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Directional surface finishing of additively manufactured components by dynamic machining with abrasive non-Newtonian fluids

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Abstract
Additive manufacturing (AM) has revolutionized component fabrication by enabling the efficient production of complex geometries and highly customized parts. However, a persistent challenge lies in the pronounced surface anisotropy inherent to AM processes, which can compromise the functional performance of finished components. Traditional post-processing techniques, such as vibratory finishing or sand blasting, lack the ability to selectively tailor surface features. Consequently, these conventional methods fall short when directional surface properties are critical to a component's intended function. Addressing this limitation is essential for realizing the full performance potential of AM-fabricated parts in advanced engineering applications. A promising solution to overcome these limitations is the targeted post-processing of AM surfaces with abrasive non-Newtonian fluids (NNF) combined with dynamic kinematic strategies. Compared to conventional fluids, NNF exhibit shear-dependent viscosity changes that enable customised abrasion through controlled variations in shear stresses resulting from specific geometries or component movements. By systematically adjusting the process kinematics, selective surface finishing can be achieved based on the desired orientation, which significantly improves control regarding the final surface properties. In the present study, NNF-assisted finishing with dynamic kinematics was applied to steel specimens produced by AM. In particular, the investigations focused on the correlation between the surface finishing and the build orientation as well as the process kinematics. The experimental findings confirmed that controlled motion profiles within abrasive NNF allowed direction-specific surface modifications with a significant improvement in surface roughness values. The results demonstrate the effectiveness of abrasive NNF in combination with optimised motion kinematics as an innovative finishing process for precise and direction-selective surface enhancements, which is specially designed to meet the high requirements of additively manufactured components.

Directional surface finishing, Abrasive non-Newtonian fluids, Additive manufacturing (LPBF)

1. Introduction

Additive manufacturing (AM) facilitates the fabrication of geometrically intricate and application-specific components [1]. The inherent layer-wise build-up process induces directional surface anisotropies, that may detrimentally affect functional performance. In addition, partially melted or sintered powder particles often remain fused to the surface after the LPBF process, further exacerbating surface irregularities and posing challenges for downstream applications. Conventional post-processing techniques frequently lack the precision and directional selectivity required to mitigate such effects effectively. In this context, abrasive non-Newtonian fluids (ANNF), notably shear-thickening fluids (STF), present a compelling alternative. STF exhibit a reversible, shear-induced viscosity enhancement [2], a phenomenon attributable to hydrodynamic clustering and friction-dominated interparticle interactions [3]. This dynamic response gives rise to transient, solid-like jammed states capable of transmitting mechanical stresses σ without direct material contact [4]. When coupled with controlled kinematic input, STF-based surface finishing permits highly selective, low-impact modification of complex topographies. Although STF-assisted polishing has demonstrated promising results in treating geometrically complex surfaces [5], its applicability to AM-fabricated components remains insufficiently explored. The present study examines the potential of motion-controlled ANNF-assisted finishing to enable directionally selective surface, with particular attention to unintended effects on non-targeted regions.

2. Material specification

The ANNF used in this investigation was formulated as a ternary mixture of deionized water (H_2O) as the carrier phase and native corn starch ($C_6H_{10}O_5$) as the shear-responsive thickening agent. The abrasive phase comprised the finishing medium HSC 1/300 from OTEC Präzisionsfinish GmbH, Straubenhardt, Germany, containing silicon carbide (SiC) with a characteristic particle size of $d_k = 80\ \mu m$ and crushed walnut shells with $0.8\ mm \leq d_k \leq 1.3\ mm$. All constituents were combined in equal mass fractions, measured using a high-precision scale PLS 1200, Kern and Sohn GmbH, Balingen, Germany. Cylindrical specimens with a nominal diameter of d = 12 mm and a height of h = 80 mm were additively manufactured from maraging tool steel X2NiCoMoTi18-9 (1.2709) via Laser Powder Bed Fusion (LPBF) on a 250 HL system from SLM Solutions Group AG, Lübeck, Germany. A laser power P = 275 W, scan speed of $v_s = 810$ mm/s, a hatch spacing of $h_s = 0.12$ mm and a focus offset of $x_F = 1.00$ mm were employed.

3. Experimental Method

The experimental setup was designed to apply controlled motion profiles on a 5-axis machining center C50 from Maschinenfabrik Berthold Hermle AG, Gosheim, Germany, in order to generate defined shear stress states τ during ANNF-assisted finishing. Tangential linear movement combined with specimen rotation was used to process the cylindrical surface M, whereas plunging motion along the specimen axis was intended to primarily act on the end surface E. The parameter configurations are presented in Figure 1. Each parameter set was applied to both motion variants and repeated three times to ensure reproducibility. The treatment time was $t_B = 60$ min. Surface modification was assessed by measuring the surface roughness Ra on both surfaces using a tactile profilometer Hommel-Etamic Nanoscan 855 from Jenoptik AG, Germany. To evaluate directional selectivity, both targeted surface modifications and collateral effects on non-targeted regions were systematically analysed. Morphological alterations were examined using scanning electron microscopy with a JCM-5000, JEOL NEOSCOPE, Tokyo, Japan, providing qualitative insight into surface integrity and the localised effects of the applied motion strategies.

4. Experimental investigation and results

Figure 1 shows the measured surface roughness Ra before and after ANNF-assisted finishing under controlled tangential and axial motion. Tangential kinematics consistently reduced Ra on the cylindrical surface M, with configuration 2 yielding both the greatest improvement and the lowest measured value at Ra = 3.62 µm. The end surface E remained largely unaffected, indicating high directional selectivity. Axial motion achieved a comparable reduction of Ra on the end surface E, with configuration 1 exhibiting the most significant improvement and configuration 3 reaching a minimum of Ra = 1.76 µm.

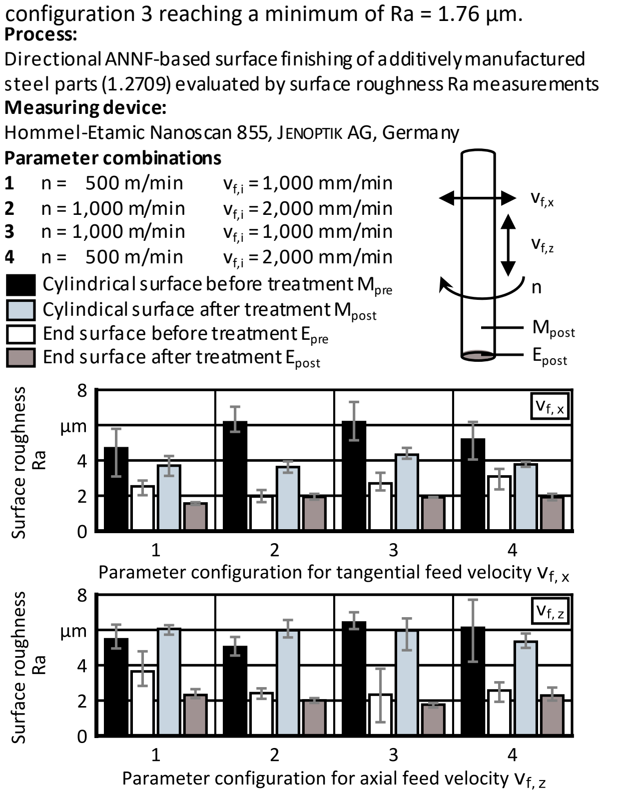

Figure 1. Results after ANNF-assisted finishing for different motion strategies and parameter configurations

A collateral smoothing effect on the cylindrical surface M was also observed. These trends reflect the spatial distribution of shear stresses τ within the ANNF, governed by the applied motion profiles. To assess directional selectivity, the influence of spindle speed n and feed velocity $v_{f,i}$ on the relative change in surface roughness ΔRa was analysed through a parameter-dependent trend evaluation for both motion directions, as shown in Figure 2.

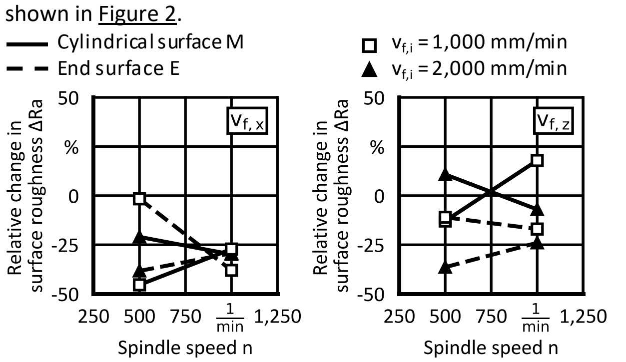

Figure 2. Influence of spindle speed n and feed velocity $v_{f,i}$ on the relative change in surface roughness ΔRa for tangential ($v_{i,x}$) and axial ($v_{i,z}$) motion during ANNF-assisted selective finishing

For tangential motion, surface improvement on the cylindrical surface M increases with spindle speed n, particularly at high feed velocity at $v_{f,x}$ = 1,000 mm/min. Collateral effects on the end surface E diminish with increasing spindle speed n. In contrast, vertical motion shows the most pronounced smoothing on the end surface E at low feeds and high spindle speeds of n = 2,000 m/min, while collateral effects on the cylindrical surface M intensify at elevated feed velocity $v_{f,z}$. These correlations confirm the parameter sensitivity of the finishing process and illustrate how directional selectivity can be adjusted through kinematic control. Figure 3 presents SEM-images of initial and post-processed surfaces following ANNF-assisted finishing. The untreated cylindrical surface M in Figure 3-a shows partially sintered particles and irregular melt track structures, characteristic of LPBF components. After tangential finishing in Figure 3-c, the surface appears homogenized, with flattened structures and significantly reduced particle residues. The untreated end surface E in Figure 3-b exhibits similar melt patterns and particle contamination, which are removed after axial finishing in Figure 3-d, resulting in a dense morphology. Local abrasion and layer blending indicate controlled ductile material removal.

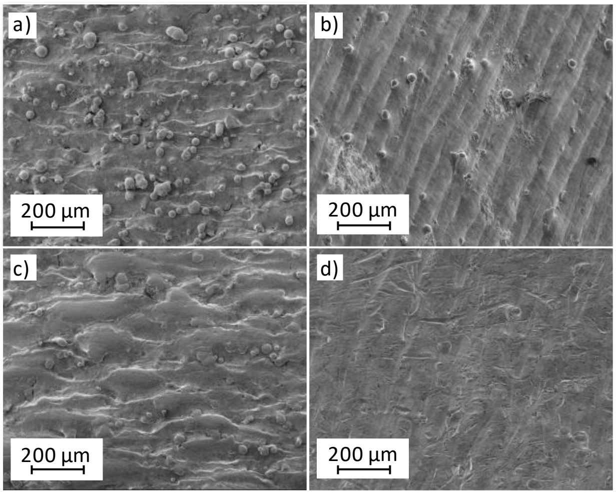

Figure 3. SEM images of the cylindrical surface M before (a) and after (c) tangential ANNF-assisted finishing (configuration 2), and the end surface E before (b) and after (d) axial ANNF-assisted finishing (configuration 1)

5. Conclusion and further investigations

The results demonstrate that ANNF-assisted finishing enables directionally selective surface modification of LPBF components. Tangential and axial motion selectively improved cylindrical M and end surfaces E, respectively. The influence of spindle speed n and feed velocity $v_{f,i}$ was evident on both targeted and collateral areas. Surface smoothing occurred via ductile removal. However, complete spatial decoupling remains challenging, underscoring the need for refined process control.

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