Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 22 (2014) 263 – 267

www.elsevier.com/locate/procedia

3rd International Conference on Through-life Engineering Services

Session: Recent Progress in Jet-Engine Regeneration

Crack repair of single crystal turbine blades using laser cladding technology

Boris Rottwinkel*, Christian Nölke, Stefan Kaierle, Volker Wesling

Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hanover, Germany

* Corresponding author. Tel.: +49 511 27 88 234; fax: +49 511 27 88 100. *E-mail address:* b.rottwinkel@lzh.de

Abstract

The formation of cracks in single crystal (SX) turbine blades is a common problem for aero-engines. To repair cracks, which are located under the tip-area, a new method is to clad with single-crystal-technology. This technology use multi-layer cladding to replace the single crystal material. To regenerate cracked material it is necessary to remove the crack affected material. The used notch geometries to remove the crack-affected area must be weldable and also permit the material solidification in the same oriented plane as the original microstructure. To solidify in the original structure a thermal gradient has to be introduced in order to guide the grain growth. This required gradient can be established by inductive heating. To reduce the thermal effected zone, a laser source is used. In addition, it is also an efficient process to fill the notch. Also the small local heat input and controlled material supply support the epitaxial growth. However, there are requirements to achieve a SX structure without cracks and pores. Current achievements and further challenges are presented in this paper.

Peer-review under responsibility of the Programme Chair of the 3rd InternationalThrough-life Engineering Conference

Keywords: turbine blade repair; laser cladding; single crystalline

1. Main text

The volume of the blade repair market all over the world is immense. Aircraft engines servicing accounts about 30 percent of the total cost of the whole aircraft maintenance. Maintenance of the single crystal turbine blades, which are used in Stage 1 or in today´s state of the art engines also in Stage 2 and 3 of the high-pressure-turbine (HPT), is still a complex process.

Due to the high thermal and mechanical stresses during operation, these parts are mainly manufactured in a complex casting procedure to achieve a single crystal microstructure. The specific morphology is oriented along the direction of axial stresses. This orientation increases the operating limits significantly compared to polycrystalline blades also used in aero-engines.

The most common failure case in turbine blades is creep. That is also the life limiting factor. Due to significant reduction of grain boundaries for epitaxial orientation, the single crystal structures withstand creep at higher temperature levels then common structures. Grain boundaries within the microstructure can initiate failure mechanisms, which decrease the high temperature strength that causes creep failure.

At their shop visit poly crystalline laser cladding is used to deposit a new tip area to the HPT-blades. The area is afterwards refinished to the original shape of the tip [1] (Fig. 1).

Fig. 1: Poly crystalline repair

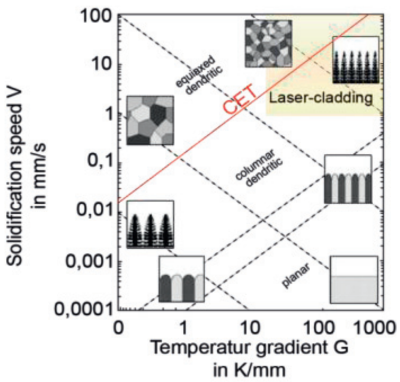
The regeneration of single crystal morphology offers beneficial mechanical properties at the repaired zones and

Peer-review under responsibility of the Programme Chair of the 3rd InternationalThrough-life Engineering Conference
doi:10.1016/j.procir.2014.06.151

enables extended limits for parts repair. In consequence, a higher quality level can be reached and the long term perspective offers an increased number of refurbished scrap parts.

As an additive manufacturing tool, the laser cladding process is a well-established method to repair turbine blades. Its advantage lies on the possibility of localized heat input, which enables a reduced heat affected zone in the repair zone, which supports the formation of a single crystalline structure. The laser cladding process can be realized using powder or wire as additive material.

To avoid nucleation in the laser cladding process, Kurz et al. [2] postulate the columnar to equiaxed transition (CET) (Fig. 2). This transition correlates the effect of the thermal gradient to the solidification speed.



Fig, 2: CET - columnar to equiaxed transition [2]

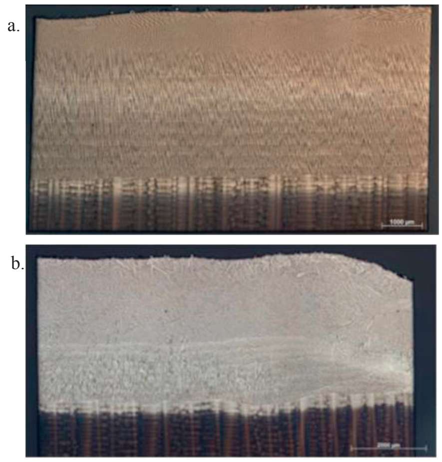
The required thermal gradient to reach columnar solidification was calculated by Gaeumann et al. [3]. This identified limits enabled the growth of equiaxed grains within the molten material.

In the present work, the laser cladding process was considered for the similar SX-repair of single-crystalline blades made of CMSX-4. Santos et al. [4] were able to clad single crystal structures on flat samples by using two different alloys. The use of Rene N4 powder on CMSX-4 substrate showed a single crystal microstructure orientation. Gaeumann et. al. [5] were able to clad crack free single track-volumes on a mono crystalline CMSX-4 substrate to rebuild single crystal structures. To clad single tracks, like small walls, Gaeumann claim three main steps for the single crystal formation:

- The temperature of the used substrate should be as low as possible.
- Preheating should be avoided.
- Avoid overheating of the melt pool by using a laser power control

Those three recommendations could be proven during our investigations (Fig. 3a). In Fig. 3b, the substrate was preheated to show the effect on the crystal formation using a preheated substrate.

During the process, a water cooled platform was used to reduce the temperature of the substrate to 18°C. The distance between heating and cooling front should support the required thermal gradient, which was calculated before. For the laser cladding process, a diode laser with maximum power of 680 W, a wavelength of 940/980 nm and a fibre diameter of 400 µm was used. The used process parameters are summarized in Table 1.



Fig, 3: SX-cladding without (a) and with (b) preheating

Table 1: single crystal clad parameter

	Without preheating (Fig. 1a)	With preheating (Fig. 1b)
Feed rate [mm/min]	100	100
Powder feed rate [g/min]	3	3
Laser power [W]	100 – 350	100 – 350
Temperature at molten bath [°C]	1400	1400
Preheat temperature [°C]	-	650

To repair turbine blades with cracks, as shown in Fig. 4 the cladding process cannot be performed with a single track.

To rebuild large areas like tips on blades, the process must be extended to multi-track cladding per layer without crack formation. The formation of cracks during notch cladding was an important fact to be analyzed. It was explicit that the notch geometry turns the SX clad into a complex system due to heat distribution and residual stresses in the region.

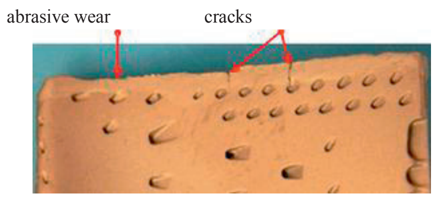


Fig. 4: Damage on turbine blade tip

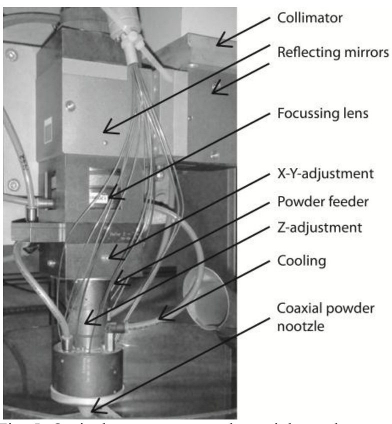
The introduction of a notch in the substrate is a method developed to optimize the crack repair on the tip of turbine blades. It consists of cutting the damaged region with a known geometry in order to remove the crack and rebuilt it. On the other hand, the clad complexity is increased due to the energy distribution inside the notch. The heat flow occurs no longer in one dimension, but in two, since the heat propagates to the lateral area as well. This phenomenon generates a region suitable for crack formation due to residual stresses resulting from tensile and compressive strength. In order to reduce stresses, a thermal induction is used to preheat the substrate by means of an electromagnetic field. This decreases the temperature gradient on the one hand, but reduces the residual stresses.

Since the SX alloys do not contain grain boundary hardening elements, it is necessary that the reshaping technique also results in a single crystal for the required material properties to avoid cracking. To avoid the formation of grains, the thermal gradient must be formed well. During laser cladding, the thermal gradient is orientated to the cold substrate and at the clad´s top rectangular to the clad direction. Using multi-track cladding, these orientations will be extended to multi direction. These directions are influenced by the clad tracks next to each other. To avoid more thermal gradient orientations, long processing times or even high energy levels should be avoided.

On the other hand, for the repair of cracked blades, the thermal expansion of nickel-base superalloys results in high tensile stresses in the cladded notch. To avoid this, preheating of the samples shows advantages, even if this was negated by Gaeumann. To overcome this problem, a specific temperature distribution is required to enable a heated and a cooled front that controls the direction of solidification.

2. Laser cladding technology

Initially the laser cladding trials were performed on small flat CMSX-4 substrates (dimensions: 30 x 30 x 2 mm³) to simplify the process setup and to reduce the number of significant parameters. The substrates were casted with single crystal orientation and cut in a subsequent step using EDM (Electrical Discharge Machining). CMSX-4 was used as substrate and also as addition powder material to process with similar materials. The focus diameter of the laser beam was adjusted to 0.860 mm. To achieve a single-step process without predeposition of additive material before laser treatment, a powder feeder and a coaxial powder nozzle were used to transport the additive powder material into the processing zone. The used powder is spherical shaped and has a grain size distribution of 25 - 75 µm. The powder particles did not show any gas inlets, which reduce the quality of the clad and lead to pores. The experimental setup consisting of the nozzle and the optical components is shown in Fig. 5.



Fig, 5: Optical components and coaxial powder nozzle

To have an inert transport atmosphere, the feeding was realized by an argon flow (8 l/min) through the conveyor. The powder feed rate was about 3 g/min. Prior to the investigations the process chamber was flooded with argon to reduce the concentration of oxygen to a value below 2.000 ppm. Additionally, the argon flow for the powder transport also shield the process zone from oxidation. This enables an oxygen level below 500 ppm. An inductive heating with a power of 3 kW and a dynamic controlled frequency of 70 – 450 kHz was used to support the thermal gradient required for epitaxial solidification. For cooling the sample a water cooled mounting was used as heat sink. The cooling medium was tempered to 18 °C. As control unit the temperature control system TemCon was used to stabilize the adjusted induction temperature.

The required distance between cooling and heating and the subsequent gradient was focused in the first part of the research. To reduce development time and costs at the 6-axis CNC-station, the gradient and the thermal distribution were numerically simulated with Ansys™. These simulations result in the mandatory parameters for the required preheating temperature, distance between crack and cooling mount and the location of the induction coil. For verification of the correct solidification direction a metallographic analysis was performed at selected samples after cladding. These results were finally proven using electron back scattering diffraction (EBSD), which is a technique commonly used to examine the crystallographic orientation of materials and to detect the preferred orientation of the crystalline material.

3. Results

Epitaxial solidification for claddings made of CMSX-4 on flat CMSX-4 substrates could be realized using a laser based process. A metallographic cross section is pictured in Fig. 6, due to the specific preparation the directional solidification is clearly visible. The cladded sample has a dimension of h 1.2 x w 1.1 x d 5 mm³ and was built by the overlap of five single clads on top of each other, without applying any additional preheating. This solidification behavior could be observed at short term processes and comparably small cladded areas only. The general processing times did not exceed 5 s.

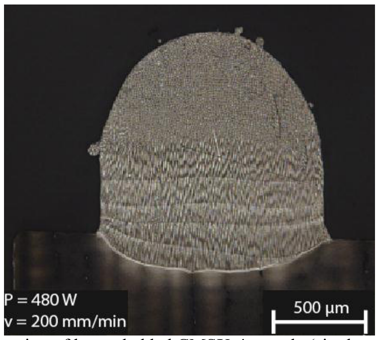


Fig. 6: Cross section of laser cladded CMSX-4 sample (single-track per layer)

To avoid cracking in larger volume, which need several clad tracks per layer, preheating was used. By using a controlled cooling rate, the formation of solidification cracks can be suppressed. The ratio between preheating temperature and laser power is crucial and has a significant impact towards the single crystal formation. To test the cladding into larger samples, the clad was built with four tracks next to each other, which were overlapped by six layers. The final dimensions of these samples were: h 1.5 x w 2.1 x d 30 mm³. A total epitaxial solidification is achieved with the removal of the last layer (Fig. 7). The required preheating temperature of 850 °C for tip cladding was determined theoretically in advance and could be transferred directly to the process.

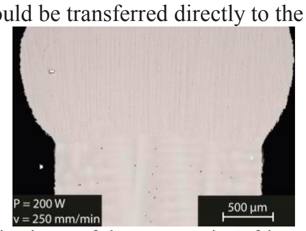


Fig. 7: Microscopic picture of the cross section of laser cladded CMSX-4 with large volume (multi-track layer)

To verify the epitaxial structure, the EDAX EBSD system, type OIM XM4 was used (Fig. 8) to detect crystallographic orientation of the cladded area. The Kikuchi patterns have been visualized in an orientation mapping using varying colors for each crystal orientation.

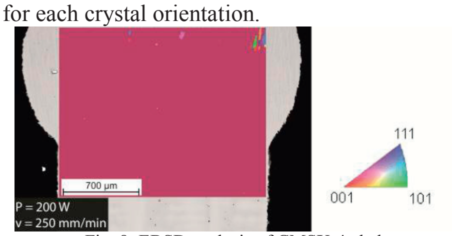


Fig. 8: EBSD analysis of CMSX-4 clad

In the EBSD analysis the directional solidification of the CMSX-4 powder on the similar substrate is shown. Generally, the clad shows a completely homogenous crystal orientation. At the top end, sporadic disorientations of the clad are visible. These disorientation areas have appeared during the bulge formation during the cladding. Within the bulky area the heat propagation is changing and consequently there are deviations regarding the appropriate value and orientation of the thermal gradient. To overcome such defects the input of the inductive heating and also the local cooling must be adjusted to reestablish the former gradient for SX gladding in these areas.

In order to clad cracks on blades, feasible notch geometries have to be determined. In Fig. 9, the used notch geometry is shown. Tests have been used to evaluate the interaction grades between notch geometry, induction system and powder supply.

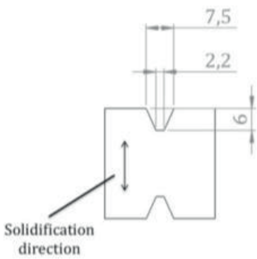


Fig. 9: Notch geometry

Table 2 shows the used parameter for the initial test. These parameters were the result of the previous experiment for the single crystal tip cladding. Preheating was set to 650°C to form the required thermal gradient inside the notch. The required preheat temperature was calculated before to fit for the clad cladding process. The gradient could be established by the induction heating and the water cooling.

Table 2: Parameter for notch cladding

Sample	Focus diameter [mm]	Feed rate [mm/min]	Temp. [°C]	Preheating [W/°C]
N1	0.860	100	1400	-
N2	0.860	100	1400	2000/650

The result of sample 1 (N1) is shown in Fig. 10.

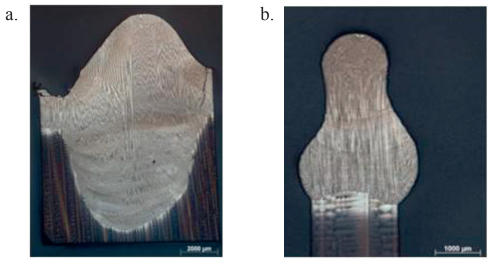


Fig. 10: Sample N1

The microstructure of N1 approximates to the single crystal solidification even in the cross section, but there are cracks and pores in it. The thermal expansion of the material result in the formation of stresses which initiated cracks. Their origin was at the top of the clad. Guided along the few grain boundaries, cracks stopped at the original SX-structure.

Sample N2 showed a crack free clad with equiaxed solidification. Since the preheating is the only difference between, it is reasonable to assume that the microstructure is vulnerable to the thermal induction influence.

These two experiments showed that preheating has a significant influence on the grain growth during solidification inside the notch. It is important to consider that the thermal induction, despite providing a crack free microstructure, is unsuitable for the formation of a single crystal clad. However, trials without preheating have shown cracks, which are also unacceptable.

To reduce crack formation, parameters were changed to pursuit the formation of thinner layers in order to reduce the required laser power and so the loss of the thermal gradient orientation. The preheating of the sample was skipped to reduce the temperature in the clad area. These small single crystal layers may be more resist against the residual stresses indicated by thermal expansion. In the next steps the powder injection was reduced to 1 g/min and 2 g/min. This results in a lower laser power through reduced powder interactions and melting energy. Also, to limit the laser power to minimum, the laser was controlled using a PID-controller with a pyrometer to control the temperature of the clad pool to 1400°C. The melting temperature of the used alloy is about 1380°C. But cracks could still be detected.

To reduce the laser interaction time with the substrate, the feed rate in the next samples was increased by 50 percent. Using the increased speed, the heat affected zone was decreased. Nevertheless, cracks occurred and the microstructure showed polycrystalline phases. To form the thermal gradient more precise the focus diameter was expand form 0.860 mm to 1.342 mm. Consequential the number of layers required to fill the notch was reduced. With the reduction of layers per area, the laser time was reduced. Also the cooling time between the single cladding steps was risen to cool down the cladding more homogeneous. In the metallographic analysis of the samples, cracks could be detected.

Another way to reduce the start of cracks was to reduce the preheating temperature. The initial temperature was calculated to fit the required gradient. Thus the gradient was reduced. The preheating was controlled by a PID-Controller to set the required temperature. By reducing the required temperature, the influence from the thermal induction was reduced and the analysis shows the initial formation of a single crystal microstructure in the bottom region. In order to reduce even more the action of the thermal induction, the inductive preheating was shut down directly after or before the cladding process. By shutting down the preheating just before the cladding process an improvement in the microstructure since there was no magnetic field acting during the process. These magnetic fields could affect the dendrites orientation or even break the dendrites. The effect of breaking dendrites was also shown by Ren et al. [6]. This has to be proven for our setup by Scanning Electron Microscope (SEM) analysis.

4. Conclusion

It could be shown successfully that laser cladding can be used to generate a multi-track CMSX-4 SX-structure on flat substrates made of CMSX-4. The use of an inductive preheating leads to a crack free clad. Metallographic analyses were carried out to determine the epitaxial solidification of the CMSX-4 substrate. Furthermore, the analyses with the EBSD system verified the epitaxial growth of the material. The regeneration of defects at the tip zone of turbine blades can be realized applying a cladding with single crystal morphology. The crack repair with notching the cracked tip and cladding with the shown parameters is not possible yet. The interaction between the inductive preheating and the dendrite growth has to be analyzed in the next step.

Acknowledgements

The work was funded by the German Research Foundation (DFG) in the framework of the work in the Collaborative Research Centre 871 (CRC871).

References

[1] Richter, K.-H. (2008) Laser material processing in the aero engine industry. Establishes, cutting-edge and emerging applications. Proceedings of the 3rd Pacific International Conference on Application of Lasers and Optics 2008, Paper 1005

[2] Kurz, E.; Bezenvon, C. & Gaeumann, M. (2001) Columnar to equiaxed transition in solidification processing. Science and Technology of Advanced Materials, Volume 2, Pages 185-191

[3] Gaeumann, M.; Henry, S.; Cléton, F.; Wagnière, J.-D. & Kurz, W. (1999) Epitaxial laser metal forming: analysis of microstructure formation. Materials Science and Engineering: A, Volume 271, Pages 232–241

[4] Santos, E. C.; Kida, K.; Carroll, P. & Vilar, R., 2010, Optimization of Laser Deposited Ni-Based Single Crystal Superalloys Microstructure. Advanced Materials Research, Volumes 154-155, Pages 1405-1414

[5] Gaeumann, M.; Bezençon, C.; Canalis, P. & Kurz, W., 2001, Single-crystal laser deposition of superalloys: Processing-microstructure maps. Acta Mater. Volume 49, Pages 1051–1062

[6] Ren, W.; Lu, L.; Yuan, G.; Xuan, W.; Zhong, Y.; Yu, J., Ren, Z. (2013) The effect of magnetic field on precipitation phase of single-crystal nickel-base superalloy during directional solidification, Material Letter 100, Pages 223-226