

Potentials of manufacture and repair of nickel base turbine components used in aero engines and power plants by laser metal deposition and laser drilling

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Abstract: High pressure turbine (HPT) parts like blades and vanes with integrated cooling channels are challenging concerning overhaul and repair. So far damaged parts have to be replaced by the operator. The aim is to design and implement a refurbishment process chain to avoid scrapping of used parts. This process chain implies three different laser applications 1. Direct Laser Forming (DLF), 2. Laser Metal Deposition (LMD) and 3. Laser Drilling (LD). The laser processing was extended in the last years towards application near materials like Nickel and Titanium base alloys. Concerning LMD and DLF the achieved results are investigated regarding macro and micro structure, hardness, defects (e. g. cracks, bonding defects, porosity) and contamination with atmospheric elements (e. g. O, N, C and H) are presented for Titanium alloys like Ti 6Al 4V, Ti 6246 and Ti 17 as well as for Nickel base alloys like Inconel 718 and Rene 80. Suitable process parameters are presented with the achieved static (tensile) and dynamic mechanical properties (HCF) and compared to those of heat treated raw materials. One innovative solution (manufacturing case) is to fabricate the small and complex shaped geometrical elements by LMD and/or DLF. By LMD these elements are built up directly. With DLF the elements are manufactured separately in the DLF machine and connected by a subsequent joining technique with the large parts. With DLF small complex shaped parts like combustor swirlers, HPT blades and vanes with internal cooling channels are manufactured completely. LMD and DLF can be used in combination with subsequent LD. Depending on the application two different drilling techniques by dominant melt ejection percussion drilling and trepanning are classified and characterised. The drilling techniques are exemplarily presented for stainless steel and nickel base alloys (diameter 0.2~0.6 mm, aspect ratio < 30, inclination up to 60°) using pulsed laser radiation (Nd: YAG, 1064 nm, 0.5~1 ms). The experimental results of coaxial process control, metallography and optical microscopy regarding hole depth and hole diameter as well as the thickness of recast are presented.

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Introduction

Expensive turbine parts like HPT (High Pressure Turbine) blades or vanes are replaced by new parts in case of damage. For example the burn through of the inner side of a blade or vane (Figure 1) is a frequently appearing damage, which cannot be repaired with common tech-

niques. Due to the high costs for new parts, a reconditioning chain is developed by combining new repair techniques like Direct Laser Forming (DLF) and well known techniques like Laser Metal Deposition (LMD) and Laser Drilling (LD).

The reconditioning chain is implemented within five steps (Figure 2). Step I: The dam-

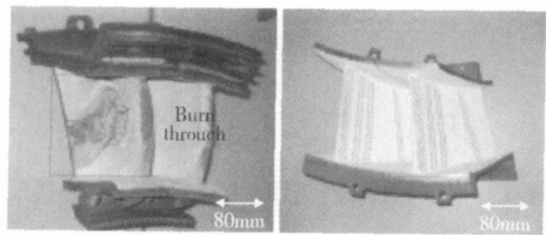


Fig 1 Burn through part (left) and new part (right)

aged parts are identified and prepared by removing the damaged volumes. Step II: A fitting patch with integrated cooling channels is generatively manufactured by DLF based on CAD data acquired by digitizing and reverse engineering. Step III: The generated patch is joined into the remaining part of the blade or vane by LMD. Step IV: The fixed part is coated by a TBC (Thermal Barrier Coating). Step V: The non open cooling channels are opened and in case of necessity reshaped by LD. Also the cooling channels damaged or destroyed in the joint zone patch substrate by the LMD joining process within Step III are reworked or inserted by LD. The order of step IV and V is changeable depending on the requirements on the fan. A precise formed fan can only be achieved by ablating the surface after coating.

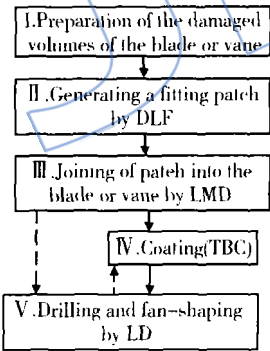


Fig 2 Five step reconditioning chain

The three main laser techniques, DLF, LMD and LD, for implementing the reconditioning chain are presented and discussed.

DLF

DLF (Figure 3) is a new additive manufacturing technology. Metal parts are built-up out of a powder material layer by layer.

In comparison to other additive metal processes(e. g. selective laser sintering) two ma-

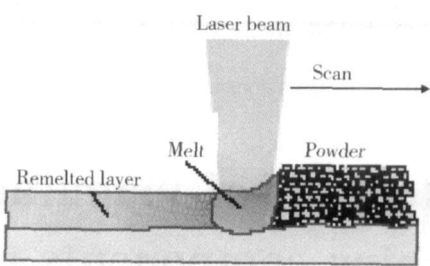


Fig 3 Basic principle of the DLF- process

for differences are pointed out. On the one hand, the material is a single component metal powder like stainless steel X2CrNiMo17 13 2, tool steel X38CrMoV 5 1, Titanium TiAl6V4 or Inconel 718. On the other hand, the physical process is a complete melting of the powder layer with a metallurgical bonding between the layers yielding densities of approx. 100% in one step. Due to the high density, DLF parts exhibit mechanical properties which are in the range of the materials specifications. These characteristics enlarge the field of application for this technology from Rapid Prototyping to the Rapid Manufacturing of functional parts and serial tools.

LMD

LMD (here used as a joining process) has specific advantages compared to other welding or cladding processes^①.

The main advantage of LMD is the low and very localized heat input. For this reason, LMD will present some improved characteristics compared to the ones obtained with other welding or cladding processes. These improved characteristics are:

- Low distortion
- Reduction of residual thermal stresses and therefore mechanical properties are less affected than in the other repair processes
- Small heat affected zone (HAZ^②)
- Low degree of porosity
- No bonding defects, cracking and oxidation^③

① TIG, MIG, PTAW, EBW, MPW.
② Heat Affected Zone.
③ MPW and EBW present similar characteristics as laser cladding concerning porosity, cracking, oxidation or the automatization of the process.

LMD parameters are adapted to obtain different geometries of the layers generated. An on-line process control of these process parameters allows varying the geometry of the clad during the repair process. The layer geometry is generated with high accuracy^①. This, and the fact that the LMD process is stable, allows the generation of complex geometries with a high degree of geometrical accuracy.

LD

Coaxial Process Control: In order to avoid back wall layer by layer. Melt Laser Beam Scan Powder damages by LD, the time of break through is investigated for percussion drilling by Coaxial Process Control (CPC). The numbers of pulses from the first pulse until break through during percussion drilling are to be detected. The hole diameter is compared to the pattern of the pictures.

Trepanning: To further improve the cooling efficiency of combined cycle power plants the aim is to increase the combustor outlet temperature up to 1 520 °C in combination with a simultaneous reduction of the cooling fluid mass flow^[1,2]. Both the improvements can be realized by an effusion cooling of the thermally highly loaded turbine components. The holes with a diameter of 0.2 mm are drilled by laser radiation at maximum densities of 100 holes per cm². An inclination angle of 60° leads to an effective hole length of up to 5 mm^[3].

To apply an efficient cooling film on the thermally highly loaded surface 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^[4,6].
- Laser percussion drilling of blind holes to form a cavity in a surface which is followed by drilling a through hole in the substrate^[7].
- Drilling of three dimensional aerodynamic

holes in a one step processing by a simultaneous five axis trepanning movement of the laser beam^[8,9].

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. 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.

1 Experimental set-up

DLF

The presented investigations have been carried out with a Trumaform LF (Figure 4).



Fig 4 Trumaform LF

The Trumaform LF uses a Disk Laser with a maximum output power of 250 W. The laser beam is focused on the build platform with a focus diameter of 0.2 mm. The building platform has a diameter of 250 mm. The platform can be preheated up to 500 °C in order to reduce ther-

① ±0.05 mm in height and width.

mal stresses of the part during the build-up process. In order to avoid oxidation the process chamber is flooded with inert gas during the build-up process.

LMD

Two devices are used to avoid contaminations of the parts generated by atmospheric elements like oxygen, nitrogen, hydrogen and carbon: A cooling device and a gas shielding device (Figure 5).

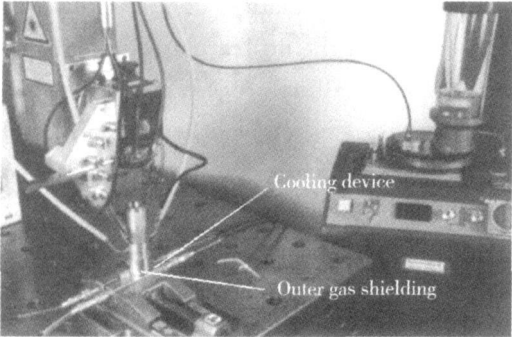


Fig 5 Experimental set up for LMD

The outer gas shielding nozzle is an empty cylinder attached to the nozzle. The cylinder covers the parts generated during LMD to create an inert gas shower around them. Thanks to this shower of shielding gas surrounding the parts, oxidation is minimized.

LD

CPC: Metal sheets (X5CrNi18-10, 2.0~8.0 mm) are drilled by laser radiation provided by a lamp pumped Nd: YAG laser ($\lambda = 1\,064\text{ nm}$, $M^2 < 25$, focal length $f = 150\text{ mm}$, focal diameter $d_0 = 0.4\text{ mm}$, 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. 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 $\approx 1.8\text{ }\mu\text{m}$ at an overall picture size of $96 \times 96\text{ pixel}^2$. The intensity of process emission is

given as 8 bit 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 (Figure 6). Each sensor is named after its maximum of sensitivity: blue sensor, green sensor, and red sensor. A dichroitic mirror is used to separate the process emission and the reflected laser radiation (Figure 7).

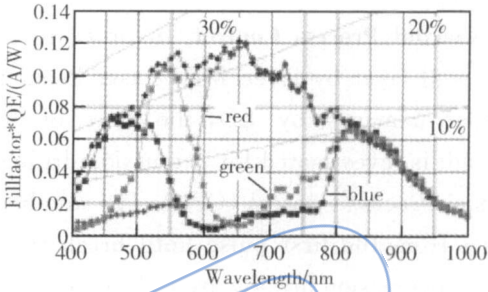


Fig 6 Sensitivity of blue, green, and red sensor

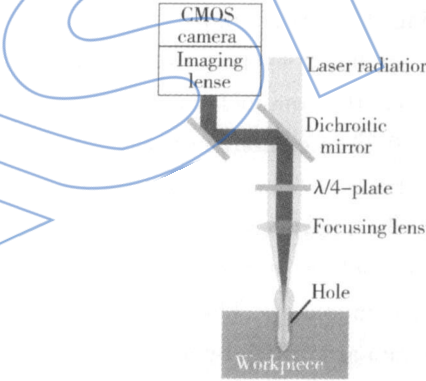


Fig 7 Scheme of experimental setup for LD and CPC

Trepanning: Holes are drilled by pulsed laser radiation using a flash lamp pumped Nd: YAG slab laser at $\lambda = 1\,064\text{ nm}$ with pulse durations in the range 0.1 to 0.5 ms. The pulse repetition frequency is fixed to 20 Hz. Using a lens with focal length of $f = 100\text{ mm}$ intensities up to 280 MW/cm^2 with a beam quality of $M^2 \leq 2$ are achieved.

The holes are drilled at an inclination angle of 60° resulting in an effective length of 5 mm in a CMSX-4 based multi-layer system: CMSX-4 substrate, bond coat MCrAlY (BC), thermal barrier coating (TBC) Yttrium partially stabilized Zirconia (YPSZ). 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 (Figure 8). The laser is mounted on a five axis positioning stage with a positioning accuracy of 1 μ m. 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.

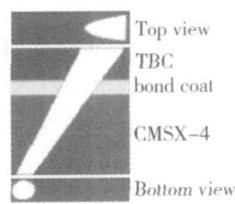


Fig 8 Scheme of a shaped hole in multi layer system

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. The nozzle is positioned 1 mm above the surface of the material. Oxygen and argon of technical quality are used as process gas at a pressure of 12 bar.

Sample preparation: The samples are grinded with successively finer silicon carbide papers down to 1200 grade and polished with 1 μ m particle size diamond paste. In order to reveal oxide and recast layer and heat affected zone (HAZ) the samples are chemically etched.

Optical microscopy (OM), scanning electron microscopy (SEM) and white light interference microscopy (WIM) analyses were carried out to identify the microstructure, morphology and physical features of recast layers including HAZ and oxide layer.

2 Results and discussion

DLF

For DLF parts a density > 99.5% could be achieved. Figure 9 demonstrates the resulting microstructure of an SLM sample manufactured out of tool steel 1.2343. A metallurgical bond

between both adjacent tracks and subjacent layers is achieved by the adaptation of the process parameters^[10].

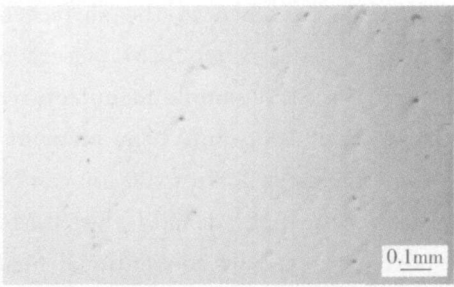


Fig 9 Cross section of SLM sample out of tool steel 1.2343

Due to the high density the SLM parts exhibit good mechanical characteristics. Tensile strength and breaking elongation have been determined by a tensile test. Exemplary results for the Titanium alloy TiAl6V4 are shown in Figure 10^[11]. For a comparison tensile test rods out of sheet metal are tested. The tensile strength of approx. 1050 N/mm² of the SLM samples is in the range of the material specification and slightly higher than the one of the sheet metal samples. With regard to breaking elongation both the SLM samples and the sheet metal exhibited lower values than the materials specification. Possible explanations for the brittle fracture of the SLM samples could be the resulting microstructure due to rapid solidification or increased oxygen content. Investigations on succeeding heat treatments in order to enhance the breaking elongation as well as chemical analysis of the parts are currently being carried out.

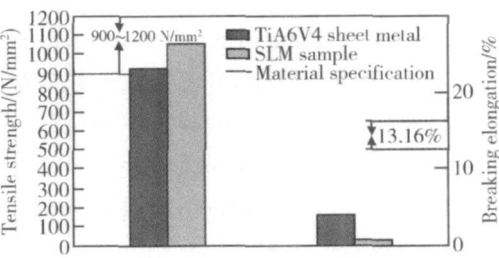


Fig. 10 Tensile strenght and breaking elongation of SLM samples out of TiAl6V4

Roughness and dimensional accuracy are decisive factors for industrial application and ac-

ceptance of the SLM-process. The roughness R_z of the SLM samples is around $30 \sim 40 \mu\text{m}$ and mainly determined by the layer structure and molten particles attached to the surface of the parts. Figure 11 shows an SEM picture of the side surface of a SLM sample manufactured in a layer thickness of $100 \mu\text{m}$. At the moment parts with a layer thickness down to $30 \mu\text{m}$ can be produced. Due to the high density the SLM parts can be post processed by conventional manufacturing without any problems to the surface quality required by the field of application. The dimensional accuracy was determined to be better than 0.1 mm in x -, y - and z -direction for different part sizes^[12]. The deviations of $60 \sim 80 \mu\text{m}$ between the CAD and the actual measure are mainly in the range of the surface roughness. The maximum part size is $120 \times 120 \times 200 \text{ mm}$ restricted by the dimensions of the process chamber, the smallest structures that can be realized at the moment are webs of $230 \mu\text{m}$ thickness.

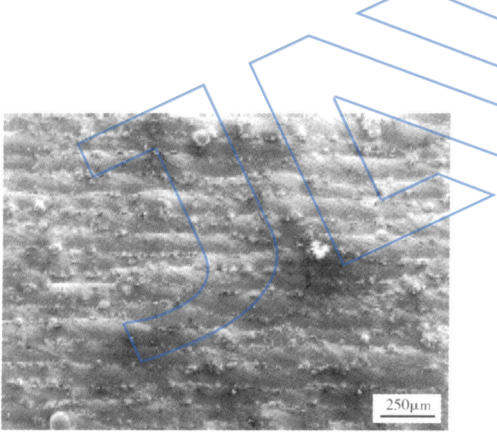


Fig 11 SEM picture of side surface of SLM sample

LMD

- By choice of the suitable process parameters
- Laser power (contour): $P_{LK} = 450 \text{ W}$
 - Laser power (hatch): $P_{LF} = 650 \text{ W}$
 - Powder mass flow: $\dot{m}_P = 4\%$
 - Laser beam diameter: $d_L = 1,3 \text{ mm}$
 - Velocity: $V_V = 500 \text{ mm/min}$
 - Shielding gas flow (coaxial, internal): $\dot{V}_{SGI} = 30 \text{ l/min}$
 - Cooling time between two layers: $\Delta t_{cooling} = 2 \text{ min}$
- a defect free volume (Figure 12) can be de-

posited.

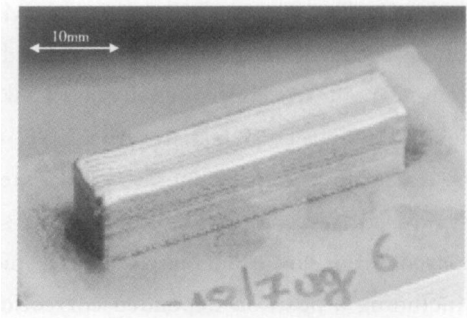


Fig 12 Part out of Inconel 718 generated by LMD

The achieved mechanical properties of heat treated and non heat treated LMD Inconel 718 were discussed by Kelbassa et al., 2004 and 2005^[13, 14]. The same or even better static and dynamic mechanical properties in comparison to a forged heat treated raw material can be achieved by heat treated LMD Inconel 718.

In Figure 13 and 14 the measured ultimate tensile strength R_m , 0.2% yield strength $R_{p0.2}$, elongation A_5 and contraction Z of non heat treated and heat treated raw material and non heat treated and heat treated laser clad material are shown. The heat treatments of the raw material (complete heat treatment, steps 1~ 3) and of the laser clad material (stress relieving/ equivalent to short ageing, PWHT, Post Weld Heat Treatment) are listed in table 1.

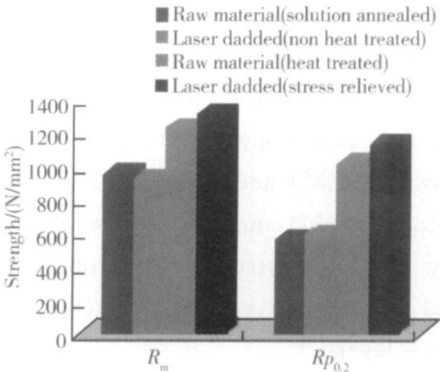


Fig 13 Ultimate tensile strength R_m and 0.2% yield strength $R_{p0.2}$ of non heat treated and heat treated raw material^[15] and non heat treated and heat treated laser clad material, room temperature, DIN 50 125 B4 $\times$ 20, DIN EN 10002

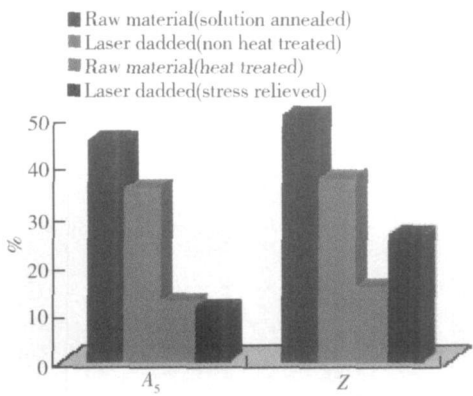


Fig 14 Elongation A_5 and contraction Z of non heat treated and heat treated raw material^[15] and non heat treated and heat treated laser cladded material, room temperature, DIN 50 125 B 4 × 20, DIN EN 10002

Table 1 Heat treatments of raw material (complete heat treatment, step 1~ 3) and of laser cladded material (PWHT)^[15]

	Temperature/ ℃	Time span/ h	Cooling	Hardness/ HRC
Step 1, Solution annealing	950~ 980	1	Air	20~ 25 (240~ 270H V)
Step 2, Ageing 1	720	8	Oven	/
Step 3, Ageing 2	620	8	Air	40~ 44 (390~ 440H V)
PWHT , Stress relieving (short ageing)	732	4	Over	/

The static mechanical properties of the material rough after cladding corresponds to those of a hot-rolled and annealed raw material while the static mechanical properties of a stress relieved (aged) laser cladded material is equivalent to those of a complete heat treated raw material.

LD

CPC: Stainless steel of 2, 5, and 8 mm thickness is percussion drilled by 10 to 30 pulses. The drilling velocity is comparable to nickel base at

loys^[16,17]. For 2 and 5 mm sheets the drilling depth per pulse is nearly constant before break through during the 5th respectively the 11th pulse (Figure 15, 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 sheet (Figure 16).

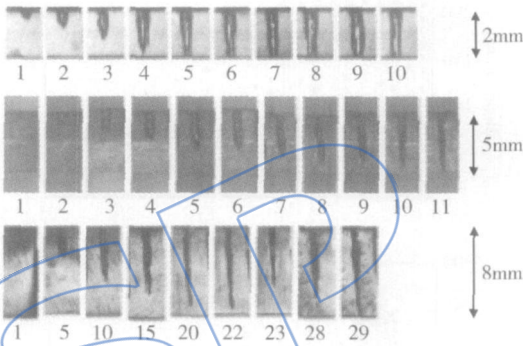


Fig 15 Longitudinal sections (percussion drilling, X5CrNi18- 10, 2, 5, and 8 mm, increasing number of pulses from left to right)

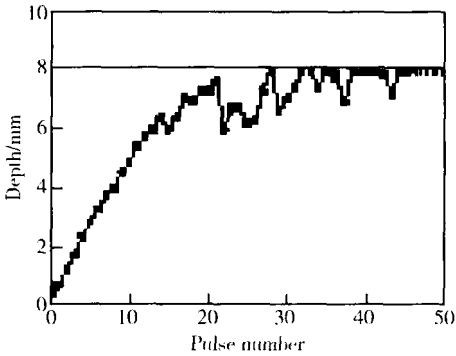


Fig 16 Drilling depth versus the number of pulses (percussion drilling, X5CrNi18- 10, 8 mm)

By drilling the 2 mm sheet 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 (Figure 17, top).

During drilling the 5 and 8 mm sheets the

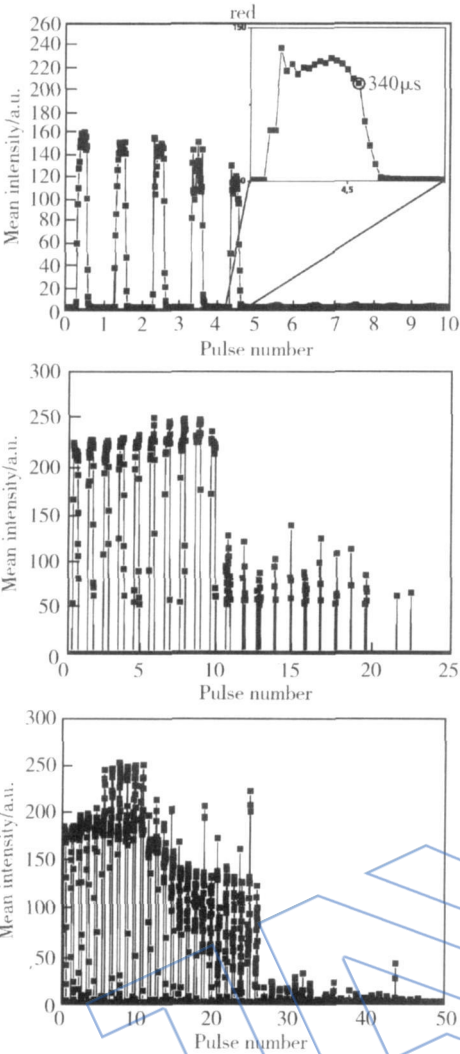


Fig 17 Mean intensity of emission detected by the red sensor (percussion drilling, X5CrNi18 10, 2.0 mm (top), 5.0 mm (middle), 8.0 mm (bottom))

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 sheet (Figure 17, middle and bottom). Due to the smaller solid angle at bigger hole depth drilling the 8 mm sample the mean intensity starts decreasing at a hole depth of about 6 mm, respectively the 13th puls. Another reason of the smaller ratio is multiple reflection of the process emission at the hole wall.

The entrance diameters of two holes drilled in a 5 mm sheet are according to the diameter of the pattern of the intensity (Figure 18). The diameter of hole 1 could be determined precisely by superposition of two patterns in case of hole

2, the imprecise determination of the diameter by measuring the pattern of intensity is consequence of the large process emission.

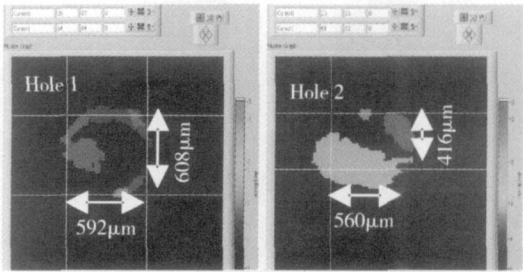


Fig 18 Pattern recognition of intensity by red sensor for two holes, left: hole 1, superposition of two patterns during 11th pulse, right: hole 2 pattern during 12th pulse (percussion drilling, X5CrNi18-10, 5.0 mm)

Table 2 Diameter of holes and diameter of pattern of intensity (Figure 18)

	$\phi/\mu\text{m}$ horizontal	$\phi/\mu\text{m}$ vertical	$\phi/\mu\text{m}$ average
Hole 1, real diameter	532	647	589
Hole 1, diameter of pattern	592	608	600
Hole 2, real diameter	561	479	520
Hole 2, diameter of pattern	560	416	488

Trepanning: The shaped holes drilled according to the original CAD data (Figure 19) 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 (Figure 8, top and bottom view). 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.



Fig 19 Scheme of the reference hole for trepanning

- 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 cross section of the multilayer system (Figure 20) 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 OM and SEM analyses of the chemically etched cross section the shaped holes exhibit a recast layer in the thickness range of 10~ 20 μm, whereas the thickness is larger at the leading edge than at the trailing edge of the hole (Figure 21). The larger recast layer at the leading edge is explained by Sezer et al. with a model characterising the heat flow during the drilling process^[18]. 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 (Figure 20 and 21). No cracks can be detected in the CM-SX-4 substrate and no significant damages are observed in the recast layer.

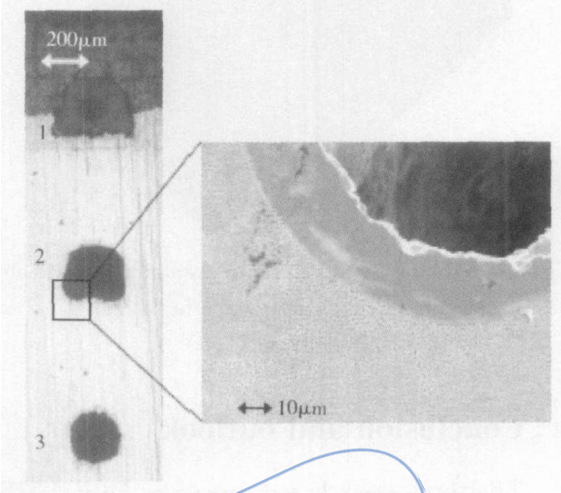


Fig 20 Shaped hole ($t_{PULSE} = 0.5 \text{ ms}$, $f_{PULSE} = 20 \text{ Hz}$, $P_{LASER} = 1.4 \text{ kW}$, $P_{AVERAGE} = 14 \text{ W}$, chemically etched)

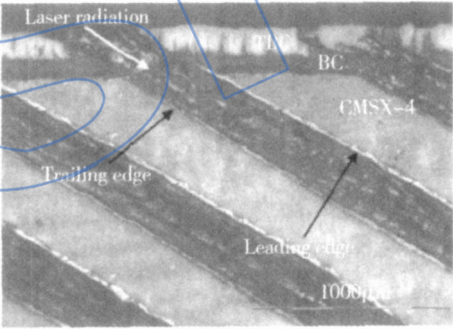


Fig 21 Longitudinal section of the outlet region of a multilayer system at 60° inclination ($f_{PULSE} = 20 \text{ Hz}$, $E_{PULSE} = 0.6 \text{ J}$, $t_{PULSE} = 0.5 \text{ ms}$, chemically etched)

The WIM analysis exhibits the surface structure, caused by the columnar growth of the YPSZ TBC when deposited by the electron beam physical vapour deposition (EBPVD) (Figure 22). The outlet region of the shaped hole obtained by the five-axis trepanning has a symmetrical geometric shape. The relatively small radius at the left and right corner of the fan shape base line, are realised by a sharp edged CNC track. These turning points lead to an extend laser/ material interaction resulting in a slight channel. The formation of the channel can be reduced by a redesign of the CNC track with an improved axis movement.

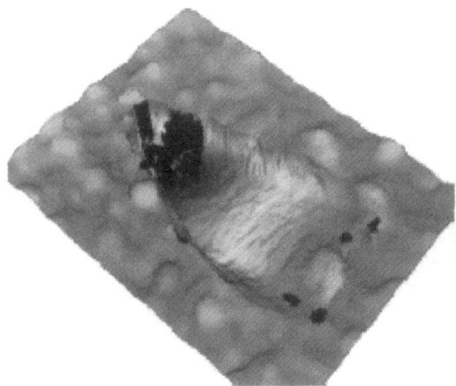


Fig 22 WIM analysis of the outlet van of a shaped hole
(no surface information could be obtained
in the black regions)

3 Conclusion and outlook

The three laser based processes DLF, LMD and LD offer adequate tools to realize and implement a repair chain for HPT blades and vanes out of Nickel base alloys due to the results achieved within specific basic R & D carried out for every process. The key challenge not solved to date is the combination of all three processes to one repair chain. In case of feasibility this repair chain will offer new possibilities in the aero engine parts repair and maintenance field.

Acknowledgments

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