Process Development and Control of Laser Drilled and Shaped Holes in Turbine Components

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Cooling holes (100 holes/cm², diameter 0.2 - 0.6 mm, inclination angle up to 60°) are drilled by pulsed laser radiation (Nd:YAG, 1064 nm, 0.1 - 1 ms) in X5CrNi18 10 and CMSX-4 multi layer systems with BC (MCrAlY bond coating) and TBC (ZrO_2 thermal barrier coating). There are two different options to drill and shape the holes: The first layout is a one-step procedure with a simultaneous five-axis trepanning movement of the laser beam. The second layout is a two-step procedure with percussion drilling or trepanning a through hole and structuring a fan by short pulse ablation in the second step.

The thermal radiation from the drilling process is detected by an in-situ CPC (coaxial process control) during percussion drilling using high speed photography (50 kHz frame rate) in order to determine the break through and prevent back wall damages by drilling hollow structures, e.g. turbine blades.

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1. Introduction

To enhance the efficiency of turbo-engines the turbine temperature has risen drastically in the last decades due to new materials and cooling technologies. To further improve the efficiency of combined cycle power plants the aim is to increase the combustor outlet temperature up to 1520 °C and at the same time to reduce the cooling fluid mass flow. This shall be realized by an effusion cooling for the thermally highly loaded turbine components. The holes with a diameter of 0.2 mm are produced by laser drilling at densities up to 100 holes per cm² and an inclination angle of 60 ° in a multi layer system (CMSX-4 substrate, bondcoat MCrAlY, thermal barrier coating Yttrium partially stabilized Zirconia) [1].

To achieve an effective film cooling different methods are known for a three-dimensional shaping of the hole outlet with laser radiation:

- Structuring of the surface by pulsed laser radiation using scanning or mask projection in a two step process layout. In the first step a through hole is trepanned and in the second step a fan shape is structured into the thermal barrier coating [2, 3].
- Laser percussion drilling of blind holes to form a cavity in a surface which is followed by drilling a through hole in the substrate [4].
- Drilling of three-dimensional aerodynamic holes in a one step processing by a simultaneous five-axis trepanning movement of the laser beam [5, 6].

For the five-axis trepanning first a through hole is percussion drilled with a fixed laser beam. After this the laser beam is guided along a geometric shape (in this case an outlet fan contour for the cooling fluid) on the top side of the plate and at the same time along a different geometric contour (e.g. ellipse) at the bottom side (Fig. 1). This allows the formation of a smooth profile transition within the drilled hole at a high reproducibility. The drilling process is supported by a coaxial process gas jet in order to eject molten material. The geometry for the five-axis movement is designed with a CAD/CAM software tool including a post processor, generating the CNC (computerized numerical control) tracks for the positioning stage. The software interface provides a high flexibility in generating variable geometric hole shapes.

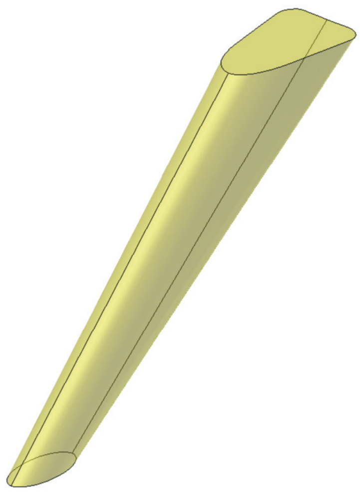

Fig. 1 Scheme of the reference hole for trepanning

There is a big challenge avoiding backwall damages by laser drilling of hollow structures like turbine blades and vanes. In order to protect the backwall during laser drilling different kinds of filling materials, e.g. wax or resin, are used. Another possibility of backwall protection is the in-situ detection of the time of drilling through by Coaxial Process Control (CPC). Due to the reduced number of process steps – the time consuming filling and cleaning of the blades or vanes – the detection of break through is investigated [7, 8], but there is still no marketable system.

2. Experimental Setup

Five-axis trepanning

Holes are drilled in turbine blades and combustion chamber plates by pulsed laser radiation using a flash lamp pumped Nd:YAG slab laser at λ = 1064 nm with pulse durations in the range 0.1 to 0.5 ms. For drilling the pulse repetition frequency is fixed to 20 Hz. Using a lens with focal length of f = 100 mm intensities up to 280 MW/cm^2 with a beam quality of $M^2 \leq 2$ are reached. The pulse energy and the pulse duration are measured by photometry using a calibrated internal photodiode in the laser system. A conical nozzle with an exit diameter of 1 mm is used to get a supersonic gas flow collinear with the laser beam in order to remove the melt from the processed surface. This nozzle is positioned 1.8 mm above the surface of the material. Processing gases of technical quality such as oxygen 3.5, helium 4.6, and argon 4.6 are used. The holes are drilled at an inclination angle of 60 ° resulting in an effective length of 4 mm in a CMSX-4 based multi-layer system (CMSX-4 substrate, bond coat MCrAlY, thermal barrier coating Yttrium partially stabilized Zirconia). The fan on the outlet side exhibits a length of 0.6 mm and a width of 0.36 mm and the ellipse on the exit side a diameter of 0.2 and 0.4 mm (Fig. 1 and Fig. 2). The laser is mounted on a five-axis positioning stage with a positioning accuracy of 1 µm. The laser and the positioning stage are controlled by a PC which includes an interface to transfer the CNC code for the axis movements generated by external CAD/CAM software tool. The positioning stage is prepared for a simultaneous five-axis movement including a position depended correction of the axis orientation.

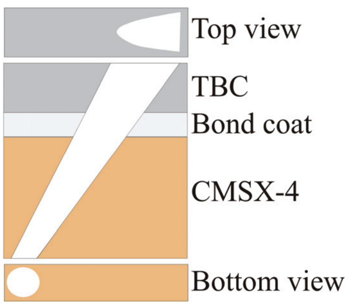

Fig. 2 Scheme of a shaped hole in multi-layer system

Coaxial process control

Plates (X5CrNi18-10, 2.0 - 8.0 mm) are drilled by laser radiation provided by a lamp pumped Nd:YAG laser (λ = 1064 nm, $M^2 < 25$, focal length f = 150 mm, focal diameter d_0 = 0.4 mm, pulse duration 0.5 ms, repetition rate 20 Hz, pulse energy 3.7 - 7.5 J). The pulse energy and the pulse duration are measured by photometry using a calibrated internal photodiode in the laser system.

The utilized processing gas argon is of technical quality 4.6 at a gas pressure of 10 bar.

The temperature radiation emitted by melt, vapor, and plasma – named process emission – is detected by CPC via photography using a CMOS camera at a frame rate of 50 kHz, an exposure time of 17 µs per frame, and a resolution of 1 pixel ≈ 1.8 µm at an overall picture size of 96 x 96 pixel^2. The intensity of process emission is given as 8bit-coding. The maxima of sensitivity of three kinds of sensors are centered in the visible spectral range at 460 nm (blue), 540 nm (green), and 650 nm (red) wavelength (Fig. 3). Each sensor is named after its maximum of sensititvity: blue sensor, green sensor, and red sensor. A dichroitic mirror is used to separate the process emission and the reflected laser radiation (Fig. 4).

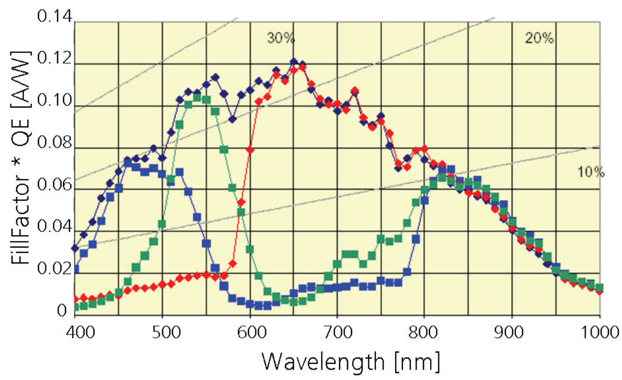

Fig. 3 Sensitivity of blue, green, and red sensor

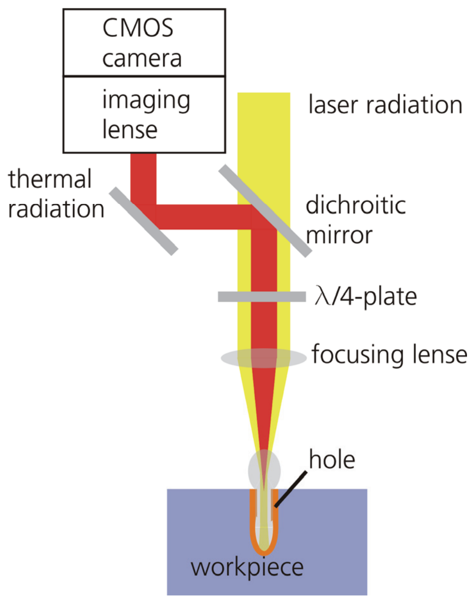

Fig. 4 Scheme of experimental setup for CPC

3. Results and Discussion

Five-axis trepanning

The shaped holes drilled according to the original CAD data (Fig. 1) did not fit the reference geometry. The geometric shapes of the entrance and exit of the hole have to be manually redesigned. The fan is split in two symmetric geometric shapes along which the laser radiation is guided. To determine the orientation of the laser beam during the cutting process the 2D geometric shape of the ellipse on the outlet side and the fan on the inlet side are segmented (Fig. 2). Each segment on the exit side is related to a segment on the entrance. Within a single segment the CAD/CAM software interpolates the feed rate and generates the CNC code for the movement of the corresponding positioning system axis. The drilling process comprises three steps:

- A through hole is formed by percussion drilling in the centre of the geometry.
- The diameter of the percussion drilled hole is increased by trepanning in order to create a core hole without violating the final geometry of the contour. The core hole prevents the formation of closures and allows a steady melt expulsion.
- The final geometric shape of the hole is cut in the massive material starting at low feed rate during the first round with the feed rate increasing after each repetition.

The process gas oxygen at a pressure of 12 bar is used taking advantage of the additional enthalpy of the oxidation and to ensure a proper melt expulsion. The inert process gases argon and helium cause closures within the hole and an extended process time.

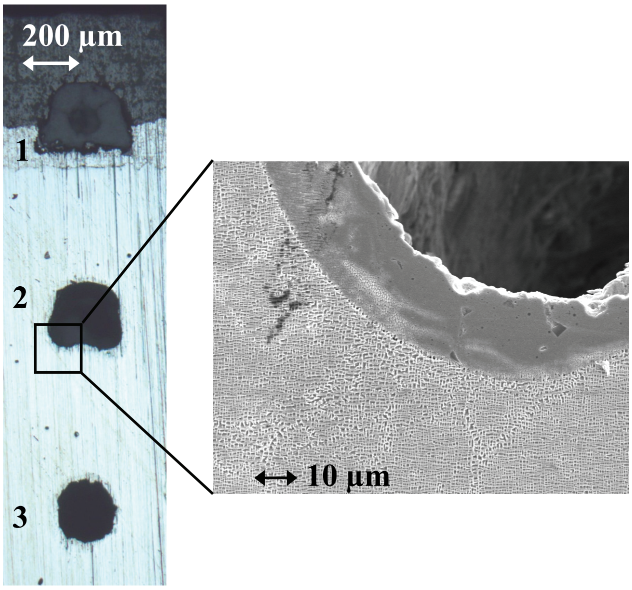

Fig. 5 Shaped hole ($t_{PULSE} = 0.5$ ms, $f_{PULSE} = 20$ Hz, $P_{LASER} = 1.4$ kW, $P_{AVERAGE} = 14$ W, chemically etched with Adler)

The cross section of the multi-layer system (Fig. 5) exhibits three holes (numbered 1 to 3) in one row with a distance of 1.2 mm between the entrances of each. The three holes are sectioned through at different positions of the longitudinal hole axis featuring a different geometric shape. Due to the five-axis trepanning there is a smooth profile transition within the hole between the fan shape on the outlet side and the ellipse on the inlet. According to SEM analyses of the chemically etched cross section the shaped holes exhibit a recast layer in the thickness range of 10 – 20 µm (Fig. 5). No cracks can be detected in the CMSX-4 substrate. The high beam quality allows the trepanning of the holes with a minimum heat input. Therefore, there is no considerable damage or delamination at the interfaces substrate/bond coat and bond coat/TBC (Fig. 7).

With the CAD/CAM interface variable geometric hole shapes can be designed to adapt the geometry for the specific requirements of the cooling system.

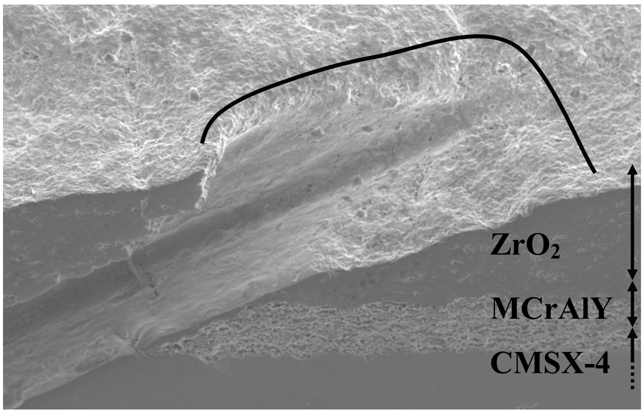

Fig. 7 Longitudinal section of outlet fan in multi-layer system at 60 ° inclination ($f_{PULSE} = 20$ Hz, $E_{PULSE} = 0.6$ J, $t_{PULSE} = 0.5$ ms, chemically etched with Adler)

Coaxial process control

Stainless steel of 2, 5, and 8 mm thickness is percussion drilled by 10 to 30 pulses. The drilling velocity is comparable to nickel-based alloys [9]. For 2 and 5 mm plates the drilling depth per pulse is nearly constant. In 2 mm- and 5 mm-thick samples the break through of the hole is achieved during the 5th pulse and the 11th pulse, respectively (**Fig. 6**, photos on the upper two lines). Due to the decreasing intensity caused by the caustic and multiple reflections the drilling process becomes unstable at a drilling depth of more than 6 mm. The number of pulses until break through varies between 29 and 47 pulses drilling the 8 mm plate (Fig. 8).

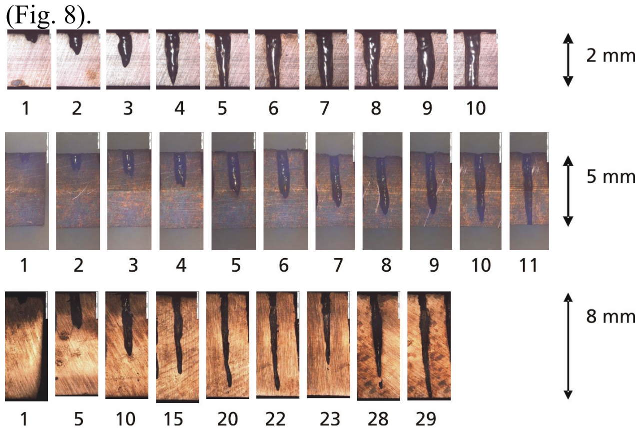

Fig. 6 Cross sections (percussion drilling, X5CrNi18-10, 2, 5, and 8 mm, increasing number of pulses from left to right)

By drilling the 2 mm plate the mean intensity of emission is decreasing after the 5th pulse for all the sensors. The ratio of the mean intensity of the 5th pulse and 6th pulse is larger for the red sensor (130:1) than for the blue (5:3) or green (4:1) one. Looking closer to the red sensor, the mean intensity is strongly decreasing after 340 µs of the 5th pulse without any increase during the following pulses (Fig. 9).

During drilling the 5 and 8 mm plates the ratio of the mean intensity before and after break through for the red sensor is smaller (2:1 and 5:1) compared to the 2 mm plate (Fig. 10, Fig. 11). Due to the smaller solid angle at bigger hole depth the mean intensity starts decreasing. This can be seen at a hole depth of about 6 mm (Fig. 11, 13th pulse) Another reason of the smaller ratio are multiple reflections of the process emission at the hole wall.

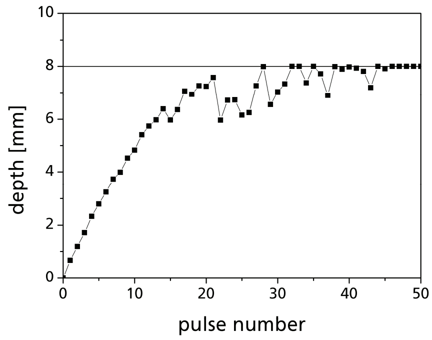

Fig. 8 Drilling depth versus the number of pulses (percussion drilling, X5CrNi18-10, 8 mm)

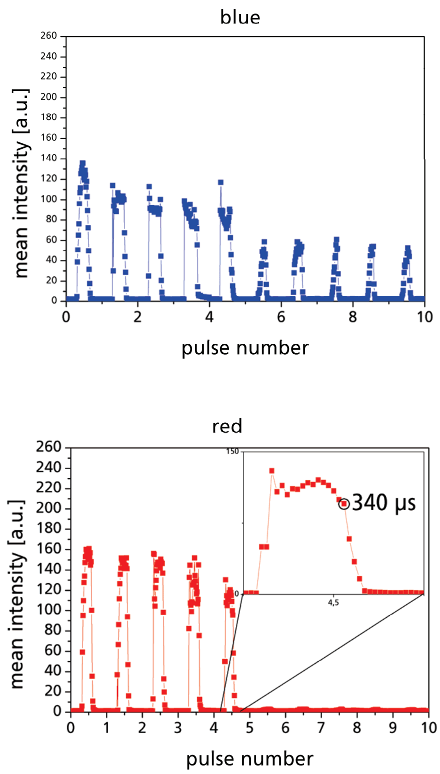

Fig. 9 Mean intensity of emission detected by the blue (top) and red (bottom) sensor (percussion drilling, X5CrNi18-10, 2.0 mm)

The minimum in the center of the wrong color depiction of process emission detected by the red sensor occurs 300 µs after the beginning of the 5th pulse drilling the 2 mm plate (Fig. 12). After 340 µs – the same time the mean intensity starts strongly decreasing (Fig. 9) – the minimum is nearly zero. The minimum is interpreted as break through. The wrong color depiction of the process emission detected by the blue or green sensor doesn't have a comparable minimum between 300 and 380 µs after the beginning of the pulse. The red signal is suitable to detect the break through.

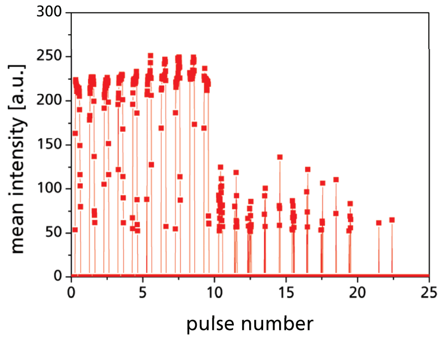

Fig. 10 Mean intensity of emission detected by the red sensor (percussion drilling, X5CrNi18-10, 5.0 mm)

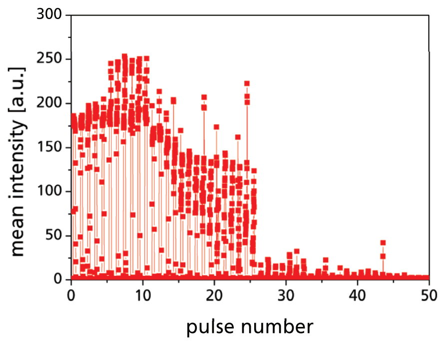

Fig. 11 Mean intensity of emission detected by the red sensor (percussion drilling, X5CrNi18-10, 8.0 mm)

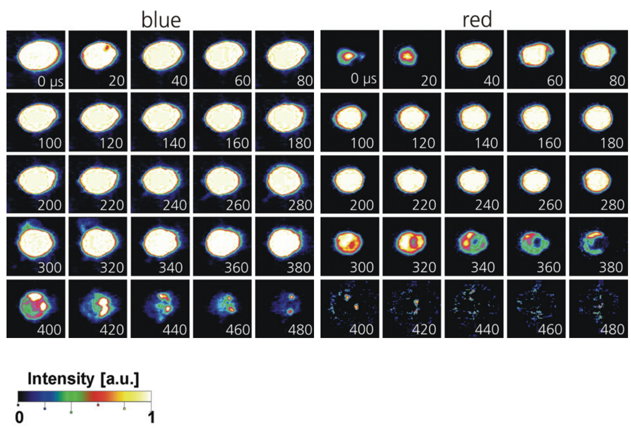

Fig. 12 Wrong color depiction of intensity deteced by blue (left) and red (right) sensor recorded during 5th pulse versus time (percussion drilling, X5CrNi18-10, 2.0 mm)

4. Conclusions

Five-axis trepanning

Holes are drilled in turbine blades and combustion chamber plates with pulsed laser radiation of a flash lamp pumped Nd:YAG slab laser at λ = 1064 nm with pulse durations of 0.5 ms. The holes are drilled at an inclination angle of 60 ° resulting in an effective length of 4 mm in a CMSX-4 based multi-layer system. The laser and the positioning stage are controlled by a PC which includes an interface for external CAD/CAM software tools. At the five-axis trepanning the laser beam is guided along a geometric shape (outlet fan) on the top side of the plate and at the same time along a different geometric contour (e.g. ellipse) at the bottom side. This allows the formation of a smooth profile transition within the drilled hole at a high reproducibility and a thin recast layer in the range of 20 µm. The drilling process is supported by a coaxial process gas jet in order to eject the molten material. The geometry for the five-axis movement can be redesigned with a CAD/CAM software tool. This provides a high flexibility in generating variable geometric hole shapes to fulfil the requirements of the cooling efficiency.

Coaxial process control

The change of mean intensity detected by the red sensor is sufficient for the detection of break through during drilling of 2, 5, and 8 mm-thick X5CrNi18-10 plate. The mean intensity of process emission is strongly decreasing during the pulse of break through and not increasing during the following pulses. CPC by high speed photography is a suitable system to provide back wall damage during drilling of hollow structures like blades or vanes.

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