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Integration of Reverse Engineering and Topology Optimization with Additive Manufacturing

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Abstract. Additive manufacturing (AM) is highly recommended for producing complex parts which mostly comes from the flexibility of integration with design aspects. Currently, design optimization techniques such as topology optimization (TO) is becoming common for the reduction of mass of the parts. However, there are some issues that are not well elaborated particularly the constraints coming to TO from the design of the parts and constraints coming from AM production. The case study presented in the paper represents a mechanical component with simple geometry, where reverse engineering (RE) and TO have been applied for CAD model creation and redesign, and production of the part using laser powder bed fusion AM process. The aim of the work has been to integrate RE, TO, and AM when the part with simple geometry becomes complex after redesigning in terms of shape, fabrication, and accuracy, taking into consideration the constraints to the TO coming from design and AM. Further investigation of the constraints from the design of the part and AM to the TO are required for the improvement of the whole process.

Keywords: Reverse Engineering, Topology Optimization, Additive Manufacturing.
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1 INTRODUCTION

Technological changes have affected product development in general. The main reasons among others can be considered the high degree of automation and speed of implementation. Reverse engineering (RE) and additive manufacturing (AM) are two of those technologies. Actually, these technologies are being seen as potentially acceptable in various industrial sectors.

RE is a process that extracts product information from the product itself [1] and restores the data for further use. This information can be, geometric, material, chemical, electrical, etc. Most often we have seen it as a process of gaining the CAD model from 3D points acquired by the optical scanner [2]. RE is considered as technology of reinvention, as a process leading to reconstruction and reproduction [3]. In most cases, RE is treated as an input for AM [4]. On the other side, AM was first developed by Charles W. Hull [5], and so far there have been many definitions of AM. AM is the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive and formative manufacturing methodologies [6]. Our research is categorized in metal AM [7], specifically in laser powder bed fusion (L-PBF). Research on the development perspective of L-PBF are presented in [8], while in [9] was presented the comparison of several AM technologies. Related to AM, design optimization is recommended and is already necessary for circumstances where technical and economic aspects are important issues. Today, some of the topology optimization (TO) methods [10, 11] are widely used as potential tools for redesigning the current geometry where in most cases the mass of the original design is reduced as a permanent target. TO mainly remove excess material based on boundary conditions and loads that are assigned to the original design and usually creates complex geometry.

However, our goal is to underline the importance of the influence of the constraints from the design of the part and from AM to the TO, which is not well presented in the literature. The limitation coming from the design side, the boundary condition for geometry, load, material, the percentage of reduction of mass, influence the outcome of TO, and also the limitation from AM, build direction and overhang angle influences the geometry of the redesigned part. The overall integrated process opens additional novelty of our investigation dealing with the quality control issue. The complexity of geometry coming from TO is solved in production with AM but complexity in quality control (QC) needs to be solved with some 3D scanning technique which is the tool of RE. That's gives the opportunity to compare the geometry of AM produced part with the final design with comes from TO and further with CNC produced part.

The general workflow (Figure 1) of the integrated process consists of four stages: RE stage, TO stage, AM stage, QC stage. In RE stage 3D scanning of the part is performed with the purpose of collecting geometry data for CAD reconstruction which finishes with the CAD model. For cases that are not going to TO stage this model can use an entry point for AM stage. TO stage starts with FEA of the existing geometry follow by TO and design validation of new geometry which concludes with the final design. The final design is the entry geometry from AM stage and model for the quality control stage. AM stage comprising of the setup of process parameters, build strategy (orientation, scanning pattern, placing supports) following by AM process, and post-processing operations (removing material and supports, polishing). Usually AM processed part required additional machining operation for reaching required tolerances and surface quality. QC stage performs 3D scanning of the AM final part and performs a comparison with the final part and final design geometries. Also, 2D comparison of the geometries is performed for certain cross-sections between AM and CNC produced parts. If the AM-produced part is additionally machined, then we can perform dimensional and surface roughness inspection. Based on this general approach we perform a case study which results are presented in the following sections.

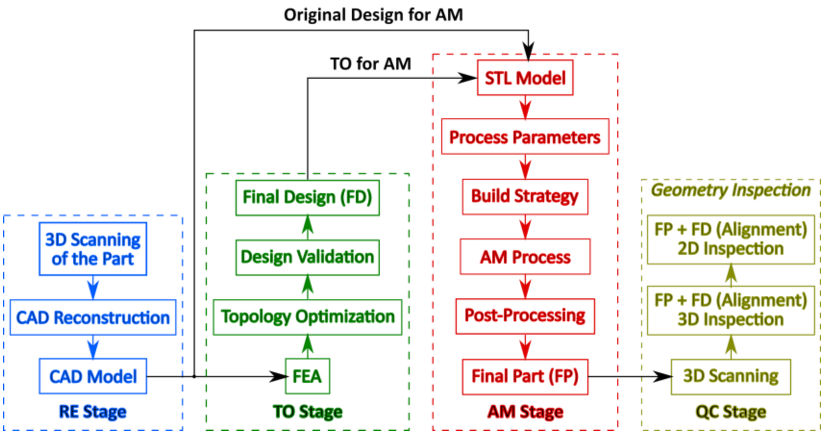

Figure 1: General workflow of integration of RE, TO, AM, and QC.

2 REVERSE ENGINEERING AND DESIGN OPTIMIZATION

2.1 Reverse Engineering of Reference Part

The model selected for investigation is mechanical bracket (reference part) and is presented with the following characteristics: 60 x 100 x 75 mm with the total mass of 0.463 kg. Fixed supports for TO are 4 holes at the bottom and load 25 kN is concentrated in the hole located at the top. The selection of the part has to do with the intention to investigate the influence of RE, TO, AM, and QC on the complexity of the part, influence of tolerances, and reduction of mass in one integrated process. Tolerance between centers of holes is ± 0.3 and from the bottom to the center of the upper hole is ± 0.2 with the surface quality of the whole Rz 1.6. Those were required from the original design of the reference part.

The RE framework including reconstruction of reference part is presented in Figure 2. The reference part (RP) was manufactured in CNC machining using 6082 aluminum alloy. The specific tolerance of the bearing hole is Ø25 J6. For data acquisition, 3D scanning technique using Go! SCAN 3D scanner was used. The CAD reconstruction process was used in our case and is explained for each step in [12]. Geomagic Design X software was used to implement it. After this, the obtained RP CAD model will be redesigned by reduction of mass using TO.

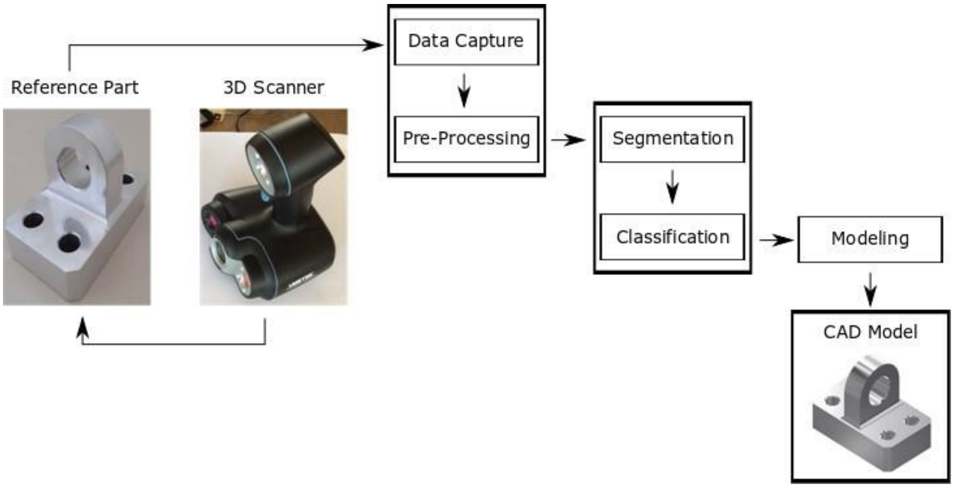

Figure 2: RE framework: reconstruction of reference part.

2.2 Redesign of Reference Part using Topology Optimization

Knowing that TO is widely used for different cases [13, 14], there are some methods that are used more efficiently. Two of the most important methods that are used in TO are: density based TO and level set based TO (LSTO). Visual representation of density based TO and LSTO for redesigned RP are presented below (Figure 3).

Figure 3: (left) Density TO of redesigned RP, (right) LSTO of redesigned RP.

These two methods have their advantages and disadvantages, but in our case, the LSTO was selected as the most appropriate method for the selected part. This method directly deals with the constraints presented in geometry during the optimization process [15]. Using this method, it is possible to calculate the optimum area while maintaining the selected region with supports or loads. An additional constraint, AM overhanging constraint is used. For each model +Z-axis as the build direction and 45° overhang angle are set, as means for reducing support structures in AM process. Our investigation has shown that those constraints coming from AM process influence the results of TO. Further investigation is required for the influence of the complexity of AM process on the TO process.

To determine design space for RP by applying LSTO for reduction of mass (ROM), two case studies were analyzed. First, the boundary conditions (prevented optimization regions) were set based on software (automatically), and in the second case study, are set manually. For each case study, two models from the RP were redesigned. The TO workflow is presented in Figure 4.

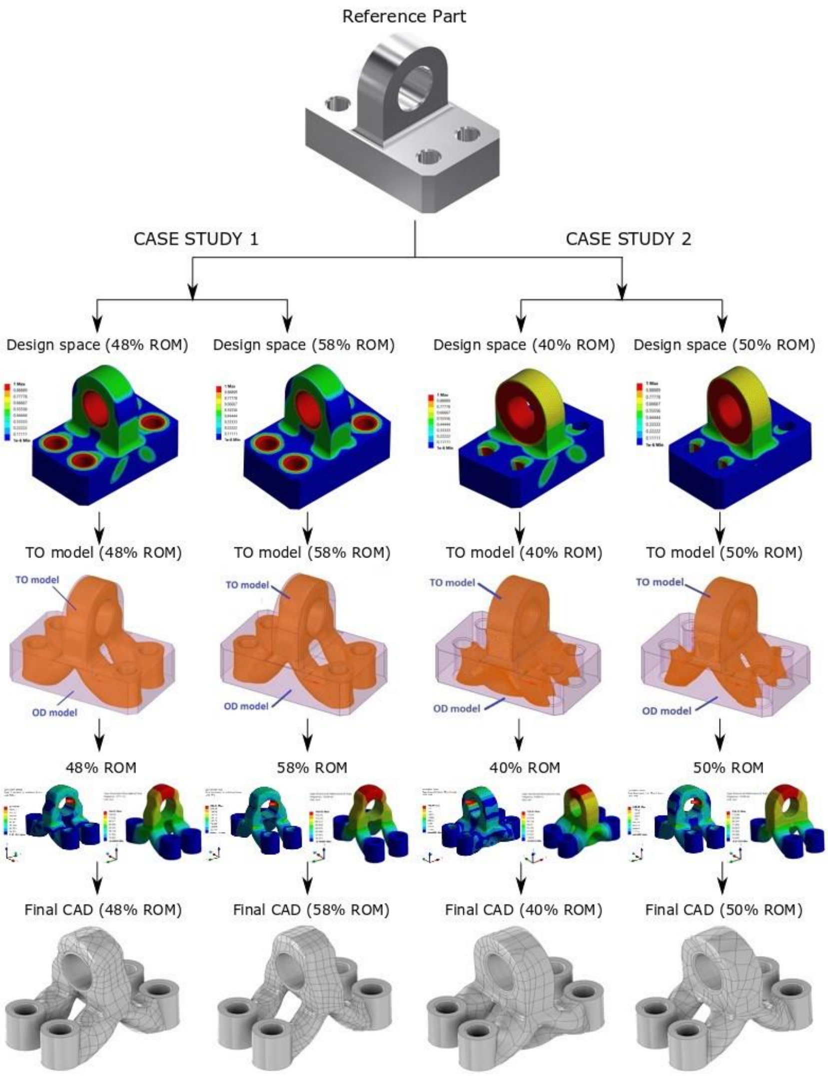

Figure 4: TO workflow for final redesigned CAD models.

After completing the TO process, the STL models are rough and irregular in different features throughout the geometry. For this reason, the same geometries are transferred for the RE process in SpaceClaim software. After some corrections, the final STL models are obtained. The last step is CAD model creation by using Geomagic Design X software. For each model obtained by the TO-RE process, finite element analysis (FEA) validation (static and modal) must be performed, so that we can be ascertained that even after changes in geometry due to changes in the total mass, key factors such as functionality and stiffness will be preserved preferably at approximate values as RP case or below the limit of yield strength allowed for the relevant material. Tetrahedron with homogeneous element sizes was selected as the mesh method. Mesh elements size for the contour was 2 mm, while for fixed supports and bearing load regions, 1 mm was select. The overall TO process is limited to 500 maximum iterations and 0.1% convergence accuracy. The primary objective of the TO is to minimize the difference between the original design and the redesigned model based on static analysis. In our investigation, the reduction of the total mass is set to be 50%. ANSYS software was used in all cases for TO and FEA validation. The boundary conditions and the load are shown in Figure 5.

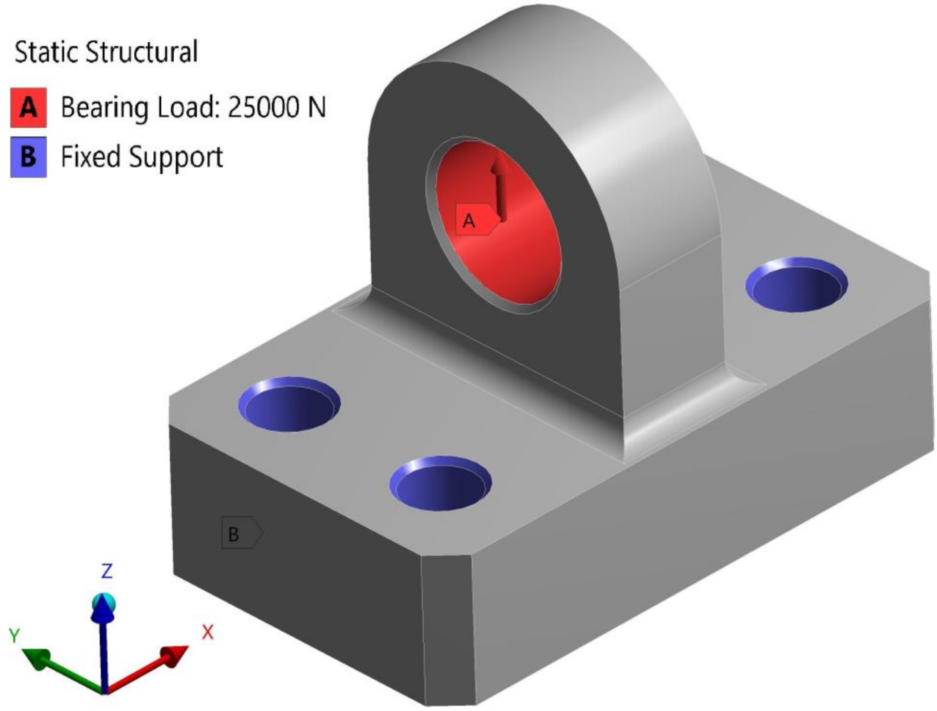

Figure 5: Boundary conditions and load configuration of the investigated part.

From the case studies presented, four different models were obtained. In the first case study, from RP through TO and RE process two models were generated. The first model reduced RP mass by 48% while the second model reduced RP mass by 58%. In both models, the LSTO method was used, where the prevented region is set automatically. In the second case study, from RP through TO and RE process two models were generated, also. The RP mass is reduced by 40% and 50% respectively. In both models the LSTO method was used, where the prevented regions were set manually. The region where the maximum load is present was protected by recommending to put a maximum of material and removed from regions where there is no concentration of stress. The summary of the results and all data collected for each model separately are presented in Table 1.

Design	*Mass (kg)*	*von Mises (MPa)*	*Deformation in Z direction (mm)*	*Safety Factor*	*Ratio of effective mass to total mass (Z direction)*
RP	0.463	200.19	0.077	1.39	0.557
48% ROM	0.239	224.00	0.092	1.25	0.560
58% ROM	0.195	237.74	0.100	1.17	0.529
40% ROM	0.276	199.91	0.082	1.40	0.625
50% ROM	0.234	200.85	0.088	1.39	0.593

Table 1: Summary results of different redesigned part models.

From Table 1 we can conclude that 40% ROM and 50% ROM are closer to RP than other models. The 50% ROM model is efficient only at the total mass which is 10% lighter in comparison with 40% ROM and other values are almost similar with small differences according to Table 1. Finally, we select the 50% ROM model (Figure 6) as the appropriate model for production with AM and further investigation including accuracy inspection.

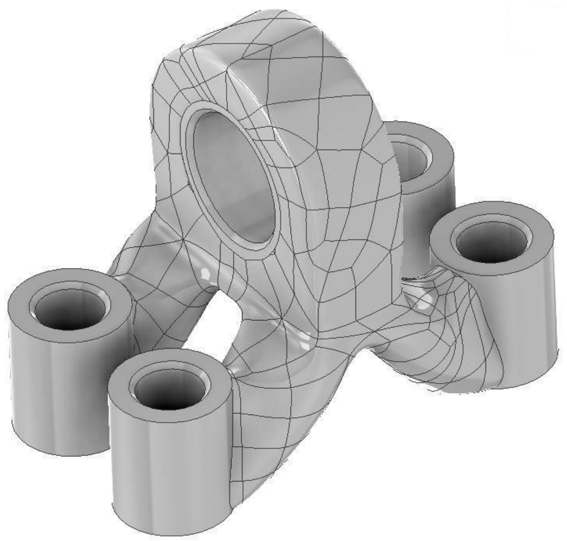

Figure 6: Final CAD 50% ROM model.

3 EXPERIMENTAL INVESTIGATION

3.1 Additive Manufacturing of Redesigned Part

Production with L-PBF process was performed in the Renishaw AM 400 machine using AlSi10Mg material. The production process in AM starts by completing the design and preparation of the STL model. The process setup starts with the preparation of the machine by filling the tank with the material, leveling the build platform, heating it to the required temperature, and filling the chamber with inert gas (argon). Once the machine parameters presented in Table 2 are set, the production process based on the build strategy begins with building a support structure until all layers are executed for completion of the part.

Layer Thickness (mm)	Laser Power (W)	Scan Speed (mm/s)	Hatch Spacing (mm)
0.03	395	1500	0.14

Table 2: L-PBF process parameters.

After completing the production process according to the 3D CAD model, the part must undergo the process of removal of powder material which covers the entire part up to the maximum height. Removing the powder enables the next step, removing the supports (Figure 7 left). As is concerns the comparison between the quantity of support material between the reference part and redesigned part, we performed simulation analysis which shown that the supports of the reference part used 0.01 kg and redesigned part used 0.03 kg for their supports. The difference comes from the complexity of geometry, which is negligible having in mind reduction of mass 0.23 kg (50%). If we compare the lost materiel in the case of reference part, it is 1 kg and in the redesign part 0.5 kg. Once the supports have been removed from the part, it is necessary to apply blasting with corundum to remove and clean any small remnants of supports and other impurities. This process is used for polishing the surfaces of the part, also. This process is mechanical treatment with grain corundum (a crystalline form of aluminum oxide) as an abrasive shot with high pressure. The completed part is presented in Figure 7 right.

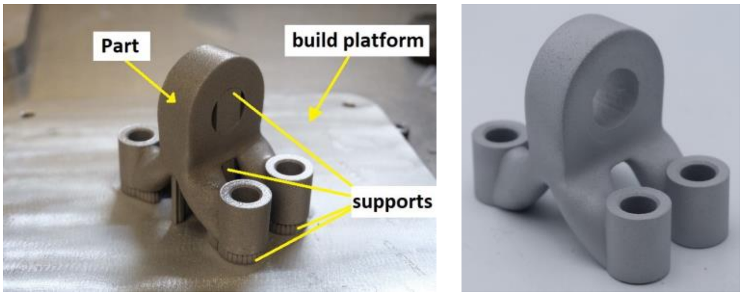

Figure 7: (left) Part with supports in build platform, (right) AM part (without finishing operation).

Furthermore, due to the tolerance required for central hole Ø25 J6, a smaller hole machining was required. The CAD model assembly and the physical part mounted on the CNC machine for machining the hole are presented in Figure 8.

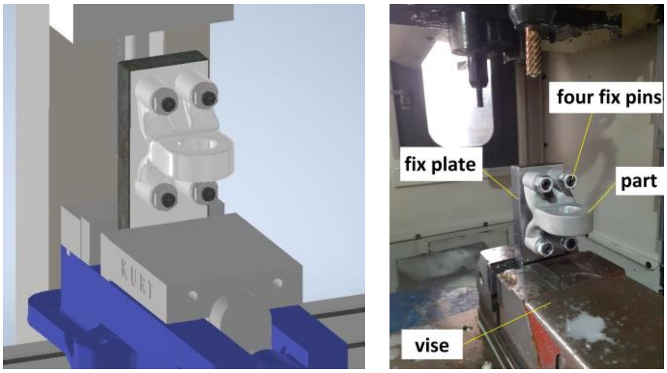

Figure 8: Finishing operation for the center hole: (left) CAD assembly, (right) physical AM part mounted in the CNC machine.

The final part, including the finishing operation, is presented in Figure 9. The part has been successfully AM produced according to the required technical dimension and machined according to tolerances and thus is functional for practical use.

Figure 9: Final AM part.

3.2 Accuracy Inspection of Part Produced

Accuracy is a very important factor, especially in industrial applications. In some cases, the accuracy comparison is made within a production technology or between different technologies. In nowadays we have several types of measurement methods [16],[17],[18]. In this case, the non-contact method through structured light technology was chosen and for measurement, Go! SCAN 3D scanner was used. Before starting the 3D scanning process, some preliminary preparations should be performed, including spraying the part with an anti-reflective material, placing markers to locate the part and space where the part is located, and determining the positions needed to scan the entire geometry of the part. Some of the images are shown in Figure 10.

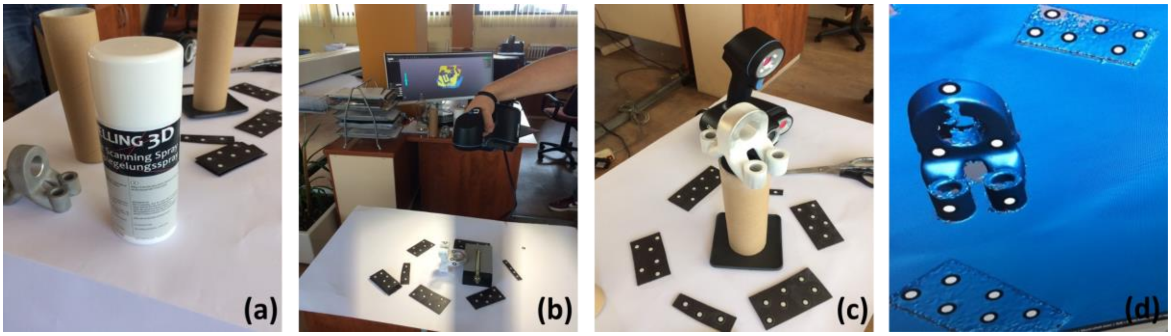

Figure 10: 3D scanning process: (a) anti reflection spray, (b) location marks in part, (c) location marks around space, (d) point cloud data after 3D scanning.

After the completion of the 3D scanning process, the geometry data are stored in the software. Depending on the device and the procedure, the point cloud data (PCD) must be cleaned from possible errors and noise that comes from acquired data. After completing the scanning process, the PCD of the AM model is compared with the 3D CAD reference model (3D CADRM) where the PCD is superimposed on the reference model using the Geomagic Control X software. The model has been successfully projected in the 3D CADRM so we can obtain data for possible deviations for the respective geometry. The method used to measure or determine the relative deviation between the PCD and the 3D CADRM is the root mean square (RMS) method. By this method, we can measure the distance between the data of the surfaces which have the same coordinate system data. Accuracy for the dataset is determined by locating where to obtain the data and then the largest value of RMS difference between them indicates the largest error for the measured region. Figure 11 shows the relative values of PCD and 3D CADRM between the CAD model and AM measure model. The absolute value of the difference in mm can be obtained by pointing certain position on the geometry of the part.

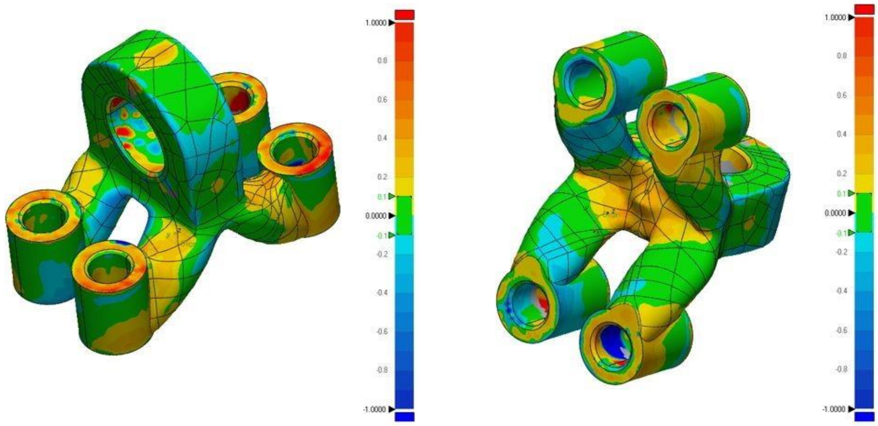

Figure 11: 3D inspection for AM part.

3D inspection data for AM part are presented in Table 3.

Min. (mm)	-6.5707
Max. (mm)	6.5756
Avg. (mm)	0.0372
RMS (mm)	0.3264
Std. Dev. (mm)	0.3242
Var. (mm)	0.1051
+Avg. (mm)	0.2099
-Avg. (mm)	-0.1364
In Tol.(%)	45.0112
Out Tol.(%)	54.9888
Over Tol.(%)	32.5115
Under Tol.(%)	22.4772

Table 3: 3D inspection data.

From Table 3 we can see all the data of 3D comparison between PCD and 3D CADRM. The important accuracy data like RMS value is 0.3246 mm. When we talk about accuracy, we are always referring to the complex geometry which covers most of the surface of the part and it is the priority of the investigation. Since the part has a complex geometry, to increase the reliability of the measurement and to compare with the part produced by CNC machining, some of the positions in the X, Y, Z reference planes have been selected as 2D inspection. The specific positions (1 to 8) are presented in Figure 12.

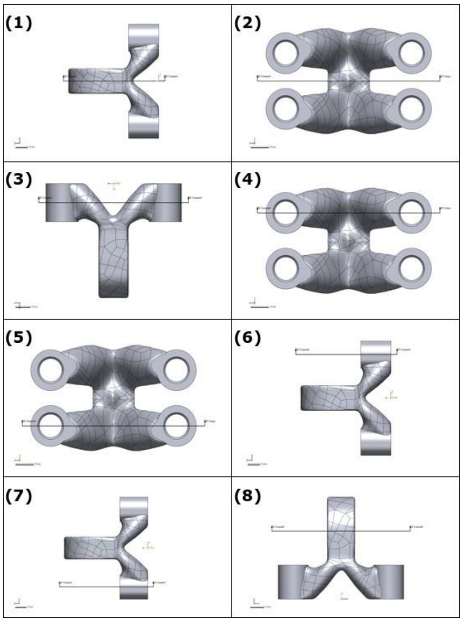

Figure 12: 2D inspection with specific reference plane.

The results of 2D inspection (RMS and standard deviation) for the part produced with AM and CNC part are presented (Figure 13).

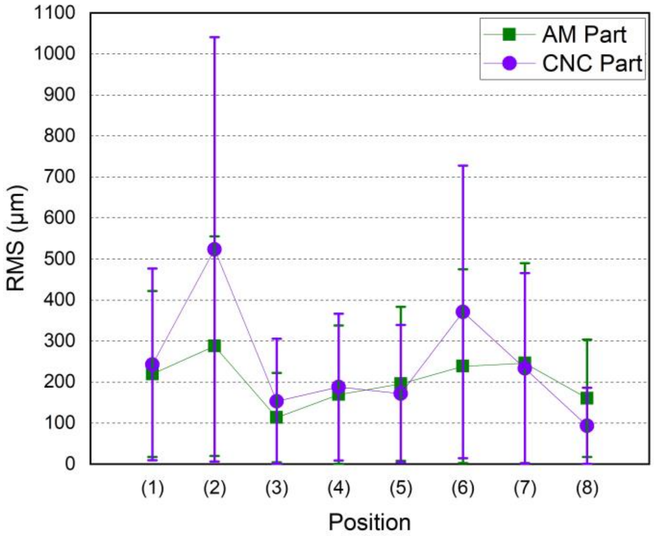

Figure 13: 2D inspection for parts produced with AM and CNC.

Based on Figure 13 we can conclude that AM produced part has five positions with higher accuracy in comparison with CNC produced part. It comes from the complexity of the shape which is fundamental difficulty for CNC machining because required appropriate tool and number of synchronized axis. AM do not require tools and many synchronized axes.

4 CONCLUSIONS

This paper deals with the integration of RE and TO with AM for the design and production of complex parts. The general workflow of the integrated process has been shown. The case study, mechanical bracket, was presented to show the complexity of the whole process coming from the changing of the geometry after TO. Based on the performed analyses and generated results, can be concluded:

- The integration of RE and TO with AM is a productive method for the design and production of complex parts. Additionally, the flexibility of the process is improved because of the absence of additional tools and auxiliary equipment usually required by traditional processes.
- For the redesign of the part and reduction of mass, LSTO method was used. From the simulation analysis use of more supporting material for a redesigned parts comes from the complexity of geometry. The difference is negligible having in mind the overall reduction of mass (50%) and lost material in AM.
- The use of 3D scanner for quality control has shown that this is a very flexible tool for the dimensional analysis of the parts, especially with complex geometry. It can be easily integrated into other systems. From the particular case study of the geometry of the investigated parts can be concluded that the geometry of AM produced complex part is more accurate if produced with AM in comparison with CNC machining.

The integrated process of RE, TO, AM, and QC has shown that further investigation is required in defining the constraints from design and AM to TO. These will improve the TO with the relevant constraints coming from both RE and AM which will produce more optimal solutions for redesign, production, and quality control of the parts.

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