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ORIGINAL ARTICLE

Assessment of surface integrity of Ni superalloy after electrical-discharge, laser and mechanical micro-drilling processes

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Abstract Currently, electrical discharge machining (EDM) is the established manufacturing process for making holes through Ni superalloy turbine blades to facilitate blade cooling. Surface integrity of these sub-millimetre holes is of paramount importance since it directly influences the fatigue life of the component. In this paper, EDM is compared against laser and mechanical micro-hole drilling of Inconel 718 alloy. The motivation was to assess alternative manufacturing methods for raising the quality threshold of micro-drilled holes. Mechanical and metallurgical characterisation of surface and subsurface regions of the holes produced by the three processes was undertaken using backscatter electron (BSE) microscopy, electron backscatter diffraction (EBSD) and nano-indentation techniques to assess surface hardness, grain misorientation, plastic deformation and the heat-affected zone. The results suggest that mechanical micro-drilling offers improved mechanical, metallurgical and geometrical properties compared to both laser and EDM processes.

Keywords Micro drilling · Micro machining · Surface integrity · Nickel alloys · EDM · Laser drilling

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1 Introduction

In the past few decades, there has been a significant shift in the aeroengine industry from easily machinable materials towards those which are difficult to cut, such as nickel-based superalloys [1]. These materials exhibit superior material properties but present formidable manufacturing challenges. The process economics are also affected by high tooling costs and stringent workpiece quality standards. For this reason, various conventional and nonconventional machining methods are utilised for aeroengine manufacture. Examples of such features include micro-holes on turbine blades and seal slots in compressor and nozzle guide vanes. Turbine blade holes provide an essential cooling envelope around the blade surface. These features are typically in the 0.2–1-mm size range, and electrical discharge machining (EDM) is the industry standard for making micro-holes on turbine blades [2]. Drilling of these holes occurs when the part has already undergone many processing stages, and hence high success rates are demanded of this operation.

Despite being an established process, there are issues relating to surface integrity and the geometrical definition of features manufactured by EDM. These include the formation of recast layers and heat-affected zones (HAZ), micro-cracking, tensile residual stresses [3–6] and the resulting hardness profile. All these factors can strongly influence the service/fatigue life of a component [6, 7]. Additionally, EDM is limited to the machining of materials that are conductive. As turbine blades are increasingly coated with electrically insulating thermal barrier (TBC) coatings, clearing of EDM holes with TBC coatings makes this process less attractive [8]. Moreover, the manufacturing of combustor nozzles and ceramic composites for the hot section of the aeroengine [9] requires new processes for the drilling of micro-holes.

Success has been reported for laser beam machining for various drilling applications [10–14]. Despite lowering the cycle time [15], there are problems associated with workpiece surface integrity. According to Kumar and Yadava [11], the challenges in relation to characteristics for laser beam machining are HAZ, hole taper, surface roughness, recast layer and the formation of micro-cracks. With regard to drilling nickel-based superalloys, spattering at the hole entrance, conical hole profiles, HAZ, recast layers and micro-cracks have been found to be the main problems [12–14]. A recast layer is formed in laser drilling as molten workpiece material is not blown away during laser drilling process, it will solidify and accumulate on side of walls of the hole in the form of recast layer [13]. The recast layer can contain micro-cracks which are initiation sites for fatigue cracking [16]. The characterisation of these surface and sub-surface modifications is important since they can affect component service life. Previously, laser drilling-induced metallurgical changes (e.g. heat-affected zones and crack formation) have been found to change the mechanical properties [10, 17], for example, flexure strength after laser beam machining was found to be lowered by 60 % [17].

Another candidate process is mechanical micro-drilling. This can produce highly cylindrical holes having good surface finish along with acceptable productivity [18]. However, surface modifications can include a micron-scale white layer having high hardness [19], below which lies a region deformed to a depth of tens of microns, at least for macro drilling RR1000 nickel alloy [20]. Sub-surface plastic deformation has also been seen for Inconel 718 drilled with minimum levels of lubrication (MQL) [21]. With regard to micro-drilling of nickel-based superalloys, a nanocrystalline grain structure layer of micron dimensions followed by a deformed grain structure extending to a depth of tens of microns has been found [19, 22, 23]. The former is characterised by high dislocation density, high hardness and strain hardening response, while the latter shows increasing levels of deformation and grain misorientation towards the surface [23, 24]. Burr formation is another issue [25, 26], while surface roughness values in the range 0.1–0.25 μm have been measured after drilling at chip loads of 0.5–8 μm/rev [27].

While the above literature suggests that both laser and mechanical drilling could be of value for drilling fine holes in Ni superalloys, a detailed side by side study is required to uncover the relative merits and short comings of these compared to EDM. That is the purpose of this study.

2 Materials and methods

Micro-drilling tests were conducted on 2.2 mm thick rectangular plates of Inconel 718 alloy, in a wrought and then annealed (at 954–982 °C) condition. The material was supplied by Goodfellow Cambridge Limited, UK. The nominal chemical composition (in wt%) was as follows: Ni 52.5 %, Cr 19 %, Fe 18.5 %, Nb+Ta 5.13 %, Mo 3 %, Ti 0.9 % and Al

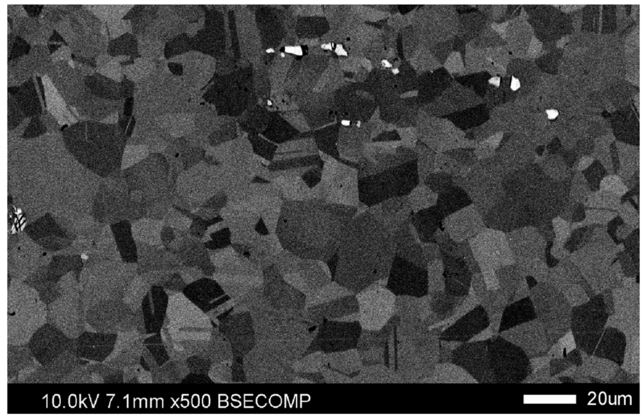


Fig. 1 Magnified backscatter scanning electron (*BSE*) image of Inconel 718

0.5 %. The average equi-axed grain size of the parent material was found to be ~12 μm. A magnified backscatter electron (BSE) micrograph of the parent material microstructure is shown in Fig. 1. The average Young's modulus and hardness of the parent material were recorded using a nano indenter (MTS XP nano-instruments, USA) as 206 and 3.67 GPa, respectively, at 500-nm indentation depth.

Table 1 summarises the electro-discharge, laser and mechanical machining parameters used in the drilling tests. In

Table 1 Description of machining conditions used in various processes

Machining processes	Machining parameters settings	
Micro-EDM	Machine used	Roboform 350 Charmilles
	Discharge current (A)	1, 1.5, 4, 6, 8
	Pulse duration (μs)	0.8, 3.2, 12.8, 25
	Voltage (V)	−160, −200
	Rotation speed (rpm)	50, 100
	Working fluid	IonoPlus IME-MH synthetic aliphatic Hydrocarbon
	Tungsten electrode diameter (μm)	400
Laser	Machine used	GSI-JK300D pulsed Nd:YAG
	Wavelength (nm)	1064
	Gas used	Oxygen
	Pressure (bar)	5
	Pulse duration (ms)	0.3
	Frequency (Hz)	40
	Energy (J)	3
Mechanical	Machine used	Mikron HSM 400
	Tool	0.5 mm, WC
	Spindle speed (rpm)	7000
	Feed (μm/rev)	8
	Peck depth (mm)	0.1
	Coolant	Hocut 3380

all cases, 500-μm diameter holes were drilled. This diameter is a representative value in the micro-machining domain reported in earlier studies [28, 29]. The selection of cutting parameters for laser drilling was taken from an earlier study [30]. The study suggested optimised cutting parameters for best hole definitions for laser drilling. Similarly, a conservative set of cutting parameters were chosen based on earlier micro-EDM study [31] to give good hole definition. In mechanical drilling, a twist drill having a higher point angle (150°) than that of a standard twist drill (118°) was used. This had a high web thickness (32 % of the diameter). An efficient cutting strategy was devised focused on centre and twist drills having different point angles (120° and 150°, respectively) [32]. The cutting parameters were selected for mechanical micro-drilling based on best hole definitions in previous study [33]. The EDM and laser drill parameters were selected based on technology developed for industry.

For metallographic examination, the drilled samples were prepared (parallel and perpendicular to the hole axis) in a hot mounting press using Conducto-Mount 2 conductive phenolic resin (supplied by MetPrep Ltd, UK) to achieve excellent edge retention at the machined surface. Considering the sensitivity of the surface and sub-surface preparation, all the samples were ground and polished on an automatic polishing machine, Presi Mechatec 334, using loads of 25 and 10 N, respectively. Grinding was carried out with 320, 600 and 1200 grit. Polishing was carried out with 9-, 6- and 3-μm liquid pastes. Final polishing was carried out at 30 nm on a suede cloth with silica to achieve a high surface quality.

All BSE and SE studies were carried out on a Hitachi 3400 scanning electron microscope. EBSD studies were conducted on a high-resolution field emission gun (FEG) Philips XL 30 FEG-SEM at a working distance of 20 mm and at 20 kV accelerating voltage. EBSD maps were analysed using Channel-5 software from HKL technologies.

3 Results and discussions

3.1 Hole definition

Figure 2 contrasts the quality of hole definition for the three methods. From this, it is evident that the laser-drilled hole is by far the worst (out of roundness ~27–31 μm), compared to (7–9 μm) and (6–7 μm) for the EDM and mechanically drilled holes, respectively. It should be noted that for the laser-drilled hole, the shape is not uniform down the length of the hole either.

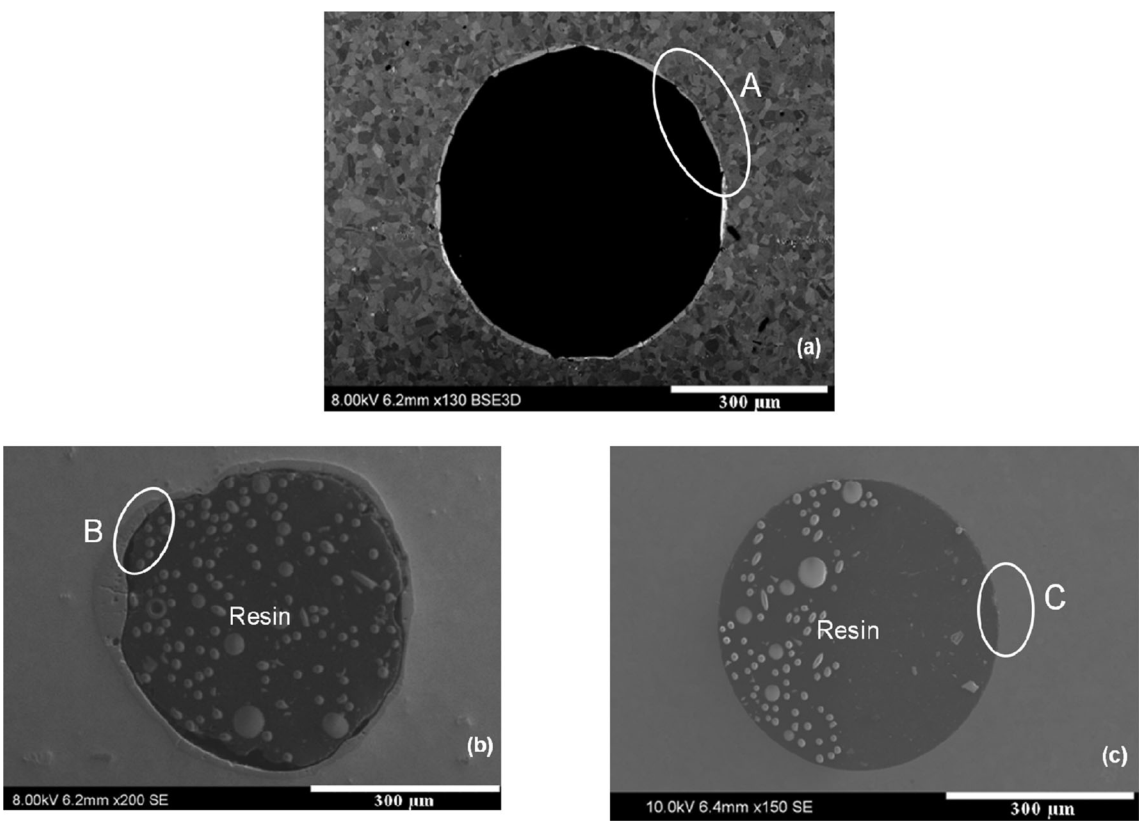


Fig. 2 The geometrical definition of **a** EDM, **b** laser and **c** mechanically drilled holes

3.2 Hole microstructures

For the EDM hole, a melted/re-solidified layer, also called a recast layer, can be observed all around the hole (Fig. 2a). High magnification secondary electron (SE) and backscatter electron (BSE) images of encircled area 'A' (Fig. 2a) shown in Fig. 3a and b, respectively, reveal the presence of micro-cracks in the recast layer. These micro-cracks are formed due to rapid shrinkage of the solidifying material [6, 34] and thus extend

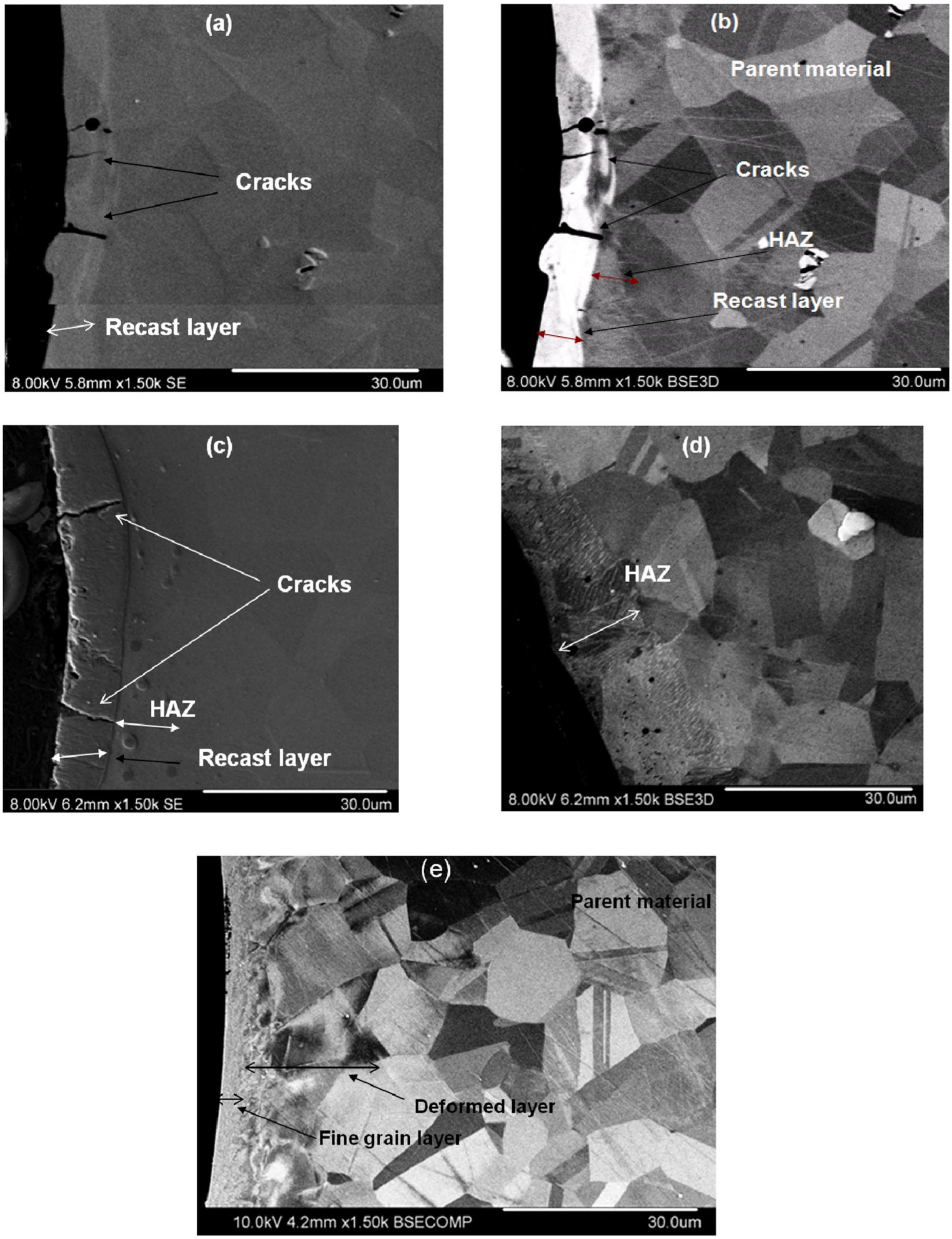


Fig. 3 Microstructural characterisation by scanning electron (SE) and backscatter electron (BSE) of **a**, **b** EDM, **c**, **d** laser and **e** mechanically drilled holes

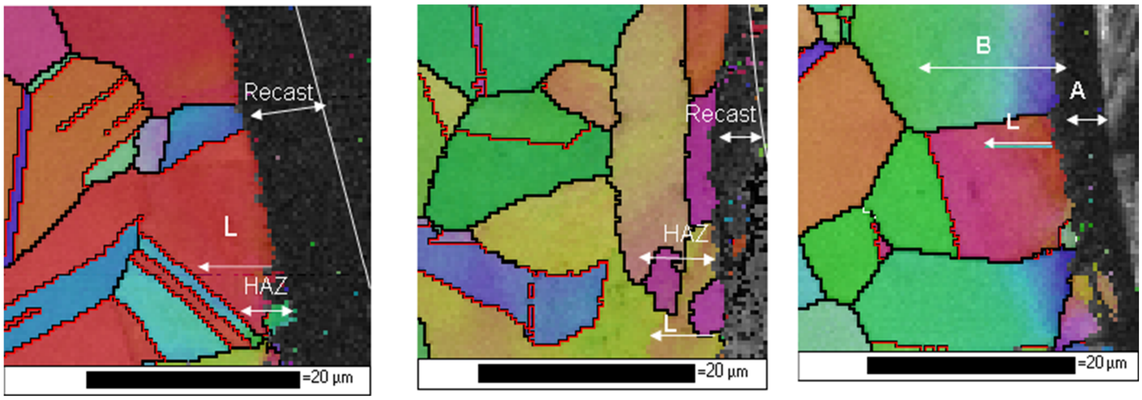


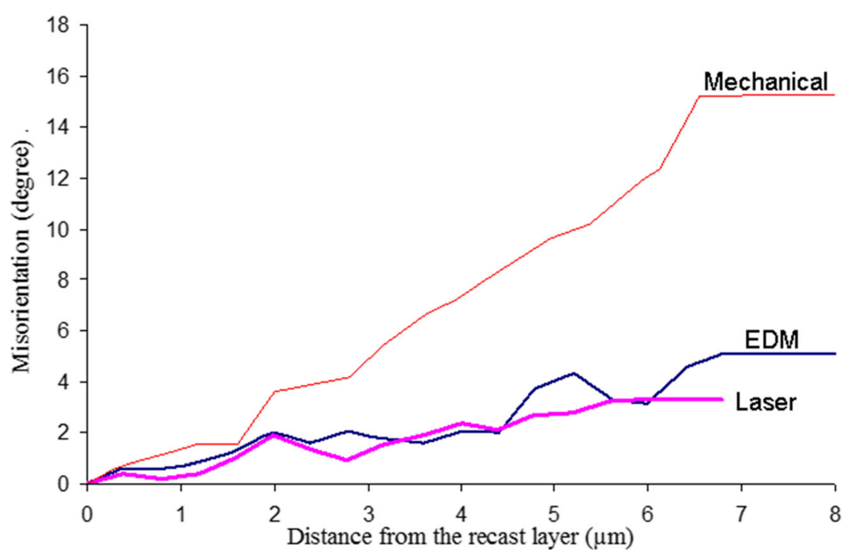
Fig. 4 EBSD IPF colour maps overlaid on band contrast maps for (from *left* to *right*) EDM drilling, laser drilling and mechanical drilling at a feedrate of 2 µm/rev and 5000 rpm

radially through the layer. The thickness of this recast layer varies from 6 to 12 µm around the hole.

The laser-drilled hole also shows a distinct recast layer in Fig. 3c (high magnification image of encircled area 'B' in Fig. 2b) and is formed as a result of the rapid heating and cooling process arising from the laser. The thickness of the recast layer varies substantially around the hole perimeter (from 9 to 45 µm). Similar to the EDM drilled holes, in laser-drilled holes, radial cracks are evident in the recast layer. One possible mechanism is that the assist gas causes the recast layer to cool rapidly forming the microcracks [13]. In both cases, the recast layer is followed by a heat-affected zone which has experienced a metallurgically significant thermal excursion. For EDM (Fig. 3b), the HAZ is rather indistinct extending to a depth of around 4 µm, whereas it is much clearer for laser drilling (Fig. 3d) extending to a depth around 10 µm.

In contrast to the severe localised heating caused by EDM and laser drilling, the twist drill does not introduce a thermal excursion sufficient for widespread local melting at the hole surface; however, it does introduce significant near-surface plastic deformation in the direction of the tool movement. Consequently, while there is no recast zone, there is an ultra-fine-grained layer followed by a deformed grain structure layer in Fig. 3e (high magnification image of encircled area 'C' in Fig. 2c). At a cutting speed of 7000 rpm and feedrate of 8 µm/rev, the average depth of the fine grain layer was found to extend to approximately 6 µm. The deformed layer extends around a depth of 25–30 µm from the machined surface, showing decreasing to levels of strains towards the parent material beneath. It may be worth mentioning here that the thickness of ultra-fine grain structure layer and deformed layers increases with higher cutting speeds and feed rates. However, no other surface anomalies were identified [35]. It is interesting to note that there is relatively a smooth transition between these three regions.

Fig. 5 Relative misorientation profile along the lines labelled L (Fig. 4) for EDM drilling, laser drilling and mechanical drilling



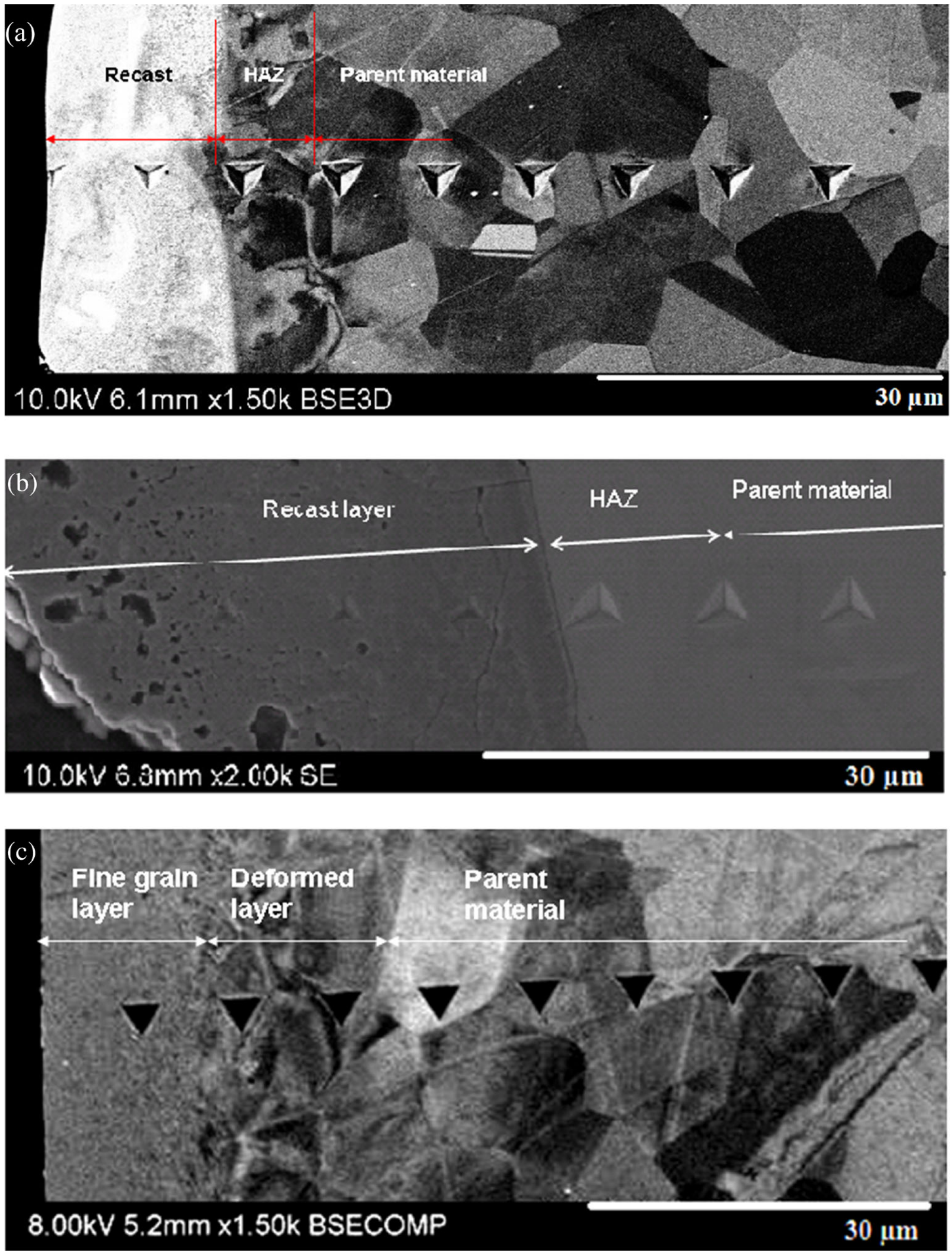


Fig. 6 Microstructure and nanoindents with distance from the hole for **a** EDM, **b** laser and **c** mechanical drilling

3.3 Grain sub-structure

Electron backscatter diffraction (EBSD) analysis can reveal the local crystal orientation point by point, enabling the texture, the stored energy and the local misorientations within grains to be quantified. EBSD was used here to compare deformations generated near-surface by the three drilling methods. Unfortunately, the EBSD patterns obtained in the recast layers (EDM and laser-drilled holes) and fine grain structure layer (mechanical drilling) were not of sufficient quality to be indexed (shown black in Fig. 4). However, in most regions of the recast layer, a simple comparison of the EBSD patterns with standard EBSD patterns suggested the presence of oxides of chromium for both the EDM and laser-drilled samples. Similar observations were reported for the presence of nickel and chromium, i.e., NiO and Cr_2O_3 in this layer [12]. Comparison of inverse pole figure (IPF) colour maps (overlaid on band contrast maps) in Fig. 4 and relative misorientation profile (Fig. 5) show the presence of significantly higher lattice rotations when moving towards the machined surface (along line L) for mechanical micro-drilling than for the other two techniques. This misorientation profile

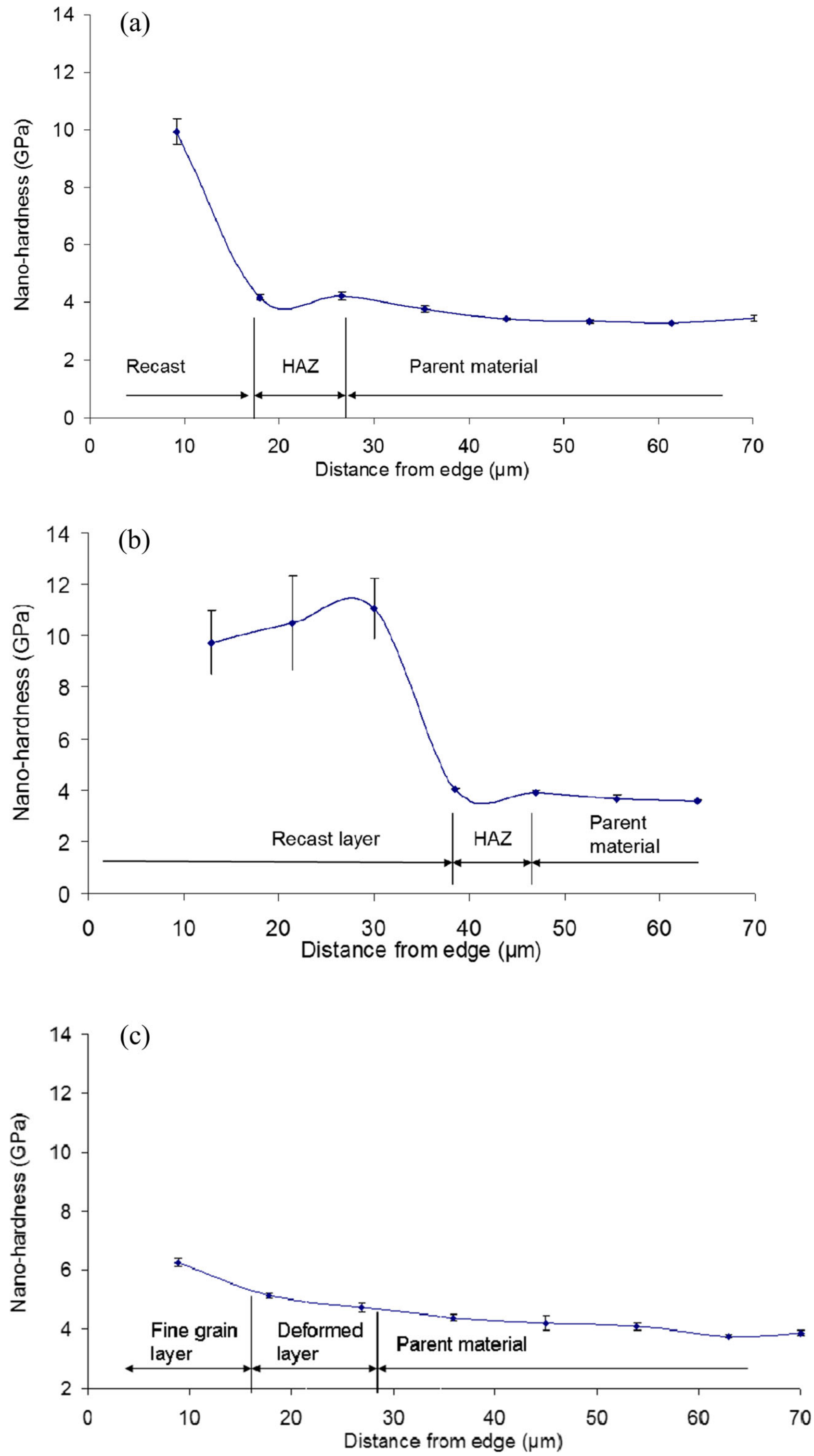


Fig. 7 Nanoindentation hardness mapped with distance from edge of the hole for **a** EDM, **b** laser and **c** mechanical drilling

shows that in mechanical drilling, the workpiece is subjected to higher plastic deformations/lattice rotations near the machined surface. This layer can be characterised by extensive stored energy resulting in higher hardness in the layer.

3.4 Local hardness

Near surface properties were assessed by nanohardness measurements. Specimens were prepared using a taper turning technique, as described in earlier study [23]. A total of four

Table 2 Comparison of different machining processes

Microhole features	Hole making processes		
	Micro-EDM	Laser	Mechanical
Out of roundness	7–9 μm	27–31 μm	6–7 μm
Surface roughness (inside hole)	Looks rougher than mechanical drilling	Looks roughest of all	0.1–0.25 μm
Metallurgical change to parent material	Recast layer and HAZ	Uneven recast layer and HAZ	Fine grain structure layer and deformed layer
Edge profile	6–12 μm recast layer	9–45 μm recast layer	No recast layer. 3–6 μm thickness fine grained zone
Hardness	8.9–11 GPa in recast layer	8.5–12.3 GPa in recast layer	6–6.4 GPa in fine grained zone
Observed anomalies	Radial micro-cracks	Radial micro-cracks	No micro-cracks. Exit burrs
Cycle time for drilling 500-μm hole in 2-mm plate	15 min	<1 s	~8 s

measurements were taken at each location. Figure 6 shows the nanoindentation locations for the three methods, while the associated hardness values are shown in Fig. 7. It is clear that for EDM, the recast layer has a substantially higher hardness than the HAZ and parent material, lying in the range 8.9–11 GPa, compared to 4–4.4 GPa in the HAZ and 3.3–3.9 GPa in the parent. The higher hardness in the recast layer can be attributed to the formation of oxides of chromium [12]. For the laser-drilled hole, the hardness of the recast layer and the HAZ appears to be similar to that for EDM. For the mechanically drilled hole, the hardness of the fine grained layer ranges from 6 to 6.4 GPa. This high hardness could arise from the fine grain structure and high dislocation density found there, while the higher hardness in deformed layer relative to the parent material is most likely due to the higher dislocation density arising from plastic deformation [23, 24]. Figure 7 shows that the mechanical micro-drilling process produces the least hardness increase. It also shows reversed hardness profiles for laser compared to EDM recast layer, with the EDM recast layer being harder on the surface. The general trend for the hardness of the mechanical drilled hole is closer to the EDM than the laser profile.

4 Summary

The surface integrity of the machined surface associated with micro-drilling of nickel-based super alloy using laser, EDM and mechanical methods was characterised. Table 2 summarises the main characteristics of the three processes. It is evident that in terms of geometric definition, laser drilling does not perform better compared to EDM or mechanical micro-drilling. Both EDM and laser drilling produce higher aspect ratio holes but give rise to hole taper, radial micro-cracks in their recast layer and significantly higher hardness. By contrast, holes made by mechanical drilling method exhibit better surface roughness [27], roundness, no recasts and micro-cracks compared to EDM drilling but exhibit tool wear and lower hole aspect ratios. This suggests improved surface integrity definition from mechanical micro-drilling compared to laser and EDM drilled holes. It is in fact a trade-off between good hole definition and hole aspect ratio. In implementing the technology, both electrode and tool wear has to be considered according to the workpiece specifications.

Overall, the mechanical micro-drilling offers improved mechanical, metallurgical and geometrical properties in comparison to both laser and EDM processes in this study. This shows better surface integrity definition which could result in longer fatigue life of the component.

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