoparticle concentrations improve damping performance through increased energy dissipation, while crack propagation intensifies with loading. The study also emphasized the role of particle dispersion and recommended frequency-domain methods for future vibration analysis. In this process, components were immersed in abrasive media and compounds within a vibratory finishing machine, where circular motion enabled consistent interaction between the media and workpieces to achieve the desired polish. VMFT had been applied to a wide range of workpieces, varying in size, quantity, and geometric complexity, and its effectiveness depended heavily on maintaining stable processing conditions to ensure product quality [7]. Prakasam et al. [8] analyzed the mechanism of surface evolution in vibratory media finishing by examining changes in surface profiles over time. Their results showed that surface smoothing occurs through a combination of material removal and plastic deformation, where peak material is displaced into valleys. This behavior explains the observed saturation in surface roughness during prolonged processing. Sato et al. [9] investigated the influence of media degradation on finishing performance in abrasive flow machining using Inconel 718 specimens. Their results showed that while surface roughness remains largely unaffected, material removal decreases with increasing media usage due to degradation. Additionally, a linear correlation between material removal and media flow rate was established, enabling easier prediction of machining performance. A distinctive feature of VMFT was the absence of a rigid relationship between the workpiece and the abrasive media (AMMF), which eliminated many limitations associated with conventional grinding processes. The lack of rigid tool-part interaction, combined with continuous elastic contact and minimal temperature rise in the cutting zone, contributed to stable cutting forces and reduced the influence of wear mechanisms such as diffusion, adhesion, and thermal effects, even during roughing operations. Overall, VMFT demonstrated a high degree of process reliability; however, the abrasive media remained the least reliable component due to its susceptibility to wear [10]. The selection of appropriate media depended primarily on the workpiece material, production throughput and processing time, and economic considerations. Abrasive media wear was identified as a critical factor influencing media consumption, surface quality, process efficiency, and operational stability [4][11]. Hashimoto et al. [4] analyzed the relationship between surface characteristics and the functional performance of components, emphasizing parameters such as surface topography, residual stress, and tribological behavior. The study compared various finishing methods and provided guidelines for selecting appropriate processes to achieve desired surface integrity and performance outcomes. Accordingly, this study focused on examining AMMF wear behavior and its role in stabilizing VMFT performance, with particular emphasis on parameters such as cutting capacity, media size and shape accuracy, and work-chamber loading conditions. Abrasive tool wear had been evaluated using two principal indicators: the average wear rate, defined as the material removed per unit time, and the specific wear, representing the volume or mass of abrasive lost during processing [11]. In practice, specific wear had been considered the more reliable indicator due to the non-linear nature of wear progression in abrasive media [12].

Several factors contributed to AMMF wear and the consequent reduction in cutting efficiency, including the blunting of abrasive grain edges, reduction in media size, decrease in work-chamber load volume, and contamination by microchips and wear debris [13][14]. During operation, interactions between the media and the workpiece generated mechanical and periodic thermal effects, which led to a decline in cutting performance as abrasive grains became worn and clogged with adhered particles [15]. Partial self-sharpening occurred in some cases through the chipping or spalling of abrasive grains caused by fatigue and impact forces, whereas more extensive self-sharpening resulted from bond breakage and grain detachment during media-to-media interactions. Figure 1 illustrated the methodological approach used to evaluate abrasive media wear during the VMFT process. Two fundamentally different mechanisms responsible for the “self-regeneration” of the abrasive cutting ability were identified. The first mechanism was micro-chipping self-sharpening, which was considered the preferred mechanism, and involved localized chipping of grain tips, removal of dulled microprotrusions, and the formation of new sharp cutting edges. This mechanism represented the classical self-sharpening behavior of abrasive media. The second mechanism involved the fragmentation of entire abrasive particles, which was regarded as undesirable volumetric wear. For softer abrasive tools, wear primarily occurred through bond failure and the removal of entire grains when bond strength was lower than grain strength [16]. These mechanisms enhanced process stability by enabling continuous renewal of cutting edges and maintaining surface quality over time [17]. Nevertheless, progressive wear altered the size, shape, and mass of the abrasive media, leading to reduced load volume within the work chamber and a corresponding decline in cutting capacity and overall process performance [18][19].

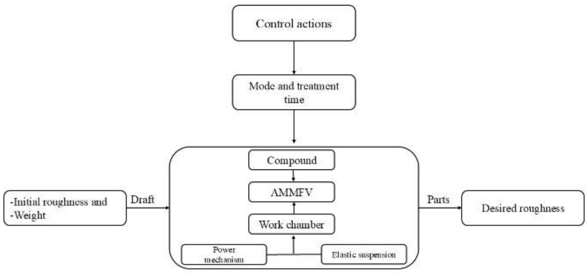

Fig. 1. Methodology for Evaluating Abrasive Media Wear in VMFT

The aim of this study was to investigate the wear behavior of abrasive media used in VMFT and to evaluate its influence on process performance and surface quality. Specifically, the research sought to identify the relationships between abrasive media characteristics, such as size, shape, load volume, and granularity and their cutting capacity and wear mechanisms. Additionally, the study aimed to analyze how these wear mechanisms affect process stability, material removal efficiency, and the overall quality of finished components, with the objective of improving the selection and optimization of abrasive media for enhanced VMFT performance.

2. EXPERIMENTAL PROCEDURE

The experimental investigations in the current study were improved by utilizing a compact vibratory machine with a toroidal work chamber as shown in figure 2, the technical features of which are detailed in Table 1. The employed machine offered several advantages, including a simple design, ease of operation, and high adaptability. The experiments were conducted using free loading of the samples into the work chamber, with the combined volume of AMMF and samples maintained at 80% of the total chamber capacity. All experimental runs were performed under continuous cleaning conditions, where the working fluid was maintained using a 3% soda solution. The oscillation parameters of the vibratory machine, including noise intensity, vibration levels, and spectral characteristics, were monitored using an ISV-1 instrument. Additionally, a vibrograph VR-1 was utilized to measure the frequency and amplitude of the machine oscillations. The relationship between oscillation frequency and the rotational speed of the electric motor shafts was also recorded using a manual magnetic tachometer (model IO-30).

Fig. 2. Vibratory machine model TVM-10

2.1. Instruments and devices for experimental studies

The samples were weighed to determine the quantity of material removed using analytical damper balances (model ADB-200) and class 2 equal-arm laboratory balances (model LBE-200), both with a measurement accuracy of up to 0.2 mg. The hardness of the samples was evaluated using a TK-2 device based on the Rockwell method, as well as a TB-type device (model TS-2M) following the Brinell hardness testing method. Surface roughness measurements were carried out using a type 296 profilometer, while profilograms were obtained with a model 201 profilometer–profilograph.

Table 1. Technical characteristics of equipment

Designation	Units	Machine model TVM-10
Volume of chamber	dm^3	10
Number of working chambers	Unit	1
Type of working chambers		Torus chamber
Oscillation drive		Unbalanced
Vibrator location		Vertical
Electric motor power	kW	0,8
Oscillation amplitude	mm	0-3
Oscillation frequency	Hz	52-58
Overall dimensions	m	0.85×0.43×0.885
weight	Kg	150
Tank volume settings	dm^3	20

2.1 Select Sample Materials

In selecting the experimental materials, consideration was given to evaluating the universality of the proposed theoretical models and the applicability of the research findings to commonly used engineering materials in industry. The samples were prepared from strip and rod rolled products, which were specifically selected to represent a defined range of mechanical properties, as detailed in Table 2. The yield strength of the steel samples was determined and controlled using the appropriate empirical equation:

$$\sigma_S \text{ (MPa)} = 0.367 \text{ HB (MPa)} - 240 \quad (1)$$

2.2 Medias Mass Finishing

AMMF were utilized to analyze the influence of their characteristics on process performance and the surface roughness of the treated components. The specific properties of the AMMF are summarized in Table 3. Prior to the experimental investigations, all abrasive media were subjected to a 30-minute pretreatment to ensure consistent initial conditions.

The experimental investigation examined the effect of varying the work-chamber load volume on the technological parameters of the VMFT process, with particular emphasis on the relationship between load reduction, AMMF cutting capacity, and wear behavior. All experiments were conducted under constant operating conditions, with a work-chamber oscillation frequency of 33 Hz and an oscillation amplitude of 2.5 mm in order to ensure consistent processing parameters. Figure 3 illustrates the relationship between work-chamber load volume and the cutting capacity of AMMF media in the form of triangular prisms (TP 10×10) during the processing of common engineering materials, including steel A570(36) and aluminum alloy 2024.

As the loading volume increases from 2 L to approximately 4 L, the cutting capacity increases for both materials due to the greater number of abrasive particles participating in the finishing process and the increased frequency of interactions between abrasives and the workpiece surface. The maximum cutting capacity is observed at around 4 L, indicating the formation of an optimal abrasive working layer that ensures efficient transmission of mechanical and magnetic forces to the abrasives. However, further increases in loading volume lead to a gradual decline in cutting capacity, which can be attributed to excessive accumulation of abrasive media that restricts particle mobility and reduces the effective cutting action. Additionally, aluminum alloy 2024 exhibits higher cutting capacity compared with steel A570(36), primarily due to its lower hardness and greater susceptibility to abrasive machining.

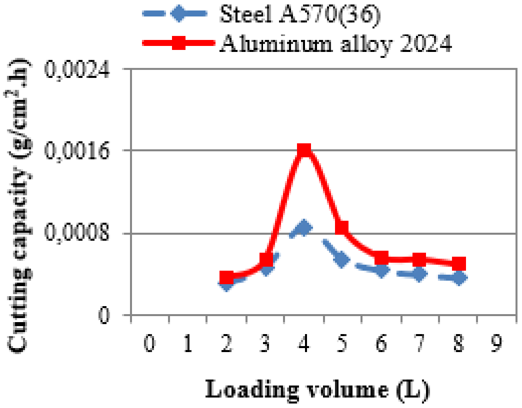

Fig. 3. Effect of work-chamber loading volume on the cutting capacity of AMMF during the finishing of Steel A570(36) and Aluminum alloy 2024.

The corresponding variation in AMMF-specific wear with changes in load volume is presented in Figures 4 and 5 shows that the specific wear of porcelain balls is relatively high at lower loading volumes, particularly within the range of 2-3 L, where the mechanical load acting on individual abrasive particles is greater. As the loading volume increases, the wear rate decreases significantly because the applied mechanical load becomes distributed among a larger number of abrasive particles, thereby reducing the stress acting on each particle. Beyond approximately 6 L, the wear rate tends to stabilize, indicating that the abrasive system approaches a steady operational condition.

Table 2. Mechanical properties of the sample material

Sample material	Heat treatment	Hardness HB	Yield strength σ_S (MPa)
Steel A570(36)	Quenched and Tempered (600˚C)	112-120	250
Aluminium alloy 2024	Quenched and Tempered (600˚C)	95-120	324-345
Steel 1045	Quenched and Tempered (600˚C)	225-230	600

Table 3. Medias Mass Finishing Characteristics

Name	Bundles	Sizes	Granularity, µm
Triangular prisms PT10	Polymeric	10×10	10-14
Porcelain bal		10	

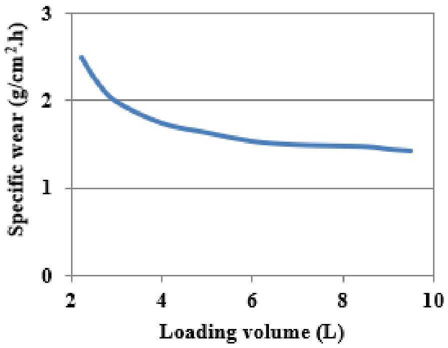

Fig. 4. Effect of work-chamber loading volume on the specific wear of porcelain balls used in the AMMF process

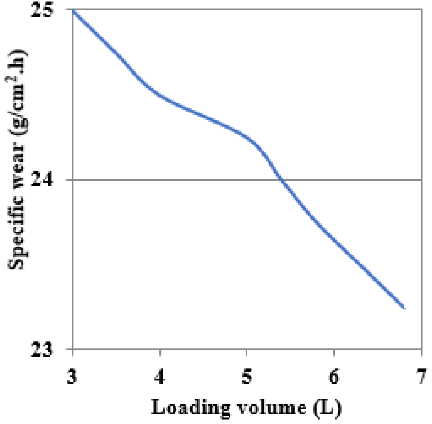

Fig. 5. Relationship between work-chamber loading volume and the specific wear of AMMF media in the form of triangular prisms (TP 10×10)

Figure 6 illustrates the relationship between AMMF wear and the shape factor of the triangular prism abrasives, which is defined as the ratio between the polygon angle at the prism base and the number of angles. The results demonstrate that AMMF wear decreases significantly as the shape factor increases from approximately 9 to about 12-13, after which the wear rate becomes nearly constant. This behavior indicates that the geometric characteristics of the abrasive media strongly influence their wear resistance. At lower shape factors, the sharper edges and smaller angles of the prism geometry generate higher localized stresses and more aggressive contact interactions with the workpiece and other media particles, which accelerates wear. As the shape factor increases, the abrasive particles exhibit more stable contact conditions and improved load distribution, thereby reducing the rate of material loss from the media. Beyond a certain value of the shape factor, further increases have minimal influence on wear, indicating that the abrasive geometry has reached a stable configuration in which wear mechanisms remain relatively unchanged.

Figure 7 shows the relationship between AMMF size and cutting capacity (g/cm².h). As the AMMF size increases from about 4 to 14, the cutting capacity rises for both materials, indicating that larger AMMF particles enhance material removal efficiency. However, Steel 1045 consistently exhibits higher cutting capacity than Aluminum alloy 2024 across all sizes. This suggests that the process is more effective when machining steel under the same conditions. The trend is nearly linear for both materials, but the slope for steel is steeper, meaning the improvement in cutting performance with increasing AMMF size is more significant for steel than for aluminum.

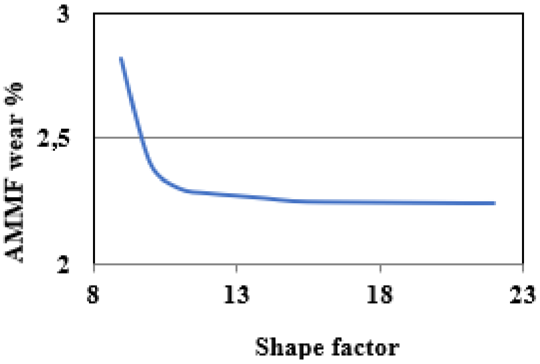

Fig. 6 Dependence of AMMF wear on the shape factor of triangular prism abrasive media

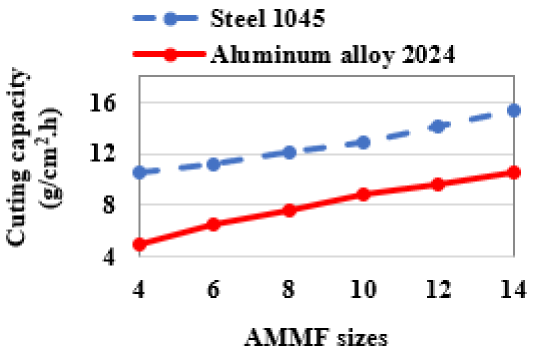

Fig. 7. Effect of polymer AMMF size on cutting capacity for Steel 1045 and Aluminum alloy 2024

Figure 8 illustrates the dependence of AMMF wear on its size. As the AMMF size increases (from around 5 to 30), the wear value also increases for

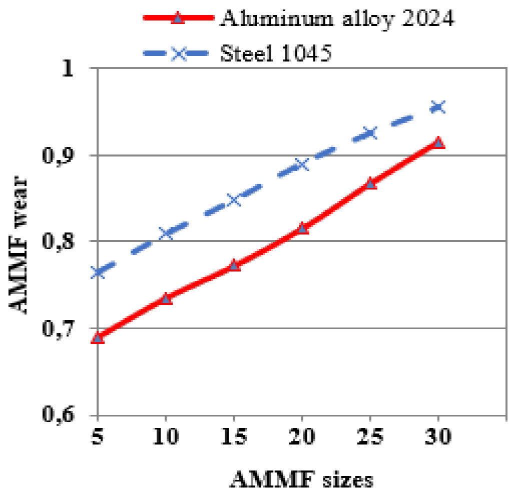

Fig. 8. Effect of polymer AMMF size on wear behavior for Steel 1045 and Aluminum alloy 2024

both materials. This indicates that larger AMMF particles, while improving cutting capacity, are more prone to wear. Steel 1045 again shows higher wear values compared to Aluminum alloy 2024 at all sizes, which implies that machining steel imposes greater stress on the AMMF, leading to faster degradation. The wear trend is gradual and consistent, suggesting a predictable increase in wear with size.

3. CONCLUSIONS

The present study demonstrated that the wear behavior of AMMF during VMFT was strongly influenced by several technological parameters, including the power mode, the ratio between the workpieces and abrasive media within the load mass, the loading volume, and the granularity and geometry of the abrasive media. The obtained results confirmed that AMMF represented one of the least reliable elements of the technological system because its progressive wear directly affected cutting capacity, process stability, and surface quality. The analysis of wear mechanisms revealed that abrasive grain blunting, bond failure, grain detachment, and media fragmentation contributed significantly to the deterioration of finishing performance. At the same time, limited self-sharpening phenomena partially compensated for cutting-edge degradation by generating new active abrasive surfaces. The experimental results further demonstrated that the wear of abrasive media directly influenced both the productivity of the vibroabrasive processing and the quality of the resulting surface layer. When the work-media volume decreased by approximately 15–20% as a consequence of wear, machining productivity decreased by an average of 12–18%, while the surface roughness increased by approximately 20–35%. In addition, process instability became more pronounced because of the deterioration in the kinematics of load motion within the work chamber. The results also showed that increasing the loading volume initially improved cutting performance by enhancing abrasive interactions; however, excessive loading reduced particle mobility and lowered cutting efficiency. Furthermore, larger AMMF sizes improved material removal rates but also accelerated abrasive wear, particularly during the machining of harder materials such as Steel 1045. The findings highlighted the importance of monitoring AMMF wear to maintain stable VMFT performance and consistent surface integrity. Based on the obtained results, partial or complete replacement of abrasive media was recommended when the batch mass loss exceeded 15%, when the reduction in high-frequency spectrum energy became greater than 25%, or when the surface roughness parameter (Ra) exceeded the permissible process limit. Such monitoring criteria could significantly reduce process instability and improve the reliability of industrial finishing operations. Although the study provided valuable insights into the relationship between AMMF wear and VMFT performance, it remained limited to a specific range of abrasive sizes, geometries, and operating conditions. Future research should therefore investigate a broader range of abrasive materials and media configurations, examine long-term operational behavior, and develop predictive models capable of accurately forecasting wear progression and process performance. Additional studies should also focus on improving abrasive durability through advanced material design, coatings, and optimized operating conditions that balance cutting efficiency with minimal media degradation.

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