Restoration of Nickel-Base Turbine Blade Knife-Edges with Controlled Laser Aided Additive Manufacturing

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Abstract

In this paper, restoration of nickel-base turbine blade knife-edges with controlled Laser Aided Additive Manufacturing (LAAM) process was investigated. The alloy contains about 9 weight percent Ti/Al composition, which makes it difficult to repair due to the cracking issue. Infrared temperature signal emitted from melt pool was adopted for process control. The deposition with and without process control was compared. The deposition with process control can avoid the hot-cracking which often occurs during deposition of nickel-base super-alloys. The results showed that the process control can also guarantee a better dimensional accuracy. The microstructure of the deposited layers in the cross-section was examined under both microscope and SEM. It displayed directionally solidified fine columnar dendrites which grew following the change of the heat conduction condition. The EDX line scanning verified that chemical composition remained homogeneous distribution in the deposited thin wall. Spot EDX analysis identified that TiC is most likely the main type of carbides formed at the grain boundaries. The results demonstrated that the LAAM process is feasible for the recondition of the gas turbine blade knife-edges.

Keywords: Laser Aided Additive Manufacturing; Process control; Nickel-base alloy; Turbine blade

1. Introduction

The efficiency and performance of a gas turbine engine depend strongly on the highest temperature in the engine at the inlet to the high pressure turbine. The parts need periodical replacement to avoid loss of engine power, efficiency and eventual breakdown. Among turbine components, the blades suffer from several damages during operation, which limit the overall life of the component: creep, life cycle fatigue and hot corrosion, etc. [1]. Therefore, in terms of maintenance requirements, manufacturing difficulties and costs, the blades are the most critical items of the nowadays gas turbines [1]. One of the main damages of the turbine blades occurs at the tip, which mainly results from the high-temperature wear or rubbing against the stator liner, due to the thermal expansion of the blades under high rotating speed and temperature [2]. In most cases, repair is a more feasible solution than replacement, as replacement will be very costly. At the early stage, some traditional repair technologies, such as Plasma spraying [3], Plasma transferred arc (PTA) welding [4], Tungsten inert gas (TIG)
welding [5] have been investigated, in order to reduce the heavy cost for replacement. However, these technologies have fatal limitations, such as huge heat input to the base material and hot-cracking in the welded layers. In recent years, laser-based metal deposition technologies have been studied for repair of gas turbine components [6-15], and demonstrated the ability to fulfil the repair requirements. During the deposition process, the laser beam melts a thin layer of the work piece and the filler material (powder or wire) fed to the melt pool simultaneously. Thus, the melted filler material and the base material are metallurgically bonded with up to full density. Due to the good focusability of the laser beam and the short processing time, very little heat input is applied to the base material and the heat is limited to the local area. A three-dimensional build-up can be achieved by deposition layer by layer. This technology has been accepted by leading engine manufacturers such as General Electric, Pratt & Whitney, Allied Signal, Rolls-Royce, Allison, Pratt & Whitney Canada, Solar and MTU. [16-18].

As turbine blades are exposed to extremely high temperature, nickel-base super alloys are widely used, owning to their excellent resistance to hot corrosion and good mechanical properties at elevated temperatures. However, Ni-base super-alloys with high Ti/Al composition display high cracking susceptibility in fusion-repair, because these alloys are hardened by the precipitation of γ’ phase [11]. When the total Al+Ti level for a particular alloy exceeds a critical value (often taken as 4wt%), it is deemed to be difficult to fusion repair and increasingly non-repairable with increasing Al+Ti composition [19]. Typically, the solidification cracking, grain boundary liquation cracking and strain age cracking are the main types of cracking for welding of high strength Ni-base super-alloys.

In this study, turbine blade made of Ni-base super-alloy with about 9.5wt% Al+Ti composition was selected. Aim of this study was to investigate the feasibility of recondition of the worn turbine blade knife-edges with controlled Laser Aided Additive Manufacturing (LAAM) process. Infrared (IR) temperature signal emitted from melt pool was adopted for process control. A path-dependent process control strategy was applied to avoid the hot-cracking and to improve the dimensional accuracy of the deposition. The metallurgical properties of the deposited layers were examined and discussed.

2. Experimental procedure

2.1. Material

The turbine blades to be repaired were made of nickel-base super alloy which is characterized by a low density and high temperature potential. In order to keep the same mechanical properties of the turbine blades at elevated temperatures, metallic powders with the same composition as the base material were applied for repair of the blade knife-edges. The composition of this super alloy is shown in Table 1. The powders are gas-atomized in spherical shape. The powder size distribution is in the range of 45–105 μm.

Table 1. Chemical composition of the Ni-base alloy blade and powders used

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt%</th>
<th>Ni</th>
<th>Co</th>
<th>Cr</th>
<th>Al</th>
<th>Ti</th>
<th>Mo</th>
<th>V</th>
<th>Fe</th>
<th>Zr</th>
<th>C</th>
<th>Si</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt%</td>
<td></td>
<td>Balance</td>
<td>18.37</td>
<td>12.54</td>
<td>5.11</td>
<td>4.36</td>
<td>3.32</td>
<td>0.748</td>
<td>0.09</td>
<td>0.07</td>
<td>0.066</td>
<td>0.022</td>
<td>0.017</td>
</tr>
</tbody>
</table>

2.2. Experimental setup

![Figure 1. Schematic of the closed-loop process control system](image-url)
A processing head with a set of coaxial powder feeding nozzles was adopted for the deposition process. In the processing head a Germanium (Ge) photodiode was integrated. Its functional wavelength is between 1300 and 1600 nm. The processing head was mounted on a 4-axis CNC-machine. A cw Nd:YAG laser HL 3006D with a maximum output power of 3 kW was used. The laser beam was focused by an optic with a 200 mm focal length. A PID-controller was built between the Ge-photodiode and the laser in the control system. Figure 1 shows the schematic of the closed loop process control system. With the Ge-photodiode the IR-temperature radiant flux was detected and converted to an IR-temperature signal. The actual value of the IR-temperature signal was compared with a set-value. The PID-controller created a control variable out of the deviation to regulate the laser power, so that the melt pool temperature was controlled.

2.3. Requirements on the deposition

Figure 2a shows the knife-edges of the turbine blade which need restoration. The edges are 30.1 mm long and 1 mm wide. In order to guarantee enough tolerance for the post machining, the deposited thin wall must be built up with oversize and no inward-shrinkage at both edges. Thus, on each knife-edge a thin wall with a dimension of 3 mm height and 1.3 mm width needs to be deposited. After the deposition, the knife-edges will be machined to the desired geometry and dimension. Totally, ten layers with a layer thickness of 0.3 mm were deposited on each knife-edge. A beam diameter of 1.3 mm was used. During the deposition, the worktable firstly moved to one direction to build one layer, and then the processing head moved up in the Z direction for an increment, and then the worktable moved back to the original position to deposit the next layer. During the process the laser beam was always on. Figure 2b shows tool path for the repair.

![Figure 2. (a) Image showing the knife-edges; (b) Schematic of the repair strategy](image)

2.4. Characterization of the samples

After repair the samples were then cross-sectioned, polished and etched. Porosity and micro-cracks were investigated under the optical microscope. The samples were etched with Kalling’s solution (40 ml HCl, 40 ml Ethanol and 2g Cupric Chloride) for the purpose of micro-structural study with optical microscopy. Metallographic observation was performed in the base material, the fusion area and the deposited area. Electrolyte etching was applied to prepare the samples for EDX (Scanning electron microscopy Philips/FEI XL30; JEOL 6400) analyses. The etching was carried out with platinum electrodes in the 10% orthophosphoric acid. The elements in the deposited layers were analyzed with Energy Dispersive X-ray (EDX). Additionally, the hardness test was carried out from the base material, via the heat affected zone, till top of the deposited thin wall with an interval of 0.25 mm. The measurement was carried out using a LECO M-400 Vickers hardness tester under a load of 0.3kg for 15s.
3. Results and discussion

3.1. Process optimization

The experiments were firstly carried out with a constant laser power of 300 W. The powder feeding rate and scanning speed are 1.5 g/min and 500 mm/min, respectively. The IR-temperature signal and laser power signal were recorded at the same time, as shown in Figure 3a. The IR-temperature signal shows that the melt pool temperature increased notably at the corners of the thin wall. This resulted in the excessive build-up and inward shrinkage of the corner (Figure 3b). Because the worktable of the CNC machine decelerated and then accelerated at both ends of the wall and the laser was kept on, more energy as well as more powder was supplied at these two positions. Both the temperature and the size of the melt pool increased. This effect got stronger with increasing building time due to the worse heat exchange conditions. This caused the inclination and excessive build-up at the coners [20]. Additionally, the melt pool temperature increased layer by layer during the whole deposition process. The increase heat input will result in the shrinkage of the metals during cooling and increased thermal strain. Therefore, the cracking sensitivity will increase [3]. As shown in Figure 3c Cracks were formed in the deposited thin wall and propagated till into the heat affected zone. This is typical solidification and grain boundary liquation cracking phenomena. Under rapid heating and cooling, residual stress is formed the grain boundary phases are unable to dissolve fully into the surrounding matrix and partial dissolution leads to the formation of a low melting point eutectic and melting of the grain boundary region [11].

Figure 3. Repair without process control (a) measured IR-temperature and laser power signals; (b) Inclination and excessive build-up at the edges; (c) Micro-cracks observed in the deposited layers
Furthermore, deposition with process control for repairing the turbine blade knife-edges was tried. Path-dependent set-value was adopted for the controlled LAAM process, as shown in Figure 4. A ramped set-value was programmed according to the length of the deposited thin wall. The set-value was optimized based on the recorded IR-temperature signal and according to the dimensional accuracy and the cracking condition of the deposited thin walls. The optimized set-value was 0.55V(2mm)-0.65V(26.1mm)-0.55V(2mm). Figure 5a shows the recorded IR-temperature and laser power signals. The front view of the restored blade knife-edge and its cross-section are shown in Figure 5b and 5c, respectively. The recorded signals showed that the temperature in the melt pool was controlled as defined by regulating the laser power. After the melt pool temperature reached the set-value, the laser power was reduced continuously, so that the melt pool temperature was controlled. The signals also reveal that the laser power was reduced further at the corners. The magnified image in Figure 5b exhibits improved dimensional accuracy in comparison to that showed in Figure 4b. The cross-section in Figure 5c verified that both the substrate and the deposited thin wall are free from cracking. The results show that the melt-pool temperature can be precisely controlled by using the path-dependent process control. As a result, the heat input can be reduced to eliminate the hot cracking for deposition of crack-sensitive Ni-base alloys, and to improve the dimensional accuracy.

Figure 4. Path-dependent set-value

Figure 5. Repair with process control (a) measured IR-temperature and laser power signals; (b) Vertical edge and non-excessive build-up; (c) Cross-section showing crack-free repair

3.2. Microstructure analysis

Figure 6a, b and c show the optical micrographs of deposited thin wall examined at the top, middle and bottom in the cross-section, respectively. The microstructure in the fusion zone and the base material is presented in Figure 6d and e, respectively. No micro-cracks were found in all the optical micrographs. The images also show very low porosity level with minor pores. Columnar dendrites can be observed growing epitaxially from the substrate. This resulted from the dominated heat conduction from the substrate. With increasing height of the deposited thin wall, condition of heat conduction changed. The deposited thin wall also functioned as heat sink. As a result, a mixture of cellular and columnar dendrite structures formed in the middle of the deposited thin wall. In the top layer of the deposit, equiaxed microstructure with obvious second-dendrite arms can be observed. Compared to the cast substrate, much finer micro-structure in the laser deposited thin wall was formed.
Figure 6. Optical micrograph taken in the cross-section of the deposited thin wall at different location; (a) top; (b) middle; (c) bottom; (d) adjacent region between substrate and first layer; (e) substrate

The SEM images in Figure 7 reveal the very fine micro-structure with very fine carbides (white particles) distributed uniformly at the grain boundaries. As shown in Figure 8, the EDX line scanning conducted in the cross-section across the deposited thin wall showed that the chemical composition remains constant in the deposited layers. All the carbides are smaller than 1 μm. Spot EDX analysis was performed on the selected carbide, as shown in Figure 9. The carbides were identified with high Ti content. This indicates that MC type; mainly TiC carbides may be formed.

Figure 7. SEM image of the deposited Ni-base alloy
3.3. Micro-hardness

The micro-hardness test was carried out from the top to the bottom with an interval of 0.25 mm, which covers the substrate, heat affected zone (HAZ) and the deposited thin wall. As shown in Figure 10, the hardness in the deposited layers lies between 420 and 450 Hv with slight fluctuation. The hardness shows a slight decrease in the substrate. This correlates to the difference of the micro-structure shown in Figure 6.
4. Conclusions

In this study, repair of turbine blade knife edges using controlled LAAM process was investigated. IR-temperature emitted from the melt pool was adopted. Path-dependent set-value was optimized for the controlled process. Based on the results obtained, following conclusions can be drawn:

- The heat input plays important role in determining the crack sensitivity for deposition of Ni-base alloy with high Ti/Al composition using laser
- The process control with a path-dependent set-value can eliminate the crack formation in the deposited layers, due to the controlled melt pool temperature, and consequently, reduced heat input
- The repaired knife edges show very good dimensional accuracy without the excessive build-up and inclination
- The cross-section and micro-structure analysis verified that the repair can achieve refined micro-structure compared to the substrate with low porosity
- Very fine carbides formed at grain boundaries with dominated Ti constituents
- Homogeneous micro-hardness was observed across the deposited layers

References