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On the challenges of hybrid repair of gas turbine blades using laser powder bed fusion

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Abstract

Additive manufacturing (AM) processes such as laser powder bed fusion (PBF-LB/M) are rapidly gaining popularity in repair applications. Gas turbine components benefit from the hybrid repair process as only damaged areas are removed using conventional machining and rebuilt using an AM process. However, hybrid repair is associated with several challenges such as component fixation and precise geometry detection. This article introduces a novel fixturing system, including a sealing concept to prevent powder sag during the repair process. Furthermore, a high-resolution camera within an industrial PBF-LB/M machine is installed and used for object detection and laser recognition. Herein, process related inaccuracies such as PBF-LB/M laser drift is considered by detection of reference objects. This development is demonstrated by the repair of a representative gas turbine blade. The final offset between AM build-up and component is analysed. An approximate accuracy of 160 µm is achieved with the current setup.

Keywords: laser powder bed fusion, additive manufacturing, hybrid repair, position detection, high-resolution camera

1. Introduction

Additive manufacturing processes are used to produce components directly from 3D mesh data. In addition to component manufacturing, hybrid approaches are becoming increasingly important. Hybrid additive manufacturing is the combination of at least two process steps. This can include additive manufacturing with subsequent machining in one clamping (Jiménez et al., 2021; Sefene et al., 2022). Another application for hybrid additive manufacturing is the build-up of geometric elements onto existing components. This approach is used, for example, in the tooling industry or in component repair (Popov & Fleisher, 2020; Zäh et al., 2021). The repair of components using metal additive manufacturing is mainly performed by Direct Energy Deposition (DED) processes (Rahito et al., 2019). The tool guidance results in a freely accessible workpiece that is less limited in size compared with laser powder bed fusion (PBF-LB/M) restrictions. DED-based repair approaches are used in the energy sector or the aerospace industry (Petrat et al., 2016; Shirui et al., 2017; Wilson et al., 2014). However, DED based repair often needs to be reworked and combined with subsequent machining to achieve the desired finish and tolerances (Sefene et al., 2022). Rework is sometimes undesirable or not possible, for example when internal geometries are within the volume to be repaired. In this case, repair by means of laser PBF-LB/M can be beneficial.

Previous work using PBF-LB/M for repair applications has investigated the formation of the microstructure and the resulting mechanical properties for Hastelloy X, 1.4542 stainless steel and AlSi10Mg (Andersson et al., 2017; Ozsoy et al., 2021; Zghair & Lachmayer, 2018). However, the hybrid repair process chain and the associated challenges using powder bed processes are currently not described in the literature. PBF-LB/M machines are usually not primarily designed for component repair. The available build volumes limit mounting possibilities and therefore maximum component size. Powder bed processes use a layer wise approach and thus require a plane surface to build upon without an offset in z-direction. The sometimes unfavourable orientation of the component caused by the repair process design can further reduce the build volume. Additionally, the laser actuating galvanometric scanning heads show deviations between the position of the actuators and the actual position of the laser spot on the build platform. This results in a deviation between the desired laser position and the actual laser position, the so called laser drift (van Le & Quinsat, 2020). In non-hybrid PBF-LB/M processes, this has no significant effect because no precise matching of the machine coordinate system (MCS) and the build plate is required. However, in hybrid repair, a deviation between the actual laser working point and the control signal of the galvanometric scanning head will result in an XY-offset between the component and the build-up. This offset results in avoidable rework and, in some cases, scrap. In addition, process stability may be compromised due to associated overhangs, for example. Measurement equipment must be installed for position detection. Inside the build chamber of the PBF-LB/M machine, the installation space is very limited due to the laser active area and gas flow requirements. Additionally, process influences such as temperature, dust or dross can have a negative effect on the lifetime of the equipment. Mounting positions outside the build chamber are often limited by the number, size and accessibility of build chamber interfaces, which results in the challenge to find an appropriate placement for position detection equipment.

The focus of this work is on the description of the process chain for the hybrid repair of gas turbine blade tips using PBF-LB/M. For this purpose, the process chain is described with its individual process steps. Subsequently, a fixturing system is presented for mounting a gas turbine blade into a PBF-LB/M machine. The fixturing system can be quickly modified for the repair of other components. A high-resolution camera is mounted outside the PBF-LB/M process chamber for position detection. An algorithm for detecting the position of the turbine blade in the workspace is then presented. Subsequently, the turbine blade tip is rebuilt using PBF-LB/M. After the manufacturing process, the offset between turbine blade and build-up is determined by 3D-scan.

2. Material and methods

2.1. Hybrid repair process chain

The process chain of a hybrid repair process using PBF-LB/M can be roughly divided into 11 process steps as shown in Figure 1. First, the worn areas to be repaired have to be machined. During the machining process it is important to create the initial geometrically defined flat surface for the build-up. After machining, the component is clamped into a fixturing system to enable subsequent process steps. Within this fixturing system the component gets grinded to create the final, plane-parallel build plane. The machined component has to be digitised to account for individual component defects, such as distortion due to creep for example. Digitalisation is carried out by 3D scanning, such as laser triangulation scanning. The 3D mesh generated by the 3D scan is used to generate each components build-up individually. This process step is called adaption. The adaption of the build-up can be realised using CAD software. After digitalisation, the fixturing system can be mounted inside the PBF-LB/M machine. The fixturing system and its installation in the PBF-LB/M machine is described in more detail in Section 3. After mounting the fixturing system, the machine can be further equipped. This includes setting of the correct plane at which the build-up starts, i.e. the building level. An incorrect building level will result in a parallax error during the position detection. The position of the component within the machine has to be determined with high precision. The positional information of the component is used for the build cycle preparation. During this step, the build-up is positioned virtually on the build-platform of the machine. Subsequently, the process parameters are assigned and the geometry of the build-up is sliced. The hybrid repair process can be started. Post-processing after the PBF-LB/M process depends on the repaired component and its associated requirements. It may include heat treatment or surface finishing. Inspection can be used to check the geometrical accuracy as well as mechanical and material properties.

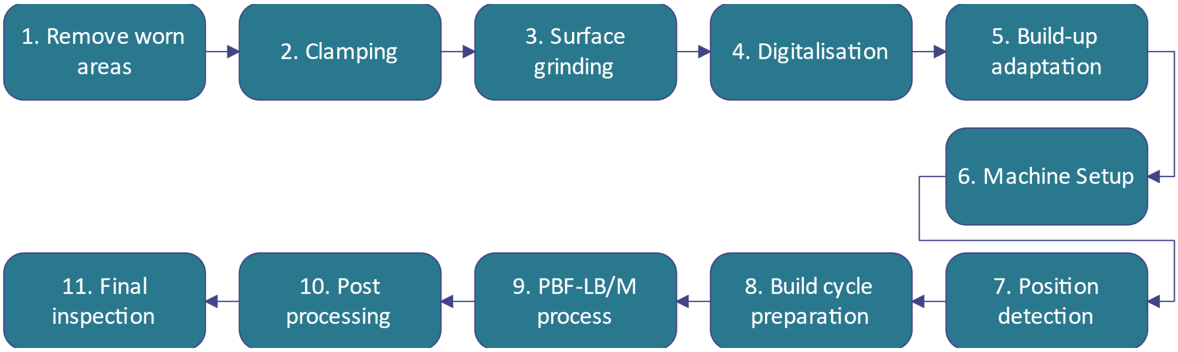

Fig. 1. Process chain of hybrid repair process using PBF-LB/M

2.2. Hardware set-up and software tools

The hybrid repair process is carried out using a PBF-LB/M machine SLM 280HL (SLM Solutions Group AG, Germany) with a build volume of 280 x 280 x 365 mm^3. The material of the additively manufactured build-up is the nickel-based superalloy Haynes®282^{TM}. According to the supplier, the particle size distribution of the powder is in accordance with ASTM B822: D_{10} = 21. µm, D_{50} = 30.0 µm and D_{90} = 40.3 µm. The blade material is the nickel-based superalloy Mar-M-247. The z-height of the turbine blade limits the maximum additional height of the fixturing system to 35 mm. The position of the object is determined using the high-resolution monochrome camera VLXT-650M.I (Baumer Holding AG, Switzerland) with approximately 65 megapixels. The lens used is a 90 mm Apo-Componon 4.5/90 (Jos. Schneider Optische Werke GmbH, Germany) with a 1025 nm shortpass filter (Edmund Optics Inc., USA) to protect the camera sensor from laser radiation. The camera is mounted in an off-axis position outside the process chamber. The field of view of the camera image is adjusted to the region of interest using a mirror deflection system. The camera setup is shown in Figure 3. According to previous work of the authors, the field of view can be calculated to approximately 120 x 160 mm² and the spatial resolution can be calculated to 17.2 µm/pixel (Merz et al., 2023).

The digitalisation for the adaptation of the build-up is performed by blue light stripe projection using an

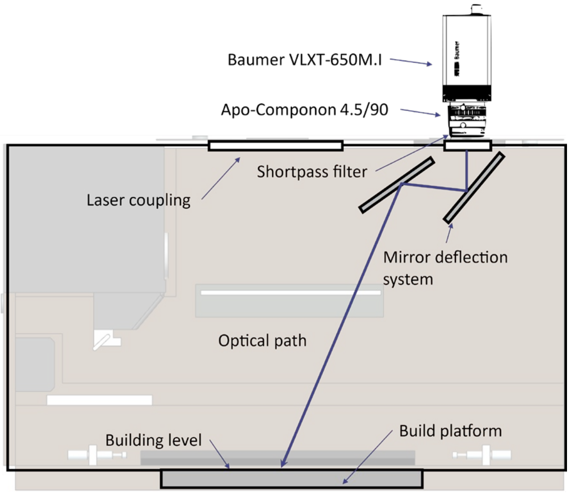

Fig. 2. Schematic experimental setup of SLM 280HL for position detection of objects

ATOS 5 Scanbox (GOM GmbH a Zeiss Company, Germany). The generated 3D-point cloud is processed into a 3D-mesh using the software GOM Inspect Pro (GOM GmbH a Zeiss Company, Germany). Based on the 3D mesh of the blade geometry, the build-up is adapted in Siemens NX 2212 (Siemens AG, Germany). The build cycle preparation, including slicing and process parameter assignment, is done in Magics 25.04 (Materialise GmbH, Germany).

2.3. Position detection of objects

The off-axis position of the camera leads to perspective in the acquired images. Due to this, pixel-to-metric compensation must be performed. A clearly defined pixel-to-metric ratio is required for positioning the build-up during build-job preparation. Perspective correction is performed using the algorithm presented in previous work (Merz et al., 2023). For this purpose, a calibration process using homography is carried out prior to the actual repair process. A homography matrix needs to be calculated so that the perspective in images acquired in the same camera setup can be corrected. To calculate the homography matrix, source and target points have to be determined. Source points are reference points in a distorted image. The target points represent the position of the source points in an ideal undistorted image. By superposing the source points with the target points, the homography matrix can be calculated (Ascencio, 2020). The target points are created by engraving reference objects on a black anodised aluminium plate with the laser of the PBF-LB/M machine. After engraving, the positions of the reference objects are detected in the distorted camera image. For engraving with the PBF-LB/M laser, the reference objects have to be virtually positioned in the CAD system. The positions of the reference objects in the CAD software correspond to the source points of the homography matrix calculation. The advantage of this approach is that the current position of the reference objects, and thus the laser working point, is superimposed on the ideal CAD positions. This makes it possible to compensate for process inaccuracies such as laser drift. By knowing the position of the reference objects in both pixel coordinates and CAD coordinates with the according MCS coordinates, any position detected in pixel coordinates can be converted to the CAD system by coordinate transformation (Merz et al., 2023).

The position of reference objects and components is determined from the camera image using Suzuki and Abes contour recognition (Suzuki & Abe, 1985). The algorithm requires a binarized input image, which is attained by applying a global threshold. After binarization, contour detection is performed. As an output, all contiguous pixels are identified as contours. An area filter is applied to identify the reference objects or components from all detected contours. In this way, small disturbances such as dust or noise are not considered in the further processing. The positions of the reference objects or components in pixel coordinates can be calculated by using image moments (Khan et al., 2014). The centroids of the segmented objects can be calculated from the first and second order image moments. The orientation is calculated from the central second order moments and can be given by the eigenvectors of the distribution (Khan et al., 2014). The main orientation of the detected object is defined by the Eigenvector with the larger Eigenvalue.

2.4. Turbine blade fixturing set-up

Fixturing of the component is associated with different requirements. The interface of the fixturing system has to match that of the PBF-LB/M machine. The dimensions of the fixturing system and thus the component dimensions are limited by the build volume. When repairing turbine blades, the available z-height is often a limiting factor. The fixturing system should therefore take up as little space as possible. In addition to laser drift challenges, the fixturing system cannot be mounted with exact repeatability. As a result, the components position varies each time the system is setup. This effect can be reduced by using zero-point clamping systems. However, zero-point clamping systems also reduce the build volume and cannot be integrated into every PBF-LB/M machine. For this reason, a zero-point clamping system is not considered for this application. To prevent the component from shifting during machining and grinding, the component must be clamped in a torsionally rigid manner.

For clamping the turbine blade, the free flank of the blade root is referenced. The load on the free flanks is low during blade operation, so only small deviations between different blades are to be expected. The blade is oriented so that the plane build-up interface faces upwards. The fixture is additively manufactured from carbon fibre-reinforced nylon using Fused Deposition Modelling (FDM). This approach for component mounting allows easy and quick adaptation to changing geometries. The clamping is done by vertical toggle clamps which apply sufficient loading force to the free flanks so that slipping of the blade after clamping does not occur. The fixturing of the blade is a friction fit design. The fixturing system is shown in Figure 2. The toggle clamps can absorb the forces generated during grinding. All components are mounted on a base plate with minimum z-height. This allows larger gas turbine blades to be repaired. A top seal is added to the fixturing system to prevent the entire build volume from being filled with powder, see Figure 3. This means less material is recirculated in the process, which reduces post processing times. To prevent the powder bed from sagging, the top plate is fitted with a felt seal. Cooling air holes are sealed with temperature resistant tape. In addition, the root of the blade was sealed with silicone against the FDM fixture. The blade tip was also sealed with silicone against the top plate, see Figure 4 (a). The internal cooling channels of the blade are filled with powder by using the recoater. Finally, the bulk density of the powder was increased by manually compressing the powder with a suitable tool.

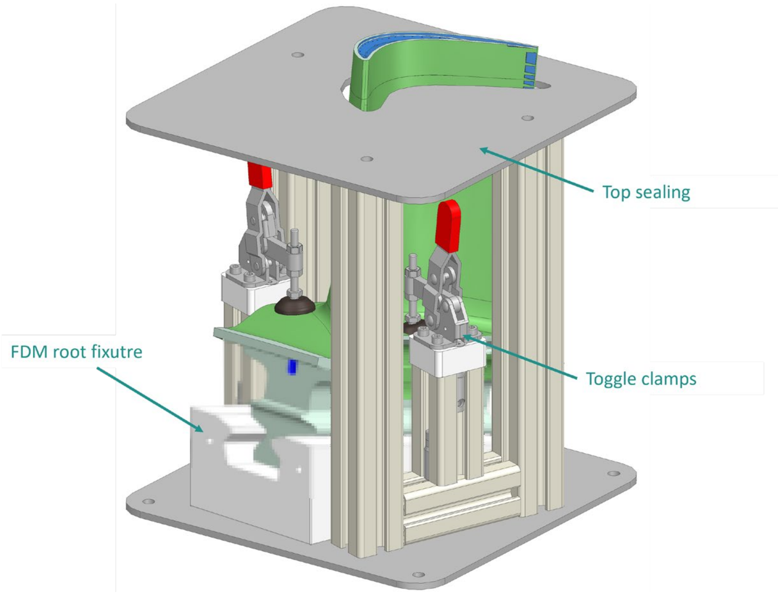

Fig. 2. Fixturing system for turbine blade including top sealing to prevent powder sag (root pixelated due to non-disclosure)

2.5. Experimental procedure

The repair process using PBF-LB/M is validated on a real gas turbine blade. The worn turbine tip is removed by machining. The blade is mounted in the fixturing system and the top surface is ground flat. The mounted fixturing system is digitised using the ATOS 5 Scanbox. The 3D-mesh is imported into Siemens NX for the adaptation of the build-up. After digitalisation, the fixturing system is mounted in the SLM 280HL. The assembled system is shown in Figure 4 (a).

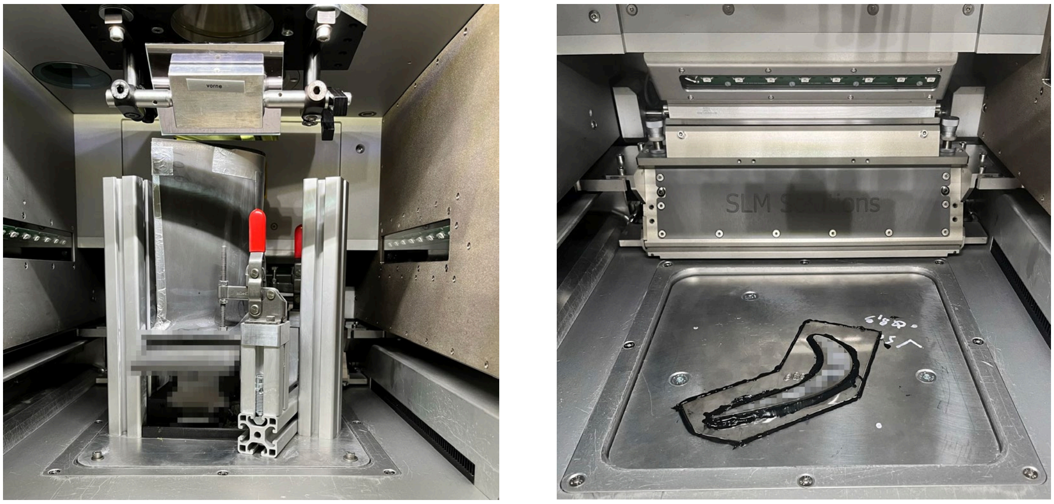

Fig. 3. (a) installation of mounted fixtuing system within SLM 280HL machine; (b) sealed turbine blade leveled during pre processing (root and cooling channels pixelated due to non-disclosure)

The build-up interface of the blade is levelled precisely to the height of the building level to avoid parallax errors in the position detection. The blade is then lowered by the thickness of the anodised aluminium plate, which is 1 mm. The reference objects are engraved on the aluminium plate and then the homography matrix is calculated. After removing the aluminium plate, the building level is restored. The last direction of movement of the platform has to be downwards to compensate for the backlash. The blade position is determined from the undistorted camera image using image moments. The position parameters can be used to virtually position the build-up in the machine's build envelope in Siemens NX. The slicing of the positioned build-up is done in Magics 25.04. The blade is then sealed to prevent powder sag as explained in Section 3.

3. Results and discussion

The manufacture of the 763 layers took approximately 391 minutes. No anomalies could be observed during the process. After the PBF-LB/M process, the fixture is removed from the process chamber. Little powder residue was found on the base plate of the fixturing system. The powder indicates that the felt seal does not provide a complete seal against the building volume. However, sagging of the powder bed was prevented so that process stability was not compromised. No powder residue was found on the blade itself, so the silicone between the blade tip and the top plate provides a reliable seal. The offset between the component and the build-up is determined by 3D scanning the hybrid component. The 3D scan is performed using an ATOS 5 Scanbox. The offset is determined using GOM Inspect Pro. Therefore, the blade geometry is fitted to the ideal CAD model using Gaussian best fit. Figure 5 shows the evaluation from GOM Inspect Pro. The histogram shows the shape deviation of the build-up 1 mm above the fusion interface of the hybrid component. The mean value of the shape deviation is approximately -40 µm. The largest shape deviations can be seen at the maximum extension of the blade tip. Possible causes are scaling factors from the adaptation or slicing, or material-specific material shrinkage. The positional deviations of the hybrid component are tabulated in Figure 5.

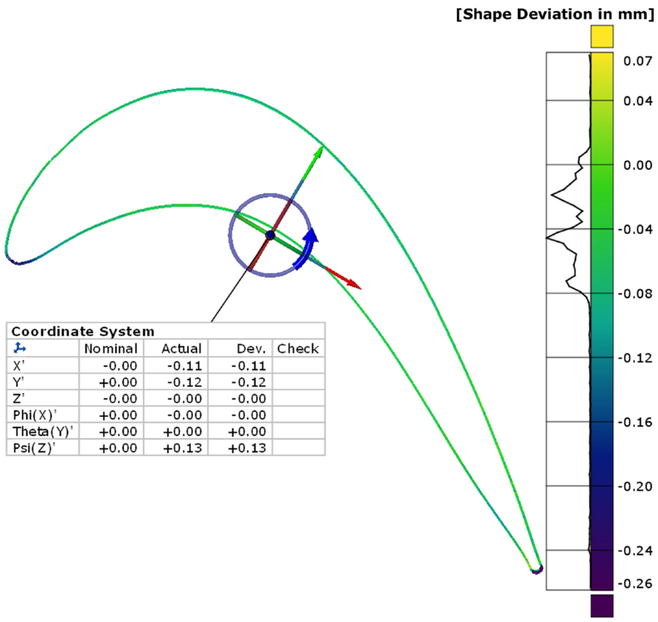

Fig. 4. Evaluation of the shape and position deviation of the hybrid repair process

The offset is -110 µm in the X-direction and -120 µm in the Y-direction, giving an offset of approximately 160 µm. The rotational deviation around the Z axis is +0.13°. According to DIN ISO EN 286-1, this corresponds to tolerance grade IT9 to IT10. This makes the hybrid repair process comparable to conventional manufacturing methods such as turning, face milling or stripping (DIN EN ISO 286-1, 2019).

The offset of the repaired gas turbine blade is more than twice as large as the 69 µm offset of a hybrid demonstrator geometry build up by the authors in previous work (Merz et al., 2023). The demonstrator geometry is an airfoil with a constant cross-section over the build-height without internal cooling channels. Compared to the demonstrator geometry, the tip geometry is tapered over the build-height. This means that even small inaccuracies during the digitisation step will result in incorrect adaptation of the build-up and therefore parallax errors in the final part. This can be seen from the shape deviation of -40 µm in Figure 5. The more complex shape, including cooling channels and bridging concepts, could lead to material-specific shrinkage behaviour in the interface, which is currently not addressed in the parameter set used. Another influence could be the uneven lighting conditions inside the PBF-LB/M machine. This results in an illumination gradient across the captured image. Segmentation by global threshold therefore has disadvantages. The off-axis position of the camera results in an area of focus in the image. A larger depth of field can be achieved by reducing the aperture. However, the amount of light from the manufacturer lighting system built into the PBF-LB/M machine is not sufficient for the camera when the aperture is narrowed.

4. Conclusion

In this work, a hybrid repair process using PBF-LB/M is performed on a real gas turbine blade. The process involves building the tip geometry out of Haynes®282™ onto a turbine blade out of Mar-M-247. A fixturing system has been developed to clamp the turbine blade for pre-processing and assembly in the PBF-LB/M machine. The fixturing system includes a sealing concept from felt and silicone to reduce the amount of powder in the process. The sealing shows good performance to prevent the powder bed from sagging. A high resolution camera is used to detect the position of the turbine blade inside the PBF-LB/M machine. The camera is mounted in an off-axis position outside the process chamber. The developed calibration process allows to correct the resulting perspective in the image by homography. During the PBF-LB/M process, no abnormalities could be observed. The offset between the turbine blade and the build-up is determined by comparing a 3D-mesh with the ideal CAD data. The 3D-mesh is calculated from a 3D-point cloud generated by blue light stripe projection. The offset is about 160 µm. The offset of this approach is more than double that of a demonstrator geometry with an offset of approximately 70 µm. One possible reason is the more complex geometry of the turbine blade build-up. Additionally, the presented approach has disadvantages in using the built-in illumination of the PBF-LB/M machine. Therefore, the global threshold for image segmentation has drawbacks. In order to increase the robustness of the developed method and to reduce the offset between the blade and the build-up, it is recommended to improve the illumination system. It is also recommended to investigate different segmentation methods or position detection algorithms.

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