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A numerical and experimental investigation on buckling behavior of additively manufactured ribbed casings

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Abstract

Laser Beam Powder Bed Fusion (LB-PBF) is a thermomechanical process and residual effects that occur during the process may affect the geometrical stability. Buckling is a type of failure mode for materials, that leads thin materials to buckle under compressive loads. For a more stable buckling behavior in gas turbine engine casings, ribbing structures are being used due to their high compression strength-to-weight ratio. With the advantages of LB-PBF process such as the ability to create complex ribs and reducing machining needs, it can be preferred to manufacture ribbed engine casings via LB-PBF method. In this study, different ribbed engine casings with identical volumes are designed and residual effects caused by LB-PBF are inspected. Buckling simulations are performed on the designed and process simulation-derived casings including the residual strains and stresses, and compressive tests are physically carried out on manufactured parts to compare with simulation results. Following the results of experiments and simulations, residual effects of additive manufacturing distortions over stability were found to be fundamental. It was found that isogrid ribbing yields better resistance towards buckling loads, hinting that lateral ribs contribute more to the overall stability of casings rather than horizontal ribs.

Keywords: Laser beam powder bed fusion, process simulation, ribbing, buckling, Ti6Al4V ELI.

1. Introduction

Casings are thin-walled components of aero-engines, that require adequate stiffness and reduced weight. The casings are expected to provide sufficient buckling resistance against the compression loads during operating conditions [1]. Ribbing structures are used on casing surfaces to improve buckling behavior and stiffness due to their high compression strength-to-weight ratio. Also, ribbing provides the ability to overcome vibration problems [2], enabling cooling and noise reduction, and they can be used as mounting interfaces.

When conventional machining methods are used, manufacturing of these relatively complex structures require extensive time periods. Laser Beam Powder Bed Fusion (LB-PBF) is an additive manufacturing process with the ability to create complex three-dimensional (3D) structures via melting materials layer by layer on a build plate. Therefore, it plays an important role when creating ribbed parts. Ribbed structures can be efficiently manufactured via LB-PBF process without any machining needs. However, with the LB-PBF method, powder particles are melted by high-speed laser scanners and then rapidly solidified. This rapid cooling phenomenon causes high-temperature gradients and induces residual stresses and plastic deformations.

In these conditions, thin-walled structures are relatively difficult to build in terms of achieving intended geometrical accuracy. Therefore, it is quite important to understand the process behavior before manufacturing to ensure good quality parts.

In this study, casings with different ribbing structures that share the same weight are designed and manufactured with LB-PBF process. Process simulations are performed before production to understand the thermomechanical effects of the process on designed parts. These simulations are also performed to understand the effect or different ribbings over printing performance. Manufacturing process simulations are conducted following the inherent strain method [3]. Buckling of the casings with the inclusion of residual effects are simulated to understand the effect of ribbing on thin parts. Buckling simulations, necessary material properties and simulation setup are composed with respect to the nonlinear nature of instability [4]. Simulation results are compared with buckling test results performed on the parts.

A comparative study for the buckling behavior of slender, additive manufactured thermoplastic structures has been conducted by Virgin [5]. Another study, focusing on selective laser melted slender beams and how they perform under buckling loads was shared by Pritam et al. [6]. Buckling behavior in both simulation and experimentation of complex casing ribbings, along with the inclusion of preliminary additive manufacturing simulations, have not previously been investigated in literature, to the best of the authors knowledge.

2. Material and methods

2.1. Design Methodology

In this study, a cylindrical casing geometry with a 100 mm outer diameter, a 50 mm height, and a 1 mm thickness was taken as the reference model. Non-ribbed (thickened), isogrid and orthogrid casings were designed to understand the effect of rib forms over buckling behavior. All three casings models correspond to a 20% weight increase compared to the reference model. Approximately the same part volume was targeted for each geometry in design. The non-ribbed casing model was designed by increasing the outer diameter of the reference casing by about 0.4 mm. For the ribbed casings, the outer and inner diameters were kept the same. To reach the aimed increase in volume, orthogrid and isogrid structures were implemented onto the reference model.

Sharp corners, where the ribs coincided with each other and the outer surface of the wall, were rounded to avoid stress concentrations. Ribs were parametrically designed as their widths and heights are equal to each other and 3 times larger than their radiuses. The parametric relationship of the rib dimensions is shown in Fig. 1. The variable “a”, which defines the rib dimensions, has been calculated separately for all casing structures and their weights have been equalized. The dimension “a” was submitted as 1.18 mm and 0.99 mm for the isogrid and orthogrid casings respectively. Ribs were repeated at 10-degree intervals for both ribbed casings.

Since the differences between contact faces of the casings may affect the buckling behavior of the components and cause local instabilities during the compression tests, flanges with the same contact area and form were added to the bottom and the top end of the casings. All three casing geometries were designed in Siemens NX and shown in Fig. 2.

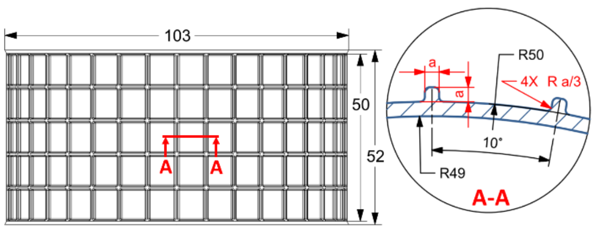

Fig 1. Parametric rib design methodology.

Fig 2. Non-ribbed, orthogrid and isogrid casing geometries.

2.2. Simulations of additive manufacturing process and buckling

The calibration for the inherent strain study was conducted in Ansys Workbench Additive for the thermomechanical analysis representing the AM of Ti6Al4V material in the CL M2 machine. Heat treatment and baseplate cut-off (W-EDM) steps were also added to the calibration model. LB-PBF simulations were carried out using Ansys Additive Suite. An axisymmetric part model, where the part and the base plate were split into 20-degree slices was used to simplify the process and reduce simulation time. A 0.3 mm layered tetrahedron mesh was used for the modeling of the process. The deformed parts acquired from the LB-PBF simulations were used as the input model of the buckling simulations. A sample simulation model is shown in Fig. 3 and Fig. 4.

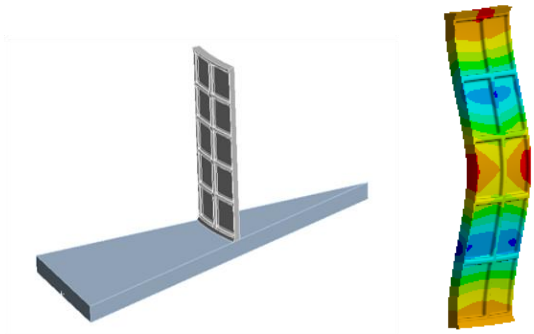

Fig 3. Sample additive manufacturing simulation model.

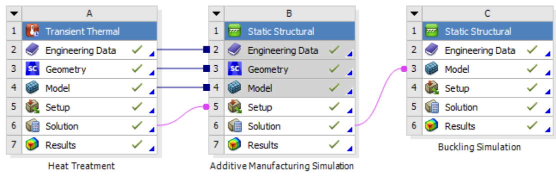

Fig 4. Simulation workflow.

Buckling simulations in this study were set up with care towards geometry and material-based nonlinearities. Boundary conditions for the buckling analysis were applied to reflect the experimental setup shown in Fig. 6.

2.3. Additive manufacturing and post-processes of the parts

The casing samples were manufactured with non-virgin Ti-6Al–4V ELI commercial powder from Concept Laser, with LB-PBF method using a Concept Laser M2 Series 5 machine. Three samples for each geometry as shown in Fig. 5, were manufactured in three production runs in total, to be tested in a compression test. During the LB-PBF process, the build plate was heated up to 200°C. A volumetric energy density of 33 J/mm^3 was used for the manufacturing of samples.

Fig 5. The casing samples after L-PBF process.

After the L-PBF process, parts were stress relieved with the build plate in a vacuum furnace according to the AMS 2801. After heat treatment, parts were cut from the upper surface of the build plate via Charmilles Cut 300Sp W-EDM machine with a wire of 0.3 mm diameter.

For compression tests, an example shown in Fig. 6, a Shimadzu testing device with a 1000 kN load cell was used and three samples were tested for each geometry. Tests were performed under 0.5 mm/min displacement control speed.

Fig 6. Isogrid casing during compression test.

Force-displacement curves of the experiments have been graphed and their values were normalized with respect to each other. A conjoined graph of the three curves can be found in Fig. 7.

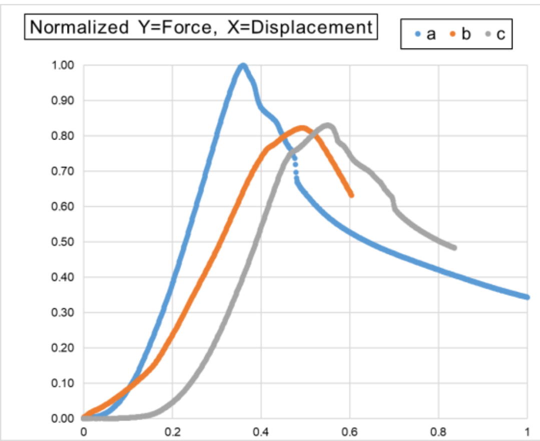

Fig 7. Normalized force-displacement curve a) isogrid, b) orthogrid and c) non-ribbed.

3. Results and discussion

By simulating the additive manufacturing and post-heat treatment processes of ribbed casings, 3D models with plastic deformation were obtained.

Deformed casing models were analyzed dimensionally, shrinkage of up to 1 mm in diameter and plastic deformations varying along height were investigated. Several steps along the simulation for the isogrid model are demonstrated in Fig. 7, and Fig. 8.

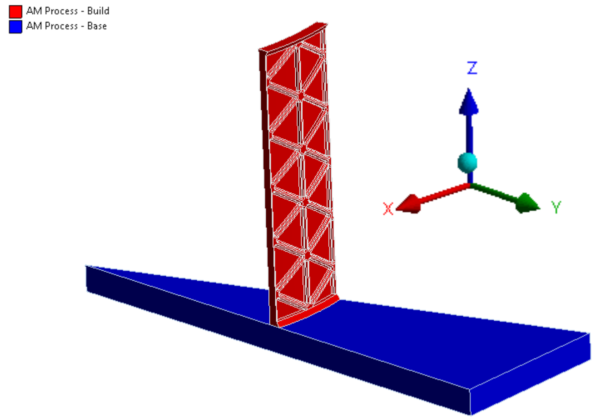

Fig 7. Isogrid additive manufacturing simulation model with the distinction of build part and baseplate.

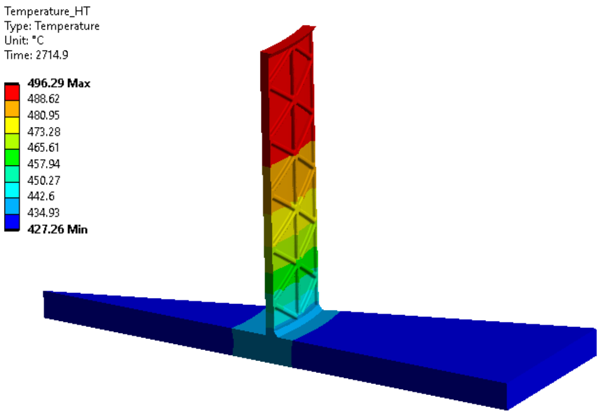

Fig 8. Temperature distribution of AMS 2081 heat treatment process, during heating.

Pre- and post-heat treatment normalized deformation results are shown in Table 1, along with a total deformation plot after cutoff for all casings in Fig. 9.

Table 1. Additive manufacturing simulation normalized total deformation result comparison for heat treatment.

Part Name	Pre-Heat Treatment Total Deformation	Post-Heat Treatment Total Deformation
Non-ribbed	1.000	1.054
Orthogrid	1.136	1.144
Isogrid	1.104	1.126

Deformations caused by additive manufacturing affected the non-ribbed casing the least, with orthogrid ribbing being the most affected as can be observed in Table 1.

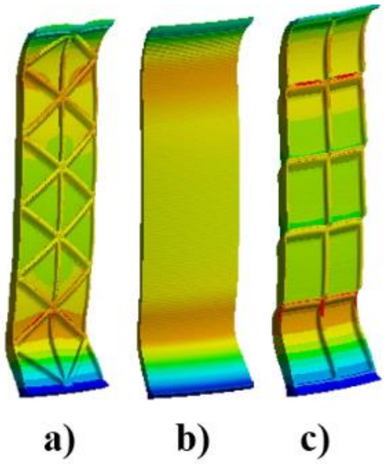

Fig 9. Total deformations a) isogrid, b) non-ribbed, c) orthogrid.

Critical load factors and buckling behavior of deformed frame models under compressive load were numerically compared between experiment and FEA results. Normalized critical load factors of mentioned casings are listed in Table 2 and a visual comparison of buckling shapes for the isogrid ribbed casing is given in Fig. 10.

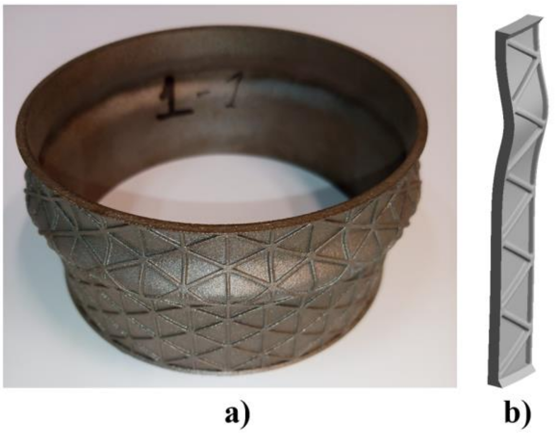

Fig 10. Buckling shape comparison of isogrid ribbing casing a) LB-PBF manufactured and b) simulation output.

Table 2. Normalized experimental and simulation results of critical load factor.

Part Name	Experimental Results	Post-AM Deformed Buckling Simulation
Non-ribbed	1.010	1.061
Orthogrid	1.000	1.112
Isogrid	1.204	1.288

4. Conclusions

In this study, it was demonstrated that different ribbing geometries have different effects on the buckling capabilities of casings. While the isogrid ribbing strengthened the casing for a buckling scenario, orthogrid ribbing had a much weaker effect on the overall stability when compared to the non-ribbed alternative. Conducted FEA studies have shown that plastic deformations that occur in the additive manufacturing process need to be carefully reviewed as they can cause the parts to fail sooner than expected. Following conclusions were deducted from this study:

1. As it can be observed in Table 1, orthogrid ribbing was found to be more prone to be affected by LB-PBF process-based warping than its counterparts. With non-ribbed casing showcasing the least warping, it can be said that horizontal and near-horizontal ribs tended to deform during additive manufacturing.

2. Horizontal ribs contributed less to the overall structural stability of the casings than lateral ribs, as can be seen on the orthogonal sample test and simulation results.

3. In terms of buckling resistance, orthogrid and non-ribbed casings yielded similar results while the isogrid casing showed a comparatively distinctive resistance to buckling during both experiments and simulations.

4. LB-PBF, heat treatment and buckling simulations were able to accurately calculate the response of the casings for manufacturing process-based deformations, thermal warps and instability characteristics. Therefore, LB-PBF simulation capability proved to be a valuable tool for accurately predicting process-based distortions.

5. Simulation tools helped with the ribbing design process, and they were useful for predicting unwanted material use, case-specific ribbing directions and overall strength of casings.

Acknowledgments

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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