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Investigation of laser decoated gas turbine blades and their recoating with regard to their mechanical hardness properties

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Abstract
Due to the intensive thermal and mechanical loads during operations, gas turbine blades must be maintained at regular intervals. This involves decoating the blades, repairing the blank blades and finally recoating them. In order to avoid conventional decoating of gas turbine components, alternatives have been investigated for some time. Besides milling and waterjet decoating, laser decoating is gaining more and more attention due to its selective and homogeneous surface treatment as a good alternative to sandblasting and the environmentally harmful acid bath. As important as the pure deposition process is the investigation of the mechanical properties of the material after laser decoating. Therefore, this research focuses on the mechanical properties after the vector-based laser ablation process of a bilayer thermal barrier coating and bondcoat system on operationally exposed blades as well as on the subsequent recoating.

The ablation result of a fiber laser on the ablation quality and the remaining surface roughness is investigated. The effect of the parameter variations on the ablation process is tested on a local spot with slight curvature. Subsequently, the hardness of the newly created surface and the layer transitions are examined. Finally, a qualitative conclusion is made whether the laser-based decoating process of gas turbines is suitable for the repair process.

Keywords: Hardness; Laser; Nd:YAG laser; Turbine blade

1. Introduction

Gas turbine blades are exposed to high thermal stress of up to 1600 °C in their application, and therefore require suitable heat protection consisting of a bilayer thermal barrier coating (TBC) and a bond coat system [1, 2]. Regular repair cycles and recoating allow the blades to be used repeatedly in turbine applications [3]. In conventional decoating the bond coat is removed in an environmentally harmful acid bath and the TBC is then sandblasted [4]. Thus, laser decoating is a good alternative manufacturing process [5]. As important as the decoating itself are the mechanical properties of the decoated material in the near-surface area and the adhesive strength of the subsequent recoating. Previous work either focused on alternative waterjet decoatings and their evaluation [6] or on the laser ablation procedure and its microscopic evaluation [7-9]. To the best of the authors' knowledge, a more detailed consideration of recoated gas turbines after laser-based decoating has not been investigated at present. Therefore, the question arises whether the process is not only suitable as a decoating method, but also positively enriches the blade repair process.

In this study, local laser ablation of blade components with various degrees of decoating is first performed in order to subsequently analyze and recoat them. For this purpose, several local decoating tests with different parameters are carried out on the blades. In the further process, the mechanical properties of the newly created surface are investigated for both the decoated and recoated samples and evaluated for their strength. In addition, different mechanical properties are measured, including hardness tests with the Vickers method [10]. Finally, a macroscopic examination of the cross-sectional areas of the different test fields is carried out. The evaluation is made in direct comparison with a conventionally machined blade. In the best case, the adhesion properties of the laser processed blade are comparable to or even better than those of the conventionally processed blade, which qualifies the laser decoating process for future use.

2. Material and characterization

The gas turbine blades were subjected to operational stress and readjusted in the turbine of the combustion chamber. They consist of a cast base material, coated with a few hundred µm thick bilayer coating system: a metallic corrosion protection Bond Coat (MCrAlY- M: nickel, Cr: chromium, Al: aluminum, Y: yttrium) and a ceramic TBC.

Figure 1a shows the cross section of the layer structure. Furthermore, different decoating stages (incompletely and completely ablated) are shown in Figure 1. The results of both, laser decoating and conventional decoating were investigated and in some cases recoated with a new Bond Coat.

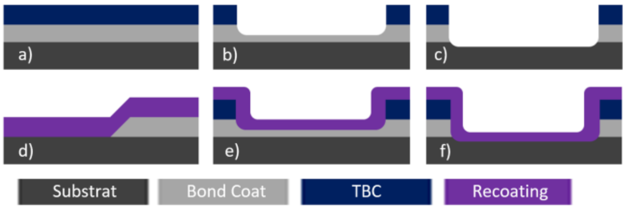

Figure 1. Cross sections of sampels: (a) Coating System; (b) incomplete laser decoating, (c) laser decoating; (d) recoating after sandblasting/conventional decoating; (e, f) recoating after laser decoating

3. Methodological and experimental approach

This paper is divided into two sections, one about the decoating process itself and the other related to the analysis of the properties of the newly created surfaces of the decoated and recoated samples.

3.1. Laser ablation

A fiber laser with a wavelength of $\lambda = 1$ µm was chosen for the laser ablation process of a turbine blade and therefore qualified for both ceramic and metallic ablation. Using three different parameters, as showen in table 1, the material removal behaves differently even though the variations are not so large between the performances. This ensured that different decoating stages were available for the subsequent investigations.

Table 1 Parameter variation of the laser ablation

Sample name	Power [W]	Velocity [mm/s]	Crossings
1	180	225	30
2	180	225	50
3	170	300	50

An ablation section of $A = 9$ cm^2 is composed of many individual surface areas of square geometry and a side length of 1 cm. The individual surfaces are always passed through in a staggered pattern (see figure 2) in order to keep the transitions between the individual sections homogeneous. Even though it would be possible to scan this size with the scanner without subdividing it, the area was split up to create the most realistic conditions possible for further experiments so that the entire blade could be decoated in this way.

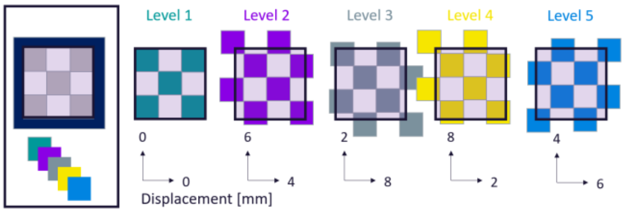

Figure 2. Strategy of Laser ablation

Subsequently, one blade was sorted out for the macroscopic and mechanical examinations. The other blade, together with a conventionally decoated one, was subjected to a recoating process in which a new bond coat was applied. To ensure that the new coating adheres to the existing surface, a blasting process is carried out between the decoating and recoating processes to activate and clean the surface. This step is performed as part of the regular coating process and is therefore not a step applied specifically for this study.

3.2. Surface and Decoating analysis

The following series of tests (chapter 3.2 and 3.3) were carried out on both blades, the laser-decoated and the conventionally decoated one, in both the decoated and the recoated states. In addition, a coated reference blade was used, illustrated as a layered system in Figure 1a.

Using cross-sections of the samples, the existing layer system was analyzed with a Keyence microscope. The roughness was determined and the visual quality was evaluated. In addition, imperfections such as blowholes were examined with respect to their size and location within the surface.

3.3. Mechanical property testing

Micro-indentation was used to determine the Vickers hardness at the layer transitions of all existing layers as well as in the layers themselves. The analysis of the onset of fracture was done by microscopic observation of residual scratches after the test as well as sudden changes in penetration depth [11]. For this purpose, a standardized test specimen made of an equilateral diamond pyramid with an opening angle of 136° is pressed into the specimen with a specific test force.

4. Results

The vector-based ablation tests show constant surface ablation over the ablation areas. The previously described surface partitioning strategy was successfully implemented. A slight material burn-in was observed on the surface, but the contour was maintained smoothly, especially at the contour boundary and in the corners.

After treatment with the fiber laser, values of below $R_a = 50$ µm were analysed for the surface roughness. Thus, this surface roughness is well suited for recoating in the course of the further repair value chain. More detailed microscopic examinations showed a few µm thick melt layer on the surface. Some sample sections contained an accumulation of melt between the patterns, which are responsible for the relatively high roughness. However, the further sandblasting process integrated into the recoating process removed the melt layer on the blade could without leaving any residue.

Figure 3 shows the different stages of the selected for coating for all three parameter variations used for decoating. The three stages consist of (a) laser decoating followed by (b) sandblasting process and rounded off by (c) recoating. The new coating thickness varies around 200 µm and was applied the same way to the conventional comparison blade.

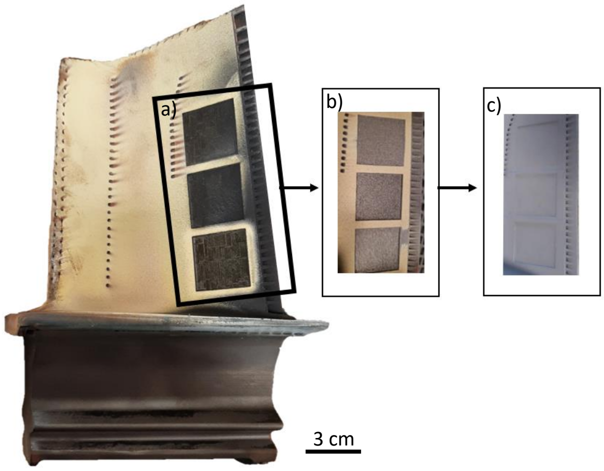

Figure 3. Turbine blade: (a) local laser decoated areas; (b) sandblasting treatment; (c) recoating of samples

Figure 4 shows the cross-sections of a laser-deposited recoated sample (from Figure 3) after incomplete decoating (Sample 1: Figure 4a) and after complete decoating (Sample 2: Figure 4b). In both samples, good adhesion of the recoated bond coats was observed. In the case of the incompletely decoated sample 1, a continuous recoating with minor shrinkage in the bond zone is visible. In the completely decoated specimen, there are fewer shrink holes directly in the bond zone, but more shrink holes in the vicinity of the bond zone.

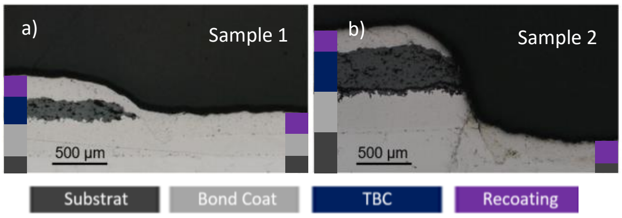

Figure 4. Recoated blade samples: (a) recoating after incomplete laser decoating; (b) recoating after complete laser decoating

The ablation depth of the laser decoating was measured for the samples and the process time was recorded and evaluated. While sample 1, treated with an energy per unit length of E = 0.422 J/mm, still had a residual bond coat of 132 µm, sample 3, treated with an energy per unit length of E = 0.309 J/mm, had already removed 394 µm of the blade base material. Thus, the decoating of sample 3 is above the actual blade decoating tolerance, and this blade should not be re-installed in the turbine.

Furthermore, as shown in Table 2, the residual layer thickness was measured and the ablation depth per crossing was calculated based on the total removal depth. The material-specific infeeds of the individual layers and the base material of the blade with regard to the material removal have similar properties. However, by approximately doubling the number of scanner passes relative to sample 1 for the remaining samples, the component is heated and kept at a higher temperature for a longer period of time, increasing the material removal per crossing.

The time aspect is unfortunately a very disadvantageous feature with up to 82 minutes of sample 2. With only 49 minutes, sample 1 could not be completely decoated; a higher output on power or an increase in the number of crossings would be necessary. In terms of surface area, the complete decoating of the blade corresponds to a larger factor of about 50, rendering the processing rather uneconomical from this point of view.

Table 2 Analysed thickness of the laser decoating

Sample name	Residual Layer Thickness [µm]	Ablation depth per crossing [µm]	Removal rate [mm³/s]	Time [minutes]
1	+ 132	16,933	0,155	49
2	- 348	22,04	0,201	82
3	- 394	23,05	0,263	73

The conventionally partially decoated blade shown in Fig. 5 serves as a comparison to the laserdecoated blade. This conventionally treated blade was sandblasted with industrial standards and then recoated. On the left side of the figure, an unintentional recoating of a cooling air hole can be observed. The newly obtained coating reduces the required air outlet, causing overheating of the blade during operation. Therefore, the cooling air holes must be reopened before reapplication [12, 13].

The sandblasted area mentioned above can be seen on the right side of the illustration. The blade was intentionally not placed in the acid bath, as otherwise no transition between the magnification, significantly fewer shrinkage cavities were visible, but they had a larger diameter than the laser-decoated blade samples.

The surface roughness of the conventionally decoated sample is very low and can be compared with the laser decoated sample. In general, good bonding between the new coating and the previous residing coating can be observed.

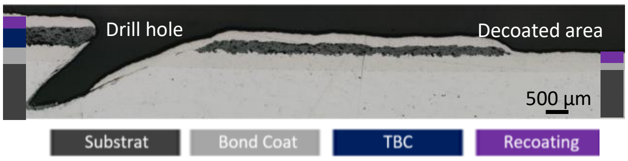

Figure 5. Re-decoated blade samples of conventional decoating

The micro-indentation test to determine the Vickers hardness was carried out on all sample interfaces, as shown in Figure 6 on a partially laser-deposited sample. Due to the previously measured roughness of about 50 µm, the crossover interface of the respective test was calibrated indivually in advance.

In addition, repeated measurements were carried out on each of the specimens, of those the value was averaged in order to make a statement about the hardness. Attention was focused on the before mentioned displacement between the layers, which is why the individual measurement points were adjusted by a height shift.

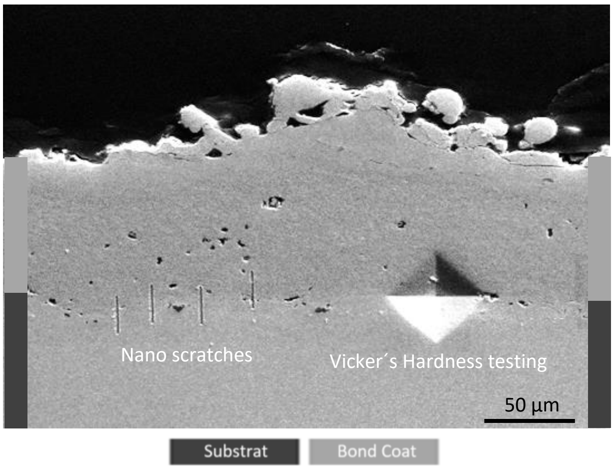

Figure 6. Interface testing of mechanical properties of a laser ablated sample

The results of microindentation test (Vickers hardness HV1) indicated that the hardness of the remaining bond coat was reduced in most cases after decoating. In the samples where intensive material removal took place (Sample 3), the hardness of the base material in the area of decoating, for example, was reduced significantly below 240 HV. However, for the other samples it could be demonstrated that the hardness of the laser decoated material showed only minimal losses with respect to the reference blade.

Table 3 lists the measured values for the transitions for each interface on all previously described blade samples. It was observed that the TBC layer of the reference blade has the highest hardness with a drastic added value of about 200 HV. The transition zone Bond Coat - TBC corresponds approximately to the hardness of the substrate with around 450 HV. The Bond Coat itself has the lowest hardness with affect HV.

Table 3 Average (n = 5) of the vickers hardness (HV1 holding time 12 s) of the differently treated turbine blades

Sample	Interface	Hardness [HV]
Reference Blade	Substrate	445
	Substrate - Bond Coat	413
	Bond Coat	405
	Bond Coat -TBC	452
	TBC	654
Laser based decoted (Sample average)	Substrate	447
	Substrate - Bond Coat	391
	Bond Coat	388

5. Evaluation of the application potential

The main goal of this research was to evaluate an alternative laser-based decoating process for gas turbine blades coated with a two-component coating system. The coating is made of a layer system consisting of a metallic bond coat and a ceramic TBC coating. Due to the fact that the blade is decoated for repair and subsequent recoating, it is a fundamental requirement that the decoating process does not damage the base material and does not affect its mechanical properties. Therefore, the decoating process is as important as the subsequent recoating.

The locally variable ablation depth combined with a very homogeneous surface is a strong argument for the laser-based coating removal process. The vector-based ablation process proved successful in large-area ablation without significant domain overlap. The feasibility of the process was demonstrated on turbine blades. With respect to the ecological point of view, this process represents a positive alternative to the conventional process.

However, it could be demonstrated that the hardness of the laser decoated material showed only minimal losses, compared to the reference blade. In addition, it could be confirmed that a renewed coating process did not affect the hardness of the boundary regions. Hardness within the old bond coat were similar to the ones in the newly applied bond coat. This proved that the laser ablation process does not significantly affect the mechanical properties of the material and is suitable for blade repair when supplemented by further process steps.

6. Conclusion

In this study, the laser-based ablation technologie for the ablation of ceramic-metal coating systems from hot gas turbine components was discussed and the mechanical properties of the so treated samples were analysed. The following results were obtained:

1) In terms of quality, laser stripping clearly scores points with its precise adjustability and good surface quality.
2) The laser decoated sample shows consistently good roughness, in the premissable tolerance for re-coating with good re-coating results.
3) A few thermally conditioned defects (blowholes) could be detected in the transition boundary layer, but this had no effect on adhesion.
4) The Vickers hardness of the laser decoated material showed only minimal losses, compared to the original hardness of the reference blade.

In this study the laser-based ablation process could be qualified as an industrially acceptable process. A limiting factor besides the time-consuming nature of the process is the locally fluctuating coating thickness, which leaves little room for tolerances in an ablation process. In future studies, a thermal study should be performed during the laser ablation test to improve the understanding of the thermal effects on the material.

Acknowledgments

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