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Citation for the original published paper (version of record):
Sadeghi Tabar, R., Lindkvist, A., Lindkvist, L. et al (2024). Fixture Layout Optimization for Remanufacturing Using Directed Energy Deposition Process. Procedia CIRP, 129: 199-204.
http://dx.doi.org/10.1016/j.procir.2024.10.035

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Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 129 (2024) 199–204

www.elsevier.com/locate/procedia

18th CIRP Conference on Computer Aided Tolerancing (CAT2024)

Fixture Layout Optimization for Remanufacturing Using Directed Energy Deposition Process

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Abstract

Remanufacturing of aero-engine blade components is vital for sustainability and cost-efficiency in aerospace and energy industries. These types of products are sometimes damaged during use but may be successfully repaired using additive manufacturing processes, *e.g.*, Directed Energy Deposition (DED). During this process, precise and reliable fixturing during machining and repairs is crucial as it impacts the final geometric outcome of the remanufactured component. In this study, the fixture layout during the DED process for optimal geometric outcome is considered. Initially, the placement zones in the part surfaces are defined, and the problem space is discretized. A greedy optimization algorithm is considered for the optimization of the clamping positions to achieve the highest geometric quality. The surface on which the material is deposited is measured and analyzed. The optimal fixture layout to achieve minimum deviation on this surface prior to the DED process is identified. The DED process is then simulated, and the deviation in the final geometry is analyzed before and after optimization. Accurate simulation of the DED process using the inherent strain approach allows for verification of the optimization of the fixture layout. The result of this study shows the importance of locating and clamping placement for the remanufacturing process using the DED process.

Keywords: Remanufacturing, Fixture, Optimization, Direct Energy Deposition, Geometric Quality

1. Introduction

Geometry assurance in remanufacturing plays a crucial role in ensuring the quality and reliability of End-of-life (EOL) products. Geometry assurance involves a set of activities that verify and validate the geometric features and dimensions of the components to meet the required specifications [22]. Turbine and compressor blades are vital components for the function and performance of the aero engines. These components are expensive to manufacture and maintain geometrically due to the precision required for the surface curvature of the blades. The blades are often damaged during use due to erosion and fatigue loads [8]. Therefore, remanufacturing and repair practices are common for these types of products. A necessary condition for the remanufacturing of the blades is to ensure the geometric quality of the surfaces follows the specification. For this reason, the additive remanufacturing processes have been the main method for repairing the surface of the components.

1.1. Additive Remanufacturing

Additive remanufacturing entails an integration of additive manufacturing (AM) technologies with remanufacturing principles. Several studies have investigated the AM techniques, *e.g.,* laster cladding [5], powder bed fusion (PBF) [15] and directed energy deposition (DED) [27], for repair and remanufacturing applications [14]. Aside from the technological advancements, the Additive Remanufacturing processes also address environmental concerns by promoting the reuse of materials and reducing waste. EOL products, *e.g.*, blades, and electrical components can efficiently be repaired and reused, contributing to resource conservation and environmental protection [3]. However, the adoption of additive remanufacturing presents challenges, particularly in the quality of the remanufactured products, which can generate additional complexities for original equipment manufacturers (OEMs) [7]. The geometric issues associated with the additive remanufactured components impose uncertainties around the final quality and the life-cycle of the components [13]. Therefore, prediction methods and

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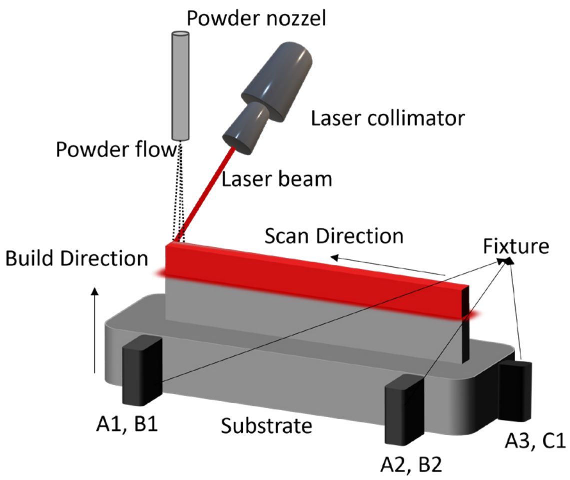


Fig. 1: DED Process

simulation-based processes have been developed to assure the geometric quality of the additive manufacturing process [21]. In this paper, a specific focus has been placed on the DED approach, which is a prominent additive manufacturing approach. The following presents an introduction to this technology.

1.2. Directed Energy Deposition

Directed Energy Deposition (DED) is an additive manufacturing (AM) technique that involves the deposition of material, typically in the form of powder or wire, through a focused energy source, such as a laser or electron beam, onto a substrate to build up a part layer by layer [1]. DED offers high geometric and material flexibility, making it suitable for fabricating complex metal parts and repairing worn-out components with intricate geometries [4]. The overview of the DED process is presented in Fig. 1. With a laser instrument, a beam is applied, establishing a melt pool. Through a powder nozzle, a powder flow is applied into the melt pool using an inert gas. For the remanufacturing process, using this technique, often the workpiece is held employing a fixture, and laser beam, and the powder is applied to the damaged volume, which has been cut out to be repaired. Later, the melted zone will cool down, and material shrinkage will occur. The laser beam is applied based on a predefined path, layer by layer, to construct the final volume. This path can be adjusted to achieve the optimal geometric outcome [21]. Precise control of the process parameters, *i.e.*, laser power, feed rate, and scanning speed, builds the ground for achieving the desired microstructural and mechanical properties of the geometry [10]. In this paper, the DED process is studied from the Remanufacturing perspective. One aspect that is often neglected in the process control parameter is the influence of fixture placement on the final geometric outcome. This perspective is further discussed in the next section.

1.3. Influence of fixture on geometric quality

In the fabrication and remanufacturing of components, fixturing the workpiece during the processes is critical, achieved through locating and clamping procedure that ensures stability in the perpendicular to the surface and in-plane directions [24]. The influence of the fixture on geometric quality hinges on the strategic placement of locating and clamping points [25]. The optimization of the fixture layout has been the subject of several studies. Moroni et al. took minimizing machining feature variation relative to geometric error as the optimization goal to carry out robust fixture design [12]. Further research by Raghu and Melkote adopted an analytical stance to model the repercussions of clamping order on the accuracy of workpiece positioning, unveiling a 20% discrepancy in predictions of workpiece location and reaction forces [17]. An improved simulated annealing algorithm aimed at automating and optimizing fixture layout design, thus reducing design and cost, is presented by Ding et al., [6]. The sequence of clamping has been introduced to variation simulation and optimized with a deterministic approach to reduce the geometric variation of the spot welded sheet metals [20, 19]. Several research has focused on introducing evolutionary algorithms for solving the optimal fixture layout problem [16, 9, 26].

Although several solutions for the optimal fixture layout has been proposed for the fabrication and assembly processes, less research has focused on developing methods for adapting to the additive manufacturing and remanufacturing processes. In this paper, a method for fixture layout optimization of the additive remanufacturing process is introduced.

1.4. Scope of the paper

Additive remanufacturing with the DED process is a prominent repair method. The process requires precise control over the parameters to achieve the desired geometric quality and mechanical characteristics. The fixturing element in the remanufacturing process is crucial in assuring the final geometric quality. Less research has focused on introducing fixture layout optimization methods suited to the specific needs of the remanufacturing with the DED process. In this paper, a simulation-based optimization framework has been introduced, increasing the geometric quality of the remanufactured component with the DED process. Section 1 presented a background to this problem. The rest of the paper is structured as follows. Section 2 presents the geometry prediction approach and the optimization framework. Section 3 presents the reference component in this paper and the simulation and optimization results. Further, the conclusions are drawn based on the achieved results, and a future research plan is put forward in section 4.

2. Proposed fixturing for additive remanufacturing

For defining the optimal fixture position, simulation-based optimization is utilized to reduce experimentation and cost [9, 24]. To adapt this strategy to an additive remanufacturing context, the inherent strain method is used to simulate the geometric outcome during the DED process. The following section introduces this approach.

2.1. Geometry Prediction with Inherent Strain

To describe the inherent strain approach, let us consider the case presented in Fig. 1. When the powder is exposed to a laser, it begins to heat up. This heating causes the powder to expand and undergo plastic deformation if the stress on it surpasses its yield stress. As the temperature reaches the melting point, the plastic deformation is eliminated because the powder melts. During the process of solidification, the now-melted material contracts. This contraction results in plastic deformation, primarily because the surrounding material constrains it. The overall deformation resulting from both the melting and solidification processes can be described by the following equation [21].

$$\epsilon_{Tot} = \epsilon_e + \epsilon_p + \epsilon_t + \epsilon_c, \tag{1}$$

where ϵ_{Tot} is the total strain, ϵ_e, is the elastic strain, ϵ_p is the plastic strain, ϵ_t is the thermal strain and ϵ_c is the negligible phase change strain.

The thermal strain is formulated as:

$$\epsilon_t = \theta \Delta T, \tag{2}$$

with θ as the thermal expansion coefficient and ΔT is the room temperature and melt temperature difference. The inherent strain of the component after solidification is expressed as:

$$\epsilon_i = \epsilon_{Tot} - \epsilon_e. \tag{3}$$

With rearranging Equation 1 and substitution of the equation 2, the inherent strain is expressed as:

$$\epsilon_i = \epsilon_p - \theta \Delta T. \tag{4}$$

While calculating the strains, boundary conditions are applied to the model to simulate the physical constraints and loads. The fixturing elements are introduced to this formulation, constraining the degrees of freedom in the specified direction. The component geometry is discretized into finite elements, and the equilibrium equations are solved for the nodal displacements. The above formulation is implemented into the FE-solver for non-rigid variation simulation built in the software RD&T [18] and used for fixture layout optimization, presented in the following section.

2.2. Fixture Model

To address the fixture layout for the additive remanufacturing process, positioning locators and clamps are considered to enhance the robustness of specific critical product dimensions. At this stage, tolerance levels are not taken into account; instead, the focus is solely on the amplification factor. This is achieved by disturbing the boundary conditions one by one and considering the reaction forces to enable the structural stability analysis [22]. The theory of positioning systems suggests applying the 3-2-1 positioning system to lock all the six degrees of freedom [24]. Three points are considered for locking a translation and two rotations, two points to lock a translation and rotation, and one point to lock the final translation. The fixture in Fig 1 is shown by the elements locking these degrees of freedom. Let us define these three fixturing elements as points, *i.e.*, three dimensional coordinates and directions, $p_1 - p_6$, where p_1 to p_3 are the A-datum points, p_4 and p_5 are the B-Datum points and p_6 is the C-Datum. The objective is to enhance the robustness of the critical dimensions. The robustness output is evaluated using amplification factors α_i, which quantifies the impact of each locator on the robustness of a particular critical dimension, d_i. Here, a critical dimension is specified by a point coordinate o_i and a direction n_i, where i indicates the specific critical dimension in focus. For every critical dimension, a vector α_i is computed, containing six amplification factors corresponding to the six locators that assess the robustness of critical dimension i. The calculation of α_i follows the equation presented below [23]:

$$\alpha_i^T = [(o_i \times n_i)^T n_i^T] J^{-1} \tag{5}$$

In this formulation, J is the Jacobian matrix defined as:

$$J = \begin{bmatrix} (p_1 \times n_1)^T, n_1^T \\ (p_2 \times n_2)^T, n_2^T \\ \vdots \\ (p_6 \times n_6)^T, n_6^T \end{bmatrix} \tag{6}$$

Utilizing the robustness index (RI) presented in 5, we define an optimization problem to identify a layout minimizing displacements caused by disturbing the positioning points in the critical dimensions.

2.3. Fixture layout optimization

The fixture layout optimization is formulated as the optimal fixturing point coordinates and their directions on the surface of the geometry to minimize the amplification of the displacements in the critical dimension [11]. This optimization problem is formulated as below:

$$\begin{aligned} \underset{\alpha_i}{\text{minimize}} \quad & \sum_{i=1}^{q} (\alpha_i^T \alpha_i) \\ \text{subject to} \quad & Rank(J) = 6 \\ & L_i \geq z \end{aligned} \tag{7}$$

Here, q is the number of the critical measurement points considered in the component. For equation 5 to have a unique deterministic solution, the matrix J must be full rank, corresponding to the number of degrees of freedom [2]. This is presented in the first constraint of the optimization problem. Secondly, the process of additive manufacturing necessitates that the fixturing element shall not be placed in the heat affected zone of the geometry. The second constraint assures that the distance of the position of p_i to the critical dimension (L_i) cannot be less than the defined z millimeters. To identify the global optimum solution for this optimization problem, all the possible solutions need to be examined. The intricacy of solving this particular optimization problem is represented by the computational complexity of ($O(n^6)$). This problem is NP-hard, indicating the absence of universally efficient computational methods for its resolution. Heuristics and meta-heuristics are among the most utilized approaches to identify a solution to this kind of problem, Section 1.3. Here, a greedy algorithm is developed considering the additional constraints and the general unconstrained problem.

In this decoupled optimization approach, initially, the optimization problem is solved, and an optimal solution is introduced to the boundary condition of the inherent strain problem. Later, the FE simulation is performed, and the displacement utilizing the enforced boundary conditions is retrieved. This strategy is mainly to avoid the computationally expensive mesoscale simulation in the optimization loop. The greedy heuristic optimization approach is composed of the following steps.

- Initialize an empty list of fixturing points and a best candidate variable.
- Generate a set of candidate positions and orientations, considering the entire geometry and the minimum distant constraint.
- For each candidate in the set: calculate the RI for adding the candidate to the current configuration of fixturing points.
- If RI > best RI then update best candidate and update best RI.
- If the best candidate is feasible, return the optimal solution.

The initialization point for the best candidate is the current in-process feasible solution developed from the experiential rule-based set of points. The general optimization approach is presented in Fig. 2, where the initialization occurs in the fixture

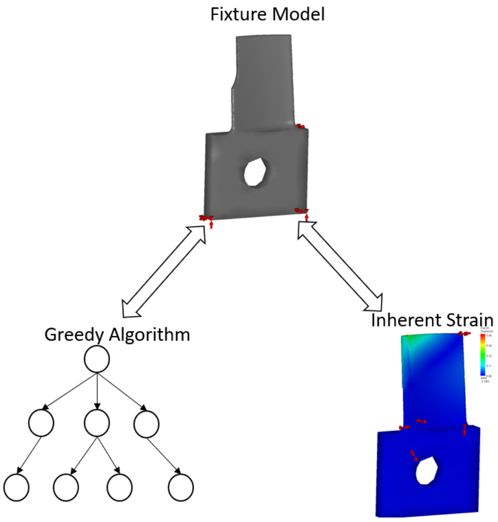


Fig. 2: Overview of the optimization approach

model. The greedy algorithm then provides the optimal fixture layout, which will be applied to the Inherent Strain approach for geometry prediction after the DED process. This proposed method is developed and implemented into the computer-aided tolerancing tool RD&T. In the following section, the results of this simulation-based optimization approach are presented on a reference workpiece.

3. Method Evaluation

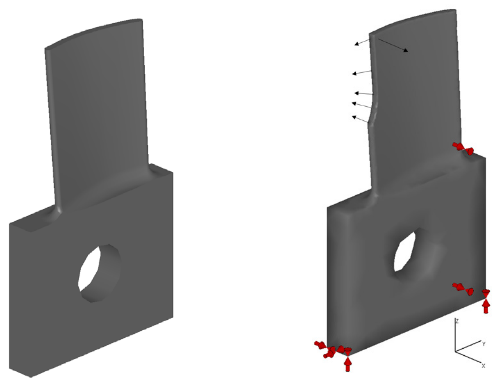
The proposed fixture layout optimization approach is applied to a reference workpiece, and the optimization results are compared with a reference fixture layout. In the following, the description of the reference workpiece is presented.

3.1. Reference assembly

The reference workpiece is an aero-engine compressor blade. This part has a dimension of approximately 65×40 millimeters. The material is of titanium alloy Ti-6Al-4V. The geometry of this workpiece is visualized in Fig.3. In Fig. 3a, the nominal geometry is shown. To prepare this part for additive remanufacturing, the part is cut out, Fig. 3b. The dimensions of the part are approximately 66 millimeters in length, the base width is 39 millimeters, and the thickness is 6 millimeters. The fixture layout optimization is solved for the cut-out geometry. The critical dimension set on the workpiece is on the normal-to-surface direction of the cut-out, ensuring minimum offset after the material addition, and the surface normal of the blade, shown by the thin arrows in Fig 3b, ensuring the functional requirements. The reference fixture layout is also presented in Fig.3b by the thick arrows.

3.2. Simulation and optimization results

The proposed fixture layout optimization for the additive remanufacturing process, Section 2, is applied to the reference



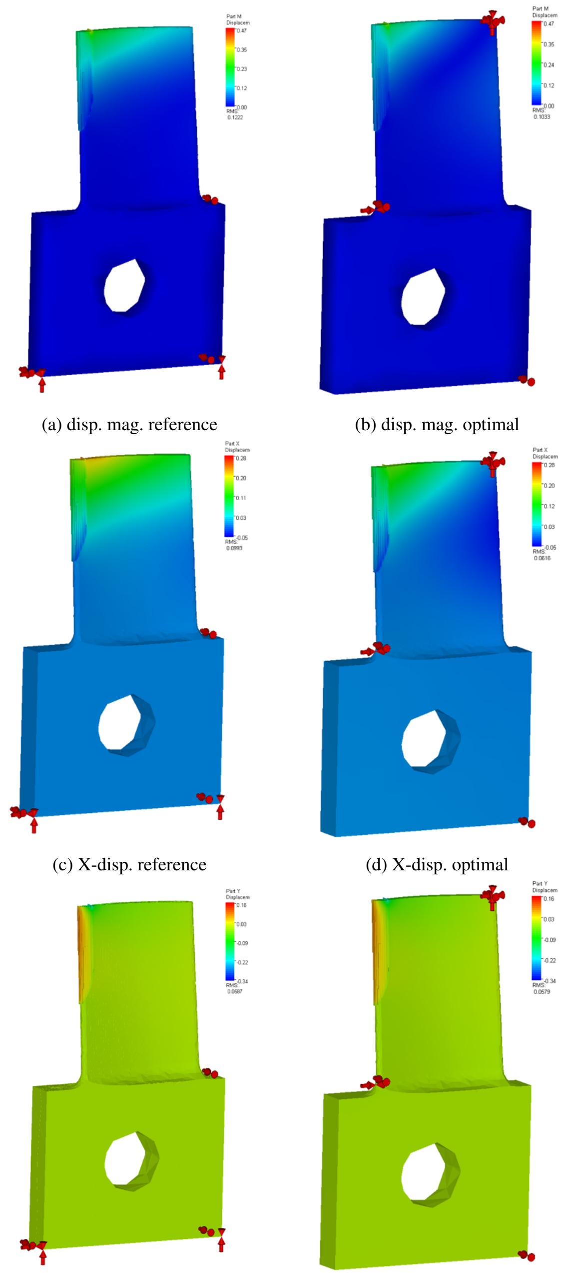
(a) Reference Workpiece Geometry (b) Cut-out geometry for repair

Fig. 3: Reference workpiece

part. The distance constraint L has been 15 millimeters from the tip of the cut-out in the normal direction, avoiding overheating of the fixture during the process. The initial reference fixture layout has been considered for comparison, and the results are presented in Fig. 4 and Table 1. Initially, the reference layout is fed to the fixture model and the greedy algorithm 2. Later, the optimal layout is retrieved from the optimization process, and the fixture model is updated accordingly. The inherent strain simulation is performed based on the retrieved boundary values, and the results are reported. The root mean square (RMS) of the displacements in all the nodes are reported in Table 1. For the magnitude of displacements, the optimal layout reduces the displacement by 15.47 % compared to the reference layout. This aspect is visualized in Fig. 4a and 4b, where the propagation of the displacement has been reduced close to the cut-out region. For the displacements in the X direction, the improvement has been more substantial, decreasing the RMS by 38%. This is also due to the small displacements in the X-direction over the whole part. In the Y-direction, the improvement achieved by the optimal layout is marginal and limited to 1.36% of the displacements of the reference layout. Based on the color plot of the displacements in the X-direction, Fig 4c and 4d, it can be discussed that the proposed optimal layout reduced the sensitivity in the cut-out region and, in general, the blade tip. Since the Y-direction displacements are not normal to the main curvature (prominently in X direction), smaller displacements are expected. This aspect is portrayed in 4e and 4f, where the differences in the additive remanufactured volume are marginal, independent of the fixture layout. However, the normal-to-surface and X-direction control of geometry in this component is crucial for functionality and was successfully improved by means of the proposed optimal layout.

Table 1: Optimization Results

Fixture Layout Optimization	Reference Layout RMS (mm)	Optimized RMS (mm)
Displacement Magnitude	0.1222	0.1033
Displacement in X-dir.	0.0993	0.0616
Displacement in Y-dir.	0.0587	0.0579



(a) disp. mag. reference (b) disp. mag. optimal

(c) X-disp. reference (d) X-disp. optimal

(e) Y-disp. reference (f) Y-disp. optimal

Fig. 4: Comparison of nodal displacement in reference and optimal layouts

4. Conclusion

The DED process is an additive manufacturing key technique for component repair, demanding precise control of process parameters to achieve the required geometric quality. The role of fixturing in this approach is critical for ensuring the geometric accuracy of the repaired product. This paper presents a simulation-based optimization framework designed to enhance the geometric quality of components remanufactured through the DED process. Initially, a fixture model is established before repair; a greedy algorithm is developed to solve the optimization problem associated with the optimal fixture layout problem, considering the process constraints. Finally, the geometric outcome is evaluated utilizing the inherent strain approach. This approach is applied to a compressor blade and the optimization results are evaluated with a reference fixture layout. The results show that the proposed method improves the geometric accuracy of the critical dimensions by up to 38%, reducing the displacement after repair.

Future studies include an integrated and computationally efficient optimization approach where the proposed algorithm is integrated into the inherent simulation approach. One key enabler, reducing the computational time for each simulation, is identifying the correlating factor prior to and after repair. In this study, it has been shown that the fixture placement to a specific threshold is coupled to the mesoscale simulation. This aspect can be further studied to establish a computationally efficient simulation-based optimization approach.

Acknowledgments

This work was carried out at the Wingquist Laboratory within the Area of Advance Production at Chalmers, and supported by the Swedish Energy Agency through the project Digital Twin fo AM-based Remanufacturing. The support is gratefully acknowledged.

Declarations

During the preparation of this work, the authors used ChatGPT in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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