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Advanced high pressure turbine blade repair technologies

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Abstract

Components in aircraft engines and gas turbines are exposed to extreme conditions in order to increase performance and efficiency of the overall engine, hence there is an increasing need for cost-effective and time-efficient repair strategies. Presented here are two novel approaches to the repair of Nickel-based components. The hybrid brazing process involves the application of a repair coating, a nickel-based filler material, a NiCoCrAlY and an aluminium layer, by thermal spraying followed by a heat treatment and combined brazing-aluminizing process. This significantly shortens the conventional repair brazing process and yields superior results. Single-crystal additive repair by laser cladding is applied for the repair of small or large defects in single-crystal turbine blades by enabling monocrystalline solidification of the cladded material by use of a temperature gradient, thereby allowing for the regeneration of these expensive components. The novel approach that combines layer-wise addition of material and laser melting enables the formation of highly monocrystalline structures.

Keywords: laser cladding; brazing; hybrid joining and coating; nickel-based superalloys

1. Introduction

Components in aircraft engines and stationary gas turbines, like turbine- and compressor blades are exposed to extreme conditions. Due to high temperatures and pressures as well as the impact of foreign objects, defects such as plastic deformations, wear by hot gas and CMAS (Ca-Mg-Al-Si) corrosion, impact damages and cracks can occur, resulting in high costs. To raise the lifetime of such parts, maintenance, repair and overhaul (MRO) play an increasingly important role. Especially manufacturers of aircraft engines obtain about 30% – 50% of their profit by MRO and they can save up to 75% of the new parts cost when MRO is carried out [1]. The lifespan of high value components, such as high pressure and creep-resistant turbine blades, is limited by blade tip erosion or cracking defects. In most cases, damaged parts are discarded and replaced with new parts, resulting in low buy-to-fly ratios, the loss of resources and high costs. Considering the complex investment casting procedures involved in the manufacturing of these parts, there arises a need for a more cost-efficient repair strategy.

Nickel-based superalloys were designed to meet a combination of challenging requirements – oxidation resistance, high temperature creep strength, fatigue resistance, coating performance and the retention of performance in complex configurations. The materials used in this study are CMSX-4, a second generated Re-bearing alloy developed by Cannon-Muskegon Corporation, and PWA 1426, developed by Pratt & Whitney [2, 3]. The use of high temperature resistant materials enables higher engine inlet temperatures, thereby increasing the overall efficiency of the turbine engine, resulting in superior performance and durability [4].

Nickel-base superalloys are most extensively used in the combustor and turbine sections of engines, where temperatures up to 1300°C can occur. Hence, these components contain either equiaxed grains, columnar grains or

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are cast as single crystals (figure 1). At high temperatures, grain boundaries are sites for damage accumulation, therefore blades in the early stages of the turbine are directionally solidified or single-crystal, while those in the cooler stages are fabricated from equiaxed alloys, thereby eliminating all high-angle grain boundaries [5]. The manufacturing of these high performance components is however expensive and extensive, involving casting techniques wherein the direction of crystal solidification is controlled, which allows for the introduction of elaborate cooling channels and the control of grain structure. During solidification, some elements partition to the dendrite core, while other elements tend to accumulate in the interdendritic liquid and then solidify as the interdendritic and eutectic regions [6] resulting in a two-phase alloy. By adding refractory elements and eliminating high-angle grain boundaries and applying appropriate heat treatment and precipitation hardening steps, the resulting material has improved creep-rupture, fatigue, oxidation and coating properties.

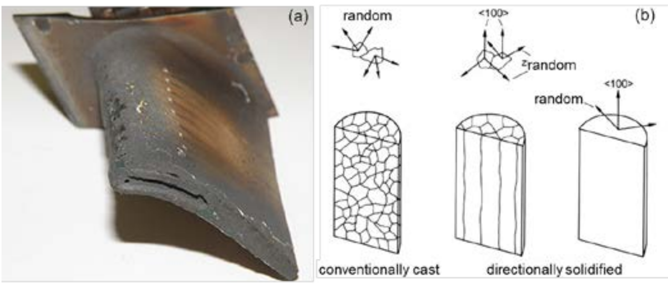

Fig. 1. Turbine blade with signs of erosion (a) and crystal structure (b) [modified from [9]

The challenge during the repair of single-crystal components is maintaining the epitaxial microstructure of the substrate as well as of the deposited material during repair [7]. The processes of brazing and/or cladding have been established for the repair of engine parts. However, due to strict regulations, the repair is only applicable in certain parts of the blades. For conventional turbine blade repair, the following steps are carried out [8]:

- Strip coating
- Cleaning of the turbine blade
- Inspection
- Material deposition
- Machining
- Coating (MCrAlY, Al)

During strip coating the worn turbine blade is stripped to the base material and is intensively cleaned by fluoride ion cleaning. After inspection of the defects present, material is deposited to repair the worn turbine blade: for repairing micro-cracks and surface defects, the brazing process is carried out, while the cladding process is used to repair deep cracks and excavations. After the material deposition, an additional coating to protect the turbine blade against hot gas corrosion is deposited, which is usually a thermally sprayed MCrAlY-layer (M = nickel and/or cobalt). To improve the protection against hot gas corrosion, the coated turbine blade is then over-aluminized. Common techniques for aluminizing are CVD-processes (chemical vapor deposition) using a pack cementation or a hydrogen atmosphere with an aluminum halide as an activator.

2. Development of a hybrid joining and coating process for repair brazing turbine blades

In this study, a two stage hybrid technology that was developed is presented, which allows for the shortening of the repair brazing process for turbine blades (Figure 2) and is the state of the art. In the current process chain the filler metal is applied manually in the form of pastes, using a spatula, a syringe or a brush. Melt spun foils and filler metal molded parts can be used for this purpose. After the brazing process, which is carried out in a high vacuum furnace, the excess filler metal is removed by grinding or machining. Subsequently, the hot gas corrosion protective coating is applied by thermal spraying and aluminized to protect the turbine blade against hot gas corrosion due to the formation of the ß-phase (NiAl).

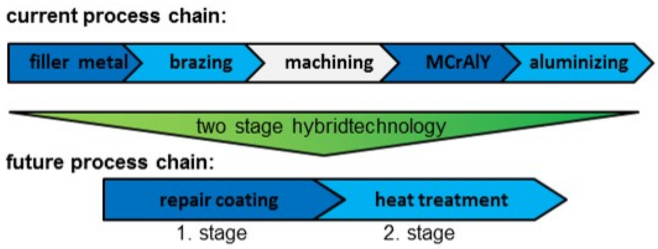

Fig. 2. Current process chain vs. future process chain

The shortening of this process chain is achieved by the simultaneous application of the nickel based filler-metal together with the hot gas corrosion protective coating (MCrAlY) and finally with an aluminum layer by thermal spraying. The material deposition represents the first stage of the hybrid technology. The second stage of the hybrid technology is the combination of brazing and aluminizing.

For the development of this coating and joining hybrid technology, basic investigations were carried out and are presented in this paper. The experimental work is described in detail in [10, 11]. For the coating, an atmospheric plasma spraying system with a F4 torch (Oerlikon Metco, Switzerland) was used. The plasma was generated by argon (55 L/min) and hydrogen (9.5 L/min). The current between the electrodes was 600 ampere. The brazing/aluminizing process was carried out in a vacuum furnace in a temperature range between 1150 °C and 1190 °C. Figure 3 shows a scanning electron microscope image of a selected example for this hybrid technology. A René 80 flat specimen was wire eroded in order to form a crack and the coating system filler metal B-Ni5 (NiCrSi), the hot gas corrosion protective layer and aluminum was applied. Subsequently, the coated specimen was subjected to a heat treatment to carry out the simultaneous brazing and aluminizing process. The cross section illustrates the crack infiltration capacity of the thermally sprayed filler metal. Figure 3a shows that the crack is completely filled up to a depth of 500 µm, while the rest of the crack is wetted, which is caused due to the limited amount of the filler metal. The element distribution (figure 3b) shows a chromium-rich phase in the middle of the crack and the formation of a diffusion zone between the René 80 and the filler metal can be observed (figure 3c). The amount of cobalt, titanium and tungsten, which can only be found in René 80, decrease towards the filler metal. At the same time, the amount of silicon, which is the melting depression element of the filler metal, increases towards the René 80 area (figure 3d). The thermally sprayed filler metal shows a sufficient crack infiltration capacity as well as bonding of the substance. These results show that the repair of turbine blades with a hybrid coating and brazing/aluminizing process is feasible.

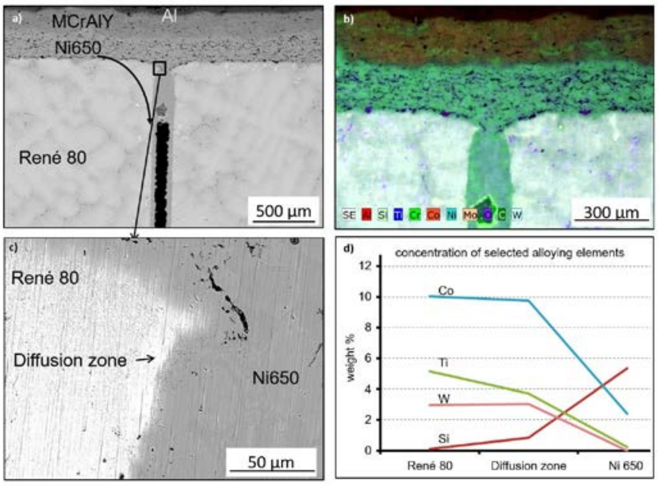

Fig. 3. SEM micrograph of a René 80 specimen with a crack [12]

The application of the complete repair coating by thermal spraying has several advantages. On the one hand conventional aluminizing, which is an expensive process step that is typically carried out in a pack cementation or in a furnace in a hydrogen atmosphere, can be omitted. On the other hand, the additional advantage of this coating system is that the combination of brazing and aluminizing can be carried out in a continuous shielding gas furnace with a protective gas atmosphere. The previous discontinuous brazing/aluminizing process can be replaced by a more advantageous continuous process and the process time could be reduced by approximately 30% compared to the state of the art technology under vacuum conditions. Basic investigations for the continuous process are planned (e.g. properties and quality of the coating).

3. Development of a repair strategy for defects in high pressure turbine blades

In order to carry out the repair of damaged single-crystal material by laser metal deposition, there is a differentiation between two types of repair: laser remelting without additional powder material for superficial defects and laser cladding for the repair of larger defects. In this study, for both repairs, a diode laser with four diode arrays producing a continuous laser beam in the TEM-00 mode was used. The focussed beam had a wavelength of 980 nm and a maximum power of 340 W while using two of the four available stacks.

Fig. 4. cross-section of track remelted without additional powder material

Tests were carried out on CMSX-4 flat substrates using powder of the same chemical composition. The particle diameter of the CMSX-4 powder was between 25 µm and 75 µm. The primary orientation of the crystals was always in the [001] direction and the tests were carried out on the (001) plane. In this study only straight clad tracks, created by the deposition of a single pass of the laser head, were created. The laser and powder focal points were on the surface of the sample for all tracks and the cladding and laser axis were maintained perpendicular to the processed surface.

3.1. Remelting

In order to develop a process for repairing superficial defects, studies were carried out on the (001) plane of flat substrates of CMSX-4. Since no powder material is added during the process, the main factors to be varied were laser power and traverse speed. The laser power was varied between 100 W and 500 W, while the traverse speed was varied from 75 $mm \cdot min^{-1}$ to 300 $mm \cdot min^{-1}$. The resulting remelted tracks were prepared for micrographic analysis by means of embedding, polishing and etching. The dendrite orientation in the remelted region was then microscopically observed in relation to the orientation in the substrate material.

Microscopic analysis of the dendrite orientation showed that low traverse speeds and high laser power resulted in the lowest percentage of epitaxy in the remelted area. Figure 4 shows a micrograph of the longitudinal cross-section of a sample remelted with 300 W and 200 $mm \cdot min^{-1}$, wherein a high percentage of epitaxy is visible with a penetration depth of about 500 µm at the deepest point. It was concluded from the study that moderate energy input per unit area (E_A) resulted in the highest restoration of dendrite orientation. E_A below 50 $J \cdot mm^2$ and above 260 $J \cdot mm^2$ presented either insufficient or excessive energy with a low or too high temperature gradient for the material to recrystallize in the desired manner. Figure 4 also shows that following remelting, the dendrite orientation reflects that of the substrate material and that recrystallization of superficial defects restores the crystal structure.

3.2. Single track and multilayer cladding

To repair defects of larger dimensions, powder material must be deposited into the cracks and melted to form a solidified filling material. In order to develop a process for repairing defects running more than 0.5 mm into the substrate material, studies were carried out on the (001) plane of flat substrates of CMSX-4. Based on strategies developed in previous studies [7], the laser power was varied between

100 W and 200 W, the traverse speed from 30 $mm \cdot min^{-1}$ to 100 $mm \cdot min^{-1}$ and the powder feed rate between 1.0 $g \cdot s^{-1}$ and 3.0 $g \cdot s^{-1}$. The deposition of single tracks yielded deposits as shown in Figure 5a.

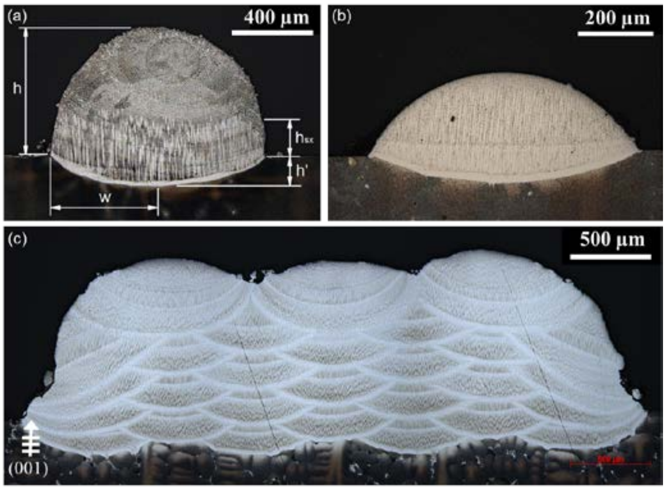

Fig. 5. single track clad with measured parameters as defined in [5] (a) before and (b) after remelting, (c) multilayer clad

However, while depositing multilayered structures, the polycrystalline areas at the top of the tracks will cause further material deposited to solidify in a polycrystalline manner, resulting in the loss of homogeneity of the deposit. Hence, the laser power ramp methodology [5, 7] and the results obtained in the previous section were applied to the tracks. This involved the remelting of the tracks with a lower laser power and higher traverse speed than that required for deposition i.e. lower E_A. The resulting tracks showed extended epitaxial structure throughout the deposited material and the elimination of the columnar to equiaxed transition as depicted in Figure 5a-b.

By creating epitaxial orientation throughout a single track, it is possible to extend this strategy to create multi-layered structures [5, 7]. Figure 5c shows the strategy of single track cladding applied several times to create multilayered epitaxial structures. Deposits with a height of approximately 1100 µm and a width of 3500 µm were created. Microscopically, the orientation in the deposited material reflects that of the substrate, including the transition zones between the deposited and remelted layers.

4. Conclusion

The results from section 2 and 3 show that the repair of high performance parts in turbine blades is possible using the novel methods presented here. In order to repair superficial defects and deposit the corrosion resistant coating, it is possible to shorten the conventional brazing and coating process using a hybrid technology that combines the brazing and aluminizing processes. The repair of superficial defects as well as deeper cracks can also be carried out by laser cladding in a more economical manner using laser metal deposition, while maintaining orientation of the substrate and recreating the required microstructure in the deposited material. Both processes display promising results that could reduce MRO costs and duration when applied commercially. Hence, further topics of interest are the implementation of said processes in an industrial setting and their feasibility in the commercial context.

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