A case study on 3D scanning, digital reparation and rapid metal additive manufacturing of a centrifugal impeller

N Kladovasilakis\textsuperscript{1,2}, T Kontodina\textsuperscript{1}, P Charalampous\textsuperscript{1}, I Kostavelis\textsuperscript{1}, D Tzetis\textsuperscript{2} and D Tzovaras\textsuperscript{1}

\textsuperscript{1}Centre for Research and Technology Hellas – Information Technologies Institute (CERTH/ITI), Thessaloniki, Greece
\textsuperscript{2}International Hellenic University, School of Science and Technology, Digital Manufacturing and Materials Characterization Laboratory, Thessaloniki, Greece

\textsuperscript{*}Corresponding author’s e-mail: nikoklad@iti.gr

Abstract. This paper demonstrates a comprehensive method for digital restoration and rapid manufacturing of a fully functional mechanical component. A damaged centrifugal impeller of an automotive engine was reverse-engineered via a 3D laser scanner, with which the 3D model of the investigated object was digitally captured. Utilizing advanced design software and surface modelling, the missing fragments were restored and the impeller’s 3D digital model was reconstructed. Metal additive manufacturing technology and more specifically the Selective Laser Melting (SLM) technique was employed to construct a functional metal impeller. Stainless steel 17-4 PH powder was used as the printed material. To ensure the exploited powder was appropriate for the part to be manufactured, we applied characterization of the feedstock material was conducted through two different characterization methods, i.e. granulometry and scanning electron microscopy (SEM) combined with energy-dispersive X-ray spectroscopy (EDX). Furthermore, Surface Distance Maps (SDM) were calculated to correlate the geometrical deviations between the physical 3D printed part and the digital model in order to examine the accuracy of the applied method.

1. Introduction

Additive Manufacturing (AM) is a rapidly evolving fabrication technology that is utilized among others for the production of complex and advanced constructs [1]. Nowadays, there is a plethora of different AM methods, such as material extrusion, powder bed fusion (PBF), material jetting etc. [2]. Almost any material can be 3D printed (plastics, ceramics, metals etc.) using the proper AM method [3]. In the last three decades, AM techniques were mainly used for research as well as for rapid prototyping purposes. However, in recent years, fully functional components are produced in various scientific fields like automotive, aeronautic and medical industries. More specifically, metal AM technologies are proved to be a sustainable and cost-efficient alternative to machining and casting for the fabrication of relatively small and geometrical complex metal components [4]. The most widespread metal AM method is the Selective Laser Melting (SLM) which belongs to the PBF category. PBF processes utilize a high-powered laser in order to selectively fuse small particles of metal, plastic or ceramic. The metal powder is the feedstock material and is spread on a build plate where the laser beam melts the powder particles...
according to the part’s cross-section geometry creating that way a thin layer of the desired geometry. In the next step, the powder bed descends for a layer thickness and the process is repeated until the entire geometry of the product is created [1]. Combining this metal AM technique with reverse engineering methods, it is possible to rapidly redesign and construct metal spare parts with particularly complex geometrical characteristics like impellers, turbines, customized parts etc. 3D scanning technologies are suitable for reverse engineering applications providing with high accuracy the digital depiction of a physical object. The most well-known 3D scanning techniques that can provide reconstruction with accuracy adequate for real-life applications are the structured-light and laser scanning [5]. 3D Laser scanning is a non-destructive method that digitally captures the external geometry of an object, utilizing a line of laser light. The acquired data from these scanning procedures could be processed in order to extract a digital 3D model that is fully editable in a CAD software. Therefore, the process of rapid manufacturing of a fully functional spare part could be divided into three steps. The first one is the 3D scanning procedure of the physical object; the second one requires the handling of the acquired data to obtain the digital 3D model and the last one comprises the metal fabrication of the desired component.

The main objective of the current paper is to prove that reconstruction and manufacturing of a functional mechanical component is feasible in order to replace an already damaged one. To this end, a metal centrifugal impeller from an automotive turbocharging system, which was heavily damaged, constitutes the use case of the present work. Centrifugal impellers for automotive applications are relatively small objects with high geometrical complexity. Hence, the majority of them are fabricated via 5 axis CNC machining processes in order to achieve the precise geometry coupled high-quality surface finish [6]. However, material removal procedures are generally time consuming and unprofitable for the fabrication of a prototype or a small batch of products. Hereupon, this study proposes a method to obtain the digital 3D model of a damaged component through 3D scanning methods and by employing rapid manufacturing techniques like metal AM technologies to replace the impaired part. Figure 1 illustrates an overview of the applied methodology.

![Figure 1. Flowchart of the overall procedure.](image)

2. Methods and Materials

2.1. 3D Scanning & Metal 3D printing

According to the flowchart exhibited figure 1, the first phase of the employed procedure includes the 3D scanning of a damaged impeller. Taking into account that the impeller’s smallest dimension is the thickness of each blade (≈300μm), a high-resolution 3D scanner is required. Moreover, the 3D scanner should be able to acquire data from multiple angles due to the object’s high complexity. Thus, the NextEngine 3D laser scanner has been employed for this process as presented in figure 2a, where the scanning process is portrayed using the specific laser scanner. The 3D laser scanner contains two arrays of four solid state lasers with 650nm wavelength, two 5.0-megapixel cameras and two lights for capturing images. Furthermore, a 360° turn-table was used in order to fully capture the geometry of the object and to facilitate the mechanical alignment between scans during the post-processing procedure. Moreover, the scanner provides texture density up to 500dpi and dimensional accuracy up to ± 125μm with scanning speed of 50,000 points per second. Then, ScanStudio software was used for the data
acquisition process as well as for various post-processing procedures. Finally, MeshMixer and SolidWorks software were applied for further processing of the scanning data extracting that way an editable CAD file. In order to reconstruct the geometry of the damaged impeller, 3D scanning and surface modelling techniques were employed to identify the missing parts of the inspected model. In particular, taking into account the symmetry of the object, it was feasible to assess the missing fragments of the damaged impeller. Hereupon, the digital 3D model of the impeller was defined including recovery of the damaged part.

### Table 1. 3D printing parameters used for the metal AM process.

| Printing parameters                  | Values       |
|--------------------------------------|--------------|
| Layer height                         | 25μm         |
| Hatching distance                    | 30μm         |
| Scan speed                           | 1200 mm/s    |
| Laser power                          | 107W         |
| Volumetric Energy Density (VED)      | 118.89 J/mm³ |
| Spot size                            | 50μm         |
| Oxygen percentage                    | 1.00% (upper limit) |

In the next step, the fabrication of a new impeller utilizing a metal AM technology (SLM) took place. For the metal 3D printing process, the ORLAS Creator metal 3D printer was employed which belongs to the PBF/SLM metal 3D printing category. The specific printer possesses a continuous Yb fibre laser beam with 250Watt maximum power coupled with a wavelength of 1067 nm. Furthermore, ORLAS Creator achieves high printing accuracy of 25μm at z direction due to the respectively small layer height. A wide range of metal powder materials could be printed via this metal 3D printer. In the context of this study, stainless steel 17-4 PH powder was used as the feedstock material due to its advanced mechanical properties [7]. Table 1 documents the major printing parameters used for the construction of the new impeller. It is worth mentioning that the lowest available values were chosen for hatching distance and layer height in order to achieve the maximum dimensional accuracy. According to the literature [8], the optimum energy density was attained through the regulation of the laser power and scan speed values.

Figure 2b illustrates the employed metal 3D printer and the printing process inside the building chamber.

2.2. Material Characterization

One of the most crucial parameters for SLM technology that possesses a severe impact on the outcome of the metal 3D printing process is the quality of the powder itself [9]. For that reason, it is essential to conduct material characterization procedures on the feedstock metal powder. In the present work, for the characterization phase, the technique used was Scanning Electron Microscope (SEM) coupled with Energy-Dispersive X-ray Spectroscopy (EDX). The Phenom ProX Desktop SEM was employed for
the investigation of the powder, which was attached on the stub with a carbon tape. The grain morphology of SS 17-4 PH powder sample was studied and the results have shown certain irregular grain shapes deviating from the spherical pattern. Furthermore, an indicative particle size distribution (PSD) was obtained measuring various powder’s samples on different scattered regions. The EDX analysis was conducted in order to identify the precise chemical composition of the metal powder and test the presence of any impurities. Figure 3a presents the electromagnetic emissions spectrum of the SS 17-4 PH powder. This analysis incorporates spectra exhibiting peaks corresponding to the elements of the investigated sample. Thus, the chemical composition of the metal alloy at weight percent was identified and listed at the right part of figure 3a. It is worth noting that the EDX analysis is in good agreement with the manufacturer datasheet (OC Oerlikon). Figure 3b illustrates an indicative PSD of a virgin SS 17-4 PH powder, which has been sieved with a 63μm mesh. PSD curve follows a typical positive skew distribution (shifted to the left). PSD outcomes are used to identify the median particle sizes of the inspected powder material in terms of size gauges (D_{10}, D_{50} and D_{90}). In the conducted experiments, D_{10}=11.5 μm indicating that the 10% of the powder sample is less than 11.5 μm, D_{50}= 16.6 μm which corresponds to the median value and D_{90}=27 μm displaying that 90% of the particles of the examined sample are smaller than this size. Figure 3c examines the morphology of the powder’s grain, where it can be observed that the majority of the particles possess a spherical shape; however, there are some grains that retain an elliptical shape and few with irregular shapes.

**Figure 3.** (a) EDX analysis and chemical composition of SS 17-4 PH powder; (b) Indicative PSD of powder’s sample; (c) SEM image of SS 17-4 PH particles.
3. Results

The evaluation of the proposed methodology includes the dimensional inspection of the printed metal impeller compared to its digitally reconstructed 3D digital model. In order to maximize the precision, various parameters were adjusted on the 3D laser scanner regarding the positioning, the number of divisions, the resolution (i.e. points/mm²), the target and the range of the scanning process. Initially, the object was coated with white powder to avoid noise and reflections. Afterwards, the object was placed on a turntable base, approximately 230mm from the scanner, on various orientations (i.e. horizontally, vertically and in front of the scanning field) ensuring that a sufficient number of points were captured for its geometrical reconstruction. Furthermore, several post-process steps were conducted utilizing the appropriate editing tools like trimming, alignment and fusion of the scans in order to optimize and refine the geometrical characteristic of the metal 3D printed impeller.

![Figure 4](image_url)

**Figure 4.** (a) Depiction of missing fragments on the digital 3D model before reparation; (b) 3D printed metal impeller; (c) Surface distance map for the reconstructed impeller.

Figure 4 summarizes the results of the present work. In figure 4a, the missing fragments of the damaged impeller as well as the reconstructed digital 3D model are illustrated. Figure 4b portrays the 3D printed metal impeller as it was constructed without any post-processing process (sandblast, shot-peening etc.). The Artec Studio software was employed to convert the input data (point clouds) from the scanning process to a fully contoured map. In order to quantify the accuracy of the applied methodology and to specify a numerical quantity concerning the quality of the printed impeller, Surface Distance Maps (SDM) were calculated correlating the dimensional deviations between the 3D digital model and the physical printed one as shown in figure 4c. Blue color represents negative maximum deviation and the red color is equivalent to the maximum positive deviation. In contrast, green color corresponds to the minimum dimensional deviation between the examined surfaces. Finally, the accuracy of the procedure was assessed via the calculation of the Mean Absolute Error (MAE) exhibiting that the printed object is in sufficient agreement with the digital one, as the MAE is equal to 0.142 mm. Therefore, implementing the suggested scan-to-print technique, it was feasible to accurately depict and manufacture a complex component in a short time period. Hence, this procedure provides an additional tool for reserve engineering approaches of geometrical complex parts compared to traditional methods. Finally, utilizing metal AM, the fabrication process was completed in a matter of hours compared to time-consuming CNC milling procedures.
4. Conclusions

The current paper presented the workflow of a scan-to-print methodology in order to replace damaged spare parts with new ones constructed via a metal AM 3D printer. More specifically, a damaged centrifugal impeller was scanned and by utilizing surface modelling and advanced design software, it was feasible to identify the object's missing fragments obtaining that way its digital 3D model. Prior to the metal 3D printing process, the characterization of feedstock was conducted through granulometry and SEM coupled with EDX in order to ensure good quality of the selected powder. In the next step, the optimal printing parameters were selected and the metal 3D printing procedure was initiated. The 3D printed impeller’s dimensions and morphological characteristics were evaluated via a laser scanner and the geometrical deviations from its digital 3D model were computed. The results showed that the reparation of functional spare parts could be achieved providing high dimensional accuracy as the deviations of the printed impeller was relatively small. Finally, in order to elaborate the research on the functionality of customized metal AM components, it is necessary to focus in the future on the evaluation of their mechanical behavior under various operating conditions.

Acknowledgments

We acknowledge support of this work by the project “Intelligent και Automated Systems for enabling the Design, Simulation and Development of Integrated Processes and Products - ODYSSEAS” (MIS 5002462) which is implemented under the “Action for the Strategic Development on the Research and Technological Sector”, funded by the Operational Programme "Competitiveness, Entrepreneurship and Innovation" (NSRF 2014-2020) and co-financed by Greece and the European Union (European Regional Development Fund).

References

[1] Gibson I, Rosen DW and Stucker B 2010 Additive Manufacturing Technologies, First ed., New York: Springer, https://doi.org/10.1007/978-1-4939-2113-3
[2] Charalampous P, Kostavelis I and Tzovaras D 2020 Non-destructive quality control methods in additive manufacturing: a survey, Rapid Prototyping Journal, 26:4:777-790, https://doi.org/10.1108/RPJ-08-2019-0224
[3] Frazier W E 2014 Metal Additive Manufacturing: A Review, Journal of Materials Engineering and Performance, 23, 1917–1928, https://doi.org/10.1007/s11665-014-0958-z
[4] Gebisa A W and Lem H G 2017 A case study on topology optimized design for additive manufacturing, IOP Conference Series: Materials Science and Engineering, 276:12-26, https://doi.org/10.1088/1757-899x/276/1/012026
[5] Karatas O H and Toy E 2014 Three-dimensional imaging techniques: A literature review Eur J Dent. 8(1):132-140, https://doi.org/10.4103/1305-7456.126269
[6] Huber M, et al. 2018 Process Setup for Manufacturing of a Pump Impeller by Selective Laser Melting (Meboldt M and Klahn C. editors) Industrializing Additive Manufacturing - Proceedings of Additive Manufacturing in Products and Applications AMPA2017 (Springer, Cham.) https://doi.org/10.1007/978-3-319-66866-6_24
[7] Lin X, Cao Y, Wu X, Yang H, Chen J and Huang W 2012 Microstructure and mechanical properties of laser forming repaired 17-4PH stainless steel, Materials Science and Engineering: A, 553, 80-88, https://doi.org/10.1016/j.msea.2012.05.095
[8] Aboutaleb A M, Bian L, Elwany A, Shamsaei N, Thompson S M and Tapia G 2017 Accelerated process optimization for laser-based additive manufacturing by leveraging similar prior studies, ISE Transactions, 49:1, 31-44, https://doi.org/10.1080/0740817X.2016.1189629
[9] Maamoun A H, Xue Y F, Elbestawi M A and Veldhuis S C 2018 Effect of Selective Laser Melting Process Parameters on the Quality of Al Alloy Parts: Powder Characterization, Density, Surface Roughness and Dimensional Accuracy, Materials, 11:2343, https://doi.org/10.3390/ma11122343