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Laser Drilling of Thermal Barrier Coated Nickel Alloy

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Abstract

Millisecond laser drilling is state-of-the-art for producing acute angle film-cooling holes over aero-engines. After the drilling, most of these components are covered with thermal barrier coating (TBC). The preferred manufacturing method would be to laser drill the cooling holes after TBC coating but is not practiced due to the issues associated with coating delamination. The recent introduction of millisecond pulse quasi-CW fibre lasers is having a significant impact on the laser drilling of metals and alloys. This paper investigates the millisecond-pulsed-quasi-CW-fibre laser drilling of angular holes over TBC coated aerospace nickel superalloy. The main investigation concentrates on understanding the quasi-CW-fibre laser parameters to control the TBC delamination. Apart from the investigation on traditional percussion and trepanning laser-drilling of acute angle holes over coated component, a new method of drilling called "laser drilling post laser scribing" was evaluated, to achieve delamination free millisecond laser drilling.

Keywords: Laser; Drilling; Thermal barrier coating; Delamination; Aero-engine;

1. Introduction

The hot section of modern aero engines and gas turbines are mostly made up of nickel *superalloy (Pollock 2006)*, due to their superior thermomechanical performance including high-temperature fatigue and creep properties. The hot section of aero engines operates at temperatures beyond the melting point of the material to achieve more engine efficiency. Hence, cooling of the aero engine components including turbine blades and vanes is paramount to avoid self-destructing under the forces and temperatures that prevail within a modern aero-engine. Film cooling achieved using acute angle cooling holes, provides a thin, cool, insulating blanket along the external surface of the component, which plays an important role in protecting the hot-secti*on components from overheating (Langston 2017). In* addition to the cooling holes, the thermal

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barrier coating (TBC) enables the parts like turbine blades with film cooling holes to satisfy the demanding structural requirements of an aero-engine.

Most laser drilling in the aero-engine/gas-turbine component is currently carried out either using percussion or trepan technique, using millisecond (ms) pulsed laser that has a peak power density between $1e^6$–$1e^9$W/cm^2. Being a thermal process, the millisecond laser drilling mechanism is based on heating, melting, vaporisation and melt ejection. The current state-of-the-art millisecond pulse quasi-CW fibre can produce holes with acceptable quality and speed over uncoated metals and alloys (*Marimuthu 2017*). However, laser drilling of acute angle holes over TBC coated material is still challenging due to the delamination of TBC coating, during the laser drilling process.

The first known article on laser drilling of TBC coated material was written by *Forget 1988*. He studied laser percussion drilling of 1.5mm thick Hastelloy sheet coated with plasma-sprayed MCrAlY bond coat plus plasma-sprayed zirconia. Over the last thirty years, numerous researches have been conducted on laser drilling of TBC coated material, but without any definite success on the control of coating delamination. Recently, *Fan 2016* and other researchers used an innovative multi-step laser drilling technique for TBCs coated material with the use of two different laser sources. This involves ns laser removal of TBC, followed by ms laser percussion and ms laser trepan drilling with low pulse energy. The use of two different laser sources brings complications on the laser system design and repositioning.

As noticed from the literature, TBC delamination has been an issue for the last three decades with no clear solution. The recent introduction of millisecond pulse QCW fibre laser has some unique characteristics compared to the traditional millisecond lamp pump Nd:YAG laser on which all the existing research were based on, and has opened new opportunities to achieve delamination free laser drilling of TBC coated material. This paper aims to achieve delamination free millisecond laser drilling of 0.75mm hole, through fundamental scientific investigation on laser drilling of TBC coated material.

2. Experimentation

A 2mm thick aerospace grade nickel alloy (C263) coated with a 250µm thick yttria-stabilized zirconia (7-8 YSZ) based TBC coating and 100µm thick MCrAlY based bond coat (BC) were used as testing samples. The lasers used were multimode ytterbium millisecond pulsed fibre laser (YLS-2000/20000-QCW-WC) with a 1070nm wavelength that can operate at a pulse duration ranging from 0.1ms to 10ms, maximum average power of 2kW and a maximum peak power of 20kW. All the holes were drilled at an angle of 30 degrees (which makes the hole length 4.7mm) to the TBC coated C263 nickel superalloy specimens by a computer numerical control (CNC) drilling machine.

3. Results and Discussions

As discussed by *Guinard 2012*, the TBC delamination starts once the laser pulse interacts with the metallic material (i.e. within the first few number of percussion pulse). Considering this effect, a two-stage investigation were performed in this study, the first set of experiment is to identify the best laser parameters for the initial piercing (or percussion hole) with minimal delamination, and the second set of parameters concentrate on the trepanning laser drilling process to achieve a hole diameter of 0.75mm with acceptable quality, in terms of recast layer thickness and coating delamination.

Figure 1 shows the effect of peak power (or pulse energy) and pulse duration on the TBC delamination. As noticed from the figure, peak power has high influence on the TBC delamination compared to the pulse duration of the laser, due to the fact that the peak power is directly related to the total heat input to the material. Increased heat input increases the coating-substrate temperature, resulting in higher thermal expansion and higher mechanical stress over the leading edge of the TBC, and subsequently increase in TBC delamination. As noticed, 2.5J with 0.25ms produced delamination less than 100µm, however, the small hole size (~0.3mm) and the large recast layer thickness (50-100µm) makes the hole not practical for real-world applications. One way of increasing the percussion hole diameter is by increasing the beam size (over the material surface) or the energy input, both of which is expected to increase the heat generation and subsequently higher TBC delamination.

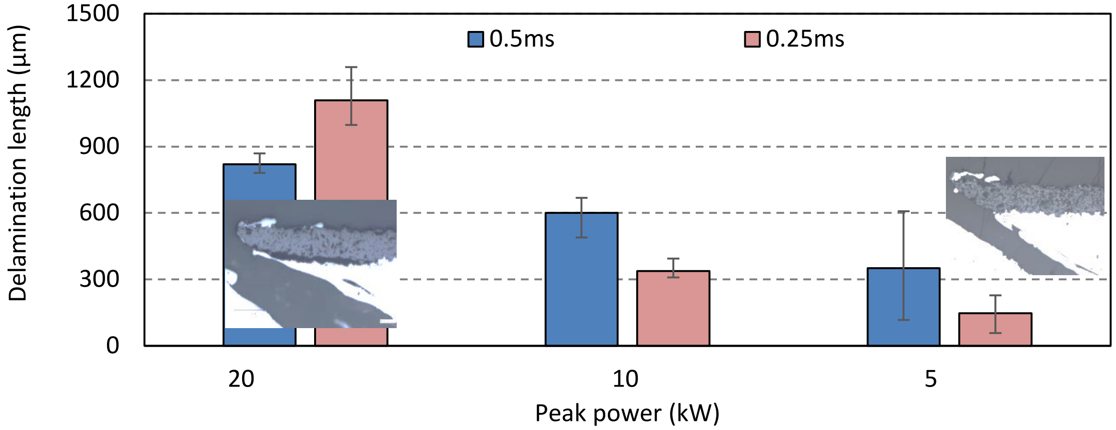

Fig. 1. Effect of laser peak power and laser pulse duration on TBC delamination during percussion drilling (pulse frequency = 50Hz; gas pressure = 6.5 bar; gas composition = air)

Laser drilling post TBC removal was performed as a single operation using a CNC controlled laser machine, i.e., laser TBC decoating at 30°, followed by laser percussion drilling/piercing at 30°, using 2.5J, 0.25ms, 50Hz, oxygen gas, followed by laser trepanning drilling. The schematic of the laser drilling post TBC removal process (at 30°) is given in Figure 2.

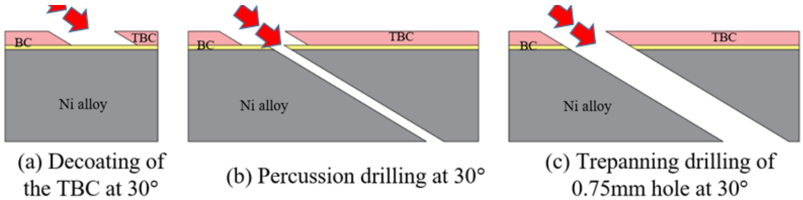

Fig. 2. Schematic of the laser drilling post laser decoating at 30°

Figure 3 shows the effect of laser process parameters on TBC delamination (post-TBC removal over the area of laser drilled hole). As shown in the figure, a TBC delamination of ~1.2mm was noticed even by using the technique of laser drilling post laser decoating process. As noticed from the Figure 3, this technique has failed to give a significant breakthrough in TBC laser drilling.

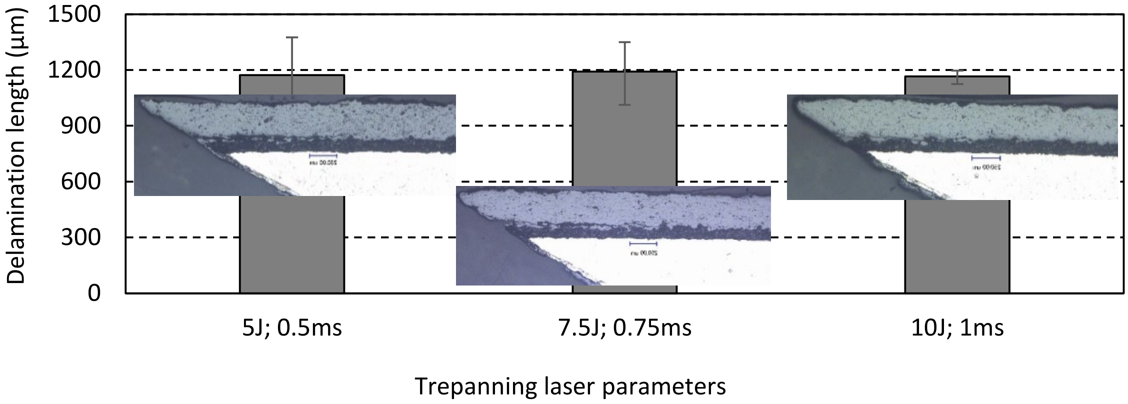

Fig. 3. Effect of laser parameters on TBC delamination after removing the TBC at 30°

Laser drilling post TBC decoating was performed this time, with TBC removed at 90°, followed by laser drilling at 30° (percussion using 2.5J, 0.25ms, 50Hz, oxygen gas; followed by laser trepanning drilling). The schematic of the laser drilling post TBC removal process (at 90°) is given in Figure 4 and the results are shown in Figure 5. As noticed from Figure 5, a significant improvement in TBC delamination was observed, after removing the TBC layer normal to the substrate. Compared to traditional laser drilling ~40-50% reduction in TBC delamination was observed. This is due to the fact that the TBC delamination due to the actions of the mechanical force is been fully/significantly eliminated.

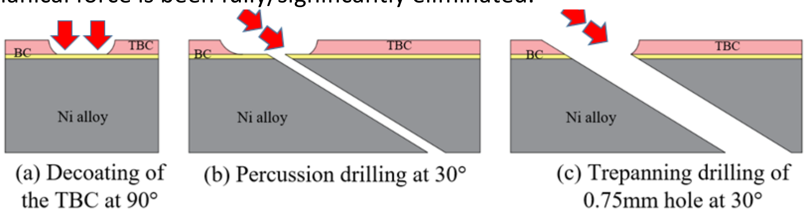

Fig. 4. Schematic of the laser drilling post laser decoating at 90° to the surface

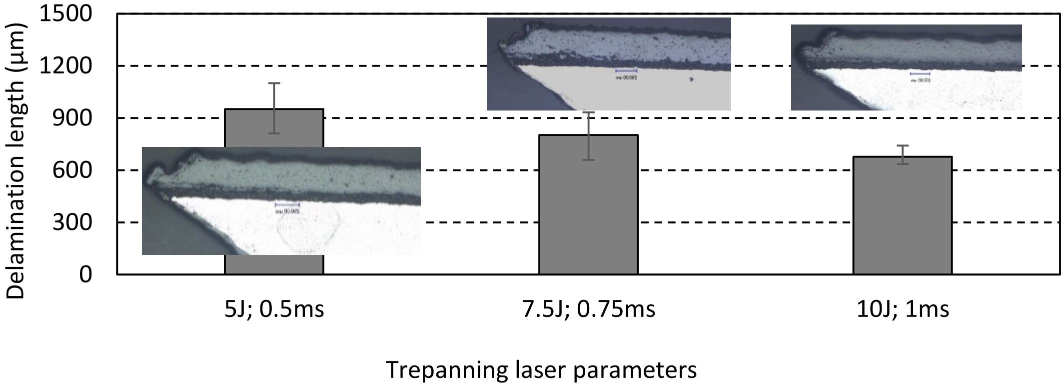

Fig. 5. Effect of laser parameters and TBC delamination after decoating the TBC at 90° (Decoating: 7.5J/cm2, 6 lasing loop, 0.07mm pitch, 300Hz, 1050mm/min, nitrogen gas, 6.5bar Trepanning: 50Hz; 10kW; 100mm/min; 2 orbit; 6.5 bar; oxygen gas)

To further control the TBC delamination due to thermal stress, experiments were performed by intentionally removing some of the TBC coating over the leading edge of the hole, as shown in Figure 6. Removing the TBC coating over the sharp tip of the leading edge should help to dissipate the heat efficiently (due to the gas jet from the nozzle) and subsequently control the TBC delamination. In practice, this was achieved by moving the trepanned drilled hole towards the trailing edge of the hole, with reference to the position of TBC decoated region.

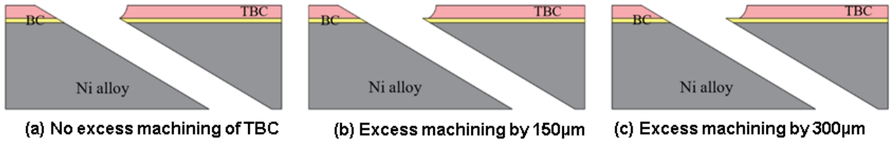

Fig. 6. Schematic of the laser drilling post laser decoating at 90° to the surface

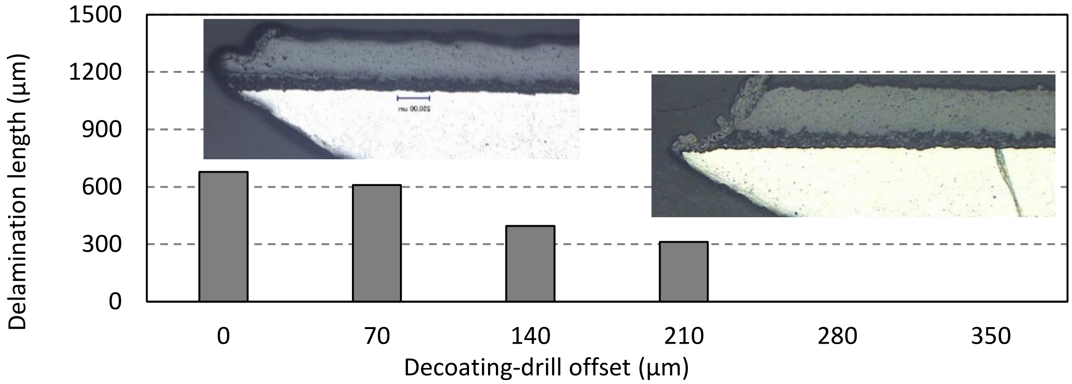

Fig. 7. Effect of laser parameters and decoating-drill offset on TBC delamination (Decoating: 90°; 7.5J/cm2; 6 loop; 0.07mm pitch; 300Hz, 1050mm/min; nitrogen gas, 6.5bar: Trepanning: 10J; 1ms; 50Hz; 10kW; 100mm/min; 2 orbit; 6.5 bar; oxygen gas)

Figure 7 shows the effect of TBC removed length (over the leading edge of the hole) on TBC delamination. As noticed from Figure 7, the TBC delamination reduces with increase in TBC removed length over the leading edge. For laser energy of 10J and 1ms pulse duration, the TBC delamination can be fully eliminated at a decoating-drill offset of ~280µm. Although this is not an ideal scenario, this is a good comprise to achieve high-speed, delamination-free laser drilling.

4. Conclusions

A scientific investigation was performed to understand the characteristics of millisecond pulse QCW fibre laser drilling of thermal barrier coated nickel superalloy, with a view of controlling the TBC delamination. QCW fibre laser percussion drilling with less energy and less pulse duration can be used to produce small holes without TBC delamination, however, percussion drilling with low energy and low pulse duration produces unacceptable hole dimension and metallurgy. The TBC delamination that happens during the percussion drilling process is significantly less/negligible, compared to the delamination that occurs during the trepanning drilling process. TBC decoating at an angle same as drilling angle neither avoids mechanical stress induced delamination nor thermal stress induced delamination. The mechanical stress induced TBC delamination can be significantly controlled by removing the TBC coating at normal to the surface prior to the drilling process. The thermal stress induced delamination can be avoided by removing a small length of TBC coating from the leading edge of the hole, prior to the trepanning drilling process.

Acknowledgements

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