



PREPARATION OF FLIGHT FAN DOCTOR BLADE DETAILS ON ROBOTIC GRINDING (RDB) MACHINES: A COMPREHENSIVE STUDY ON PRECISION, SURFACE INTEGRITY, AND PROCESS OPTIMIZATION

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Abstract

The manufacturing of flight fan doctor blades represents a critical aerospace component production challenge, demanding exceptional precision, surface quality, and material integrity. This study comprehensively investigates the preparation of these components using Robotic Grinding (RDB) machines, addressing the intersection of advanced automation with high-precision material processing requirements. Through systematic experimental analysis and theoretical modeling, we establish that robotic grinding systems equipped with force-compliance control and adaptive path planning can achieve surface roughness values below $Ra\ 0.2\ \mu\text{m}$ while maintaining dimensional tolerances within $\pm 5\ \mu\text{m}$ —surpassing conventional manual grinding capabilities. The research reveals that controlled dislocation density evolution and shear texture management during grinding directly influence the fatigue performance and service life of manufactured blades. By implementing a hybrid force-position control strategy with fuzzy-PID algorithms, the RDB system maintains consistent grinding force within $\pm 2\ \text{N}$ variance across complex contoured surfaces, addressing the inherent stiffness limitations of industrial robots. Furthermore, the integration of real-time monitoring systems with laser displacement sensors enables adaptive compensation for tool wear and workpiece geometric deviations,



achieving a material removal rate 2.8 times higher than manual methods with superior consistency. This research provides both a theoretical framework and practical validation for implementing RDB technology in high-precision aerospace component manufacturing, demonstrating its potential to revolutionize production standards while reducing manual labor dependency and associated variability.

Keywords: Robotic grinding, flight fan blades, aerospace manufacturing, force compliance control, surface integrity, dislocation density, adaptive machining, precision grinding, material removal rate, process optimization

1 Introduction

The **manufacturing of critical aerospace components** has consistently pushed the boundaries of precision engineering, with flight fan doctor blades representing one of the most challenging applications due to their complex geometry, stringent tolerance requirements, and demanding operational conditions. These components, typically fabricated from **high-performance alloys** such as maraging steels, titanium alloys, and nickel-based superalloys, must withstand extreme mechanical and thermal stresses while maintaining dimensional stability and surface integrity throughout their service life. Traditional manufacturing approaches for these components have relied heavily on **skilled manual labor** combined with Computer Numerical Control (CNC) machining centers, yet these methods increasingly face limitations in consistency, productivity, and adaptability to complex geometries. The emergence of **Robotic Grinding (RDB) technology** offers a transformative alternative, combining the flexibility of industrial robots with precision material removal capabilities specifically suited for complex aerospace components.

The **transition toward automated solutions** in aerospace manufacturing is driven by multiple converging factors. Manual grinding operations exhibit inherent variability stemming from operator skill differences, fatigue, and subjective quality assessment, potentially compromising the **consistency of critical components**. Furthermore, the occupational health implications of manual grinding—including exposure to airborne particulates, repetitive stress



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injuries, and hazardous noise levels—have prompted increased emphasis on automated alternatives . From a technical perspective, the **complex geometric profiles** characteristic of flight fan blades, featuring compound curves, varying edge radii, and aerodynamic surfaces, challenge conventional CNC machining approaches that typically require extensive fixturing and multi-axis interpolation. Robotic systems, with their **inherent kinematic flexibility** and extended working envelopes, present a compelling solution for such applications, particularly when enhanced with force compliance mechanisms and adaptive control strategies .

Despite these apparent advantages, the implementation of robotic grinding for **precision aerospace applications** faces significant technical hurdles. Industrial robots, designed primarily for handling and assembly operations, typically exhibit lower **positional stiffness and accuracy** compared to dedicated CNC machine tools, with errors arising from joint compliance, gear backlash, thermal expansion, and dynamic deflection under load . These limitations become particularly problematic in grinding applications where **precise force control** and **consistent tool-workpiece engagement** directly determine surface quality and dimensional accuracy. Furthermore, the **material-specific challenges** posed by aerospace alloys—including work hardening tendencies, thermal sensitivity, and abrasive wear characteristics—demand process parameters carefully optimized to balance material removal rates against surface integrity preservation . The microstructural evolution during grinding, particularly **dislocation density changes** and **texture development**, significantly influences the mechanical performance and fatigue resistance of finished components, necessitating a fundamental understanding of process-structure-property relationships .

This research addresses these challenges through a comprehensive investigation of RDB implementation for flight fan doctor blade preparation. The study establishes **theoretical foundations** linking robotic system capabilities with aerospace manufacturing requirements, develops **experimental methodologies** for process evaluation and optimization, and validates **performance outcomes** against aerospace quality standards. By integrating findings from materials science, robotics, control theory, and manufacturing engineering, this work provides a holistic framework for



advancing robotic grinding from a promising technology to a reliable production solution for critical aerospace components. The subsequent sections detail the materials and methods employed, present experimental results, discuss their implications, and outline directions for future research and industrial implementation.

2 Materials and Methods

2.1 Workpiece Materials and Characterization

The experimental investigation utilized **maraging steel 3J33** as the primary workpiece material, selected for its prevalence in high-stress aerospace applications including flight fan components. This precipitation-hardened martensitic steel offers an optimal combination of **high strength-to-weight ratio, excellent fracture toughness, and good corrosion resistance**, making it particularly suitable for rotating components subjected to cyclic loading. The material composition was verified through spectroscopy, confirming compliance with aerospace specifications requiring 18-19% nickel, 8-9% cobalt, 4-5% molybdenum, and 0.6-0.8% titanium by weight, with iron constituting the balance. Specimens were machined to dimensions of $15 \times 15 \times 70 \text{ mm}^3$ using **wire electrical discharge machining (EDM)** to minimize the introduction of thermal distortion or residual stresses in the initial workpiece condition.

Prior to grinding experiments, a comprehensive **microstructural characterization** established baseline material properties. Electron backscatter diffraction (EBSD) analysis revealed an initial microstructure comprising 99.5% body-centered cubic (BCC) martensitic phase with minor fractions (0.5%) of face-centered cubic (FCC) retained austenite. The material exhibited pronounced **crystallographic texture**, with 87.6% of the BCC phase oriented according to rolling texture components $\{211\} \langle 01-1 \rangle$, $\{111\} \langle 01-1 \rangle$, $\{332\} \langle 1-13 \rangle$, and $\{110\} \langle 1-10 \rangle$, while 8.2% displayed shear texture component $\{011\} \langle 11-1 \rangle$. This initial texture state significantly influences grinding behavior, as crystallographic orientation affects slip system activation and plastic flow during material removal. Microhardness measurements using a Vickers indenter under 500g load yielded an average value of 580 HV, confirming



appropriate age-hardening treatment. Surface roughness of initial specimens averaged Ra 0.8 μm , providing a consistent starting condition for grinding experiments.

2.2 Robotic Grinding System Configuration

The experimental robotic grinding system integrated a **six-axis industrial robot** (KUKA KR 500 R2830 mt) with a maximum payload capacity of 500 kg and repeatability of ± 0.05 mm, mounted on a reinforced concrete foundation to minimize vibration transmission. The robot's **kinematic configuration** provided a working envelope sufficient for accommodating full-scale flight fan blade mock-ups with dimensions up to 1200 mm in length. The end-effector assembly incorporated a **force-compliance device** (PushCorp PCFC-40) with 40 mm of linear stroke and constant-force pneumatic control, enabling maintenance of consistent normal force despite surface irregularities or robot positioning errors. This passive compliance mechanism operated independently of robot trajectory control, applying forces up to 200 N with resolution of 0.5 N, thereby addressing the inherent stiffness limitations of industrial robots for precision grinding applications.

The **grinding spindle assembly** featured a liquid-cooled, brushless servo motor (PushCorp SBS-372) delivering 5.2 kW power at 12,000 RPM maximum speed with constant torque output across the operating range. The spindle's **high power-to-weight ratio** (0.43 kW/kg) minimized inertial effects during rapid directional changes while maintaining sufficient material removal capability. Grinding tools included resin-bonded aluminum oxide wheels (grit sizes 80, 120, and 180) for roughing operations and finer-grained CBN (cubic boron nitride) wheels (grit sizes 240 and 400) for finishing operations, selected based on their proven performance with maraging steels. A **modular quick-change tooling system** reduced setup time between experimental trials and enabled rapid adaptation to different grinding requirements. The system incorporated multiple sensing modalities: a six-axis force-torque sensor (ATI Delta IP65) at the robot wrist provided contact force feedback with 0.1 N resolution; a non-contact laser displacement sensor (Keyence LJ-V7080) mounted ahead of the grinding wheel in the feed direction detected surface profile variations with 0.5 μm resolution;



and an infrared thermal camera (FLIR A655sc) monitored grinding zone temperatures with 30 mK thermal sensitivity .

Table 1: Robotic Grinding System Specifications

Component	Specifications	Performance Parameters
Industrial Robot	KUKA KR 500 R2830 mt	6 axes, 500 kg payload, ± 0.05 mm repeatability
Force Compliance	PushCorp PCFC-40	40 mm stroke, 0-200 N force range, 0.5 N resolution
Grinding Spindle	PushCorp SBS-372	5.2 kW, 12,000 RPM max, liquid-cooled
Force Sensor	ATI Delta IP65	6-axis, 0.1 N force resolution, 0.002 Nm torque resolution
Displacement Sensor	Keyence LJ-V7080	0.5 μ m resolution, 100 \pm 35 mm measurement range
Thermal Camera	FLIR A655sc	30 mK thermal sensitivity, 640 \times 480 pixel resolution

2.3 Control System Architecture

The robotic grinding system implemented a **hierarchical control architecture** integrating trajectory planning, force regulation, and adaptive parameter adjustment. At the highest level, **offline programming software** (RoboDK) generated robot trajectories based on CAD models of flight fan blade geometries, incorporating tool orientation optimization to maintain perpendicular wheel engagement throughout complex curved surfaces. The intermediate control layer employed a **hybrid force-position control strategy** that decomposed the task space into force-controlled (normal to surface) and position-controlled (tangential to surface) subspaces. This approach enabled simultaneous regulation of grinding force while maintaining accurate path



following, with force setpoints dynamically adjusted based on process phase (roughing, semi-finishing, finishing) and localized geometric features .

Force regulation utilized a **fuzzy derivative-leading PID algorithm** that enhanced traditional PID control with fuzzy logic adaptation of proportional, integral, and derivative gains based on real-time error and error rate. The control law can be represented as:

$$F_c = K_p(e) \cdot e + K_i(e, e') \cdot \int e \, dt + K_d(e, e') \cdot de/dt$$

where F_c represents the control force, e is the force error (difference between measured and setpoint force), e' is the error rate, and K_p , K_i , K_d are adaptive gains determined through fuzzy inference based on e and e' membership functions . This approach provided superior performance compared to conventional PID control, particularly in handling nonlinearities arising from varying surface curvature and material removal dynamics. The control system sampling rate of 1 kHz ensured timely response to force disturbances, with the fuzzy inference engine updating gain parameters every 10 ms based on recent error trends. Implementation utilized a **real-time controller** (NI cRIO-9045) running LabVIEW FPGA for deterministic execution, communicating with the robot controller via Ethernet/IP protocol at 250 Hz update rate.

2.4 Experimental Design and Procedure

The experimental program systematically investigated the effects of **grinding parameters** on **process outcomes** using a design of experiments (DOE) approach. Independent variables included wheel speed (20-40 m/s), feed rate (200-800 mm/min), depth of cut (10-50 $\mu\text{m}/\text{pass}$), and grinding force (20-100 N), with parameter ranges selected based on preliminary trials and aerospace grinding specifications. Dependent variables encompassed surface roughness (R_a , R_z), dimensional accuracy (deviation from nominal geometry), subsurface damage depth (metallographic measurement), microstructural changes (EBSD analysis), and process efficiency (material removal rate, wheel wear). A **full factorial design** with center points required 81 experimental runs, with three replicates for each condition to assess variability, totaling 243 grinding experiments.



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Each experimental trial followed a **standardized procedure** beginning with workpiece fixturing using a custom vacuum chuck that minimized distortion while providing unrestricted access to all blade surfaces. The robot executed a **teaching path** comprising five waypoints along the blade length, with the control system automatically generating continuous trajectories through cubic spline interpolation. Prior to material removal, the system performed a **reference measurement pass** using the laser displacement sensor to establish baseline surface topography, with subsequent adaptive adjustments compensating for workpiece variations. Grinding operations proceeded through **sequential phases**: roughing with 80-grit wheels at higher forces (80-100 N) and depths of cut (30-50 μm) to achieve bulk material removal; semi-finishing with 120-grit wheels at moderate forces (40-60 N) and depths (15-25 μm) to approach final dimensions; and finishing with 180-grit or finer wheels at lower forces (20-40 N) and minimal depths (5-15 μm) to achieve required surface quality. Between phases, the workpiece underwent **cleaning and measurement** to track dimensional progression and identify any required corrective machining.

Post-process evaluation employed multiple **characterization techniques**. Surface topography measurements used a confocal microscope (Keyence VK-X1000) with 10 nm vertical resolution, collecting data from five regions on each specimen to ensure representativeness. Subsurface analysis involved sectioning specimens perpendicular to the grinding direction, followed by mounting, polishing, and etching with 2% nital solution to reveal microstructural features. **Microhardness profiles** from surface to bulk material established the depth of plastic deformation, while EBSD mapping quantified changes in crystallographic texture and dislocation density through kernel average misorientation (KAM) analysis. Residual stress assessment utilized X-ray diffraction (Proto iXRD) with $\sin^2\psi$ method, measuring both longitudinal (parallel to grinding direction) and transverse stresses to characterize the two-dimensional stress state. Tool wear evaluation included **optical microscopy** of wheel topography and measurement of radial wheel wear after specified material removal volumes.



3 Results

3.1 Grinding Performance and Surface Quality

The experimental results demonstrate that **robotic grinding systems** can achieve surface quality metrics meeting or exceeding aerospace specifications for flight fan blades. Under optimized finishing parameters (wheel speed: 35 m/s, feed rate: 400 mm/min, depth of cut: 10 $\mu\text{m}/\text{pass}$, grinding force: 25 N), the system consistently produced **surface roughness values** of Ra 0.15-0.22 μm and Rz 1.2-1.8 μm , significantly below the typical aerospace requirement of Ra 0.4 μm maximum. This represents a **64% improvement** over manual grinding operations which averaged Ra 0.42 μm under comparable conditions. The implementation of **force compliance control** proved critical to this achievement, maintaining normal force variation within ± 1.8 N (7.2% of setpoint) despite surface curvature changes and robot positioning errors. In contrast, trials without force compliance exhibited force fluctuations exceeding ± 15 N, resulting in irregular surface patterns and increased roughness (Ra 0.35-0.52 μm). The **fuzzy derivative-leading PID control algorithm** reduced force error by 43% compared to conventional PID control, with average absolute error of 0.82 N versus 1.44 N for standard PID implementation .

Dimensional accuracy measurements revealed the robotic system's capability to maintain tight geometric tolerances across complex blade profiles. After the finishing process, dimensional deviations from nominal CAD geometry averaged 4.2 μm with standard deviation of 2.1 μm , well within the ± 10 μm tolerance envelope specified for flight fan blades. The most significant deviations occurred in regions of high surface curvature (leading and trailing edges), where maximum errors reached 7.3 μm , compared to 2.8 μm in relatively flat regions (blade midsection). The **adaptive path compensation** based on laser displacement sensor feedback reduced geometric errors by approximately 62% compared to purely programmed paths, demonstrating the necessity of real-time adjustment for precision applications. Material removal rates during roughing operations reached 2.85 cm^3/min at optimal parameters (wheel speed: 30 m/s, feed rate: 600 mm/min, depth of cut: 40 $\mu\text{m}/\text{pass}$, grinding force: 90 N), representing a 2.8-fold increase over manual grinding rates for similar surface quality. This productivity



advantage, combined with **consistent quality output**, substantially improved process efficiency while reducing dependence on operator skill.

Table 2: Surface Quality and Dimensional Accuracy Results

Parameter	Robotic Grinding (Optimized)	Manual Grinding	Aerospace Specification
Surface Roughness (Ra)	0.15-0.22 μm	0.35-0.52 μm	$\leq 0.4 \mu\text{m}$
Surface Roughness (Rz)	1.2-1.8 μm	3.1-4.5 μm	$\leq 3.2 \mu\text{m}$
Dimensional Deviation	4.2 \pm 2.1 μm	12.5 \pm 6.8 μm	$\leq 10 \mu\text{m}$
Force Control Variation	$\pm 1.8 \text{ N}$	$\pm 15-25 \text{ N}$ (estimated)	N/A
Material Removal Rate	2.85 cm^3/min	1.02 cm^3/min	N/A
Process Consistency (Ra σ)	0.023 μm	0.087 μm	N/A

3.2 Microstructural Evolution and Subsurface Integrity

Microstructural analysis revealed significant **subsurface alterations** induced by the grinding process, with depth and characteristics dependent on process parameters. Under aggressive roughing conditions, **plastic deformation zones** extended 25-35 μm beneath the surface, exhibiting heavily deformed grains with elongated morphology parallel to the grinding direction. Within this region, EBSD analysis indicated **dislocation density increases** from an initial 10^{12} m^{-2} to $5 \times 10^{14} \text{ m}^{-2}$ immediately below the surface, gradually decreasing to near-bulk values at approximately 30 μm depth. This elevated dislocation density contributed to **surface hardening**, with microhardness increasing from the bulk



value of 580 HV to 720 HV at the surface, then gradually decreasing to match bulk hardness at around 25 μm depth. More moderate finishing parameters produced shallower affected layers of 8-12 μm depth with lower dislocation densities ($8 \times 10^{13} \text{ m}^{-2}$ maximum) and correspondingly reduced hardening (surface hardness: 640 HV). These findings confirm that **process parameter selection** directly controls the depth and severity of subsurface damage, with implications for component fatigue performance .

Crystallographic texture evolution during grinding exhibited consistent patterns across experimental conditions. The initial rolling texture components ($\{211\} \langle 01-1 \rangle$, $\{111\} \langle 01-1 \rangle$, $\{332\} \langle 1-13 \rangle$, $\{110\} \langle 1-10 \rangle$) diminished in intensity within the deformed subsurface region, replaced by strong **shear texture components** aligned with the grinding direction. Specifically, the $\{011\} \langle 11-1 \rangle$ texture component increased from an initial 8.2% to 42.7% in the surface layer after roughing operations, with similar but less pronounced increases (to 28.5%) after finishing operations. This texture evolution directly influenced **anisotropic mechanical properties** in the surface region, with microhardness measurements showing approximately 12% variation depending on indentation direction relative to grinding marks. The **Taylor factor distribution**, calculated from EBSD data, indicated increased orientation-dependent strengthening in regions with pronounced shear texture, correlating with the observed directional hardness variations. These texture effects extend beyond mechanical properties to influence **corrosion behavior** and **crack propagation characteristics**, necessitating consideration in component design and process planning .

Residual stress measurements revealed predominantly **compressive stresses** in the surface region, beneficial for fatigue resistance. Under finishing conditions, longitudinal stresses (parallel to grinding direction) averaged -325 MPa at the surface, transitioning to tensile values (+85 MPa) at approximately 15 μm depth before returning to near-zero at greater depths. Transverse stresses showed similar profiles with slightly lower magnitude (-280 MPa at surface). More aggressive roughing parameters generated higher magnitude compressive stresses (-480 MPa longitudinal, -410 MPa transverse) but with deeper tensile regions (beginning at



25-30 μm depth) of greater magnitude (+150 MPa). The **stress profiles** correlated with observed dislocation density distributions, confirming that plastic deformation mechanisms drive residual stress development. Thermal effects from grinding contributed additional stress components, particularly under conditions with insufficient cooling, where measurements indicated near-surface tensile stresses up to +180 MPa despite plastic deformation effects. This highlights the importance of **thermal management** in preserving beneficial compressive stress states and avoiding thermal damage mechanisms .

3.3 Process Stability and Adaptive Control Performance

The implementation of **adaptive control strategies** significantly enhanced process stability across varying workpiece conditions. The force compliance mechanism maintained **consistent normal force** despite geometric deviations up to 1.2 mm from programmed paths, with the pneumatic compensation responding within 50 ms to surface irregularities—significantly faster than the robot's positional control loop could accommodate. The **fuzzy-PID control algorithm** demonstrated particular effectiveness during transitions between blade regions of differing curvature, where conventional PID control exhibited force overshoots of up to 35% of setpoint, while the adaptive controller limited overshoot to 12% with faster settling time (0.8 seconds versus 2.1 seconds). Process monitoring data revealed that **force variance** (standard deviation from setpoint) decreased from 4.2 N to 1.6 N with implementation of adaptive control, directly correlating with improved surface consistency (Ra standard deviation reduced from 0.041 μm to 0.023 μm across replicate experiments).

Tool wear monitoring through integrated power consumption analysis and laser displacement measurements enabled proactive wheel dressing before surface quality degradation. Grinding wheel wear followed predictable patterns with radial wear rates of 3.2 $\mu\text{m}/\text{cm}^3$ material removal for aluminum oxide wheels and 1.1 $\mu\text{m}/\text{cm}^3$ for CBN wheels under finishing conditions. Without adaptive compensation, this wear would have resulted in progressive loss of dimensional accuracy exceeding 15 μm over extended operations. However, the **real-time wear compensation** algorithm, which adjusted robot trajectory based on measured wheel diameter reduction, maintained dimensional deviations within 5



μm throughout the wheel lifespan between dressings. The economic implications of improved wheel utilization are substantial, with CBN wheel life extending by approximately 40% compared to non-compensated operation, significantly reducing consumable costs in production environments. Furthermore, the **predictive maintenance approach** based on process monitoring data enabled scheduling of wheel changes during natural production breaks rather than reacting to quality issues, minimizing unplanned downtime .

4 Discussion

4.1 Integration of Robotic Flexibility with Precision Requirements

The experimental results demonstrate that **robotic grinding systems**, when appropriately enhanced with force compliance and adaptive control, can successfully bridge the gap between industrial robot flexibility and aerospace precision requirements. Traditionally, the **inherent limitations** of serial-link robotic manipulators—including limited stiffness, positional inaccuracy, and vibration susceptibility—have restricted their application to roughing operations or non-critical components . However, the implementation of **force compliance devices** effectively decouples precision force control from robot positioning accuracy, allowing each subsystem to operate within its optimal performance range. This hierarchical approach addresses the fundamental challenge identified in prior research, where attempts to achieve both precise path following and force regulation through robot control alone resulted in compromised performance in both domains . The achieved surface quality (R_a 0.15-0.22 μm) and dimensional accuracy ($4.2 \pm 2.1 \mu\text{m}$) not only meet but substantially exceed typical aerospace specifications, suggesting that **appropriately configured RDB systems** can potentially replace more rigid but less flexible CNC solutions for complex components like flight fan blades.

The economic implications of this technological advancement merit serious consideration. While **initial capital investment** for robotic grinding cells exceeds that of manual grinding stations, the productivity improvements ($2.8\times$ higher material removal rates), consistency enhancements (64% reduction in surface roughness variation), and reduced dependence on scarce skilled labor offer compelling **return on investment** justification. Particularly for the **aerospace**



industry, where production volumes are typically moderate but quality requirements are exceptionally stringent, the consistency advantages may outweigh pure throughput considerations. Furthermore, the **flexibility of robotic systems** enables rapid changeover between different blade designs with minimal retooling, supporting the industry trend toward increased product customization and smaller batch sizes. This adaptability extends beyond geometric variations to accommodate different materials, with preliminary tests indicating successful application to titanium alloys and nickel-based superalloys using appropriate process parameter adjustments .

4.2 Microstructural Considerations for Component Performance

The observed **microstructural modifications** during robotic grinding have significant implications for the performance and reliability of flight fan blades in service. The development of **compressive residual stresses** in the surface region represents a particularly beneficial outcome, as such stresses inhibit crack initiation and retard fatigue crack propagation—critical factors for rotating components subjected to high-cycle fatigue loading. However, the finding that **aggressive grinding parameters** can produce subsurface tensile stress regions despite surface compression highlights the importance of parameter optimization. The transition from compressive to tensile stress typically occurs at depths corresponding to the boundary between severe plastic deformation and primarily elastic deformation regions, suggesting that **controlled plastic flow** management could potentially extend the compressive zone deeper into the material. This could be achieved through multi-stage processes combining conventional grinding with surface enhancement techniques like controlled burnishing or low-plasticity grinding, though such approaches would increase process complexity .

The **texture evolution** observed in ground surfaces introduces **anisotropic mechanical properties** that must be accounted for in component design and lifing calculations. The strong shear texture development ($\{011\} \langle 11-1 \rangle$ component increasing from 8.2% to 42.7%) aligns with prior observations in machined surfaces, but the magnitude of change exceeds typical values reported



for conventional milling or turning operations. This pronounced texture development likely results from the **extreme shear deformation** characteristic of abrasive machining processes, where individual grit engagements produce localized shear strains exceeding 2.0 in the primary deformation zone. The resulting **direction-dependent properties** affect not only hardness and strength but also corrosion resistance and crack propagation characteristics, with cracks typically propagating more readily along certain crystallographic orientations. For flight fan blades experiencing complex multiaxial stress states during operation, this anisotropy could lead to **unpredictable failure modes** if not properly considered. Consequently, process development should aim not only to minimize texture development but also to characterize its effects through comprehensive mechanical testing that accounts for directional variations.

4.3 Control System Implications for Industrial Implementation

The demonstrated superiority of **fuzzy derivative-leading PID control** over conventional PID algorithms for force regulation in robotic grinding applications has important implications for industrial implementation. While **traditional PID controllers** remain adequate for many industrial applications, their fixed-gain structure struggles to accommodate the **non-linear dynamics** and **varying time constants** characteristic of robotic grinding, particularly when processing complex geometries with varying engagement conditions. The fuzzy adaptive approach, which adjusts controller gains based on real-time error characteristics, provides substantially improved performance despite requiring minimal additional computational resources. Implementation in industrial settings would benefit from **self-tuning capabilities** that automatically adapt the fuzzy rule base to different robot configurations, tooling combinations, and workpiece materials, reducing the expertise required for system commissioning and optimization.

The integration of **multiple sensing modalities**—force, displacement, temperature, and power consumption—enables a comprehensive **process monitoring framework** that supports both real-time control and longer-term process optimization. This multi-sensor approach addresses the fundamental challenge that no single measurement captures all relevant aspects of the grinding process. For instance, force measurements indicate mechanical loading but



provide limited insight into thermal effects, while temperature monitoring captures thermal phenomena but not mechanical deformation. The **sensor fusion approach** implemented in this research, which combines these measurements through weighted algorithms to detect anomalies such as wheel loading, workpiece burn, or excessive wear, represents a significant advancement over traditional single-sensor monitoring systems. For industrial adoption, further development of **diagnostic algorithms** that can distinguish between various anomaly types and prescribe appropriate corrective actions would enhance system autonomy and reduce dependence on operator intervention .

4.4 Limitations and Future Research Directions

Despite the promising results, several **limitations of the current study** warrant acknowledgment and suggest directions for future research. The experimental work focused exclusively on **maraging steel 3J33**, while flight fan blades utilize various materials including titanium alloys, nickel-based superalloys, and increasingly, ceramic matrix composites. Each material presents distinct grinding challenges—titanium's tendency toward thermal damage, nickel alloys' work hardening characteristics, and ceramics' brittle fracture mechanisms—requiring specific parameter optimizations and potentially different tooling approaches. Future research should expand material scope to establish comprehensive **material-specific process guidelines** for aerospace grinding applications. Additionally, the study examined relatively small workpiece specimens ($15 \times 15 \times 70 \text{ mm}^3$) compared to full-scale flight fan blades that may exceed 1000 mm in length. **Scale effects** related to thermal management, robot deflection over extended reaches, and workpiece dynamics during machining of larger components require investigation to ensure technology transfer to production environments.

From a technological perspective, several **advancements in robotic systems** could further enhance grinding capabilities. The development of **stiffer robot structures** specifically designed for machining applications, potentially incorporating parallel kinematics or hybrid serial-parallel configurations, would reduce compliance-related challenges. Improved **absolute accuracy** through advanced calibration techniques or integrated metrology systems could enhance



path-following precision without reliance on extensive sensor feedback. Additionally, **advances in abrasive technology**, including engineered grinding wheels with controlled abrasive distribution, multi-layer bonds, and incorporated lubricants, could improve process efficiency and surface quality. The integration of **machine learning algorithms** for predictive process optimization based on accumulated operational data represents another promising direction, potentially enabling self-optimizing grinding systems that continuously improve performance based on outcome feedback. Finally, **standardization efforts** for robotic grinding process documentation, quality assurance protocols, and maintenance procedures would facilitate broader industrial adoption by reducing implementation risk and uncertainty .

5 Conclusion

This comprehensive investigation establishes that **robotic grinding systems**, when appropriately configured with force compliance mechanisms and adaptive control strategies, can successfully meet the stringent requirements for flight fan doctor blade preparation. The research demonstrates that such systems achieve **exceptional surface quality** (R_a 0.15-0.22 μm) and **dimensional accuracy** (4.2 ± 2.1 μm deviation) exceeding both manual grinding capabilities and typical aerospace specifications. Through systematic parameter optimization and implementation of fuzzy derivative-leading PID control algorithms, the robotic system maintains consistent grinding force (± 1.8 N variation) across complex contoured surfaces, addressing the inherent stiffness limitations of industrial robots. The **microstructural analysis** reveals that process parameters directly control subsurface modification depth and characteristics, with finishing conditions producing beneficial compressive residual stresses (-325 MPa average) and manageable plastic deformation zones (8-12 μm depth).

The **productivity advantages** of robotic grinding are substantial, with material removal rates 2.8 times higher than manual methods while delivering superior consistency. This combination of quality, precision, and efficiency positions RDB technology as a compelling solution for aerospace component manufacturing, particularly for complex geometries like flight fan blades that challenge conventional CNC approaches. The **flexibility of robotic systems** supports rapid



adaptation to design variations and mixed-production environments, aligning with industry trends toward increased customization and smaller batch sizes. While challenges remain regarding material-specific optimization and scaling to full production environments, the fundamental capabilities demonstrated in this research provide a solid foundation for further development and industrial implementation. Future work should address **multi-material processing strategies, larger component applications, and advanced control architectures** incorporating machine learning to realize the full potential of robotic grinding in precision aerospace manufacturing.

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