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Assessment of workpiece surface integrity and dimensional/geometrical accuracy following finish plunge end milling of holes drilled with worn tools in PM-processed nickel based superalloy

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Abstract

Powder metallurgy (PM) processed nickel-based superalloys are increasingly employed in the hot section of gas turbine engines for parts such as high-pressure (HP) compressors and turbine rotor discs over more traditional cast and wrought options such as Inconel 718 due to its improved high-temperature properties. In this paper, the surface integrity and geometrical/dimensional accuracy of holes initially rough drilled using worn tools and subsequently finish plunge end milled in a proprietary PM-processed Ni-based superalloy, were assessed and compared. The influence of tool wear on hole quality after finish plunge end milling was also investigated. Significant improvement in hole quality was evident following finishing with reductions in surface roughness (up to ~86%), subsurface microhardness (up to ~125 $HK_{0.05}$) and workpiece microstructure deformation/damage (up to ~80% in terms of average depth) compared to corresponding rough drilled holes. Evidence of chatter marks on holes machined with worn plunge end mills was observed, despite exhibiting reduced surface roughness levels (~45-73%). Generally, somewhat improved hole surface integrity (reduced subsurface deformation by ~47-64%) and geometrical accuracy (circularity decreased by ~10-25%) were produced when employing new tools.

Keywords: Drilling; Superalloy; Wear

1. Introduction

Powder metallurgy (PM) processed nickel-based superalloys have been increasingly employed by the aeroengine industry typically in turbine discs [1,2] over traditional cast and wrought alloys due to their enhanced properties including greater tensile and creep rupture strength. A key feature on superalloy disc components are holes for mechanical joining, which are usually produced by a combination of rough drilling and finish plunge end milling operations in order to meet stringent surface metallurgical criteria demanded by the aerospace industry. Surface alteration and surface quality resulting from machining operations play a crucial role in determining the functional performance of parts. Surface integrity characteristics such as roughness, microhardness and microstructure alterations directly impact factors such as fatigue, creep, corrosion and wear resistance, ultimately influencing the overall performance and reliability of the components [3,4]. However, research relative to workpiece surface integrity and dimensional/geometrical accuracy following hole-making operations in PM-processed Ni-based superalloys are comparatively limited. Soo et al. [1] assessed workpiece surface integrity following drilling of 8 mm diameter holes in PM processed RR1000 Ni-based superalloy at different cutting

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speeds (30, 45 and 60 m/min) with a constant feed rate of 0.05 mm/tooth. Results showed that variation in cutting speed had a negligible effect on workpiece roughness (~0.8-0.9 µm Ra) and microhardness depth profiles (all with hardened layers up to a maximum of ~130 $HK_{0.05}$ above the bulk hardness and extending to ~100 µm beneath the machined surface) of holes drilled with new tools, whereas use of worn/blunt tools (~90 µm flank wear) were found to reduce hole surface roughness (~0.3 µm Ra).

For applications requiring holes with precise tolerances and high surface quality, the typical approach involves using twist drills for initial roughing due to their high material removal rate [5,6]. This is followed by finishing operations such as reaming to achieve more demanding dimensional/geometrical and surface integrity criteria [7]. Axinte and Andrews [8] assessed the finishing capability of a plunge milling cutter against two reamers with different relief designs (standard reamer with only one relief face and a modified reamer consisting of a double-relief geometry) for holes drilled in RR1000. It was found that the standard reamer failed to achieve satisfactory hole quality, including dimensional and geometrical out-of-tolerances (diameter and circularity), relatively high and inconsistent surface roughness, presence of white layers as well as severely distorted microstructure of the machined subsurface. This was attributed to inappropriate chamfer edge and relief design, which led to greater contact/friction at the tool-workpiece interface. In contrast, superior hole quality was obtained when finishing with the modified reamer and plunge milling cutter, where more consistent surface roughness and reduced deformed layer thickness over 50% was observed, especially with the latter. The effectiveness of plunge milling for finishing holes drilled in RR1000 under various cutting conditions was further evaluated by Kwong et al. [9]. The secondary plunge milling operation significantly improved the surface roughness of boreholes by over 55%, including those initially drilled dry. Furthermore, the continuous white layer formed after dry drilling was successfully removed by the finishing operation, with no sign of distorted layers or other subsurface anomalies such as microcracks detected in any of the finished samples.

The current paper initially investigates the baseline workpiece surface integrity and dimensional/geometrical accuracy of holes produced following rough drilling of a PM-processed nickel-based superalloy using worn tools. Finishing of the holes were subsequently evaluated using both worn and new plunge end mills.

2. Experimental work

2.1. Workpiece materials, cutting tools and equipment

The PM-processed nickel-based superalloy employed for the experiments were prepared in the form of square plates having dimensions of 120 × 120 × 10.7 mm, with the general chemical composition of the material listed in Table 1.

Table 1. Chemical composition (in weight %) of workpiece [10].

Co	Cr	Mo	Ta	Ti	Al	Hf	B	Zr	C
15	18.5	5	2	3.6	3	0.5	0.015	0.06	0.027

Experiments were carried out on a Matsuura FX-5 vertical high speed machining centre having a maximum spindle rotational speed of 20,000 rpm rated at 15 kW. The tools for rough drilling used in the tests were worn TiN-TiAlN coated tungsten carbide (WC) twist drills (TD), see Fig. 1a. The 12.2 mm diameter twin-fluted drills were designed with a 140° point angle and 30° helix angle. For the finishing operations, worn and new four-fluted, square-end plunge end mill (PEM) cutters were utilised to machine the holes to their final diameter. The tools were coated with TiSiN coating and manufactured from submicron WC (carbide grade: K20-30) with a hardness of 91.8 HRA, see Fig. 1b for sample end mill in the worn condition. The cutting fluid used in all trials was an emulsion containing water-soluble Houghton Hocut 795 BR mineral oil at a concentration of ~7%vol. During the rough drilling operation, cutting fluid was supplied externally through three nozzles positioned around the tool at a pressure of ~3 bar and flow rate of ~25 l/min (flood coolant) together with high-pressure through-tool coolant delivery (pressure of 20 bar and flow rate of ~12 l/min) via a spindle adaptor. In contrast, all of the finishing trials using the PEM tools were undertaken only with external flood coolant conditions.

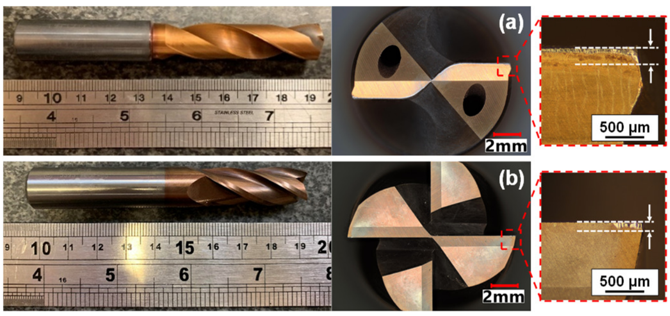

Fig. 1. Worn condition (a) twist drill (TD) for rough drilling process, and (b) plunge end mill (PEM) for finishing operation.

Tool flank wear was evaluated relative to the main cutting edge (Fig. 1) utilising a WILD M3Z toolmakers microscope equipped with a X-Y digital micrometre platform having a resolution of 1 µm. Hole diameter and circularity was measured using a three-axis Mitutoyo Euro-Apex C544 coordinate measuring machine (CMM), which has a resolution of 0.5 µm and includes a fully indexable CNC probe head (Renishaw PH10T) equipped with a TP200B probe mounted with a 2 mm diameter ruby ball stylus. Ten replicated hole diameter measurements were taken at several depths below the top surface (at intervals of 1 mm), with the mean calculated for each depth and hole. A Mitutoyo Surftest SJ-310 portable surface roughness tester equipped with a 2 µm radius diamond tip stylus was used to determine 2D surface roughness profiles of the drilled holes. A Gaussian profile filter with a cut-off length of 0.8 mm and evaluation length of 4 mm was adopted according to the ISO 4288 standard [11]. In terms of surface shape parameters, machined surface topography and surface defects analysis, an Alicona G5 InfiniteFocus microscope was utilised at a magnification of 50× and resolution of 10 nm (vertical) × 1.3 µm (lateral). For workpiece subsurface integrity assessment, all samples were sectioned in the hoop and axial direction by wire electrical discharge machining (WEDM) before hot mounting in edge retentive bakelite, grinding/polishing (using SiC paper and diamond suspension), as well as etching electrolytically with 10% orthophosphoric acid according to standard procedures for nickel-based superalloy materials. Machined subsurface microstructural alterations were analysed using the Alicona microscope. Microhardness depth profile measurements were taken using a Mitutoyo HM-100 series hardness unit equipped with a Knoop indenter and 50 g load. Fourteen measurements were taken at various depths (10, 20, 30, 40, 50, 75, 100, 125, 150, 200, 250, 300, 400 and 500 µm) below the machined surface with four replications at each depth to calculate mean values.

2.2. Experimental procedure and test parameters

Prior to commencement of trials, the maximum flank wear of all worn TD and PEM tools were evaluated, with three of each cutter having comparable wear levels/condition selected for the tests. Three holes were initially machined using a worn TD at a cutting speed of 25 m/min and feed rate of 0.035 mm/tooth. Two of the rough drilled holes were then finished by a new and worn PEM respectively at a cutting speed of 66 mm/min and feed rate of 0.030 mm/tooth. The rough drilled hole and two finish milled holes were subsequently subjected to dimensional/geometrical and surface integrity assessment. This was repeated a further two times (a total of three trials denoted as Tests 1, 2 and 3), each with a different set of tools.

3. Results and discussion

3.1. Tool wear and workpiece surface roughness

Fig. 2a depicts the maximum flank wear of the worn twist drills measured before (ranging between 143 and 174 µm) and after drilling 3 holes in each test. Flank wear of drills increased by between 45 – 94 µm after machining 3 holes, where the largest rise was seen in Test 1 with the tool having the highest initial wear level (174 µm). However, the TD used in Test 2 exhibited a considerably higher increase in maximum flank wear of 85 µm after drilling compared to Test 3 (45 µm), despite both tools having similar starting wear values (143 and 146 µm). Conversely, no appreciable change in flank wear was observed on any of the worn PEM cutters following finish machining one hole, with the pre-test wear levels (117 – 143 µm) shown in Fig. 2b. Similarly, no measurable wear was detected on any of the new plunge end mills after each test.

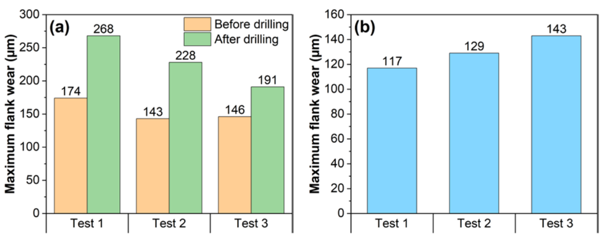

Fig. 2. Maximum flank wear of the worn (a) TD and (b) PEM tools used for the trials.

Fig. 3 shows the average surface roughness (Ra and Rt) of the boreholes following rough and finish cutting for each test.

The mean surface roughness (Ra) of rough drilled holes using worn tools varied between ~1.4 µm and ~0.32 µm, with the corresponding average total height of the roughness profile (Rt) measuring between ~13.6 µm and ~3.3 µm. The relatively high variability in hole surface roughness following roughing was likely caused by the presence of randomly distributed surface defects such as grooves and redeposited material. These are further discussed in the following section. The worn TD used in Test 3 resulted in holes with the lowest roughness, which was possibly due in part to the reduced flank wear level of the tool following machining. Comparable results were reported by Soo et al. [1], where roughness values of ~0.3 µm Ra were recorded when drilling RR1000 using a worn tool. In general, hole surface roughness was significantly improved by the finishing operation, with more consistent Ra results obtained and reductions of up to 86%, as well as considerably lower Rt values. The average Ra values were found to be over 45% lower when finishing with worn tools (~0.12 to ~0.20 µm) in contrast to new cutters (~0.37 to ~0.52 µm). This was likely associated with increased burnishing/rubbing between the cutting edge and machined surface as a consequence of tool wear, causing reductions in height of the roughness profiles or 'flattening' of the peaks [12].

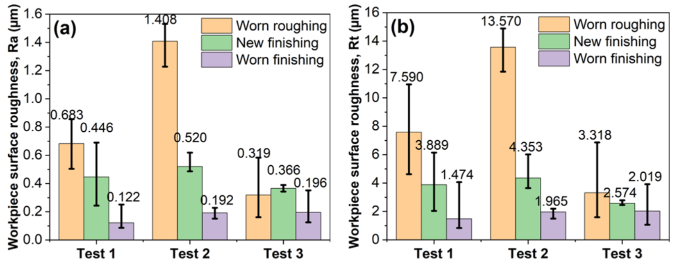

Fig. 3. Average surface roughness (a) Ra and (b) Rt of holes following rough and finish drilling.

Fig. 4 details the areal surface skewness (S_{sk}) and kurtosis (S_{ku}) measurements of the holes following roughing and finishing in each test. The S_{sk} values were negative for all samples regardless of drilling operation, suggesting that the hole surfaces were mainly dominated by valleys [13]. In terms of the kurtosis parameter (S_{ku}), all of the rough drilled holes exhibited S_{ku} values > 3, indicating the presence of sharper peaks and valleys on the surface profiles. In contrast, the S_{ku} values were found to be < 3 after finish plunge end milling with both new and worn tools, which meant that the profile peaks and valleys tended to be more rounded/less sharp [13].

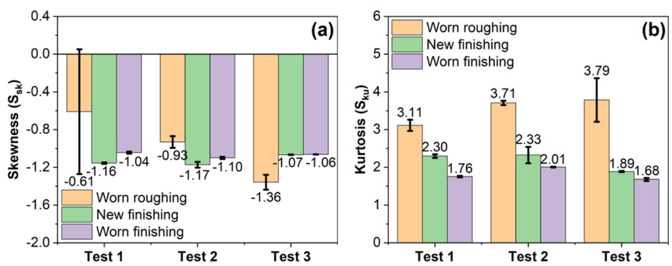

Fig. 4. Surface shape parameters involving (a) skewness and (b) kurtosis following rough drilling and finish machining.

3.2. Hole surface topography

Fig. 5 illustrates typical surface topography/texture contour plots and optical micrographs of holes produced by the worn twist drills. The hole topography due to rough drilling was generally inconsistent and wavy, with signs of considerable surface anomalies and defects observed. In addition to surface scoring generated during drill retraction, deep grooves/scratches parallel to the cutting direction were evident, which were likely caused by swarf, adhered material or hard detached tool particles trapped at the workpiece-tool interface. Significant workpiece smearing/plastic flow was also apparent, which was attributed in part to the high temperatures generated during drilling leading to increased material deformability as a result of workpiece softening [14]. This was coupled with greater extrusion and severe plastic deformation at the tool-workpiece interface due to use of worn tools [15]. Furthermore, redeposited/adhered material was evident on all of the samples machined with the worn twist drills.

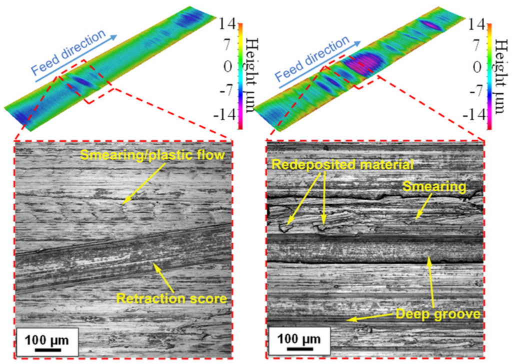

Fig. 5. Hole surface topography and optical micrographs showing anomalies/defects following rough drilling.

Representative surface topography and defects of hole samples following finishing with new and worn PEM tools are detailed in Fig. 6. In general, the surface profiles were more regular/consistent compared to the condition of rough drilled boreholes, even when employing worn milling cutters. This can be correlated with the lower surface roughness measured after finishing as shown previously in Fig. 3, which also removed much of the surface anomalies and defects caused by the preceding rough drilling operation. More distinct feed marks and retraction scores were seen on surfaces machined using new PEM tools, which accounts for the higher surface roughness values recorded compared to holes finished with worn cutters, see Fig. 3. This was a consequence of the relatively shaper cutting edges of new tools providing more efficient shearing and penetration into the workpiece material, resulting in greater profile heights [12].

Chatter marks were also found on the surfaces of several hole samples finished using worn tools, see Fig. 6b, which are characterised by periodic (short pitch) undulations on the machined surface typically generated by vibration of the tool [12], despite relatively low surface roughness values recorded in this region. Chatter vibration is detrimental to machining accuracy and tool life, which could lead to acceleration of tool wear/breakage as well as damage to the machine tool [6].

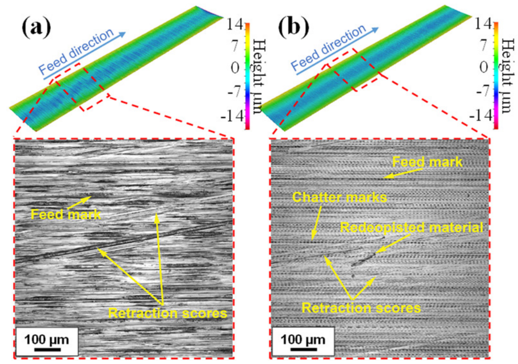

Fig. 6. Hole surface topography and optical micrographs showing anomalies/defects following finishing using (a) new and (b) worn PEM.

3.3. Dimensional and geometrical accuracy

Fig. 7a shows the average diameter and circularity of the holes following rough and finish drilling in each of the tests. Despite machining with twist drills having different initial wear levels, the diameters of all rough drilled holes were largely consistent across all three tests and ~0.2% larger in size than expected given the tool diameter. The corresponding circularity of the rough drilled holes however varied between 9.4 µm to 11.7 µm.

Fig. 7b illustrates the average hole diameters following finishing with new and worn cutters, which were marginally (5 µm to 11 µm) larger than the target value, except for the hole finished in Test 3 with a worn PEM. As with the rough drilling operation, all of the finished holes were within the specified dimensional tolerance. The results suggest that the minor differences in hole sizes were likely due to variations in tool diameter within the manufacturing tolerance as well as potential inaccuracies in the test setup (machine spindle/toolholder/tool runout), rather than wear levels. In general, holes finished with worn PEM showed somewhat higher deviations from the target diameter than new tools, with the latter also exhibiting marginally better circularity, which were largely similar across all 3 tests. This was likely in response to the elevated cutting temperatures generated when machining with worn end mills, leading to higher thermal expansion of the workpiece [16].

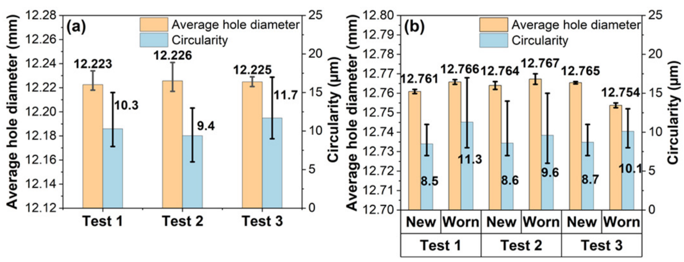

Fig. 7. Average diameter and circularity of the holes (a) drilled by worn TD; and (b) finished by PEM.

3.4. Microstructure analysis

Micrographs of typical workpiece subsurface microstructure of hole samples cross-sectioned in the axial direction following rough and finish drilling (with new and worn end mills) are detailed in Fig. 8. Compressed/deformed regions of primary γ' precipitates with no distinct evidence of directional material drag together with several instances of apparent discontinuous white layers were observed on holes machined with the worn TD. However, as there were further severely distorted primary γ' phases found directly beneath the possible white layer, it was likely the anomalies were etched redeposited/adhered material on the machined hole surface (see Fig. 5) rather than actual white layers developed as a result of material grain refinement.

Hole subsurface microstructural alterations were significantly reduced following finishing operations. A potential discontinuous white layer (thickness of ~3 μm) was also seen on one of the samples finished using a worn PEM, although this was also thought to be the etched cross-section of redeposited material on the hole surface. Potential plucking was detected on surfaces machined with a new PEM, however with a depth of ~2.8 μm, this was more likely attributed to the removal of small particles from redeposited/adhered material during machining.

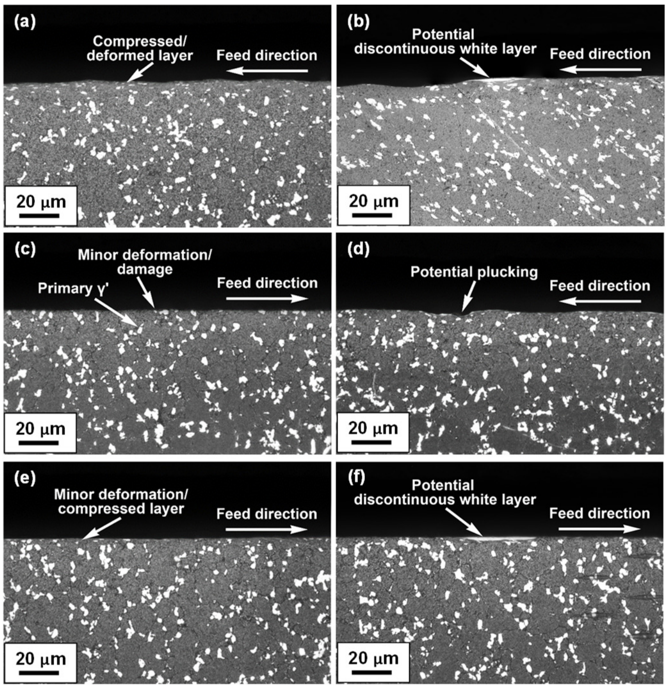

Fig. 8. Typical axial cross-sectional micrographs of hole subsurface microstructure machined using (a), (b) worn TD; (c), (d) new PEM; and (e), (f) worn PEM.

More severe signs of material drag/subsurface microstructural deformation were observed on all of the drilled samples viewed in the hoop/radial cross-section, where some of the primary γ' precipitates were elongated and bent towards the cutting direction, see Fig. 9. This was due to mechanical loads as a result of tool rotation, which was also reported by Soo et al. [1]. Somewhat wider apparent discontinuous white layers were visible on certain sections of hole surfaces after rough drilling and finish plunge end milling using worn tools respectively, see Fig. 9b and Fig. 9f. Evidence of possible surface plucking was also found on the borehole machined with a worn TD, which could be a consequence of chip/swarf entrapment or hard fractured tool particles pulling out or eroding the workpiece material [15]. Although free of apparent white layers, potential surface laps were found on a sample finished with a new PEM. This may have been caused by swarf packing due to the formation of long continuous chips in the hole observed during cutting together with instances of ploughing, leading to plastic deformation and material folding on the machined workpiece surface [9]. The depth of microstructural deformation was generally higher following roughing operations in both the hoop and axial directions. A significant reduction in the level of subsurface workpiece deformation was generally achieved (over rough drilled holes) by subsequent finishing operations even with worn end mill cutters. In addition, thicker distorted layers were observed in holes finished with worn PEM in comparison to new tools, which was due to increased contact/rubbing at the tool-chip interface in the former.

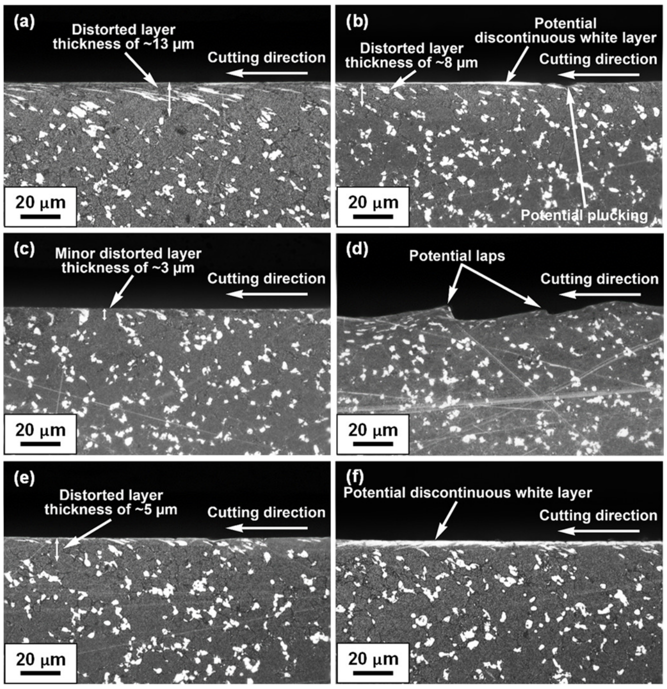

Fig. 9. Typical hoop cross-sectional micrographs of hole subsurface microstructure machined using (a), (b) worn TD; (c), (d) new PEM; and (e), (f) worn PEM.

3.5. Microhardness analysis

The subsurface microhardness depth profiles for hole samples produced in each test (measured in both hoop and axial cross-sectional directions) are detailed in Fig. 10. Strain-hardened layers were observed on all the assessed specimens, with varying depths and magnitudes depending on the operation and tool condition. Holes drilled with worn TD generally exhibited the largest increase in microhardness levels for all tests, which were up to 35% above the bulk value of ~550 $HK_{0.05}$ and extending to a depth of 100 μm to 200 μm below the machined surface. While also showing subsurface hardened layers, the level of work hardening following finishing operations was significantly reduced compared to the rough drilled holes, with maximum hardness of ~18% - 25% and ~4% - 15% above the bulk value when machining with worn and new PEM cutters respectively. The depth of the hardened layers in the finished holes were similarly lower, which did not exceed 50 µm and 100 µm beneath the machined surface when using new and worn cutters respectively. However, subsurface microhardness levels in finished holes were found to be higher when using worn end mills over new tools. Comparing the microhardness values assessed in the hoop and axial cross-sections revealed minor differences for finished holes, while a somewhat higher maximum hardness was obtained in the axial cross-section of samples drilled with worn TD, which could be due to the large variation/spread in measurement data recorded for the rough drilled holes.

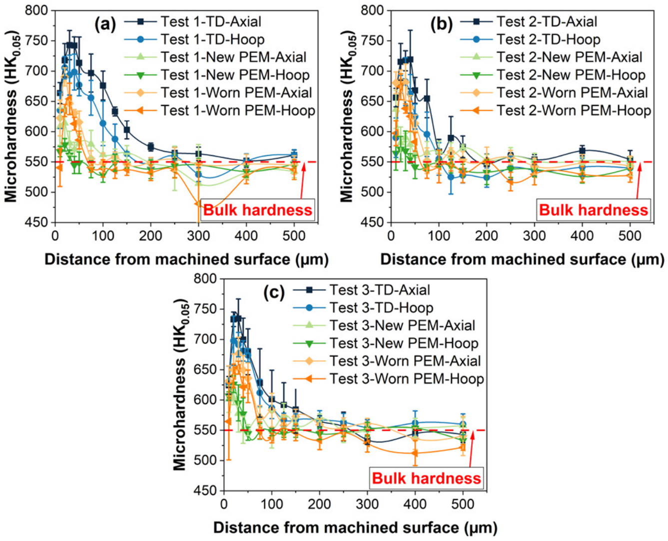

Fig. 10. Subsurface microhardness depth profiles (axial and hoop direction) for hole samples drilled in (a) Test 1; (b) Test 2; and (c) Test 3.

4. Conclusions

- The average Ra of holes machined using the worn TD varied between ~0.32 µm and ~1.4 µm. The finishing operation significantly improved hole surface roughness however, slightly higher roughness levels were produced by the new PEM compared to the worn cutters. This was likely attributed to an increased burnishing/rubbing effect associated with the worn tool.
- The topography of holes drilled using worn TD tended to be wavier, with considerable surface defects including grooves, retraction scores, redeposited material and smearing observed. In contrast, more consistent surfaces with considerably reduced anomalies were obtained after finishing operations, although there was evidence of chatter marks on holes machined with worn PEM.
- The diameter of all holes was within the respective dimensional and geometrical requirements, although the majority showed average values above the target size even for worn tools, which were likely due to manufacturing tolerances of the cutters and run-out during machining. Somewhat improved hole circularity was observed in holes finished with new PEM.
- Finishing of holes with the PEM significantly reduced subsurface anomalies and thickness of the distorted layer. However, potential laps and plucking were seen on the surfaces machined with new tools.
- Strain-hardened layers below the machined surface was observed following both rough and finish drilling. The depth and peak magnitude of the subsurface hardened layers were typically up to two-fold and 22% larger respectively, in the rough drilled compared to post finishing holes.
- To ensure compliance with operational safety and functional performance standards, it is imperative that holes drilled with worn TD in PM-processed Ni-based superalloys are finished using PEM cutters.

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References

[1] Soo SL, Hood R, Aspinwall DK, Voice WE, Sage C. Machinability and surface integrity of RR1000 nickel based superalloy. CIRP Ann - Manuf Technol 2011;60:89–92.

[2] Reed RC. The Superalloys: Fundamentals And Applications. 1st ed. Cambridge Univ. Press. New York: Cambridge University Press; 2008.

[3] Liao Z, la Monaca A, Murray J, Speidel A, Ushmaev D, Clare A, Axinte D, M'Saoubi R. Surface integrity in metal machining - Part I: Fundamentals of surface characteristics and formation mechanisms. Int J Mach Tools Manuf 2021;162:103687.

[4] la Monaca A, Murray JW, Liao Z, Speidel A, Robles-Linares JA, Axinte DA, Hardy MC, Clare AT. Surface integrity in metal machining - Part II: Functional performance. Int J Mach Tools Manuf 2021;164:103718.

[5] Kalpakjian S, Schmid SR. Manufacturing Engineering and Technology. 7th ed. Pearson Educ. Inc. New Jersey: Pearson Education; 2013.

[6] Stephenson DA, Agapiou JS. Metal Cutting Theory and Practice. 3rd ed. Boca Raton: CRC Press; 2016.

[7] Groover MP. Fundamentals of Modern Manufacturing: Materials, Processes, and Systems. 5th ed. Wiley. 2012.

[8] Axinte DA, Andrews P. Some considerations on tool wear and workpiece surface quality of holes finished by reaming or milling in a nickel base superalloy. Proc Inst Mech Eng Part B J Eng Manuf 2007;221:591–603.

[9] Kwong J, Axinte DA, Withers PJ. The sensitivity of Ni-based superalloy to hole making operations: Influence of process parameters on subsurface damage and residual stress. J Mater Process Technol 2009;209:3968–77.

[10] Hessel SJ, Voice W, James AW, Blackham SA, Small CJ, Winstone MR. Nickel alloy for turbine engine components. United States Patent 6,132,527. 2000.

[11] ISO4288:1996. Geometrical Product Specifications (GPS) — Surface texture: Profile method — Rules and procedures for the assessment of surface texture. Int Stand Organ.

[12] Mills B. Machinability of engineering materials. Springer Science & Business Media; 2012.

[13] Davim JP. Surface Integrity in Machining. 1st ed. Springer London. 2010.

[14] Zhou JM, Bushlya V, Stahl JE. An investigation of surface damage in the high speed turning of Inconel 718 with use of whisker reinforced ceramic tools. J Mater Process Technol 2012;212:372-384.

[15] Thakur A, Gangopadhyay S. State-of-the-art in surface integrity in machining of nickel-based super alloys. Int J Mach Tools Manuf 2016;100:25-54.

[16] Bono M, Ni J. The effects of thermal distortions on the diameter and cylindricity of dry drilled holes. Int J Mach Tools Manuf. 2001;41:2261–70.