Surface texturing of fan-blade body by random-orbital polishing with in-line aqueous mist

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Abstract

Mechanical polishing is the most common process to remove surface irregularities on fan blades such as scallop height features, while maintaining the required dimensional limits and textures. After the polishing process, the part will undergo shot peening, vibratory finishing, and later painting and coating at the final stages. It is therefore essential for the fan blade surface to be pre-treated with appropriate surface conditions to promote good surface-to-surface adhesion at the end of the manufacturing cycle. The existing method uses a single-axis rotary polishing tool where an external water coolant source is performed ad-hoc. This polishing method can produce average surface roughness, \( Ra \), of 1.0 \( \mu \)m that satisfies the requirement. However, this form is aggressive and has a high material removal rate, resulting in excessive reduction in material thickness, and thus warrants rejection of costly fan blade. The main objective of this study is to better understand the influence of water and air coolant-induced surface texturing and its characterization by a proposed random-orbital polishing method. The criteria require surface roughness, \( Ra \), between 0.8 and 1.0 \( \mu \)m and maximum height profile, \( Rz \), between 5.0 and 6.0 \( \mu \)m for post-polishing condition, while maintaining low material removal rate to prevent under-thickness of the fan blade. Experimental trials are performed on fan blade specimens at the leading-edge sections and its surface topography characterized by coherence correlation interferometry. A range of different abrasive grit sizes is tested for suitability of media selection. Integrating in-line cooled air with deionized water to the process achieved desirable surface roughness, \( Ra \), of 0.8 \( \mu \)m and height profile, \( Rz \), of 5.8 \( \mu \)m, while simultaneously removing all traces of scallop height features and maintaining the leading-edge thickness within tolerance. Taking into consideration that the surface texture measurements are random in nature, the corresponding polishing methods were also analyzed with statistical functions by fast Fourier transform (FFT) and power spectral density (PSD). Comparison between the surface texture parameters or statistical functions with the corresponding polishing methods are then established. The surface integrity of the polished fan blade and wear condition of the abrasive disk are also reported in this study.

Keywords Random-orbital polishing · Finishing · Surface texture · Airfoil · Fan blade

1 Introduction

Free form surfaces of machined fan blades have smooth textures before subsequent processes such as shot peening and vibratory finishing. Sometimes, poor machining output will produce defects such as scallop height features. Surface peaks are sharp and considered stress concentration where cracks may be initiated and subsequently propagate, causing fatigue failure—which is non-compliance of airworthiness standards for fan blade components in aero-engines. Therefore, surface defects must be removed, typically by mechanical polishing while attaining the required surface finish and thickness dimension. The existing production method of polishing fan blade deploys the use of a single-axis rotary tool with abrasive grit size of P320 and application of deionized water to cool and clean the part. This type of tool has a singular rotational movement where the abrasive pad spins primarily around its axis. The challenge of using a rotary polishing tool is the generation of lay in the surface texture which is detrimental to the functionality of the part. The other challenge is high rate of material removal which would result in edge thinning (under-thickness) of the fan blade.
Abrasive disk motion is the determining factor for effective polishing by generating the required surface roughness. Axinte et al. [1] used belt polishing for final finishing of components to improve dimensional precision and surface quality. Xiao et al. [2] developed a similar abrasive belt polishing method for blades to achieve the desired surface properties. A proposed polishing method by random-orbital motion is proposed for the fan blade polishing. Random-orbital disk moves in two directions as opposed to one direction. This tool uses a mechanism that causes the disk to simultaneously rotate in a circle and oscillate in an eccentric pattern inside the circle to generate the vibration amplitude. Therefore, the mechanical action of the abrasive by random orbit is vibratory motion instead of fixed rotation. Mechanical polishing may be performed either in dry or wet condition and with or without air-cooling. Surface topography of the roughness value is usually based on the $R_a$ parameter and may be influenced by different conditions. Wu et al. [3] used flexible abrasive cloth wheel to polish titanium alloy blades in dry condition. The results showed that unevenness and other defects of the blade surface are effectively removed and the dry method effectively improved the surface roughness without exceeding the dimensional limits of the workpiece. The surface roughness is reduced from $R_a$ of 1.2 to less than 0.40 μm.

Surface roughness is influenced by the properties of friction of fixed abrasives lubricated by water. When deionized water is applied to the abrasive material, slurry is formed, corresponding to the abrasive mechanism in chemical mechanical polishing. The relative movement of the slurry drawn between the polished surface and the pad creates the material removal mechanism [4]. In some studies, the effect of dry and wet polishing showed that polishing without water increased the surface roughness of the samples because the abrasive grains detached from the polishing tool may embed into the workpiece surface [5]. Wong et al. [6] investigated the effect of surface roughness on frictional characteristics in deionized water. It is discovered that the friction coefficient and surface roughness decreased with sliding distance in the materials tested with deionized water.

The effects of impinging air jets by compressed cold air have been studied by Choi [7]. It was reported that the effectiveness of the cold air in reducing thermal defects was almost similar to that with liquid coolant with negligible material loss. The formation of tensile stresses in the surface was more evident, and surface roughness would rise as the depth of cut increases. It was found that the lack of liquid coolant in using dry cold air was almost certainly the main reason for this phenomenon to occur. The application of cold air showed some improvements compared with dry polishing. However, many important points of surface characterization have not been closely examined [8].

Saberi et al. [9] used a grinding technique called minimum quantity lubrication (MQL) technique by compressed cold air jet from a cold gun (vortex tube principle). This technique involved spraying a mixture of air and oil mist onto the cutting zone directly. MQL improved cooling and lubrication performance through the use of a cold gun which generated conditioned air at lower temperatures than ambient. The study of cooling effect with minimum quantity lubrication with air jet of 0.4 MPa pressure and 14°C temperature concluded that surface quality improved when compared to dry condition. Because of this reason, a condition has been set aside in this study to deploy the MQL technique and verify its combined effect (of water and air).

Use of pure air is another alternative, but it has relatively poor cooling ability which may lead to low specific heat and low heat conductivity. Due to low mass flow rate of air streams (measured at 1.0 m/s) exiting the holes in the abrasive disk, the heat transfer coefficient will be smaller, regardless of its low temperature.

Design configuration of the abrasive end effector varies from circular wheels or belt types to cylindrical or conical grinding heads. For the circular type of wheels (round-shaped disk), a foam or inflatable backing pad may be used for flexibility on the free form geometry [10]. Axinte et al. [11] demonstrated that combining dual finishing methods (belt and bob) as a hybrid process would be beneficial for components with complex geometries, removing both machining marks and achieving required surface roughness to some extent. Zhao et al. [12] optimized the key process parameters for polishing of aero-engine blades to reduce the surface roughness and improve quality of the finish.

This paper presents the feasibility of using random-orbital polishing with an in-line cooling system for surface texturing of defective aero-engine fan blade in terms of improving quality and cost. The aim of this study is to analyze the effects of cold air, and water on random-orbital polished surfaces, including the impact on the abrasive disk life. Roughness measurement is used for surface topography characterization in pre- and post-condition. The fast Fourier transform (FFT) and power spectral density (PSD) functions are also used to evaluate the effects between the rotary and random-orbital polished surfaces. This provides the statistical information to understand the differences or relationship between the various methods.

2 Materials and methods

In practice, rotary polishing is accepted as the most common method to remove surface irregularities and achieve a uniform finish. Geometrical features and texture parameters of a properly polished surface depend on selection of the polishing method for the target workpiece material. The analytic work assigned for this study compares the measured surface textures and features of aluminum fan blades processed by four conditions of random-orbital polishing and one condition of rotary polishing.
2.1 Workpiece material

The workpiece material of the fan blade specimens is made from aluminum alloy 7255-T7751. All specimens have similar scallop height features at the leading edge. The material composition is shown in Table 1.

2.2 Abrasive material

Aluminum oxide ($\text{Al}_2\text{O}_3$) media is selected for the polishing trials. Because the composition of aluminum oxide is more compatible to the workpiece material (aluminum alloy), silicon carbide is not considered for the experimental trials. Aluminum oxide has a very hard crystal structure with a Mohs value of 9. This strength enables the abrasive to be slowly dulled and hard to fracture, making it suitable for polishing. The aluminum oxide-coated abrasive disks are supplied by VSM abrasives (part number KK712J), and each disk used for the random orbital tool measures 127 mm in diameter with holes to allow air and water to pass through.

For the rotary tool, the abrasive disk measures 102 mm in diameter with no holes. A total of five grit sizes (P120, P180, P240, P320, and P400) are selected for the random-orbital trials. The grit classification has been established by the association of European abrasive manufacturers (FEPA) where P is the international standard of the FEPA. The grain size of the abrasive grit number is shown in Table 2.

2.3 Equipment material

A standard cold gun system (ExAir model 5215) with a single outlet is used. As shown in Figure 1, the cold gun module generates two streams at different temperature from a single compressed injection. The cold gun separates the compressed air into two opposite directions, where hot air is exhausted from the rear end and forcing the cold air at the front end due to the lowered pressure gradient at the cold section [13]. The cold gun is continuously activated by a foot pedal switch throughout the process cycle time of 9 min per section at an outlet pressure of around 172 kPa.

This enabled the random-orbital tool to flow multiple streams of cold air out of the holes in the disk. By adjusting the incoming air pressure at the regulator at 620 kPa, the cold gun maintained an air pressure of 300 kPa in-line and 172 kPa at the outlet port to the tube. The rate of cold air flow escaping out if the abrasive disk holes in running operation is measured at 1.0 m/s using a standard anemometer.

2.4 Experimental methodology

The existing method uses a single-axis rotary grinder, Toku model TAG400 with an abrasive disk of P320 grit size. The air pressure is fixed at 620 kPa, and the speed is set at 10,000 rpm. As shown in Figure 2a, a plastic squeeze bottle sprays deionized water on the surface for spot cooling, at 3-min intervals over a total process time of 9 min. The random-orbital method uses a dual-axis Dynorbital® tool (model number 57583). Figure 2b shows the random-orbital tool with in-line air-cooling and water spray.

The 9-min process time is a standard operating procedure established by the existing method. Therefore, the experimental plan follows this fixed standard time. All specimen sections are polished in stationary condition with 50% of the abrasive disk diameter ($126 \text{ cm}^2$) making contact to the leading-edge surface and the remaining 50% over-hang. This is because of the curvature of the fan blade and flexibility of the backing pad which limits full contact surface. The backing pad is made of foam, and its soft density ensures conformal contact between the abrasive disk and leading-edge surface.

The random-orbital tool is set at a fixed speed of 10,000 rpm by an adjustable knob, and the disk is kept in motion by depressing the lever with the index finger. The tool load is measured to be approximately $3.485 \pm 0.1 \text{ kgf}$. If the load exceeds 4.8 kgf, the tool will stop rotating. This is due to the safety design limit of the internal motor shaft balancer and bearing, which is important in ensuring that the polishing load is maintained below this value.

### Table 1: 7255-T7751 Aluminum alloy maximum composition limits (% weight)

| Specimen         | Alloying elements |
|------------------|-------------------|
|                  | Zn    | Cu   | Mg   | Zr    | Mn   | Cr   | Ti   | Si   | Fe   | Al   |
| 7255-T7751 Alloy material | 8.4   | 2.6   | 2.3  | 0.15  | 0.05 | 0.04 | 0.06 | 0.06 | 0.09 | Remainder |
| Others:          | 0.05  |       |      |       |      |      |      |      |      |       |

### Table 2: Grit number and corresponding grain size according to FEPA (Europe)

| Grit number | Grain size ($\mu\text{m}$) |
|-------------|-----------------------------|
| P120        | 127                         |
| P180        | 78                          |
| P240        | 58.5                        |
| P320        | 46.2                        |
| P400        | 35                          |
Figure 3 shows the polishing plan for all conditions, 1 to 4: P120 grit for section 1, P180 grit for section 2, P240 grit for section 3, P320 grit for section 4, and P400 grit for section 5. For wet conditions 2 and 4, deionized water with average pH of 7.4 at 23 °C is triggered by the valve at every 3-min interval. For cold air conditions 3 and 4, the cold gun is started up for 3 min until the air temperature dropped to a minimum of 15.5 °C. At the end of the trials, the parts are verified for dimension conformity where the leading-edge thicknesses are measured using a digital dial indicator Mitutoyo 543-400B.

Polishing parameters for both methods are shown in Table 3.

2.5 Measurements

The Zeiss Smart Zoom 5 digital microscope is used to examine the general condition of the specimen surface after polishing. The main purpose is to examine for induced tool defects such as swirl lines or scratch marks. The switchable ring-light on the microscope enabled viewing of these deviations by using intensity variations.

The Talysurf CCI 3000 coherence correlation interferometry (CCI) is used for detailed measurement of 2D and 3D surface roughness and furrow parameters in accordance with ISO 4287 and ISO 25178, respectively. The measurement strategy is transverse direction to the tool lines which would be the direction that will give the maximum height parameters. Because the imaging system is “traversed” through its range by the piezo drive system, the focal point is noted for each pixel in the CCD array. For 2D roughness measurements, an average of three readings are recorded for each sample, while 3D roughness measurement is conducted over a 9-square grid area.

The software configuration is set in XY mode (1024 × 1024 pixels) as the lateral resolution. The specimen is mounted at normal incidence angle to the optical lens in order to capture an accurate pattern. This allows the camera to detect the fringe pattern macro as the scan range needed to fully cover the height of the surface. The stand-off distance between the lens and the specimen is approximately 4.7 mm.

Parameters for auto-stitching mode are optimized to match offset and tilt. The XY scanning area is a 3 × 3 square grid (9 squares, single level) with 20% field-of-view (FOV) and 2.0 μm Z-overlap. The 9 squares stitched together to form a total area of 6.45 × 6.45 mm (41.60 mm²) for the areal measurement, as shown in Figure 4a. The image of the initial a-machined condition reveals an array of undulating scallop height features perpendicular to the machining feed direction, as shown in Figure 4b.

2.6 Statistical functions

Detailed characterization of surface texture features is necessary to understanding the relationships between various polishing methods. The fast Fourier transform (FFT) spectrum is used to analyze the spectral components of the surface by displaying patterns to show up periodicities and orientations.
**Fig. 2**  
(a) Existing method by single-axis rotary tool with external spot cooling with a plastic bottled water. Thermal images of the abrasive disks during the polishing cycle indicate an elevated temperature of around 82 °C, from initial ambient temperature. The bright, orange-yellow spectrum indicates a relatively hot signature;  
(b) random-orbital tool with in-line cold air and deionized water. The water causes a slurry to be formed during orbital motion. Thermal images of the abrasive disks during the polishing cycle show that the temperature can be lowered to around 15 °C by mixing cold air with water. The darker, purple-blue spectrum indicates the colder regions.

**Fig. 3** Polishing plan of the random-orbital trials for four specimens and four conditions. Each specimen consists of 5 sections with 5 different grit sizes per section. Grit sizes are P120, P180, P240, P320, and P400. The four conditions are condition 1 (dry, ambient air), condition 2 (wet, ambient air), condition 3 (dry, cold air), and condition 4 (wet, cold air). The fifth specimen for the rotary polishing method is not shown in this figure.
Each point in the spectrum corresponds to a frequency, and its color indicates the amplitude of this frequency. The surface may contain periodicities in the X and Y direction, generating useful information about the magnitude and phase of each wavelength.

Power spectral density (PSD) function analysis is useful for studying the weights of various periodic components in a surface profile. It decomposes the measured surface texture geometry into different components of spatial frequencies using Fourier transforms and provides more information than single-value parameter such as $Ra$ [14]. Instead of graduating the horizontal axis in frequencies as compared to standard FFT spectrum, PSD inverts the horizontal axis and thus proposes a linear reading of the wavelengths to gain a better understanding.

2.7 Specimen thickness and metallographic cross-sectioning

After the polishing process, the thicknesses of the polished sections are measured using a digital dial indicator Mitutoyo 543-400B. The cross-hair lines are marked at 25-mm distance perpendicular from the leading-edge section.

Next, metallurgical examination is used to analyze the cross-section of the polished samples. A precision cutting wheel is used for this task and operated at 3,000 rpm with a feed rate of 15.2 mm/min and is later processed in a hot mounting machine with phenolic resin. Buehler Ecomet 300 grinding machine is used to lap the sample mounts with 3 $\mu m$ and 0.05 $\mu m$ diamond suspension under 5 N force. Keller’s etchant by swab method is used to reveal the surface details by Olympus microscope BX53.

2.8 Abrasive disk life study

Studying the abrasive disk life for the various conditions by the random-orbital method can be used to determine the required number of consumables needed. Furthermore, for wet conditions, it is important to determine the quality of the abrasive disk in terms of wear and cleanliness.

A high precision Ohaus PX323JP model analytical weighing balance is used to measure the weight loss of the abrasive disk after polishing. Before weight measurements, the abrasive disks are cleaned by a pneumatic gun for approximately 3 min and until no visible traces of loose dust or water are present on the abrasive disk surface. Then, a section of each abrasive disk measuring approximately $L10 \, mm \times W10 \, mm$ is cut out and inspected by digital microscope using dino-lite edge model number AM7915MZTL.
3 Results and discussion

3.1 Surface topography

From the microscopic images, rotary polishing exhibited signs of fine tool lines on the surface in a circumferential pattern. The surfaces processed by random-orbital polishing show a clear difference between wet and dry condition.

Three distinct groups of surface textures are classified for clear identification: group 1, matte with anisotropic finish resulting on rotary polished sample shown in Figure 5b; group 2, shiny with fine scratch marks in cross-hatched circular pattern shown in Figure 5c and e; and group 3, satin with isotropic non-directional finish and homogeneous, resulting on wet orbital polished samples depicted in Figure 5d and f. All methods under all conditions can remove the sharp-peeked scallop height features.

The rotary and random-orbital tool is successful in the removal of scallop height features. For dry conditions shown on Figure 5c and e, the fine scratch marks appear to be shiny in nature, which is an indication that the abrasive grains have not contacted the surface valleys.

Figure 6 shows the trend of mean surface roughness ($R_a$) across the selected grit sizes for random-orbital polishing. In
comparison to rotary polishing, random-orbital polishing for all conditions produces lower $Ra$ values. Condition 1 produces the lowest $Ra$ value.

Results of varying grit size indicate that conditions 2 and 4 produce higher $Ra$ than conditions 1 and 3. Overall, all the specific grit sizes for conditions 1 and 3 produce an $Ra$ of below 0.8 $\mu$m, which is not ideal. Moreover, conditions 1 and 3 produce the lowest $Ra$ values as compared with condition 2 and 4. Three grit sizes for condition 2 (P320 and P400) and condition 4 (P320) produce ideal $Ra$ values between 0.8 and 1.0 $\mu$m.

In Figure 7, the maximum height profile ($R_z$) for all conditions by random-orbital polishing are lower than rotary polishing, except for condition 2. Results of varying grit size indicate conditions 2 and 4 produce higher $R_z$ than conditions 1 and 3. Conditions 1 and 3 produce the lowest $R_z$ values as compared with conditions 2 and 4. Condition 3 generates the lowest $R_z$ value which is not ideal. Condition 4 generates a
higher $R_z$ as compared to the initial surface. P320 grit size for condition 4 produces ideal $R_z$ value of 5.8 μm, thus making it a potential candidate which fulfills both $Ra$ and $R_z$ requirements simultaneously.

The $Sa$ parameter is the arithmetic mean deviation of the surface which provides a detailed interpretation and comparison of the surface texture, although no known target values are available. In Figure 8, it can be observed that all the grit sizes for conditions 1 and 3 produce a lower $Sa$ value as compared to initial value. Condition 1 produces the lowest $Sa$ value. P320 grit size for condition 2 produces a $Sa$ value marginally higher than initial value after polishing ($\Delta 0.096$ μm). In order to produce a $Sa$ value lower than the initial value, it is necessary for condition 2 to use a finer grit size such as P400. Another observation is found in condition 3, where there is no significant drop in $Sa$ value between P320 and P400 grit size. The data suggests that the abrasive reaches its saturation point and is unable to lower the $Sa$ value any further.

Figure 9 shows the results of the areal peak-to-valley heights ($Sz$) for random-orbital polishing. Similar to the $Sa$ parameter, no known target values are available. All random-orbital polishing conditions produce lower $Sz$ values as compared with rotary polishing. Condition 1 produces the lowest $Sz$ value, indicating the lack of height for the coating adhesion to be effective. Conditions 1 and 3 show potential in producing similar profiles, both values significantly lower than the initial value. Conditions 2 and 4 have a higher $Sz$ value than 1 and 3, but both lower than values produced by rotary polishing.

Table 4 shows a summary of the roughness measurements for both polishing methods with P320 grit size, including furrow data. Values of post-processes by shot peening and vibratory finishing are shown as reference. The target (ideal) values, $Ra$ between 0.8 and 1.0 μm and $R_z$ between 5.0 and 6.0 μm, are associated with vibratory finishing at final processing. Random-orbital polishing with condition 4 using P320 grit size achieved both the ideal $Ra$ and $R_z$ values simultaneously. This means that the surface texture produced by this condition and grit size, although not identical, correlates to vibratory finishing since both processes utilize vibratory mechanism.

In Table 4, the $R_{sk}$ or $S_{sk}$ parameter (skewness) can be used beneficially to understand the shape of surface texture height distribution. For a surface which meets Gaussian distribution and has a symmetrical profile, its $S_{sk}$ value equals to 0. This parameter may determine the presence of sharp features on the surface. The positive value of skewness ($S_{sk}$, rotary polishing = 0.34) means comparatively more sharp peaks and rounded valleys for the rotary polished surface, while the negative value of skewness ($S_{sk}$, random-orbital polishing = −1.90 to −0.48) indicates a majority of rounded peaks and sharp valleys for the random-orbital polished surfaces.

$S_{ku}$ (kurtosis) parameter can be used to characterize the spread of the height distribution. For a surface which meets Gaussian distribution, its $S_{ku}$ equals to 3; for a centrally distributed surface, its $S_{ku}$ is typically larger than 3, whereas for a surface meeting well-spread height distribution, its $S_{ku}$ is smaller than 3, as found in as-
machined value of 2.45. The kurtosis value for rotary polished surface ($S_{ku}$, rotary polishing = 7.31 > 3) and similarly for random-orbital polished surfaces (conditions 1 and 3) indicates that the values have more distribution tails, while the $S_{ku}$ for random-orbital polished surfaces (conditions 2 and 4) is approximately 3, indicating that the surface textures have normal distribution.

3.2 FFT and PSD analyses of the rotary and random-orbital polished surfaces

Based on Fourier analysis, surface texture is assumed to be composed of a series of sine waves with different frequencies and amplitudes. PSD is a measure of the amplitude of each harmonic part for a specific frequency and along a given di-

![Results of Areal Height Profile ($S_z$)](image)

**Fig. 9** Results of maximum height profile ($S_z$ parameter) for all conditions with P320 abrasive grit size. Measurement instrument used is Talysurf CCI 3000

| Process condition | CNC milling A s - machined | Rotary polishing Wet | Random-orbital polishing 1: Dry | Random-orbital polishing 2: Wet | Random-orbital polishing 3: Dry, cold air | Random-orbital polishing 4: Wet, cold air | Shot peening S e m i - final | Vibratory finishing Final |
|-------------------|----------------------------|----------------------|-------------------------------|-------------------------------|-----------------------------------|-----------------------------------|--------------------------|---------------------------|
| Height parameters |                            |                      |                               |                               |                                   |                                   |                          |                           |
| $Ra$ (μm)         | 0.90                       | 1.05                 | 0.32                          | 0.97                          | 0.34                              | 0.82                              | 2.11                     | 0.99                      |
| $Rz$ (μm)         | 4.30                       | 6.06                 | 3.95                          | 6.93                          | 3.83                              | 5.86                              | 8.83                     | 5.69                      |
| $Rsk$             | −0.04                      | −0.84                | −1.53                         | 0.14                          | −2.03                             | −0.84                             | −0.15                    | −0.94                     |
| $Rku$             | 1.76                       | 2.71                 | 9.56                          | 3.13                          | 13.07                             | 3.45                              | 1.54                     | 2.52                      |
| $Sa$ (μm)         | 1.15                       | 1.39                 | 0.35                          | 1.25                          | 0.29                              | 0.78                              | 1.86                     | 1.18                      |
| $Sz$ (μm)         | 7.54                       | 19.83                | 4.94                          | 10.97                         | 4.88                              | 7.73                              | 13.24                    | 9.09                      |
| $Sek$             | 0.16                       | 0.34                 | −0.97                         | −0.60                         | −1.90                             | −0.48                             | −1.09                    | −1.72                     |
| $Sku$             | 2.45                       | 7.31                 | 7.61                          | 3.78                          | 14.65                             | 3.85                              | 3.68                     | 5.68                      |
| Furrow parameters |                            |                      |                               |                               |                                   |                                   |                          |                           |
| Max. depth (μm)   | 4.94                       | 17.64                | 3.89                          | 9.18                          | 3.98                              | 5.85                              | 11.85                    | 8.85                      |
| Mean depth (μm)   | 2.14                       | 3.42                 | 0.69                          | 2.34                          | 0.56                              | 1.51                              | 2.21                     | 1.36                      |
| Mean density (cm/cm 2) | 903.12                  | 1126.82               | 1124.72                       | 1120.09                       | 1125.91                           | 1132.34                           | 892.77                   | 2206.07                   |
rection. Thus, for 3D surface texture, the PSD plot emerges as color-scaled function values upon an X–Y plane. The magnitude of PSD (displayed on the Z-axis) represents the amplitude of the sine wave at a specific spatial frequency for a given direction. In addition, it could average all X or Y profiles’ PSD to obtain the PSD values along only the X or Y direction.

Figure 10 illustrates the statistical function results of the surfaces by using coherence correlation interferometry (CCI). Figure 10a shows the FFT magnitude of the rotary polished surface; its average profile PSD profile along the Y direction, as shown in Figure 10c, fluctuates with respect to the spatial frequency, and trend shows a monotonic descent. Figure 10b shows that the FFT magnitude of the random-orbital polished surface (condition 4, P320 grit size) is generally much smaller (−48.7631 dBc) than that of rotary polished surface (−66.5650 dBc).

Figure 10d shows the average PSD along the Y direction having a spatial frequency which is relatively flat (horizontal) at the beginning and gradually descends from 1.0E-02. A number of spikes in the curve indicate that there are high-frequency harmonic components along the Y direction. This could be due to the random motion of the abrasive grains in the polishing disk.

By comparison between Figure 10a, b, c, and d, it can be seen that FFT and PSD characteristics differ significantly between rotary and random-orbital surfaces; it shows that PSD could be a perceptive way to differentiate surface textures produced by different polishing methods.

(a) FFT plot of the rotary polished surface

(b) FFT plot of the random-orbital polished surface

(c) Average PSD along Y of the rotary polished surface

(d) Average PSD along Y of the random-orbital polished surface

Fig. 10 Comparison of FFT and PSD for rotary and random-orbital polished surfaces
3.3 Effect of air-cooling and deionized water on the specimen and abrasive disk surface

In the material removal mechanism, the dislodged abrasive particles will start rolling between the surface of the disk and the workpiece, thus creating a series of furrows. A furrow is defined as depressions in the surface structure caused by mechanical abrasion. A surface texture with higher furrow depth and density will promote better coating adhesion layer due to the enhanced anchoring effect in the structure.

From Table 4, random-orbital method condition 4 produces the highest mean density of furrows as compared with other conditions. The mean depth for condition 4 is closest to that produced by vibratory finishing, and this is desirable. It is possible to verify the effect of temperature between conditions 2 and 4, in order to understand why condition 4 shows evidence of furrows with less significant depths. The air stream in condition 4 may change the viscous flow in the sliding mechanism, thus affecting the rolling effect of the abrasive particles.

This phenomenon can be understood as furrows not caused by cutting action alone, instead, the distinct tracks are deepened by particles rolling over the surface due to the meniscus force of the water. It is the free moving abrasives present in the slurry that create swallow valleys in the surface, resembling that of three-body abrasion. The furrows are enhanced by the meniscus force produced due to the water surrounded by the abrasive [15].

In Figure 11, random-orbital polishing shows evidence of grooving indicated by the furrow features produced on the...
surface structure. This is due to the hard-abrasive grain plowing the aluminum alloy because of its ductile properties. The application of deionized water in conditions 2 and 4 is determined to be the key contributing factor that influences the surface texture. Conditions 2 and 4 (wet) have deeper, more prominent furrows as compared to conditions 1 and 3 (dry). Condition 2 produced the largest furrow depth at sparse locations randomly, which is not ideal. The texture of condition 4 appears to be homogenous as it has a better distribution of furrows on the surface at approximately 0.5 mm spacing distance. In summary, furrow properties are similar for condition 1 and 3, while condition 2 shows localized, deep furrows, and condition 4 shows a uniform distribution of furrows.

Heat dissipation during the random-orbital polishing is important as it influences the abrasive disk life. A forward-looking infrared (FLIR) camera is used to record the abrasive disk temperatures for each condition, and the results are given in Figure 12. For the existing method by rotary polishing, the temperature is recorded at 82°C after 9 min of polishing time. The average temperature of the random-orbital abrasive disk is recorded at 3-min intervals from 0–9 min.

A method to visually inspect the quality of the abrasive disk after polishing is by color comparison. The original crystalline form of aluminum oxide abrasive is corundum, and its distinct color is a mixture of deep reddish-brown. During the polishing process, it is imperative that the abrasive is maintained clean throughout for effective cutting action. Accumulation of debris on the abrasive can be identified by the grayish-white color due to the residual particles of the parent material. Conditions 1, 2, and 3 show signs that the abrasive is affected by the accumulation of debris. This engulfment would dull the agglomerated abrasive structure, which reduces cutting effectiveness with the polishing time.

Figure 12 shows the abrasive disk temperature change over 9 min for P320 grit size. The images on the right show the corresponding condition and wear pattern on the abrasive disk at the end of the polishing cycle. The accumulation of debris (grayish-white color) is clearly seen in conditions 1 and 3 of the abrasive surface. Abrasive surface for condition 2 is generally clean (deep reddish-brown color), while other areas show evidence of debris (grayish-white color). This implies that there is inhomogeneous water distribution within the disk. Abrasive surface for condition 4 is the cleanest as compared with the rest, signifying a homogeneous air-water distribution within the disk.

Condition 2 lacks additional cold air, and this creates a flood-coolant embodiment on the surface. It is important to note that a certain amount of wettability is crucial to ensuring cleanliness of abrasive disk, as proven in condition 4. All conditions operate at different temperature levels, and these variations do not provide significant evidence to justify its influence on the abrasive structure. However, elevated temperatures in mechanical polishing are known to cause thermal defects within the surface. Therefore, a lower operating temperature for polishing operation is preferred.

Adding air-cooling for condition 4 has shown a significant reduction in temperature by approximately 63 % as compared with condition 1 and 27 % as compared with condition 2. The understanding from condition 4 is that the abrasives must be moist and not excessively wet, in order for better performance. In addition, the air stream removes the build-up of debris and keeps the surface clean.

![Fig. 12](image_url) Average relative temperatures measured by FLIR on the random-orbital abrasive disk at 3-min intervals up to 9 min. Images taken by dino-lite edge microscope, model number AM7915MZTL.
3.4 Metallurgical analyses

The micrographs of the cross-sectioned coupons are shown in Figure 13. All samples are examined under 500× magnification with white light and checked for evidence of distortion and defect in the surface structure. For conditions 1 and 4, there are no visible evidence of defects, which is acceptable by quality standards. Condition 2 shows signs of unevenness in the surface. In Figure 10c, a gouge measuring approximately 25 μm in length and 5 μm in depth is observed in condition 3. These surface flaws depicted in conditions 2 and 3 are not desirable. Apart from these flaws, there are no additional surface distortion, strain lines, and abrasive particle embedment on the specimens’ surface for all random-orbital polishing conditions.

3.5 Evaluation of the abrasive disk life

The abrasive disk life study is beneficial in determining process suitability of random-orbital polishing from a consumable requirement or cost perspective. Figure 14 shows the abrasive disk life study in terms of weight loss measurements before and after polishing. Conditions 2 and 4 experienced the highest weight loss as compared with conditions 1 and 3 after polishing. Conditions 2 and 4 are estimated to consume a total quantity of five disks in effort to polish a full fan blade leading-edge section, whereas conditions 1 and 3 require only one disk for the same process.

3.6 Material removal and thickness measurement

In order to remove the scallop height features and retain the specimen thickness within tolerance, the polishing method needs a lower material removal rate. Figure 15 shows the calculated cutting speed (Vc) based on the specimen thickness before and after polishing for a process time of 9 min. Condition 1 has the highest cutting speed for most grit sizes, hence a higher material removal rate. Conditions 2, 3, and 4 of grit sizes P320 and P400 have identical values which show uniformity in the cutting speed. P240 for these 3 conditions show similar uniformity but slight lower values by 0.0018 mm/min. A low cutting speed of 0.0026 mm/min may be insufficient to remove scallop height features on the initial surface.

![Fig. 13 Microstructure of the random-orbital polished specimens (P320 grit size) cross-sectioned in the longitudinal direction: a condition 1, dry; b condition 2, wet; c condition 3, cold air; d condition 4, wet, cold air. The images are captured by Olympus BX53 microscope](image-url)
In this analysis, condition 1 is considered unsuitable for polishing because of the cutting speed generated due to the absence of air and water loading. As a result, condition 1 may increase the likelihood in producing an under-thickness dimension of the fan blade leading edge. Therefore, P320 and P400 grit sizes for conditions 2, 3, and 4 are identified as suitable candidates for random-orbital polishing in terms of good material removal control. Overall, the thickness height difference for random-orbital polishing is a small value of \( \Delta 0.15 \) mm, which is well within allowable stock material removal for the process. In summary, P320 and P400 grit sizes for conditions 2, 3, and 4 generate desirable cutting speed values, and values are identical.

Fig. 14 Abrasive disk life study by calculating the total weight loss after polishing. Measuring instrument used is Ohaus PX323JP model analytical weighing balance.

Fig. 15 Random-orbital cutting speed (mm/min) calculated based on thickness height measurement of the specimen before and after polishing.
4 Conclusion

This paper demonstrates and evaluates the feasibility of a random-orbital tool categorized by four different conditions for localized polishing on fan blade leading edges. The post-polished surface texture of the specimens shows the success in removing scallop height features while keeping the edges within dimensional tolerance and producing the required surface finish. Evaluation of the proposed method narrows the feasibility from four conditions to one recommendation: condition 4 (wet, cold air). Condition 4 performs the best in terms of achieving the target roughness and texture close to final finishing condition. The recommended method produces no microstructural defects. However, the disadvantage for this method is the shorter abrasive disk life after the polishing process, which may be slightly costlier in a high-volume production scenario.

Condition 1 (dry) is excluded in the down-selection because of the high abrasive temperatures, generation of dust, and formaldehyde, creating a safety hazard to the operator. Furthermore, the surface topography ($Ra$) is beyond the desired target, and there are visible scratch marks on the surface. Condition 3 is unsuitable because of gouging defect and uneven profile in the microstructure. In addition to this, the surface topography ($Ra$) and scratches are similar to that of condition 1. The key findings can be made in the following comments:

1. Surface roughness. Random-orbital polishing conditions 2 and 4 can produce the desired surface roughness $Ra$ 0.8 to 1.0 $\mu m$ and maintain the threshold value of $Ra \leq 2 \mu m$. It is axiomatic that conditions 1 and 3 have lower peak-to-valley heights ($Sz$) by 75% as compared with the existing single-axis rotary method. This reduction in height may not be beneficial for coating adhesion in subsequent processing. However, conditions 2 and 4 have a $Sz$ reduction of 45% and 61%, respectively, as compared with the exiting method. Although the $Sz$ value does not have a determined target value, it is adequate to consider a certain amount of acceptable height which is close to the final process. The $Sku$ value of conditions 1 and 3 are similar to the rotary polished surface, which have a higher indication of distribution tails, whereas the conditions 2 and 4 have normal distribution. The $Ssk$ value for rotary polished surface indicates more sharp peaks, which is not ideal, whereas random-orbital polished surfaces indicate a majority of rounded peaks, which is ideal. When compared with the 2D or 3D single-valued surface texture parameters, statistical functions could produce more information which occasionally show a specific functional property of the polished surfaces. FFT and PSD analyses provided further information of the randomness or periodicity of the surface textures. In this aspect, condition 4 is identified as the prime technique.

2. Surface integrity and defects. All conditions 1 through 4 have adequate ability to remove scallop height features on the as-machined fan blade specimens. The thicknesses of the leading edges are all measured and found within acceptable limits. Metallographic cross-sectioning proved that there is no surface distortion, strain lines, and abrasive particle embedment on the polished specimens. However, metallurgical analysis showed that random-orbital polishing in conditions 2 and 3 can lead to uneven surfaces and gouging, respectively. Although condition 1 reached an elevated temperature of 43.8°C after 9 min with P320 grit size, no significant surface degradation is observed in the metallurgical analysis, except for the fine scratch marks.

3. Abrasive life. The wear condition of the abrasive disk is highest for conditions 2 and 4 and lowest for conditions 1 and 3. The use of deionized water in conditions 2 and 4 is found to be the key contributor to influence the wear behavior. It is concluded that abrasive disk for condition 4 is moistened, whereas the abrasive disk for condition 2 is heavily wetted by the application of deionized water. As a result, conditions 2 and 4 require 5 times the number of abrasive disks as compared to conditions 1 and 3 for the polishing work. The lower air temperatures generated by the cold gun for conditions 3 and 4 is not observed to have any noticeable effect on the abrasives or slurry.

Condition 4 is found to be most favorable without any defects or dimensional issues. This also means that it takes less time and effort to treat the surface in subsequent processing. By replacing the existing rotary method with random-orbital method, the component surface is expected to be more homogenous after the final processing stage. Based on the evaluation from this study, it is recommended to use random-orbital polishing with deionized water and cold air for combined defect removal and surface finishing. The key process variables are established to keep the abrasive disk cold and moist during operation.

Author contribution We would like to declare the contributions made by the following authors:

1) Edgar J Danaraj—Development of the experimental methodology, collection and compiling of data, and manuscript preparation
2) Swee Hock Yeo—Outline of the manuscript and review, analyses, and editing of the manuscript.

Data availability Nil.

Declarations

Consent to participate This is to confirm that all the authors have agreed to participate and have contributed in the content of the paper.
Conflict of interest  The authors declare no competing interests.

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