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Qualification of additively manufactured aerospace brackets: A comparison between thermoelastic stress analysis and theoretical results

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ABSTRACT

Metal brackets made in titanium based-alloys are one of the most diffused case studies in the field of Additive Manufacturing (AM) technologies: the current generation of satellites relies on metal brackets to serve as a link between the body of the satellite and the reflectors and feeder facilities mounted at its upper end. In this scenario, one of the main focal points is the qualification of the 3D printed-products, including both the characterization of the micro/macro-structure of the component, and the definition of its mechanical behavior. Despite the high presence, in literature, of works dealing with the detection of defects in the structure, no dissertation can be found about stress analysis on the actual component, and this is what this paper focuses on. This topic is crucial because some morphological or dimensional differences between the nominal (CAD) structure and the manufactured one could lead to non-predicted stress concentrations at the end. We performed a feasibility study of the Thermoelastic Stress Analysis on a titanium based-alloy space bracket, made by Electron Beam Melting (EBM). The success of our study, plus a Non-Destructive Dimensional Measurement (triangulation system for reverse engineering) could enable the classical topology optimization processes to be implemented a posteriori, thus providing an additional time and cost saving.

1. Introduction

During the last few decades, the increase of demand of customized and sustainable products with highly specific requirements (weight reductions, increase of functionality, savings in time and costs, optimized parts, etc.) in the Aerospace Industry made Additive Manufacturing (AM) an appropriate solution for this challenge. Additive Manufacturing can be defined as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [1]. In [2] a table compares AM with Traditional Manufacturing in terms of costs, time, resource consumption, product complexity, post fabrication processing, material quality, material wastage and prototyping, explaining why AM is gaining much more success in air and space-crafts design. Metal brackets made in titanium based-alloys are one of the most diffused case studies in the field of Additive Manufacturing (AM) technologies: the current generation of satellites relies on metal brackets to serve as a link between the body of the satellite and the reflectors and feeder facilities mounted at its upper end. The brackets must fix securely to the satellite body and withstand high thermal stresses caused by extreme temperature fluctuations in space, ranging from $-180\,^{\circ}\mathrm{C}$ to $+150\,^{\circ}\mathrm{C}$. AM of titanium is of particular interest due to its thermal and galvanic compatibility with composites [3]. In literature, many industries and institutions (Airbus, NASA, Rolls-Royce [2], Oak Ridge National Laboratory [4], etc.) are involved in research projects dealing with AM Technologies implemented on aerospace components, especially on titanium alloy made-brackets. Generally, this kind of products requires design optimization processes searching for a component geometry that satisfies all structural and manufacturing constraints while maximizing the objectives associated with the application. Minimal mass and minimal costs objectives are associated with stiffness, strength and allowable volume constraints [5,6]. For this purpose, in [7] Orme et al. developed a Holistic Process-Flow from concept to validation for Additive Manufacturing of light-weight, optimized, metallic components suitable for space flight, that they validated both on an edge insert and on a Star-Tracker bracket. This process includes: candidate part selection, topology optimization (as explained in [5,8], it is based on initial

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Fig. 1. Titanium based-alloy satellite bracket made by Additive Manufacturing.

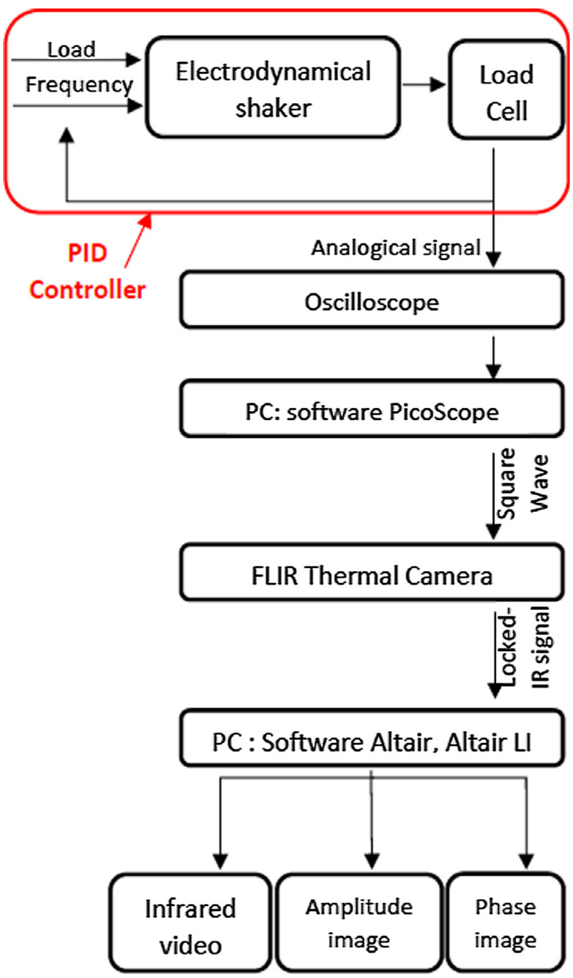

Fig. 2. Measurement chain for thermoelastic tests.

conditions, including: input load, physical constraints, allowable volume and material properties), FEM design validation (for example modal characteristics verified by modal analysis), Additive Manufacturing (once having reached the convergence of the previous feedback loop), and finally, mechanical and material verification (in that case they performed tensile, microscopy, and structural testings, according to either ASTM, American Society of Testing and Materials, or DIN, German Institute for Standardization, Standards). The step of testing the produced component, both during the manufacturing process [9,10,11] and after that, is crucial for the component certification and for the process optimization. In the first mentioned case (process monitoring) certification could be challenging because of the continuous deposition of successive layers: the non-destructive examination of each of them is made difficult by metallization on inside surfaces caused by evaporation and condensation of metal from the melt pool. In [9,12] an in-situ Infrared imaging method trying to overcome this problem is presented. On the other side, the use of Non Destructive Testing (NDT) methods for the verification of quality and structural integrity of additively manufactured parts is necessary for the inspection of discontinuities and possible failures without destructing and damaging the part. In this scenario, developing or improving new NDT techniques could also pave the way for a posteriori topology optimizations, implemented on the actual component, enabling additional time and costs savings. In [10,13–15] the state of the art of NDT on AM components is reported. Many efforts have been made in order to perform reliable dimensional characterization, defect detection and micro/macro structure investigation. In particular the current methods are: Visual Testings, Computed Tomography, Digital X-ray, Acoustic Methods, Infrared Testings, Laser Profilometers, Microscopy, etc. Moreover, in [10,16] and [17] a further method enabling to overcome the issue of inspecting only the observed surface, i.e. Laser Ultrasonics is reported. In this inspection, in order to produce components with sufficient material integrity for the aerospace sector, an understanding of the effect of changing the input Power Bed Fusion parameters is required and, as such, many studies have been undertaken, see references in [16,18]. From the cited reviews, it emerges that no work has been done about performing stress analysis on the actual component, in order to compare the experimental results with the expected, nominal, mechanical behavior: this is what our work focuses on. In fact, dimensional, roughness-generated, structural deviations between the nominal and the manufactured component could even lead to discrepancies in the stress distributions across the component. In this paper, a feasibility study of Thermoelastic Stress Analysis (TSA) implemented on a satellite bracket made in titanium-based alloy is presented. This methodology could act as a support for dimensional inspection in order to define the amount and the kind of deviations between the nominal and the actual component, making available a more complete inspection. In Section 2 a brief dissertation on Thermoelastic Stress Analysis is provided, in Section 3 the authors describe the adopted methodology (first a reverse engineering process on the printed component, then the design of the measurement chain). Finally, in Section 4 the experimental results are described and compared with two kinds of Finite Element Analyses. In Section 5 the authors summarize the conclusions of the presented work.

2. Thermoelastic stress analysis (TSA)

The Thermoelastic effect is based on the fact that “the temperature of a substance can only be raised by working up on it in some way so as to produce increased thermal motions within it, and from this effect the mutual distances or arrangement of its particles which may accompany a change of temperature. The work necessary to produce this total mechanical effect is proportional to the quantity of the substance raised from one standard temperature to another. Therefore when a substance loses or receives heat, a mechanical effect is produced, which is proportional to the heat which it emits or absorbs” [19,20]. This statement can deduct the thermoelastic equation:

$$\Delta T = -\frac{\alpha \cdot T}{\rho \cdot C_P} \cdot \Delta\sigma \tag{1}$$

where ρ is density, C_P is heat capacity at constant pressure, α is coefficient of thermal expansion and T is the temperature of the environment. Therefore, a temperature change ΔT is strictly related to the variation of the first stress invariant $\Delta\sigma$: in this way, by observing a