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Sensor integration in hybrid additive manufactured parts for real-time monitoring in turbine operations

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Abstract
Real-time monitoring of operation conditions such as tempeatures and vibrations enables efficiency enhancement for maintenance tasks. In energy industry monitoring of critical components such as turbine blades is essential for the operation safety. But the effective recording of critical process data is a challenging task due to the extreme operating conditions. With a hybrid processing approach combining two additive manufacturing technologies new classes of self-monitoring components become possible allowing data acquisition directly inside the component. Using the example of a turbine blade, the hybrid process chain is described. The turbine blade blank is produced via Laser Powder Bed Fusion (L-PBF) with channels for the integration of high temperature sensors. After integration cavities were closed by Laser Directed Energy Deposition (L-DED) followed by classical milling operations for part finishing. The data acquisition is integrated in state-of-the-art product lifecycle monitoring (PLM) software to create a digital twin. Evaluation shows that temperature could be successfully monitored at conditions of Θ = 550°C.

additive manufacturing, smart maintenance, industry 4.0, IoT, hybrid manufacturing, cyber physical systems

1. Introduction

Real-time monitoring of operation conditions such as tempeatures and vibrations in components and machines enables efficiency enhancement for the planning and execution of maintenance tasks as well as the rapid response to system-critical states. In energy or oil and gas industry monitoring of critical components such as turbine blades regarding corrosion, cavitation or temperature irregularities is essential for the operation safety [1]. However, the effective recording of critical process data is a challenging task due to the extreme operating conditions in terms of temperature and pressure [2]. The integration of sensors close to point of interest is in many cases not possible or only achieved through high technological effort and expense. With a noval hybrid processing approach combining two additive manufacturing technologies new classes of self-monitoring components become possible where sensors such as thermocouples are safely embedded directly inside the part. The so called cyber physical systems allow data acquisition directly inside the component instead in its environment and thus a more robust evaluation of the overall system [3].

2. Methodology

Methodology and embedding strategy of this work was first introduced in [4] and is now applied for a turbine blade demonstrator. The component covers typical features of an state of the art stationary gas turbine blade such as included cooling channels and has a height h = 30 cm. It is shown that by redesigning the component for additive manufacturing, its functionality can be extended. The turbine blade blank is produced via Laser Powder Bed Fusion (LPBF) with the necessary channels for the integration of high temperature sensors. After integration the cavities were closed by Laser Directed Energy Deposition (LDED) using new strategies to prevent the electronics from being damaged by the welding heat. After this, classical milling operations were used for finishing the turbine blade. The data acquisition is integrated in state of the art PLM software to create a digital twin.

3. Hybrid manufacturing process

3.1. L-PBF of turbine blade blank

First, a measurement point was defined at the blade tip which is the most critical area of a turbine blade in operation. Second, a channel was designed to include type-k thermocouple like shown in Figure 1. (left). The channel was designed open for a robust implementation of sensors. Also, chosen thermocouple can handle temperatures T ≤ 1,200 K, it is likely that they will be damaged by even higher processing temperatures T_P ≥ 2,500 K of L-DED embedding process. To avoid this problem, a special channel design with an undercut was chosen, were heat input to sensor is reduced like visualized in Figure 1. (right).

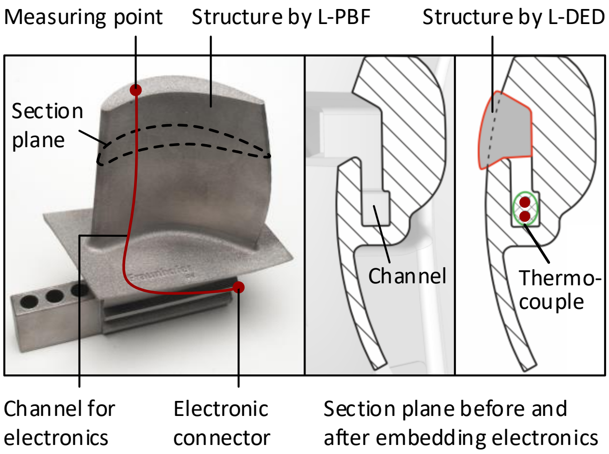

Figure 1. L-PBF-built part and embedding strategy for electronics

3.2. Sensor embedding via L-DED

Turbine blade blank is manufactured from stainless steel 1.4404 (X2CrNiMo17-12-2) via single laser device SLM 250 HL from company SLM SOLUTIONS GROUP AG, Lübeck, Germany within a process time t = 38 h. After obligatory support structure removal, cleaning and heat treatment of L-PBF produced blade blank, thermocouples were added manually. To close channels a TRUMPF TRUDISK 2.0 kW Yb:YAG laser and a coaxial annular gap nozzle was used to process stainless steel 1.4404 metal powder. Even if thermocouples are shielded partly, a proper regulation of the temperature input is essential to avoid damages. It is necessary to prevent heat-related deformation on the very small blade walls thicknesses $2.0\ mm \leq t_w \leq 4.0\ mm$. The groove was filled conducting low heat L-DED repair strategy with more than 20 weld beads according to [5]. A laser power P = 800 W and a welding speed v = 600 mm/min leading to a total processing time $t_P \leq 10$ min. Figure 2. shows setup for the embedding process.

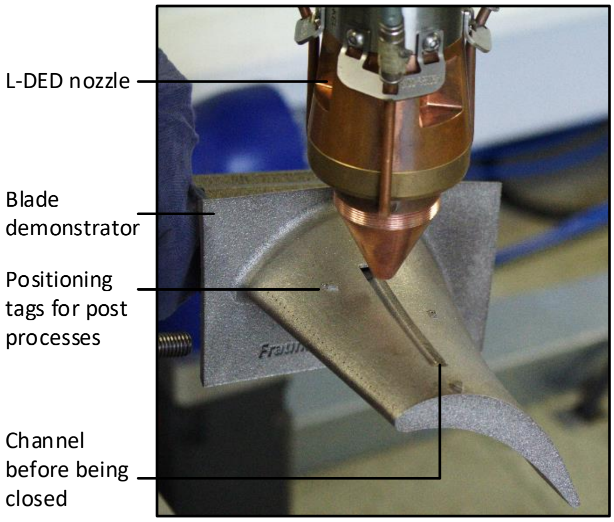

Figure 2. L-DED-process to close channels after including electronics

3.3. Finishing procedures

Since L-DED technology is not able to provide targeted precision and roughness the process was conducted with an local oversize $dt_w = 1.0$ mm. Also the blade root made by L-PBF process does not meet the high precision specifications. Thus a final finishing operation is necessary using 5-axis milling machine RXP 600 from the company RÖDERS, Soltau, Germany. The two-stage machining of the free-form surface requires a processing time $t_P \leq 5$ min. However, positioning of part in machine is the major challenge, which can be handled using positioning tags (see Figure 2.). These were produced within the LPBF process and are also removed in the same process step. After an additional grinding process using vibratory finishing according to [6] a homogeneous smooth surface was achieved with no significant traces of the LDED operation recognizable.

4. Digital Twin

The turbine blade demonstrator was connected to a RASPBERRY PI single board computer as data acquisition tool using a electronic connector inside the part holder (Figure 3.). Measurement values were send wireless to an edge computer feeding a digital twin of blade inside the cloud platform ELEMENTS FOR IOT from company CONTACT SOFTWARE GMBH, Bremen, Germany [7]. By using this set-up turbine blade condition such as critical high or low temperatures can be monitored location-independent in real time on any device. In addition, noticeable operating conditions from the entire component life as well as information regarding maintenance history and part manufacturing conditions can be analyzed.

5. Experimental results

To show the feasibility of approach, the turbine blade demonstrator can be heated up manually using a simple bunsen burner (see Figure 3.). With the thermocouple positioned close to the blade wall from the inside, a significant temperature increase dT of several Kelvins can already be observed after a latency period t_L of under two seconds.

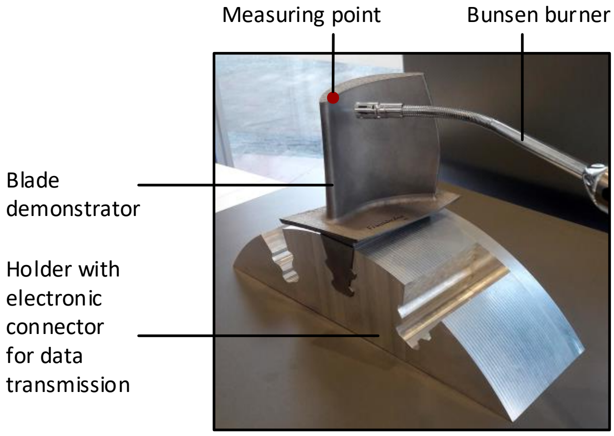

Figure 3. Turbine blade demonstrator at Fraunhofer Institute

To prove methodology also for higher temperature T, the blade was heated in an industrial furnance up to $\Theta = 550°C$ for a duration t = 1 h, bringing the system close to maximum operation temperature of chosen steel. It was shown that for this temperature, the measurement operated reliably and no damages could be detected on part or sensors afterwards.

6. Conclusion and outlook

This works shows that by combining two additive production strategies, a new functional component can be produced opening up significant potential for monitoring, smart maintenance and IoT approaches. The methodology of producing specific designed channel geometries which are closed via DED after sensor embedding could be also applied to new applications fields with even more complex designs or dimensions. Possible areas are temperature and pressure sensors in pressing and diecasting tools as well as vibration sensors in pumps. The monitoring of ship propellers by included wear sensors could also be an interesting field since down times and efficiency losses have a huge monetary impact [8].

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