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Prediction of Residual Stresses and Distortion in Complex Metallic Components Using Additive Manufacturing Process Simulation

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ABSTRACT: In recent years, additive manufacturing (AM) has become a real area of interest for the fabrication of metallic parts in industries like aerospace and defence, industrial machinery, automotive industry etc. However, there are still some limitations to this application including distortion and residual stresses due to the rapid solidification of melted powders, and microstructural changes because of cooling rates. In particular, due to physical phenomena inherent to the process of melting a small amount of material upon a larger, cooler body, the expansion and contraction of both the added material and the existing component led to the permanent warping of the part and can leave high residual stresses. As a result, these stresses lead to distortions of the building part and possibly crack initiation, propagation, and complete failure during printing. In an AM system, the final quality of a metallic part depends on many process parameters, which are normally optimized by a series of experiments on AM machines. To avoid costly trial- and error prototype approaches to achieve successful part printing, the numerical simulation dedicated to the AM process is an alternative for metallic parts fabricated by additive manufacturing. The main aim of this work is to demonstrate the additive manufacturing process simulation by finite element analysis approach. The ANSYS AM module is used to simulate the entire additive manufacturing process simulation including pre-processing of AM simulation, setting process parameters, and thermal-structural analysis to predict the residual stresses and distortion. This work is mainly focused on the effect of supporting structures to decrease distortion and residual stresses. In this work, the closed impeller of the centrifugal pump casing is considered to demonstrate the simulation approach.

KEYWORDS: Additive Manufacturing, AM Suite, Residual Stress, Distortion, SLM, ANSYS.

I. INTRODUCTION

Over the last decade, Additive Manufacturing (AM) technology has been established as a sustainable and cost-effective solution to traditional metallic manufacturing processes, resulting in innovative design opportunities for complex parts. Among a large number of AM-classified processes [2], Laser Direct Energy Deposition (LDED) and powder-bed-based processes, such as Selective Laser Melting (SLM), are considered the most important and dominant metal additive manufacturing techniques currently available in the market [3,4,13]. Due to the rapid solidification of melted metal powders and high thermal gradients of non-uniform surface heating in the metal AM processes, significant residual stresses are created within the part as well as the build platform [5–7]. As a result, these stresses lead to distortions of the building part and possibly crack initiation and complete failure during printing, if their magnitudes are above the yield strength or tensile strength, respectively [8]. In order to avoid costly trial-and-error approaches to achieve successful part printing, it is important to investigate and quantify the level of residual stresses and distortion during and after the additive manufacturing process for full-scale and complex 3D components [9]. Simulation-driven AM can be used to predict distortion and residual stresses before proceeding with the printing process. Additive manufacturing simulation through commercial FEA tools is an alternative approach to reduce the amount of unused inventory, manufacture custom parts, and rapid prototyping. The use of these simulation techniques during the product and process design reduces the number of trials before part printing compressing the product development cycle. Commercial finite element-based software packages have recently released AM modules to predict printed part microstructure, stresses, and distortions. In this work, the Ansys Additive suite is used to demonstrate the role of the

orientation of the built and support structures to provide a successful product. The closed impeller of the centrifugal pump was considered to demonstrate the procedure of AM process simulation. The objective of this work is to predict the distortion and residual stresses of the closed impeller at various orientations of building parts and proper support structures. In oil and gas applications, the casting of pump components like closed impellers in the required quality is difficult or impossible because of their low wall thickness and their unfavourable ratio of impeller diameter to channel height [9]. Selective Laser Melting (SLM), one of the primary metal additive manufacturing technologies, is well-suited to be used for such impellers as the full potential of SLM can be achieved best with such small, complex parts. Improper orientation of the impeller and insufficient support structures lead to unsuccessful manufacturing components as shown in Figure 1.

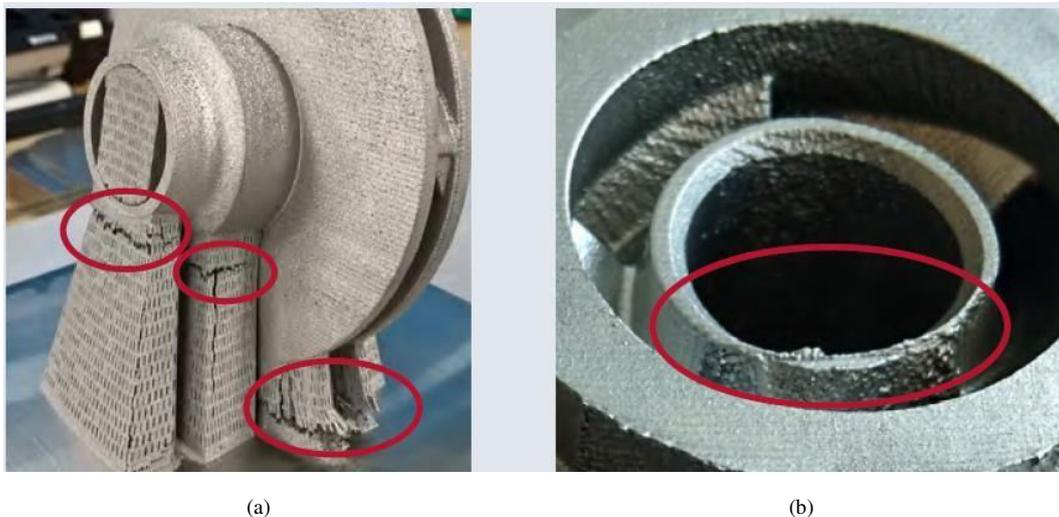


Fig.1. Manufacturing trial of the first support design iteration. (a) showing large-scale cracking in several areas. (b) After support removal (and post-machining trial), severe geometric irregularity in the lower part of the hub [9]

II. ADDITIVE MANUFACTURING SIMULATION APPROACH

1.1 3D MODEL

Using a pre-defined impeller blade profile and body, the computer-aided design (CAD) model for the closed impeller was obtained using Solid Works software (Fig.2.1).

1.2 SIMULATION APPROACH THROUGH ANSYS ADDITIVE PRINT (AAP)

AAP is a user-oriented software for simplified simulation of SLM processes, based on material input parameters: elastic modulus and Poisson ratio as well as yield strength and bilinear elastic-plastic deformation characteristics. Within AAP, the SLM build-up process is simulated by layer-wise activation of voxel elements that initially all feature the same inherent strain. After activation of every voxel layer, the deformation at mechanical equilibrium is calculated [10]. The software offers both purely elastic and elastic-plastic simulation options for the following three simulation types. In this study, the plasticity model has been used to predict the residual stress level and the associated residual deformation more accurately.

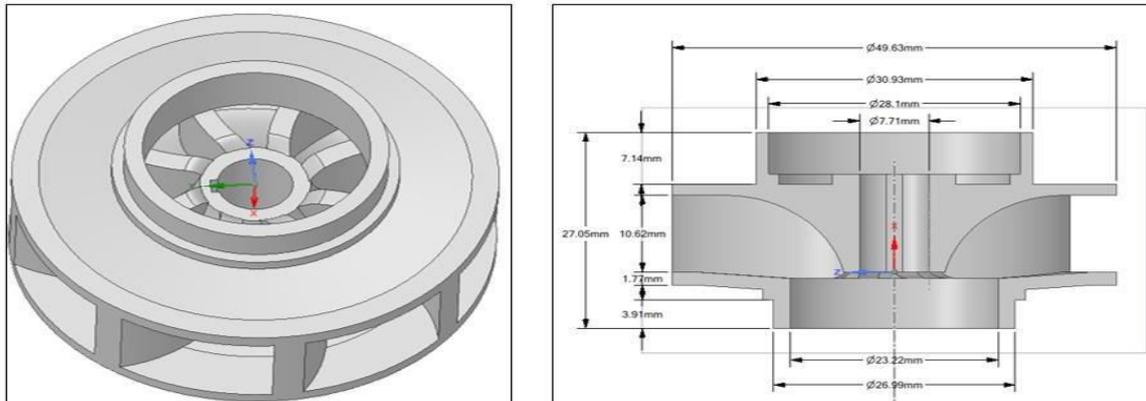


Fig. 2.1: 3d Model created in SolidWorks

Successful AM component depends on the orientation of the building part and supporting structures. Support structures are used to support the geometry that has an overhang or angle below 45° . Direct connection is created during the layering process between the base plate and overhang geometries using these support structures. Support structures are fabricated with the same material as a part. These support structures must be weightless and strong enough to keep a part fixed during fabrication. However, once the part is complete, the supporting material must then be removed. If the support geometries are too strong, it can add unnecessary post-processing time to a build. Hence, proper selection and placement of support structures play an important role in producing accurate AM components. By default, the automatic algorithm in Additive prep will generally consider support structures to all areas with an overhang angle (angle between the surface and the horizontal plane) of less than 45° . In this study, support structures at blade vanes and between shrouds are removed as it is difficult to remove after manufacturing. Two aspects were considered when the orientations of the component were chosen, avoiding the attachment of the support structure to the blades, and avoiding the overhanging of the shroud (self-supporting area).

A total of 4 possible locations were iterated for the appropriate print location. A comparison of the orientation of components in 3D printing, including a graphical preview of the supporting material, is shown in Fig.2.2. For demonstrating AM process simulation, the model with the orientation of 45° was chosen as per earlier observations [12];

1. For all three closed impellers ($0^\circ, 32^\circ$ and 45°), it was observed that by increasing the printing angle, a better dimensional stability is obtained, for both the exterior regions as well as for the blade surface accuracy.
2. The part printed using the 0° of orientation presented the most thickness deviations from the CAD model.
3. The one printed at 32° is within the imposed limits, but with higher profile deviations.
4. The component with 45° presents the best geometrical correlation between blade deviations and thicknesses.
5. Based on results obtained from the earlier work, the model with 45° is considered in two iterations as follows.
6. 45° orientation without support at the overhung location of the shroud.
7. 45° orientation with support at the overhung location of shroud Table 2 presents the process parameters used for the closed impeller fabrication as previously performed in the work done [11,12]

TABLE I: SELECTIVE LASER MELTING (SLM) PROCESS PARAMETERS

Laser power (W)	250.00
Scanning Speed (mm/s)	750.00
Layer Height (mm)	0.70
Base Plate Temperature (C)	20.00
Hatch Spacing (mm)	0.07
Slicing stripe width	5.00

After the optimal build orientation was determined, a first support structure design (A model with 45° -without support structure at an overhung location) was carried out. Support structures are created in additive prep and converted into .stl files (Fig. 2.3). These files are taken into mechanical and created additive printing simulation using additive wizard. The material used in the study was A35 steel.

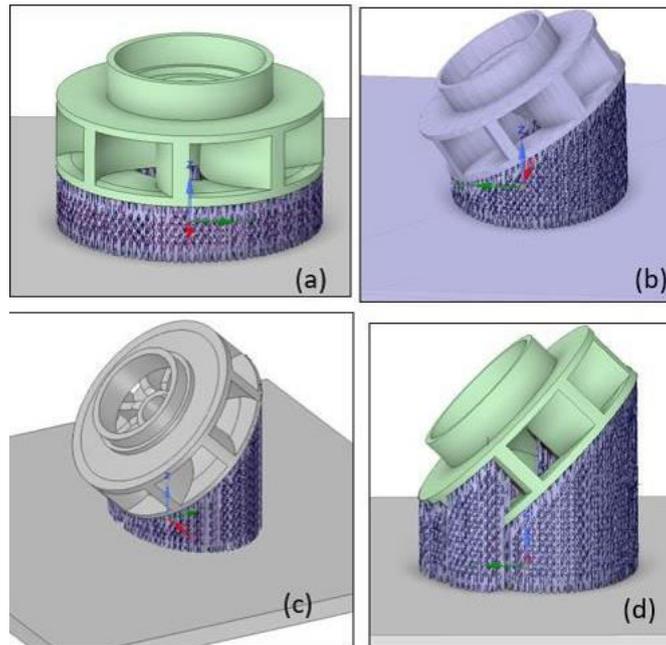


Fig. 2.2: 3d print position orientation using additive prep. (a) 0° (b) 32° (c) 45°-without support structure at overhung location (d) 45° with additional support

Fig.2.4 illustrates the impeller with many sliced layers used for the investigation. The layer thickness of each layer is 0.7 mm. The component is meshed with individual layers of either the voxel or cartesian elements. A mesh of around 277493 elements was used in the study.

III. EXPERIMENTAL RESULTS

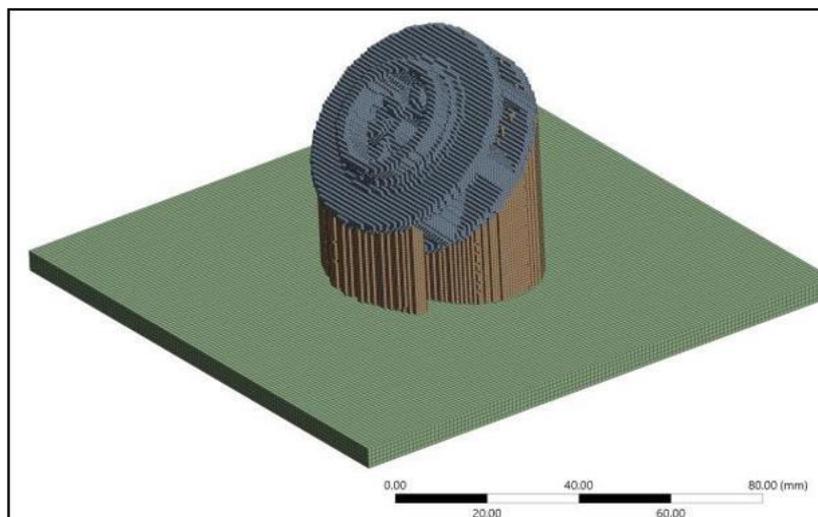


Fig. 2.4: 3D meshed model

III. PREDICTION OF DISTORTION AND RESIDUAL STRESSES

3.1 SUPPORT STRUCTURE DESIGN- I

The AM thermal analysis results shown in Fig.2.5 confirm that the effective thermal stress is proportionally related to an increase in the layer height from the bed surface. The initial temperature was 20°C. The procedure of this numerical study was first started with building the first sliced layer at a temperature of 1370°C. Then, the next sliced layers were repeatedly built one by one until all part layers were completed. After thermal analysis, structural AM analysis was performed. For mechanical conditions, the bottom face displacement of the building platform was set to constrain in the vertical direction. From the AM process simulation, it is observed that the displacement plot of the closed impeller (without support at the overhung location at the shroud) is 3.47 mm as shown in Fig.2.6. High residual stresses are observed at the shroud and vane interface (Fig.2.7).

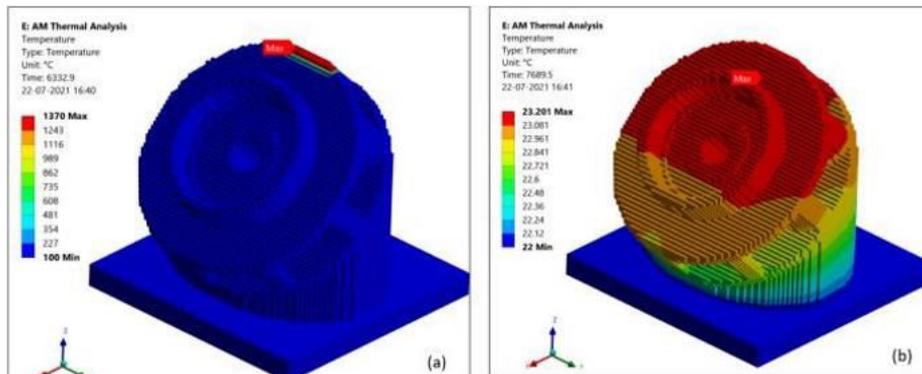


Fig. 2.5: Temperature distribution plot

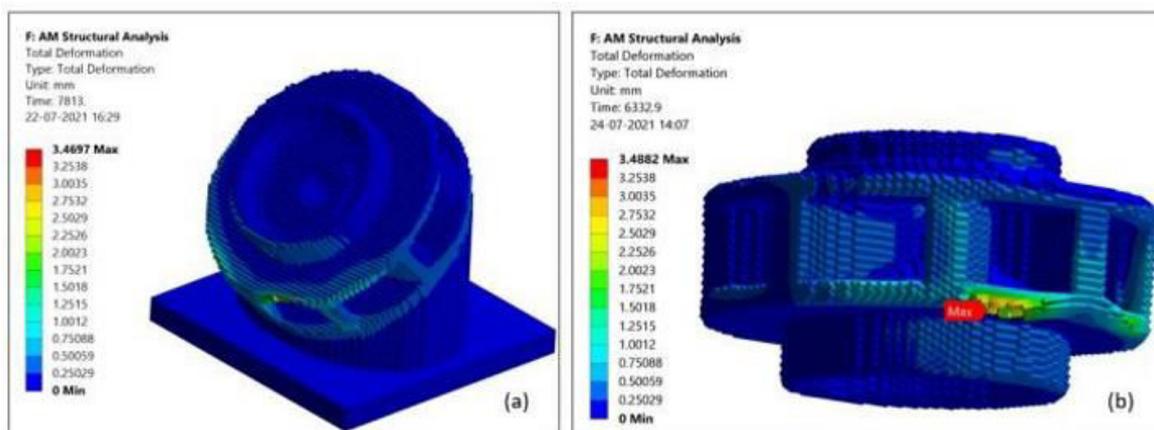


Fig. 2.6: Displacement plot of the impeller without additional support

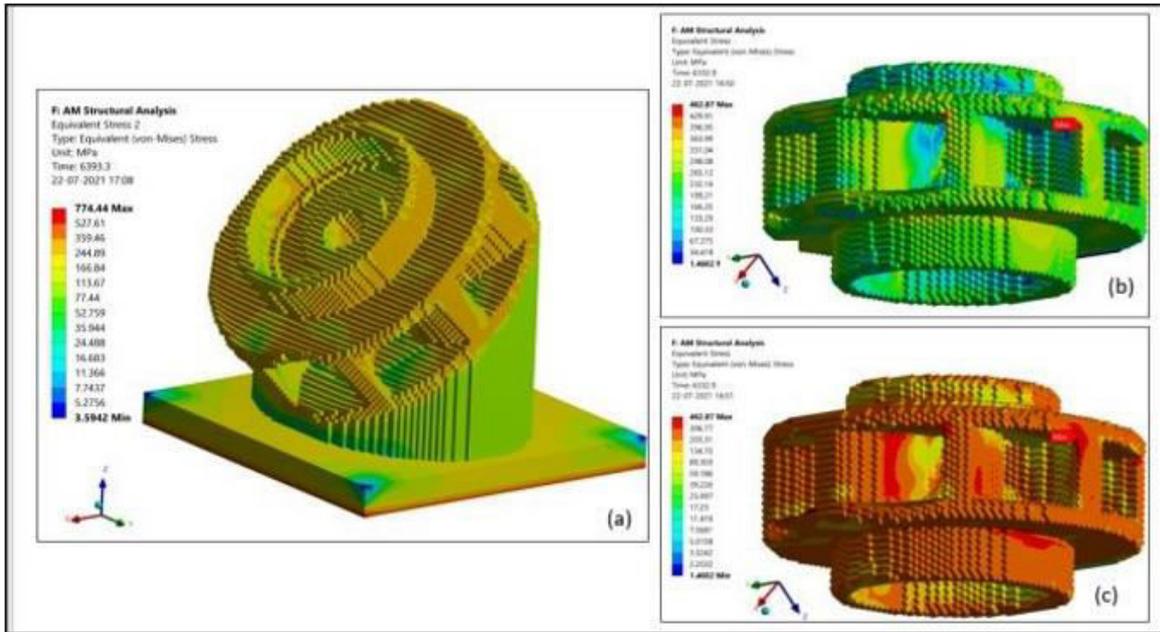


Fig. 2.7: Stress distribution plot of the impeller without additional support

3.2 SUPPORT STRUCTURE DESIGN ITERATION -2

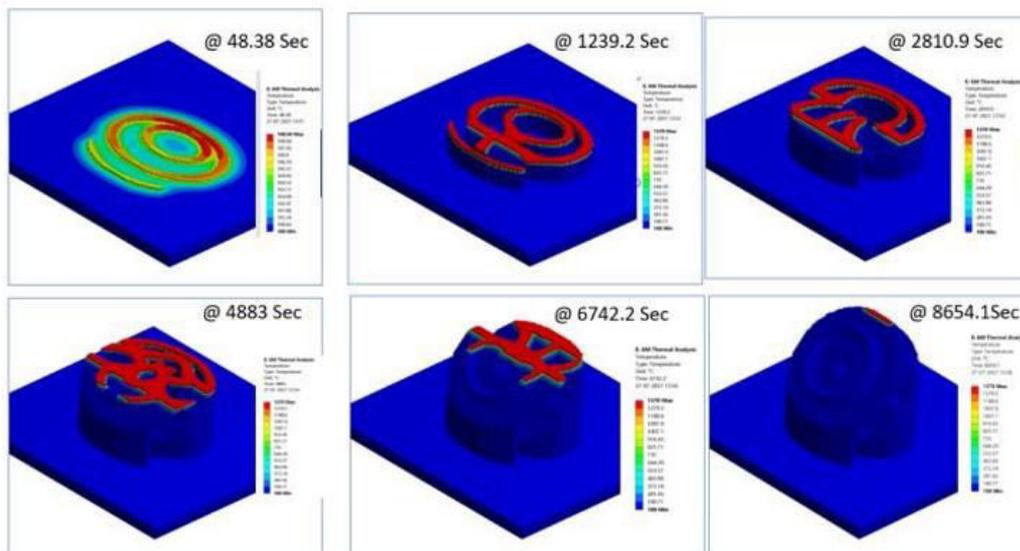


Fig. 2.8: Transient Temperature distribution during additive manufacturing process

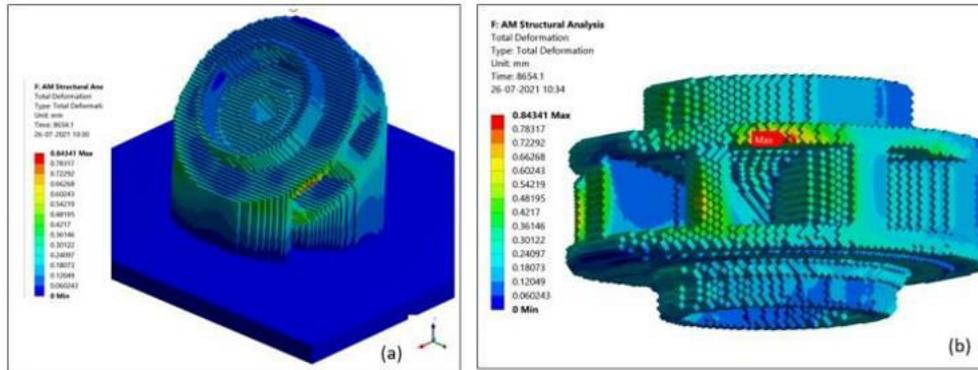


Fig. 2.9: Displacement plot of the impeller with additional support

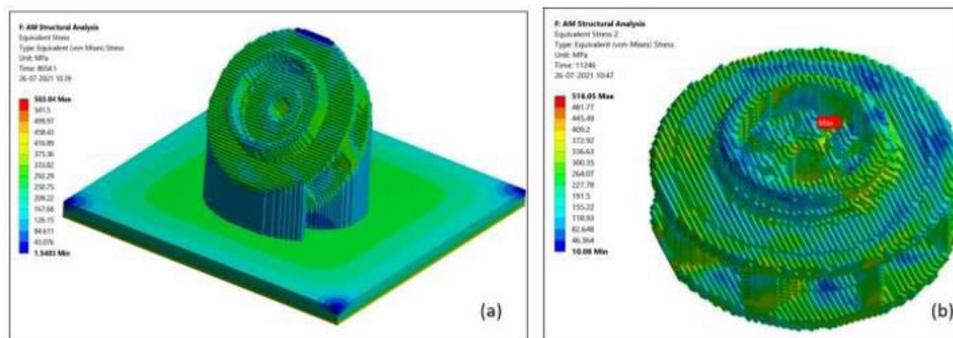


Fig. 2.10: Equivalent stress distribution of the impeller with additional support

To avoid distortion and high stresses at the shroud location, the additional support structure is attached as shown in Fig. 2.3. The AM printing process over time is shown in Fig.2.8. From the simulation results of this study, it was found distortions reached 0.8 mm at the edge of shroud, as shown in Fig. 2.9. The highest stress is showing at vane location Fig.2.10. The printed component on the building plate is illustrated in Fig.2.11. The work revealed that by increasing the printing angle, a better dimensional stability is obtained, for both the exterior regions as well as for the blade surface accuracy. It was concluded that a printing orientation of 45° presents the best geometrical correlation between blade deviations and thicknesses [12].

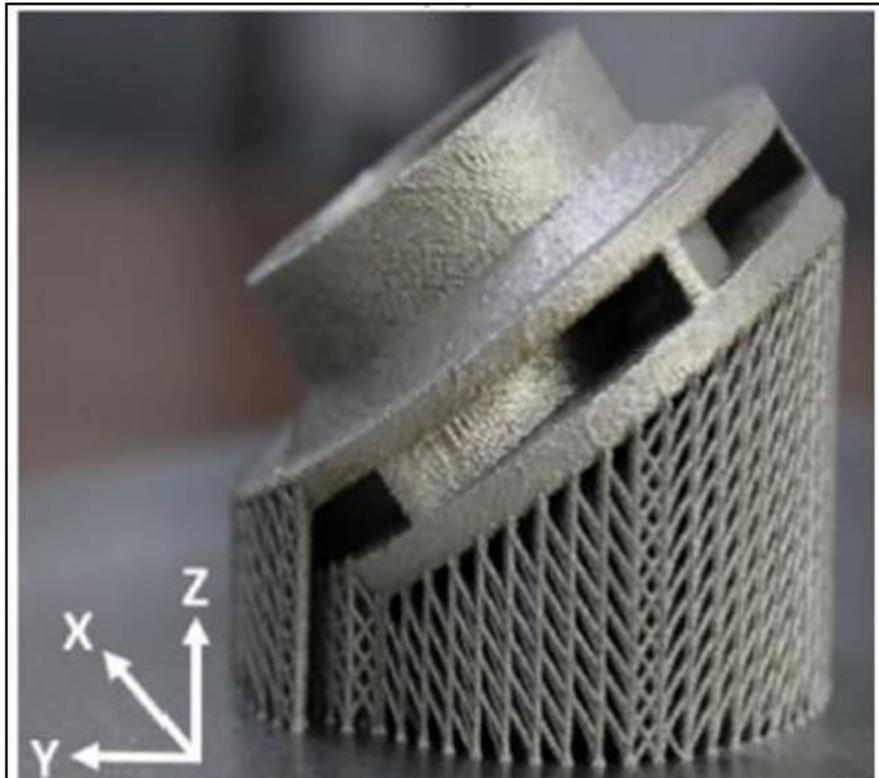


Fig. 2.11: printed component closed impeller-built orientation +45 deg [12]

IV. CONCLUSION

This work demonstrates the Additive Manufacturing process simulation approach using ANSYS software. The paper mainly focuses on finding the optimal build direction and designing suitable support structures through a simulation approach. First, the orientation of the impeller surfaces was analyzed and categorized according to the degree of difficulty in removing possible support structures. Possible impeller orientations were considered, and a suitable build direction was chosen. Subsequently, support structures were designed in the commercial software ANSYS. In this paper, the review of a computer simulation of metal 3D printing can be summarized as follows: (1) The numerical modelling and computer simulation are useful for the investigation and prediction of the underlying physical phenomena, and thermal-mechanical behaviour that can occur during the metal 3D printing process, (2) The numerical modelling can now support various types of metal 3D printing processes such as selective laser melting (SLM).

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