Laser micro-hole drilling in thermal barrier coated nickel based superalloy

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Abstract. This investigation deals with laser drilling of micro holes in yttria stabilised zirconia coated nickel based superalloy using a power modulated fiber laser. The parameters taken into account are assist gas pressure, modulation frequency, pulse on time and hole inclination angle. These parameters affect the important geometrical characteristics of holes, e.g., hole diameter, hole wall smoothness, taper angle and recast layer thickness. It has been found that the assist gas pressure has a significant effect on hole entry and exit diameter, taper angle and hole wall smoothness. It has also been observed less number of pulses of higher energy produces a hole with smaller entry and exit diameter, smaller taper angle, smoother hole wall and a thin stretched recast layer (~ 15µm). The minimum achieved hole entrance diameter, exit diameter and taper was 342 µm, 200 µm and 3.54° respectively. Off normal drilling produces a hole with elliptical entrance. The eccentricity of such holes increases with inclination angle. Thick recast layers are produced at high inclination angles.

1. Introduction
Modern aero engine turbine blades are made up with Ni based superalloys like N738, CM247LC, Rene80, CMSX-4 etc[1] due to their superior fatigue and creep life. These blades are operated at temperature near to melting point of the blade material to achieve more engine efficiency. Therefore these blades are further protected with thermal barrier coatings and film cooling to increase the life of the blade [2, 3].

There are many micron size holes on blade which facilitates film cooling by forming the air blanket on the blade surface [4]. These cooling holes are characterised by their micron size diameter, high aspect ratio and inclination with respect to the blade surface. Plasma sprayed TBC usually consists of two layers; bond coat and top coat. The bond coat is an oxidation and corrosion resistant alloy designed to reduce the thermal expansion mismatch between the substrate and the top coat, and also to provide a naturally rough surface to enhance the adhesion of the top coat. The top coat is the actual thermal barrier which insulates the blade material from the high temperature gases. Yttria stabilised zirconia (YSZ) is commonly used as a thermal barrier coating [5]. This coating is deposited using either plasma spraying or electron beam physical vapour deposition (EB-PVD) process [6].

The hole drilling process has been discussed elaborately by Yeo et al. [7] in this case a focused high power laser beam is used to remove material from the workpiece by vaporisation. Apparently, laser drilling is well suited for drilling of TBCs, since it can vaporise both ceramic and metallic layers.
However, the process poses a number of challenges owing to the layered structure of the coating and the difference in thermo-physical properties of the materials constituting the layers.

Such holes are found to contain several geometrical as well as metallurgical defects. Common geometrical defects are hole taper, entrance and exit hole circularity, barrelling, chamfer at hole entrance and shoulder feature near the coating-substrate interface. Common metallurgical defects are heat affected zone (HAZ), recast layer, cracking, dross, oxidation and coating delamination etc. Kamalu et al.[8] investigated laser drilling of YSZ coatings deposited on 1.5-mm-thick, C263 Nimonic alloy, using several sets of parameters. Coating delamination and barrelling near the hole entrance was found to occur for holes having large inclination from the normal. The role of the coaxial assist gas jet on melt ejection using a numerical model was studied by Sezer et al.[9] The model showed that the molten material accelerated towards the leading edge of hole under the action of the coaxial assist gas jet, causing greater damage to the leading edge in the process. In a subsequent investigation, Sezer et al.[10] studied the effect of beam angle on the heat affected zone (HAZ), the recast layer and the oxide layer in the vicinity of the hole formed during laser drilling of YSZ coated Nimonic 263. It was found that the thickness of the recast layer and the HAZ increased with the deviation of the beam from the normal to the workpiece surface. The HAZ was more prominent near the leading edge at the hole entry side and trailing edge at the hole exit side. The situation was exactly opposite in the case of the recast layer. This was attributed to the fact that heat transfer was higher at the leading edge on the entry side and trailing edge on the exit side. A higher heat transfer rate resulted in a larger HAZ and smaller recast layer.

Formation of a shoulder feature at the coating and substrate interface during laser drilling of vertical holes was reported by Voisey et al. [11]. This shoulder was found to inhibit the melt flow and might also result in coating delamination.

The literature survey shows that the major research studies include the laser drilling of YSZ with Nd YAG laser. To the knowledge of the authors no literature on micro hole drilling of YSZ coated CM247LC alloy substrate using fiber laser has been published yet. This specialised substrate alloy is of interest because it is extensively used to produce castings of directionally solidified (DS) turbine blades and vanes. The objective of the present investigation is to study the effect of parametric variation on the features of laser drilled vertical and inclined micro holes on YSZ coated CM247LC Ni base superalloy with a power modulated fiber laser.

2. Experimental Procedure
As cast CM 247 LC Ni based superalloy disc of 15mm diameter and 1 mm thickness was used as substrate in this investigation. The substrate material had the following composition; C 0.07wt%, Cr 8.1wt%, Co 9.2wt%, W 9.5wt%, Mo 0.5wt%, Ta 3.2 wt% Al 5.6 wt%, Ti 0.7 wt %, Hf 1.4 wt%, B 0.015wt%, Zr0.015wt% and balance Ni. The substrate was metallographically polished and observed under microscope and SEM for its micro structure and phases Figure 1.

![Figure 1. Microstructure of as cast CM247LC alloy (a) microscopic view (b) SEM image](image-url)
The test coupons were grit blasted with Al₂O₃ grits, subsequently the ultrasonic cleaning with acetone solution were carried out. Finally samples were preheated to 150-200°C with plasma jet and deposition of a NiCrAlY bond coat (AMDRY 962, Sulzer Metco) and YSZ (204 B NS, Sulzer Metco) top coat carried out using Sulzer Metco 3 MB atmospheric plasma spraying (APS) using appropriate parameters (Table1). The deposited bond coat and top coat thickness varied from 150-250 µm and 50-150µm respectively. The coated samples and typical cross-section of achieved coating layers have been shown in Figure 2.

| Coating      | Current (A) | Voltage (V) | Stand-of-distance (mm) | Primary gas(N₂) flow rate (slpm) | Secondary gas (H₂) flow rate (slpm) | Nozzle diameter (mm) | Powder flow rate (kg/hr) |
|--------------|-------------|-------------|------------------------|-----------------------------------|-------------------------------------|----------------------|--------------------------|
| Top coat     | 500         | 74          | 150                    | 50                                | 5                                   | 7                    | 1.5                      |
| Bond coat    | 400         | 68          | 150                    | 50                                | -                                   | 7                    | 1.5                      |

Figure 2. Schematic of (a) coated samples (b) coated layers structure

Laser drilling in percussion mode was undertaken using a 2kW fibre laser (YLR 2000, IPG Germany) integrated with a five axis CNC table. The laser parameters that are kept constant during the experiments are listed in Table 2.

| Parameter                              |
|----------------------------------------|
| Peak Power                             | 1800 W |
| Laser beam Assist gas: N₂              |
| Pulse burst time: 120 ms               |
| Beam spot diameter: 250µm              |
| Power density: 0.047 W/µm²             |
| Focal plane position: 0.2 mm below the top surface of the sample |
| Stand-of-distance: 0.8mm               |
The assist gas pressures, drilling angle, pulse frequency and pulse on time were varied during the vertical and inclined hole drilling experiments (Table 3&4). Drilling at an inclination angle of 70° could not be performed using pulses of on-time 50 µs and hence, in this case the on-time was increased to 100 µs. Additionally, for this hole, the machining time was increased from 120 ms to 1620 ms, as the effective thickness of material to be drilled increased with inclination angle. There are two aspects of hole quality, the hole diameters and taper angle were analysed. Hole diameters were calculated by taking average of measured diameters at four different positions at equal angular interval at both entry and exit of the hole. Hole taper had been calculated with formula given below.

\[ \text{Taper angle (°)} = \tan^{-1}\left(\frac{\text{hole diameter at entrance- hole diameter at exit}}{2 \times \text{sample thickness}}\right) \]

| Table 3. Experimental plan for vertical hole drilling |
|----------------------------------------------------|
| Ex.No | Frequency (Hz) | Pulse Input Parameters | Output parameters | Sample ID |
|-------|----------------|------------------------|------------------|-----------|
| 1     | 1000          | 100 900                | 3 120            | p         |
| 2     | 500           | 100 1900               | 3 60             | q, r      |
| 3     | 50            | 1000 19000             | 3 6              | s, t, u   |

| Table 4. Experimental plan for inclined hole drilling |
|------------------------------------------------------|
| Ex.No | Frequency (Hz) | Pulse Input Parameters | Inclination angle | Sample ID |
|-------|----------------|------------------------|------------------|-----------|
| 1     | 1000          | 50 950                | 120 10           | v         |
| 2     | 500           | 100 1900              | 1620 70          | w, x, y   |

3. Results and discussion

Laser drilled samples were sliced along a line about 1mm away from the hole area using a low speed diamond cutter. The sliced sample was held in a resin mould and the moulded sample was ground and polished metallographically so as to expose the longitudinal section of hole for microscopic analysis (Figure 3, 4 & 5). The polished sample was examined using SEM and Ziess optical microscope. The polished cross section was etched using an etchant composed of HCl, HNO₃ and glacier acetic acid in 4:3:3 volume ratio.

It has been observed that at given frequency, Ton and Toff, the increase in assist gas pressure increases the hole entrance diameter. This happens because at higher gas pressure (6 bars) the residual liquid is blown off more effectively resulting in an increase in the entrance hole diameter. Similar observation was made while CO₂ laser drilling of YSZ coating [12].

At the same pulse energy, increase in off-time from 900µs to 1900µs at 6 bar gas pressure also increases the hole entry diameter significantly from 472µm to 497µm (sample q & s respectively). This may attribute due to a higher gas pressure and more off time results in efficient ejection of the melt.
Figure 3. SEM pictures of (a) longitudinal (b) entrance (c) exit of vertically drilled hole

Figure 4. Microscopic view of vertically drilled holes from entrance and longitudinal side
In general, hole exit diameters also show a tendency to increase with assist gas pressure. Sample q is an exception. The average exit hole diameters for sample p and r are 255µm and 200µm, respectively. This decreasing trend can be attributed to a decrease in number of pulses. It may be noted that a through hole has been produced only with 60 laser pulses in the case of sample r. Additional laser pulses after the breakthrough has removed more material from the lower sections of the hole and has efficiently flushed out the recast materials [13]. This is why the exit hole diameter for sample p, produced with 120 pulses, is higher.

Figure 5. Microscopic view of inclined drilled holes from entrance and longitudinal side

Hole t was obtained using 6 pulses only and according to the above explanation the exit diameter for this hole should have been smaller than that of r. However, contrary to the expectation it is 219 µm, i.e., similar to that of sample r. In this case the pulse on time was increased to 1000 µs from 100 µs. Wider pulse delivers energy deeper into the workpiece and hence this effect has offset the effect of
A reduction in number of pulses. Hence, no decrease in exit hole diameter has been detected in this case. A similar observation has been made while laser drilling of holes in Cu using pulsed laser [14].

The taper angle depends on the difference in hole entrance and exit diameters for given material thickness. This difference is found lowest in holes drilled in expt3 therefore taper angle is also lowest as compared hole taper achieved in expt1&2. The holes in expt3 were produced using a smaller number of pulses of larger duration and hence energy per pulse was much higher in this case. Such pulses are useful for drilling relatively deeper holes. On the other hand the energy of the shorter pulses (expt1&2) is more likely to get absorbed at the entry wall enlarging its diameter and possibly a smaller fraction of the energy can reach deep inside the hole. As a result the entry diameters and tapers angles of the holes produced in expt1&2 are larger compared to those of expt3.

The longitudinal sections of the holes are shown alongside the cross sections in Figure 4. In comparison to sample q, sample p shows a bell shaped entry section and a rough hole wall. Sample p was produced at a lower assist gas pressure of 3 bar. Sample q on the other hand shows a stretched recast layer and a smoother wall. The smoothening of the hole wall and stretching of the recast layer is attributed to the more intense blowing effect of the higher pressure assist gas in the case of sample q. Sample r and s were produced at a lower pulse frequency. For this frequency, a bell shape has formed at the hole entrance at a higher assist gas pressure (6 bar) and no significant difference in wall roughness is detected. However, the recast layer is stretched to a greater depth at a higher gas pressure, as expected. The hole quality has improved significantly in samples t and u. This is attributed to a higher pulse energy used for producing these holes. A higher energy pulse is expected to produce more efficient vaporisation and higher vapour pressure to a greater depth with a smaller volume of remnant liquid adhering to the inner wall [15]. Consequently the assist gas has blown off a smaller volume of liquid in such cases. Finally a thin and uniform recast layer has formed on the inner wall of the hole.

Figure 5 shows the entrance and longitudinal sections of the inclined holes. The entrance of hole in all cases is elliptical and the eccentricity has been found to increase with the angle of inclination. For hole drilled at 70°, the entrance of the hole has shown a highest degree of ellipticity along with significant barrelling. A recast layer is observed in all the cases. The recast layer for the 70° hole is much thicker than the others. When laser beam is made inclined, the beam spot will also be enlarged with elliptical shape which reduces the available power density at the substrate. Bathe et al.[16] drilled the TBC coated IN718 material and reported that at lower power density the laser beam entrap in drilled hole and produces barrelling due to multiple reflection of the laser beam. And also at lower power density, the melting dominates over vaporisation which stays for longer time. These facts could be the appropriate reason for thicker recast and barrelling of the hole for 70° angled hole.

![Figure 6](image-url)

Figure 6. (a) Sections in EDX (b) elemental composition in the coating area along the drilled hole
EDX analysis along the hole at three sections top (in coating area), middle and bottom (Figure 6) shows presence of higher concentration of Ni near entrance of hole that means the melt ejected out in upward direction and solidified at hole entrance. Zr is traced out more at top and some amount at middle of the hole and there is no Zr at bottom section of the hole. It shows that Zr flows slowly from top to bottom and solidified in between the hole area well before hole exit.

4. Conclusion

YSZ coated Ni based superalloy sheet has been successfully drilled using a power modulated fiber laser. An increase in assist gas pressure from 3 to 6 bar has resulted in an increase in the hole entry and exist diameters and also the taper angle. It has also resulted in stretching of the recast layer and smoothening of the hole wall. At a higher gas pressure the residual liquid adhering to the inner wall is blown off more effectively. An increase in number of pulses results in an increase in the entry hole diameter and the taper angle. Energy from shorter pulses is more likely to be absorbed in the entry side of the hole resulting in an increase in entry hole diameter. A smaller number of higher energy pulses, on the other hand, produce holes with smaller taper angles. Possibly such pulses deliver energy more effectively in greater depths. A flushing effect is also associated with an increase in number of pulses. The entry hole takes an elliptical shape when the laser beam is incident on the workpiece surface at an off normal angle. The degree of ellipticity increases with an increase in inclination angle. A thicker recast and significant barrelling has been observed with high inclination (70°) of the hole.

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