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NOVEL LASER CLADDING PROCESS FOR LOCAL TBC REPAIR

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ABSTRACT

In laser-based additive manufacturing of Ni-based superalloys, significant progress has been made in recent years. This enables now targeted repair and the realization of novel component designs by means of laser-based processes such as direct laser deposition or selective laser melting. In the case of ceramic materials, the necessary high processing temperatures and the lack of ductility of ceramics often lead to high local stresses and crack formation even in relatively small structures.

In the field of gas turbine applications, however, there are microstructure requirements, particularly for ceramic thermal barrier coatings (TBC), which can in principle be met by laser-based additive manufacturing. Due to the high demands on the thermal shock resistance of the coatings, the presence of porous areas or segmentation cracks, for example, can not only be tolerated, but supports the function and lifetime of the coatings. In this contribution, a novel laser cladding process (Clad2Z) for the deposition of columnar structures is presented, which can be used for localized fabrication and repair of thermal barrier coatings. The stability and durability of the so-prepared TBCs were investigated under realistic gradient conditions in burner rig tests. The durability and failure mode qualify the coatings as at least equivalent to conventional atmospheric plasma sprayed (APS) TBC systems.

INTRODUCTION

Modern cladding technology combines a concentrated energy source with computer-controlled robotics and powder metallurgy manufacturing. It is widely used to deposit overlays. Bulk metal components can be produced using slicing technology, where the component is built up in several individual layers. The coating material is transferred to the substrate either by powder injection, pre-positioned powder or wire feeding, with powder injection described as the most effective method. In the course of additive manufacturing processes, laser light or electron beams have become established as energy sources in direct metal laser melting (DMLM) and electron beam melting (EBM). A characteristic feature of the process throughout is that the substrate is partially molten and the added material is fused into this melt pool. A standard variant of laser cladding with powder as feedstock uses a coaxial powder feed. This has the advantage that coating takes place independently of the direction of movement. This process has been used in the combination of metal powder on a metal substrate for several decades for the repair of turbine blades, especially at their tip (Toyserkani et al., 2003).

When processing dense ceramics with concentrated laser sources, on the other hand, cracks are almost inevitably formed as a result of high residual stresses and low toughness. These stresses are generated during the processing of ceramics with comparatively poor heat conduction due to the resulting large local and temporal temperature gradients during solidification and cooling (Weng et al., 2014; Ouyang et al., 2001). Accordingly, the scope of applications in ceramic laser cladding is significantly lower compared to metallic laser cladding. This is even more true for ceramic-to-metal cladding, since the mismatch of thermal expansion coefficients between the coating and the substrate further complicates processing.

Thermal barrier coatings (TBC) are used in the high-pressure section of gas turbines for structural parts made of superalloys such as turbine blades and vanes which are exposed to extreme temperature loads. They usually consist of a ceramic top layer on a metallic sublayer. The main purpose of the usually porous top layer is to insulate against high temperatures. When the substrate is cooled from the rear side, the low thermal conductivity of the ceramic layer creates a temperature gradient from the surface of the protective layer to the protected material. The metallic sublayer, so called bond coat, protects the substrate from oxidation and it improves the adhesion of the top coat. The performance of a TBC system is significantly influenced by the microstructure of the ceramic top layer. On the one hand, porosity and horizontal cracks can further reduce heat conduction, and on the other hand, vertical cracks or columnar structures reduce the stresses that occur due to different coefficients of thermal expansion during thermal cycling, which can lead to catastrophic crack growth (Bakan and Vaßen, 2017; Zhou et al. 2019).

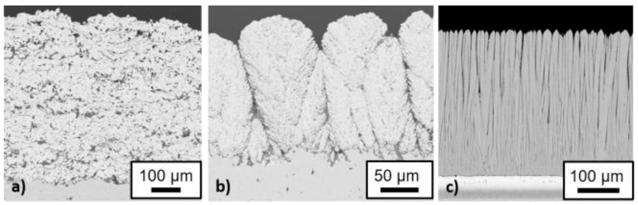

Figure 1: Typical microstructures of thermal barrier coatings manufactured by widely used processes: (a) atmospheric plasma spraying (APS, from Mack et al. 2019), (b) suspension plasma spraying (SPS, from Zhou et al. 2019), (c) electron-beam physical vapour deposition (EB-PVD, proprietary).

Common processes used for manufacturing TBCs are atmospheric plasma spraying (APS), suspension plasma spraying (SPS), and electron beam physical vapor deposition (EB-PVD). Figure 1 shows typical microstructures of TBCs produced by these processes. While the microstructure of the APS coatings is characterized by high porosity and micro-crack density, the EB-PVD coatings are characterized by their columnar structure and relatively low intracolumnar porosity. In the case of SPS coatings, fine-structured, partially very high porosity can be combined with segmentation cracks or coarse columnar structures.The established coating processes have in common that they are covering larger-scale area at once. A coating of closely limited areas or the application of adapted coating parameters in separate areas of the component can only be realized by extensive masking and repeated coating runs, respectively. Accordingly, the flexibility now achieved in manufacturing components by additive processes is hardly transferable, and it is generally not possible to repair the coatings without complete removal of the old coating.

NOMENCLATURE

APS	Atmospheric Plasma Spraying
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
Clad2Z	Laser Cladding Process to Lateral
DMLM	Direct Metal Laser Melting
EBM	Electron Beam Melting
EB-PVD	Electron Beam Physical Vapour Deposition
SPS	Suspension Plasma Spraying
MCrAlY	Ni/Co Based Alloy with Additions of Chromium, Aluminium, and Yttria
TBC	Thermal Barrier Coating
TGO	Thermally Grown Oxide
YSZ	Yttria Stabilized Zirconia

LASER CLADDED COLUMNAR TBCS

In a recent paper (Vorkötter et al., 2022), we presented a novel laser cladding process for the manufacture of columnar TBCs. In this process, "Clad2Z", a coaxial laser cladding nozzle is moved in the vertical direction (z-direction) with respect to the substrate plane during deposition instead of the conventional movement in the horizontal direction (x-y-direction).

Initially, a narrowly confined melt pool is created just in the surface plane of the component, out of which in the further course of the process, the column is built up (Fig. 2a). Laser power and nozzle positioning are coordinated in such a way that the melt pool and powder supply stay always at the tip of the column. The dimension of the melt pool is also closely linked to the heat conduction and geometry of the ceramic column that is being built up.

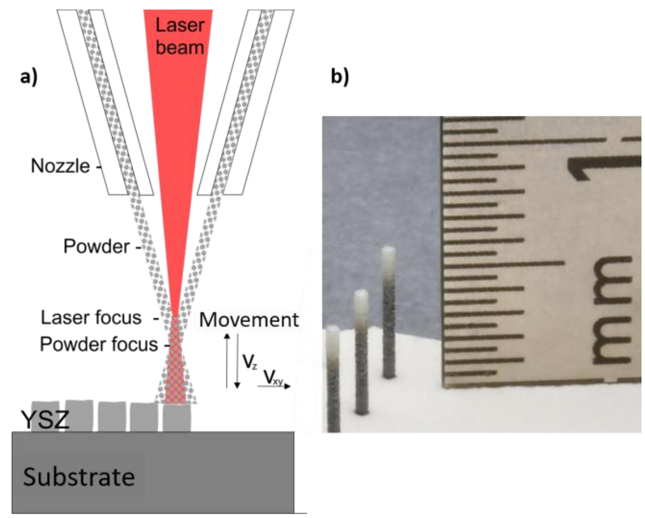

Figure 2: Novel laser cladding process “Clad2Z”: (a) schematic drawing of the vertical cladding process, (b) example of solitary columns of 6 mm height.

Figure 2b shows an example of 6 mm high columns with a diameter of approx. 450 µm. Those were generated with an energy input of each 24 J and a travel distance in the z-direction of 6 mm. The columns with diameters in the sub-millimetre range produced by Clad2Z do not show any crack formation, since the dimensions in the horizontal direction are not sufficient for the formation of critical stresses and the cooling in the lateral direction is mostly homogeneous. Figure 3a shows columns deposited with a distance of travel in the z-direction of 0.3 mm and an energy input of about 1 J each. The columns have a uniform diameter and exhibit an almost completely dense microstructure. Only at the tip of each column is a coarse pore found, which is probably due to the inclusion of porosity from the porous feedstock during the rapid cooling of the tip after the laser was switched off under an argon flux.

Considering similar column diameters of 100–400 µm in the case of suspension plasma sprayed TBCs or largely dense columns in the case of EB-PVD TBCs, the fabrication of TBCs using the Clad2Z process is obviously worth considering. When the columns are arranged in a narrow pattern, a thermal barrier layer with high strain tolerance and high thermal insulation efficiency can be produced. At first sight, the thermal conductivity of the clad columns is likely to be of a similar order of magnitude to that known for EB-PVD coatings, although the influence of the large pores at the column tips and the geometry of the column gaps needs to be further investigated in more detail.

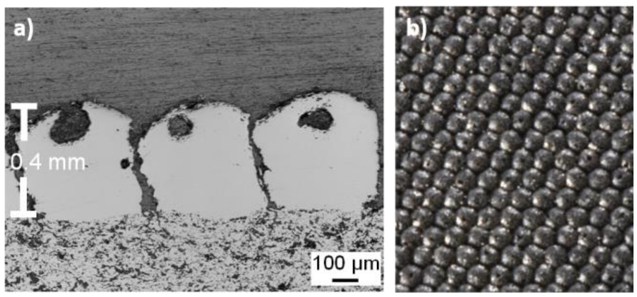

Figure 3: Microstructure of laser cladded TBC manufactured by Clad2Z process: (a) cross section of columns (adapted from Vorkötter et al., 2022) (b) surface view of densely packed columns.

As shown in Fig. 3, for a basic design of such a TBC, a dense package of laser-clad YSZ columns of about 400 µm height was deposited on an intermediate layer of about 150 µm thickness produced by the APS process. This was based on a proven design of a SPS-based TBC (Zhou et al., 2019). Figure 3b shows the uniform surface of the densely packed columns. As all columns are processed one after another, this shows the high repeatability of the process.

Cyclic burner rig tests were used to test the durability of the new TBCs under relevant thermo-mechanical loads (Traeger et al., 2003). For these tests, button type specimens made of Inconel 738 (IN738) and having a conventional vacuum plasma sprayed MCrAlY bond coat layer were used and coated with double layer TBC including ceramic Clad2Z top layer as described above. Figure 4 shows the results of the burner rig tests together with results for conventional TBC systems produced with APS, SPS or EB-PVD processes from previous studies (see figure caption) The lifetimes (calculated from the number of cycles multiplied by the dwell time at maximum temperature) are shown as a function of the reciprocal temperature at the interface between the bond coat and the ceramic interface (calculated from surface and substrate temperatures logged throughout the test), which essentially determines the growth rate of the oxide layer (TGO) at the interface and obviously causes an Arrhenius correlation (Nordhorn et al., 2016, Vaßen et al., 2021). All of the TBC systems mentioned, with the exception of the commercial EB-PVD coatings, were tested on the same burner rig system with a dwell time of 5 minutes at surface temperatures of about 1400 °C ensuring that results can be well compared. In the case of the EB-PVD coatings, the surface temperatures were limited to about 1300 °C due to the reduced coating thicknesses as the only difference.

It can be clearly seen that the performance of the bilayer TBCs with Clad2Z top coat layer significantly outperforms the single-layer porous YSZ-APS TBCs as well as the bilayer systems with a columnar top layer applied by SPS (improvement indicated by red arrows in Fig. 4). The advantage over the double-layer systems with an SPS-applied columnar top layer is promising, since these were used as a model for the basic design of the Clad2Z system. The comparison with commercial EB-PVD coatings is also positive, as the Clad2Z coatings allow operation at higher surface temperatures with similar lifetime due to the higher coating thicknesses.

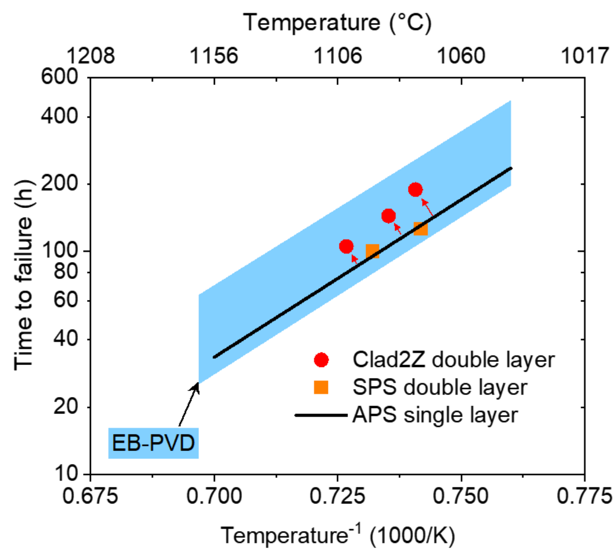

Figure 4: Results of burner rig tests for Clad2Z top coat TBCs (circular symbols) as a function of reciprocal bond coat temperature. Data for double layer top coat TBC samples with columnar SPS top coat layer (square symbols), single layer porous APS coatings (black line), and typical range of results for commercial EB-PVD TBCs (blue shading) (Figure was adapted from Vorkötter et al., 2022; data considered included also Nordhorn et al., 2016, Zhou et al., 2019, and Kumar et al., 2021).

SEM images showing the microstructure of the Clad2Z TBCs after failure are given in Fig. 5. The failure mode observed after thermal cycling is comparable to that of conventional APS TBCs or double-layer SPS TBCs with a similar thickness of about 500 µm. In the case of a moderate thermal gradient during cycling, crack propagation is observed predominantly in the immediate vicinity of the TGO interface. In case of higher temperature gradients, a shift of the crack position into the ceramic surface layer takes place. However, the bond of the columns to the APS YSZ coating remains intact and no crack growth is observed in the interface or within the columns. This result can be taken as an evidence that the toughness of the APS interlayer is not critically affected by the laser processing and the increased lifetime of the Clad2Z TBCs could be attributed to an effective reduction of the energy release rate under cyclic loading.

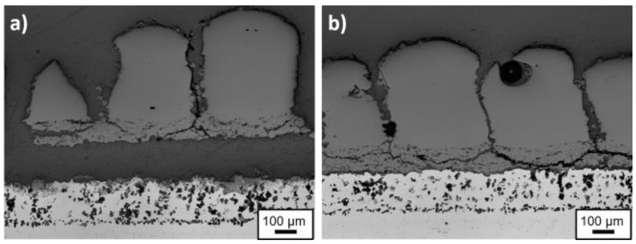

Figure 5: Failure modes of laser cladded columnar TBCs cycled in burner rig testing at (a) moderate and (b) high thermal gradient conditions (adapted from Vorkötter et al., 2022).

OPPORTUNITIES IN COATING DESIGN AND REPAIR

As mentioned at the introduction, the established manufacturing processes for TBCs only offer complex routes for the deposition of coatings, optionally with specifically adapted properties, in narrowly defined areas. Such capabilities would be of essential advantage in order to coat different areas of a component, such as the leading edge of a blade, the transition area between components or even the vicinity of cooling holes with TBC layers with optimized microstructural parameters or to omit them during the coating process. The new Clad2Z process offers precisely these degrees of freedom in a simple manner, since the position, height and diameter of each individual column, i.e. the microstructure of the coating layer, can be chosen in the course of its build-up on the length scale of the column dimensions. Figure 6 shows simple examples of local adaptation of the layer thickness or cutouts. In Fig. 6a), 8 adjacent areas of dimension 5x5 mm² were gradually coated with columns of height 200 µm to 500 µm. To improve contrast, these areas are arranged in opposite directions. Figure 6b) shows cutouts in the shape of the letters I-E-K, which are surrounded by a two-step graded rim.

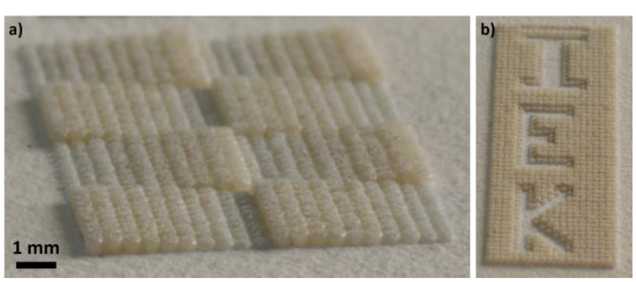

Figure 6: Examples of Clad2Z height variations: (a) 8 areas of dimension 5x5 mm² with graded height of 200– 500 µm, (b) cut-outs of shape I-E-K with total area size of 10x30 mm².

Figure 7 schematically shows further examples of how the Clad2Z process can be used to build more complex microstructure variants. As well as the variations shown in the height of the layer structure (Fig. 7a), it is possible to create multi-layer or, more general, multi-material TBCs by using different feedstocks without losing flexibility in terms of positioning and dimensions (Fig. 7b). By building up overhang structures, it is practically possible to create open 3D structures by offsetting the column segments when successively building up several layers (Fig 7c). By varying the column diameters during the build-up, intercolumnar gaps may be reduced or stabilizing effects may be generated (Fig. 7d).

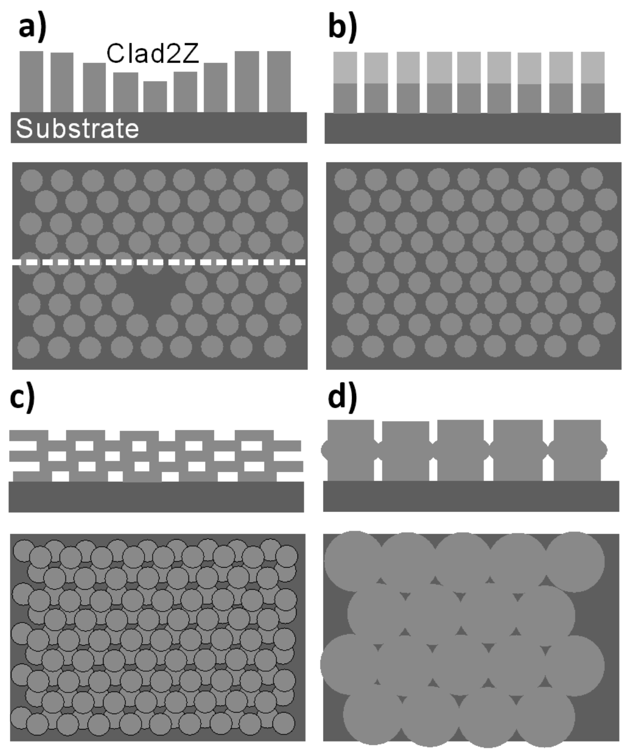

Figure 7: Examples of microstructural variants which can be realized with Clad2Z processing: (a) height variation and blanking, (b) stacking of various materials, (c) overhang structures, and (d) diameter variation.

Once the new Clad2Z coating technology is consistently integrated into computer-aided manufacturing (CAM) processes, the production and repair of coatings can be largely automated using laser-assisted processes. For example, for the build-up of the coating in production of new parts, it is envisaged that a prepared component, which has previously been coated with a bond coat layer and an optional ceramic intermediate layer, will be mounted in a CAM system, followed by an input inspection of the position and dimensions by means of a 3D scanner. The CAD model of the coating will be matched with the topography data, and the build-up of the coating by Clad2Z processing will take place with high precision without further intervention by an operator (Fig. 8). In the case of a locally damaged coating, an initial 3D scan would be followed by a topographic analysis and assessment of the damaged areas, a CAD model of the areas to be removed would be created, and these areas would be highly selectively removed by laser ablation in an appropriately enhanced CAM system. After that the replacement of the coating would be done in the way described before using Clad2Z. This marks a distinct difference to current repair technologies which require a complete stripping of previous coatings (Yang et al., 2020).

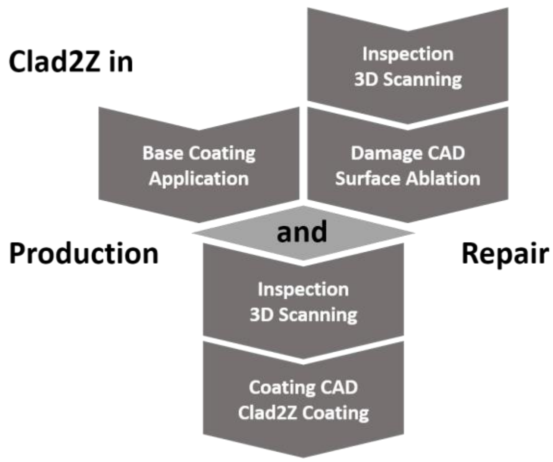

Figure 8: Flow chart of Clad2Z coating deposition integration into in computer-aided production and repair.

The novel laser processing technologies generally have significantly reduced requirements in terms of infrastructure and media supply when compared to the established TBC manufacturing processes. It is therefore realistic to assume that such production units will also be available decentral or even on-site for the manufacture of spare parts or repairs in the nearer future.

SUMMARY

A novel laser cladding process (Clad2Z) for the deposition of columnar structures is presented, which can be used for localized deposition and repair of TBCs. The stability and durability of the so-prepared TBCs is investigated under realistic gradient conditions in burner rig tests. The durability and failure mode qualify the coatings as at least equivalent to conventional TBC systems. Coating deposition by the Clad2Z process offers large degrees of freedom for a local adaption of TBC microstructure design, since the position, height and diameter of each individual column can be decided in the course of its build-up on the scale of this columns. By full integration of the Clad2Z technology into CAM processes, the production and repair of coatings with laser-based processes can be automated to a large extent.

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