Tool life and surface integrity aspects when drilling nickel alloy

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Abstract. Nickel based super alloys manufactured through powder metallurgy (PM) route are required to increase the operational efficiency of gas turbine engines. They are material of choice for high pressure components due to their superior high temperature strength, excellent corrosion, oxidation and creep resistance. This unique combination of mechanical and thermal properties makes them even more difficult-to-machine. In this paper, the hole making process using coated carbide inserts by drilling and plunge milling for a nickel-based powder metallurgy super alloy has been investigated. Tool life and process capability studies were conducted using optimized process parameters using high pressure coolants. The experimental trials were directed towards an assessment of the tendency for surface malformations and detrimental residual stress profiles. Residual stresses in both the radial and circumferential directions have been evaluated as a function of depth from the machined surface using the target strain gauge / center hole drilling method. Circumferential stresses near workpiece surface and at depth of 512 µm in the starting material was primarily circumferential compression which was measured to be average of –404 MPa. However, the radial stresses near workpiece surface was tensile and transformed to be compressive in nature at depth of 512 µm in the starting material (average: -87 Mpa). The magnitude and the depth below the machined surface in both radial and circumferential directions were primarily tensile in nature which increased with hole number due to a rise of temperature at the tool–workpiece interface with increasing tool wear. These profiles are of critical importance for the selection of cutting strategies to ensure avoidance/minimization of tensile residual stresses that can be detrimental to the fatigue performance of the components. These results clearly show a tendency for the circumferential stresses to be more tensile than the radial stresses. Overall the results indicate that the effect of drilling and milling parameters is most marked in terms of surface quality in the circumferential direction. Material removal rates and tool flank wear must be maintained within the control limits to maintain hole integrity.

Keywords Nickel alloy, Drilling, Residual stress, Surface integrity, Tool life

1. Introduction

Nickel base super alloys possess superior high temperature strength and creep resistance and are being employed on gas turbine engines to operate at elevated temperatures to improve fuel efficiencies. These alloys are choice of material for components that are located on the hot section of the engine. Several types of holes such as the bolt holes, flange holes and cooling holes needs to be machined on components manufactured using these difficult-to-cut materials. Drilling is one of the most important processes in aerospace manufacture and is often the last operation performed. Due to their superior material properties, any uncontrolled machining processes can significantly alter their microstructure, which may result in premature nucleation of surface fatigue cracks and result in an uncontained component failure [1,2]. Herbert et al. [3] conducted a comprehensive study of the key characteristics of a set of workpiece anomalies (while layers, material) generated at two levels of magnitudes along with damage-free surfaces when drilling of a Ni-based superalloy. Their evaluation of the influences of low cycle at high temperature fatigue performances of the test pieces indicated that certain anomalies, particularly hard brittle white layers at both tested magnitudes (5 μm and 10 μm), can have particularly deleterious effects on fatigue life that cannot be tolerated. They also reported that material drag had lesser effect on the fatigue life compared to residual stresses which was found to play a pivotal role in obtaining high number of cycles to failure in the case where no significant surface anomalies are produced on the test pieces. Kwong et al. [4] have studied the hole making process for a new nickel-based superalloy in respect to surface anomalies, microhardness and residual stresses. Their results show a tendency for the hoop stresses to be more tensile than the axial stresses. They have concluded that even for abusive roughing (drilling), high integrity holes can be achieved by a careful plunge milling finishing process.

Similar results were reported by Li et al. [5] during surface finish turning of nickel-based superalloy where they found that the residual stresses tend to have a tensile character at all depths in the hoop direction, but exhibit a compressive nature in the radial direction. Axinte et al. [6] have optimised the rough and finish turning parameters to produce low cycle fatigue samples from powder metallurgy nickel based alloys. They assessed the capability of shaping these materials through a multi-objective quality criterion using tool life, surface finish, workpiece surface integrity and residual stress distributions. Surface integrity characteristics of machined Inconel 718 with coated carbide and PCBN tools have been investigated by M'Saoubi et al. [7]. Their study showed that PCBN tools appeared to be less prone to develop notch wear on secondary edge when compared to coated carbide and consequently are able to maintain an acceptable surface finish even in the presence of severe flank wear.

Arunachalam et al. [8] have investigated the residual stress and surface finish generated during facing age hardened Inconel 718 with CBN cutting tools as a function of speed, depth of cut, coolant, tool geometry and nature of the tool coating. The results of their study showed that residual stresses and the surface roughness generated by CBN cutting tools are more sensitive to cutting speeds than depth of cut. They have reported that the use of coolant results in either compressive residual stresses or lowers the magnitude of the tensile residual stresses, whereas dry cutting always resulted in tensile residual stresses. Their recommendation is to use coolant to achieve compressive or minimal tensile residual stresses and good surface finish. Axinte el al. [9] have studied the hole-making processes for powder metallurgy based nickel alloys. This involved a succession of roughing (drilling) and finishing (normal/special reaming or plunge milling) operations which were evaluated through a multicriteria procedure. They have reported that drilling and normal reaming could lead to surface overheating (white layers) and material dragging. They have suggested a change of edge preparation on the special reamers or the use of alternative cutting strategies (e.g. plunge milling) could generate finished holes within the required surface integrity standards. Results from the dry drilling of powder metallurgy nickel alloy revealed relatively thick white layers present over the hole subsurface and indicated that use of cutting fluid (preferably through spindle) is vital to ensure acceptable hole integrity when drilling this material [10]. Despite excellent tool life when milling at low cutting speed and feed rate, white layers were detected in some of the surfaces assessed. The following sections detail results of drilling and plunge end milling of powder metallurgy nickel based alloy, achievable tool life, surface integrity and residual stress distributions. As powder processed forged material, it is finding increased use for combustor and turbine parts, but is thought more difficult to machine than mainstream products.

2.Experimental set-up

The composition and microstructure of nickel alloy material used in this study manufactured through powder metallurgy technique is shown below in Table 1 and Figure 1. The material has higher percentage of chromium, and cobalt for high temperature creep strength. Representative hole size used

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in this study (40 off ϕ12.99 ±0.04mm) was initially rough machined by drilling followed by plunge milling as finishing operation on a CNC Hermle C50 machining center. Machining conditions are presented in the Table 2. The flange holes were 40 x Ø12.99mm equally spaced flange holes. The first procedure involved using an Ø12.5mm carbide drill as there were 40 holes to drill around the flange face. As well as this the drill was taken out of the machine at the end of hole numbers 20, 30 and 40 and more detailed pictures were gathered on the laboratory microscope, with the drill wear being measured on the microscope after the final hole (40). Tool wear was measured with a microscope fitted with a digital colour camera AxioCam ERc 5s from ZEISS and analyzed with the AxioVision software. The magnifications were selected to be the highest for the measured area and ranged from 0.65x to 20x optical zoom The second procedure involved using an Ø12.99 mm carbide end mill as there were 40 x Ø12.99mm holes to be plunge milled around the flange top face. As well as this the end mill was taken out of the machine at the end of hole number 20, 30 and 40 as well as before hole 1 was milled, and more detailed pictures of the end mill were gathered on the laboratory microscope, the end mill wear was also being measured on the laboratory microscope after the final hole (40).

Table 1. Material properties

Material	UTS (Avg) (MPa)	0.2% yield strength (MPa)	Elastic Modulus (GPa)	Hardness
PM Nickel Alloy	1600	1200	230	450 HV

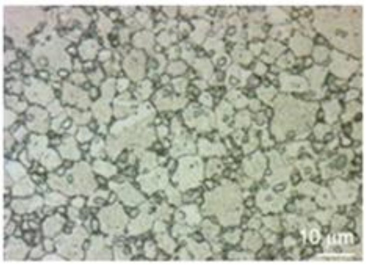

Figure 1: Microstructure of nickel based powder metallurgy alloy

Table 2. Hole machining conditions

Stage Description	Feature Name	Tool/ Insert	v_c (m/min)	f (mm/ rev)	a_p (mm)	Machining Time (min)	Coolant type	Coolant pressure	Coolant application- Pressure or flood/directional etc.
Drill 1-40	12.5mm hole	Seco TCG01000305827	25	0.05	4	2.02/hole	Hocut 795B	70*	Thru and flood
Plunge Mill 1-40	12.99mm	Technicut End/Mill - TCD 2706	35	0.05	4	1.05/hole	Hocut 795B	70	Thru and flood

The work part condition of supply and geometry and fixtures used in this study is shown in Figure 2. This choice of fixturing was justified because of its ability to offer high levels of clamping force coupled with its ability to centralize the work piece. Tools used in the study were Sandvik drills (R840-1250-30-A1A 840 Delta C) and Technicut end mills (TCD 2706) (Figure 3). Every tool used was accompanied by high pressure coolant, flood coolant and through tool coolant where possible. The holders were equipped with HSK100 back ends. An SMW 3 jaw chuck was used for all the machining undertaken in this project.

Figure 2: Workpart and fixture used in this study

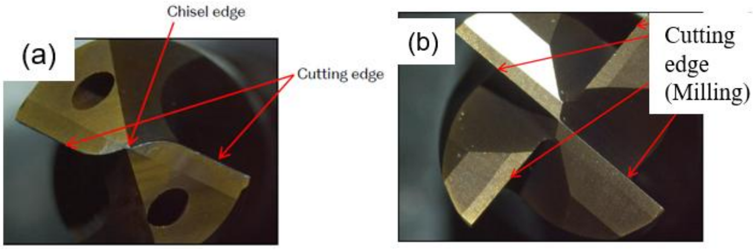

Figure 3: (a) Sandvik drill and (b) Technicut end mill

Machined sample for microstructural investigation was etched through the following process. The each cut hole was sectioned into 2 halves, ensuring that a sufficiently thin cutting wheel is used so as to minimise consumed material. Assess one half by polishing down onto the axis of the hole (Face A) and the other half by polishing through the cross-section of the hole (Face B).

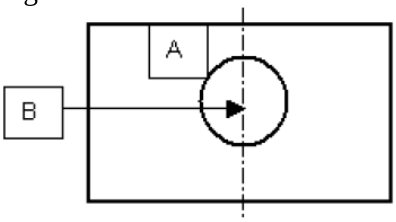

Figure 4: Graphical illustration of method and labelling scheme for hole features

The samples from the machining trials were then subsequently re-prepared and etched in 10% ortho-phosphoric acid at 2 Volts for approximately 10 seconds to generate a more uniform etch response. SEM analysis was also selected to replace optical microscope inspection to increase magnification and aid microstructural definition used in this exercise. Residual stresses have been determined using the target strain gauge / centre hole drilling method. This method evaluates the distribution of residual stresses to a depth of 1024 μm from the surface for the gauges selected. Target strain gauges (equally spaced at three around the circumference) were installed and drilled. Strain gauges were installed on the surface of the work part at different positions. Three gauges were installed at each position, equi-spaced at 120° intervals. The work part was fitted to a drilling frame for alignment with a PC-controlled miniature 3-axis drilling machine. Orbital drilling was carried out at each gauge in turn using an inverted cone tungsten carbide cutter (one per gauge) with a pre-set orbital eccentricity. The datum depth was detected at each hole using an iterative command in the drill control software to advance the rotating drill bit in 2 μm increments. Between successive advances, intervening orbit and withdrawal movements were carried out so that the target site could be inspected for penetration through the gauge backing material and adhesive layer. The incremental hole drilling procedure was carried out at each gauge noting the changes in relaxed strains at sixteen drill depth increments (4 x 32 μm + 4 x 64 μm + 8 x 128 μm), giving a completed hole depth of 1408 μm.

3.Results and discussion

3.1. Tool life and Surface Quality

Tool life studies were carried out at 25 m/min (drilling) and 35 m/min (plunge milling). The criteria for tool life was set as an anomaly free surface. The number of holes on the actual component was 20. However, in order to take factor of safety in to account, the tool life criteria was doubled to 40 holes without any remarkable surface deterioration. After 40 holes, the maximum wear recorded was 0.135mm in the case of drilling operation and 0.241mm in case of plunge milling (Figure 5). The drill tool experienced less wear compared to end mill. The wear land was more uniform with no evidence of tool chipping or edge fracture. The primary mode of wear on the chisel edge and the cutting edge was found to be abrasion. No traces of adhered material were found on the tool edges (Figures 5 and 6). High pressure coolant (Hocut 795B) delivered through tool to a greater extent aided to control the tool wear progression (Figure 6).

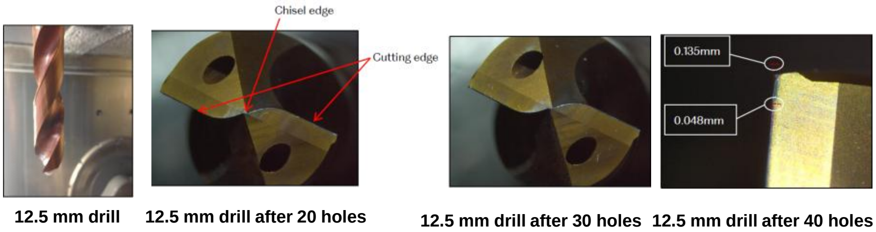

Figure 5: Drill tool edge condition after 20th, 30th and 40th hole

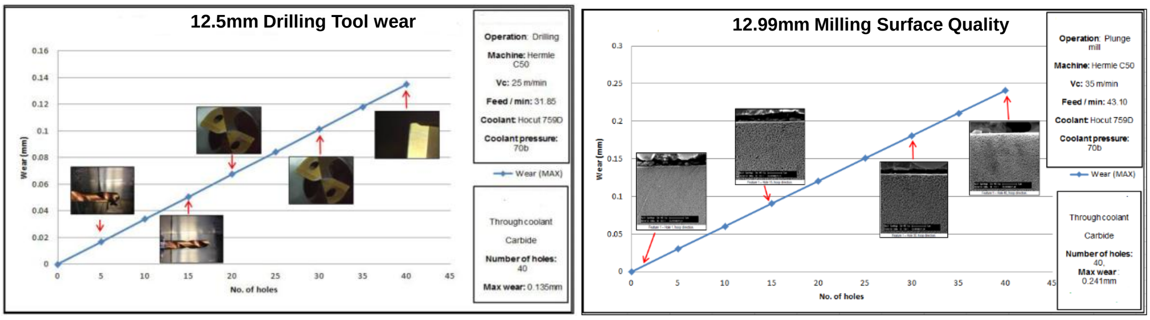

Figure 6: Tool wear progression for drill and end mill

On the other hand, the end milling tool showed evidences of tool abrasion, chipping and fractured edge as noticed towards the 40th hole(Figure 8).. However, this damage to the tool edge did not affect the machined surface as checked through the surface and sub-surface inspection carried out on the 40th hole which passed surface requirement criteria.

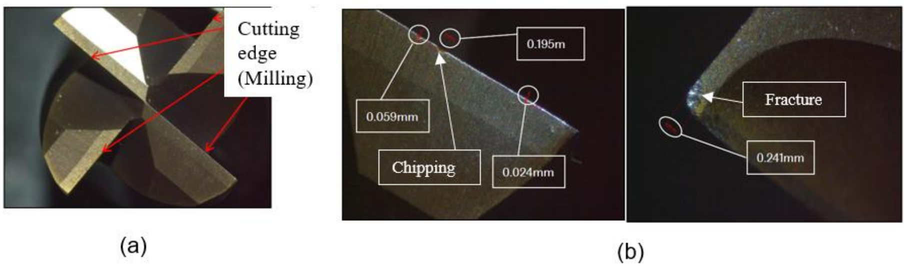

Figure 7: Tool wear of end mill after 40th hole

The machined surfaces were inspected for anomalies such as white layer, amorphous layer, distorted layer, surface drag, redeposited material, laps, plucking, flaking, score, surface roughness and strain hardened layers. All holes inspected showed hardened layers to a depth of less than 5μm. An allowable distorted layer/surface drag was 10μm. The effect of plunge milling was clearly evident on the circumferential direction where the surface drag showed an increasing trend as the number of holes machined increased. The maximum distorted layer/surface drag recorded was 8.5 μm on the 30th hole. On the other hand, distorted layer and surface drag were very minimal along the axial direction (Max: 2.1 μm).

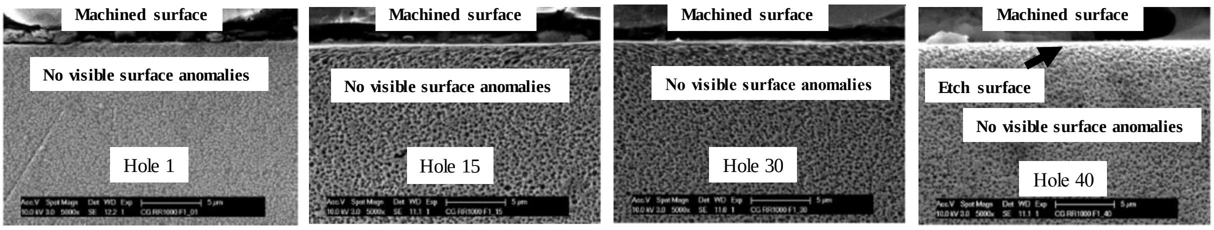

Figure 8: Surface integrity inspection micrographs for 1st, 15th, 30th and 40th holes

3.2 Residual Stress Profiles

The residual stress profiles measured on the condition of supply (before machining) and machined surface along the depth of the hole after hole-drilling and plunge milling are shown in Figure 9. Results from individual gauges confirm that near-surface circumferential stresses are compressive between -200MPa and -400MPa up to a depth of 100 μm and remains compressive (-400MPa) in the bulk of the material. Also, the near-surface discontinuities caused by machining do not extend beyond depth 352 μm. Distributions of stresses over the depth range 352 μm to 1024 μm contain no significant irregularities at any position; stresses in this depth range are generally linear in distribution with gradients not exceeding 300 MPa / mm. Accordingly, the summary values quoted for depth 512 μm may be considered to characterise the underlying distributions within the forging and independent of surface effects (caused by machining, etc). The radial stresses were tensile in nature near surface on the condition of supply sample which had a max magnitude of 190MPa near position 0° before turning compressive at a depth of 60 μm and remains compressive (-50MPa) in the bulk of the material.

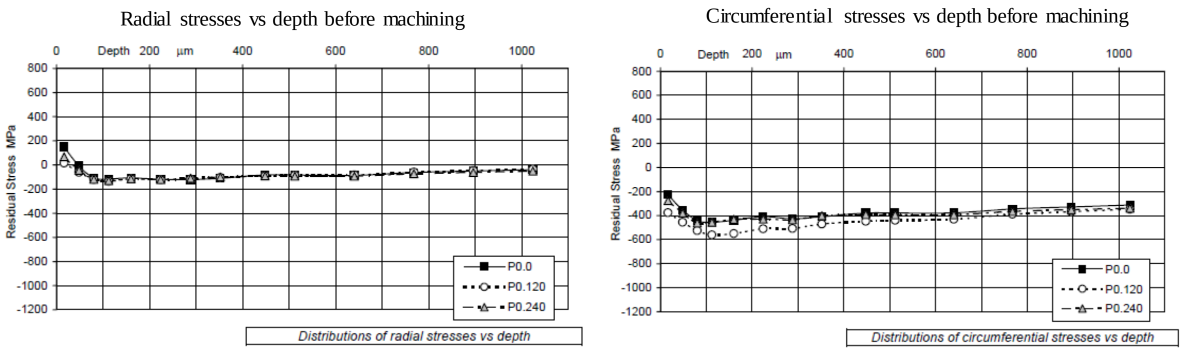

Figure 9: Residual stress distribution in sample condition of supply (Before machining)

Residual stress profiles for 3 hole numbers 2, 18 and 17 is shown in Figure 9. It can be seen that the radial stress profiles near surface is found to change from compressive to tensile in nature as the hole number increased from 2 to 17. The tensile residual stress for hole 17 was measured as 410 MPa near surface. This transition is attributed to increasing tool wear resulting in higher heat generation as machining progressed. These tensile stresses turn to compressive in nature (-200 MPa) around a depth of 50 μm and decays slowly to zero at a depth of around 100 μm. On the other hand, circumferential stress profiles all show tensile nature near surface for all the 3 holes measured (Figure 10). Maximum tensile stress was measured for hole 17 which was 690 MPa before turning compressive in nature of -190 MPa at around depth of 50 μm and decays to zero at a depth of 200 μm. Hole 17 had higher magnitude of circumferential stress. Overall the results indicate that the effect of milling parameters are most marked in terms of surface quality in the circumferential direction. Material removal rates and tool flank wear must be maintained within a process window to maintain hole integrity. This indicates that even in the case of abusive roughing, high integrity holes can be achieved by a careful plunge milling finishing process.

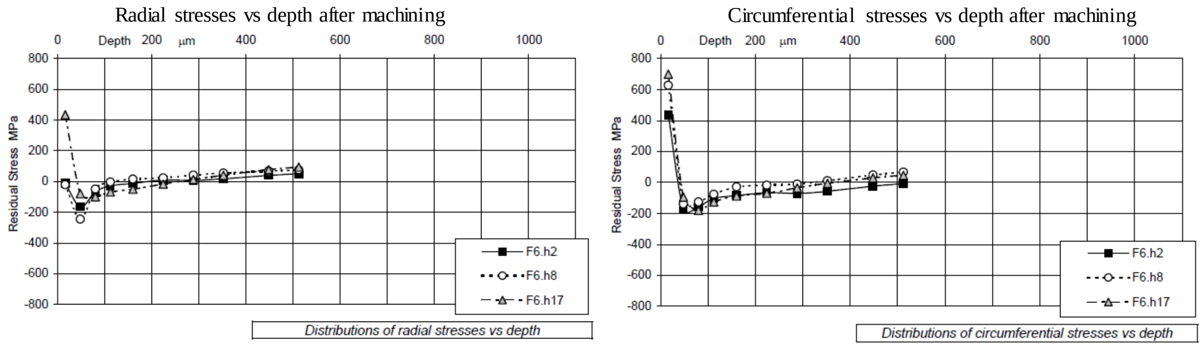

Figure 10: Residual stress distribution in hole numbers: 2, 8, 17

4.Conclusion

The hole machining process for a nickel-based powder metallurgy alloy has been investigated. The hole was machined through drilling and plunge milling process. Quality of machined holes in respect to tool life, surface anomalies and residual stresses was characterized. The results indicate that the effect of plunge milling parameters is most marked in terms of surface quality in the circumferential direction. The selected cutting tool and machining conditions satisfied the tool life criteria which was demonstrated through machining of 40 off 12.99mm flange holes. The maximum tool wear measured after 40th hole for drill tool was 0.135mm and 0.241 mm for end mill. Surface and sub-surface integrity of all holes machined did not show any signs of deterioration and were within acceptable limits. Material removal rates and tool flank wear must be maintained within a process window to maintain hole integrity. Residual stresses in both the radial and circumferential direction have been evaluated as a function of depth from the machined surface for drilled and plunge milled holes. These profiles are of critical importance for the selection of cutting parameters to ensure minimization of tensile residual stresses that can be detrimental to the fatigue performance. These results clearly show a tendency for the circumferential stresses to be more tensile than the radial stresses and suggest that high speed and high tool wear conditions, leading to thermal stresses may be dominant as the hole making process progresses.

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