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Non-Contact Measurement Techniques for Qualification of Aerospace Brackets Made by Additive Manufacturing Technologies

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Abstract. In recent times, additively manufactured aerospace brackets made in titanium based alloys are gaining a great importance in the design of spacecrafts and satellites. In this scenario, one of the main focal points is the qualification of these 3D printed-products, including their mechanical behavior. In literature, no dissertation can be found about stress analysis on the actual component, and this is what this paper focuses on. The importance of this study relies on the fact that some morphological or dimensional differences between the nominal (CAD) structure and the manufactured one could lead to non-predicted stress concentrations. We describe 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 could enable the classical topology optimization processes to be implemented a-posteriori, thus providing an additional time and cost saving.

1. Introduction

In recent years, the request of weight reductions, increase of functionality, savings in time and costs, optimized parts in Aerospace Industry encouraged the increase of Additive Manufactured (AM) parts. In [1] it is explained 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: they serve as a link between the body of the satellite and the reflectors and feeder facilities mounted at its upper end. They are able to withstand high thermal stresses due to extreme temperature fluctuations in space, ranging from -180°C to +150°C. AM of titanium is of particular interest due to its thermal and galvanic compatibility with composites [2]. In literature, many industries and institutions (Airbus, NASA, Rolls-Royce [1], Oak Ridge National Laboratory [3], etc.) are involved in research projects dealing with AM Technologies implemented on aerospace components, especially on titanium alloy made-brackets. These products require geometry optimization in order to satisfy all structural and manufacturing constraints and to increase its functionality: mass and cost savings, stiffness, strength are some of the most important constraints [4]. For this purpose, many authors developed appropriate Process-Flows for Additive Manufacturing of light-weight, optimized, metallic components suitable for space flight, see [5]. This process includes: candidate part selection, topology optimization, FEM design validation, Additive Manufacturing, and finally, mechanical and material verification (for example, tensile, microscopy, and structural testings). The step of testing the produced component, both during the manufacturing process [6],[7] and after that, is crucial for the component certification and for process optimization. Concerning the 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 [6] an in-situ Infrared imaging method trying to overcome this problem is presented. On the other side, the use of 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. In [7], [8], [9], [10], [11] the state of the art of NDT on AM components is reported. Many efforts have been made in order to perform defect detection and micro/macro structure investigation. The current methods are: Visual Testings, Computed Tomography, Digital X-Ray, Acoustic Methods, Infrared Testings, Laser Profilometers, Microscopy, etc. However, no work has been done about performing stress analysis on



the actual component, in order to compare the experimental results with the expected mechanical behavior. In fact, dimensional structural deviations between the nominal and the manufactured component could generate discrepancies in the stress distributions. 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.

2. Thermoelastic Stress Analysis

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” [12]. This statement can deduct the thermoelastic equation:

$$\Delta T = - \frac{\alpha \cdot T}{\rho \cdot C_p} \cdot \Delta \sigma \quad (1)$$

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 loaded component through a thermal camera, it is possible to store its stress distribution. However, the temperature changes generated by the most commonly used engineering materials are very little and rapidly disappear because of heat transfer. It is therefore necessary to dynamically load the component at proper frequency [13].

3. The method

We developed a NDT methodology implemented on a titanium based-alloy satellite bracket made by AM (figure 1). It could put the basis for a more exhaustive product qualification. The methodology is structured as follows:

- a. Design of a test bench for TSA
- b. Comparison between experimental and expected results.

We are going to describe the steps in the following paragraphs.

3.1. Design of a test bench for TSA

Figure 2 shows the measurement chain designed for the determination of the stress distribution by thermoelastic effect; see the final test bench in figure 3. The component has been black painted, in order to increase its emissivity. The adiabatic conditions, necessary for a reliable measurement, are obtained by periodically loading the component (fixed by a rigid body constraint as shown in figure 3) by an electrodynamic shaker, regulated by a PID controller. The shaker produces a sine wave characterized by the imposed load and frequency, and a load cell is exploited as feedback sensor. Now, due to the fact that the used thermal camera (a FLIR Cedic Titanium Series SC700 thermal camera) has a Noise Equivalent Differential Temperature (NEDT) < 18 mK, while the temperature changes related to thermoelastic effect are of the order of 1 mK, we exploited the Lock-In Amplifier technique to overcome the problem. The thermal camera receives a periodical signal having the load frequency as input, and multiplies the Infrared signal with the input one, in order to remove all the noise relative to frequencies different from the load one. For implementing it, the load cell signal is conducted to a double channel oscilloscope interconnected with a PC, where it is possible to generate a square wave having the same frequency as the load cell-signal. The square wave is sent back to the oscilloscope, whose output channel is linked with the thermal camera input. Finally, the thermal camera communicates with two specific software, installed in a second PC: Altair for the camera calibration and Altair LI for the thermoelastic processing. At the end, the output is a thermal film whose complex analysis gives back an amplitude image and a phase one, representing respectively the stress distribution across the pixel array and the stress sign (compression or traction). It is important to mention that the described analysis is only qualitative; for obtaining real stresses expressed in MPa, a calibration process is required, as described in [14].



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

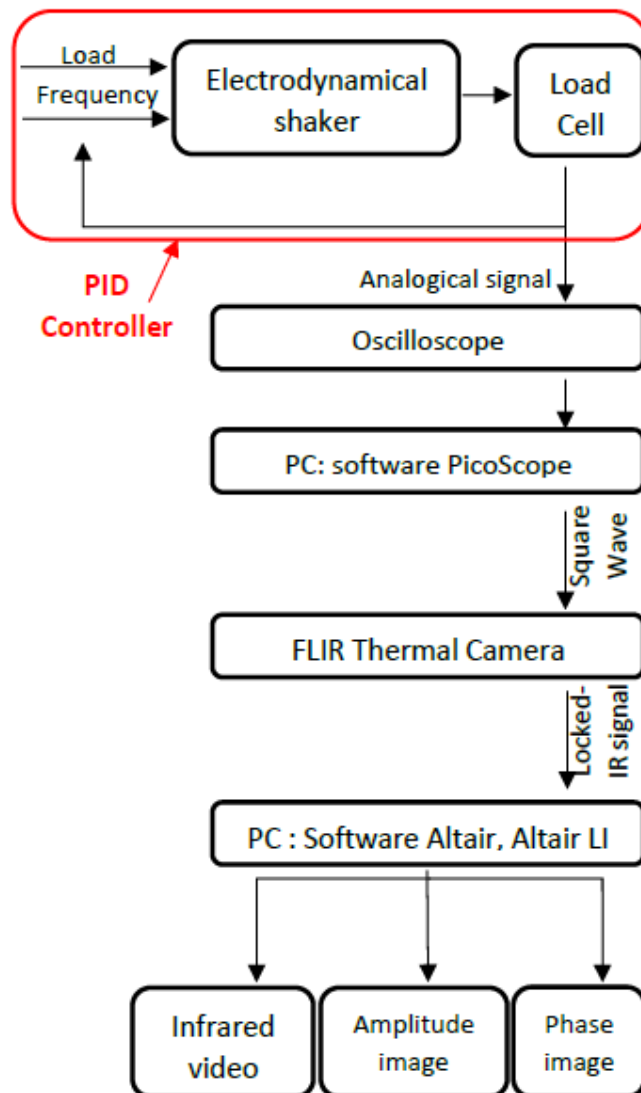


Figure 2. Measurement chain for thermoelastic tests

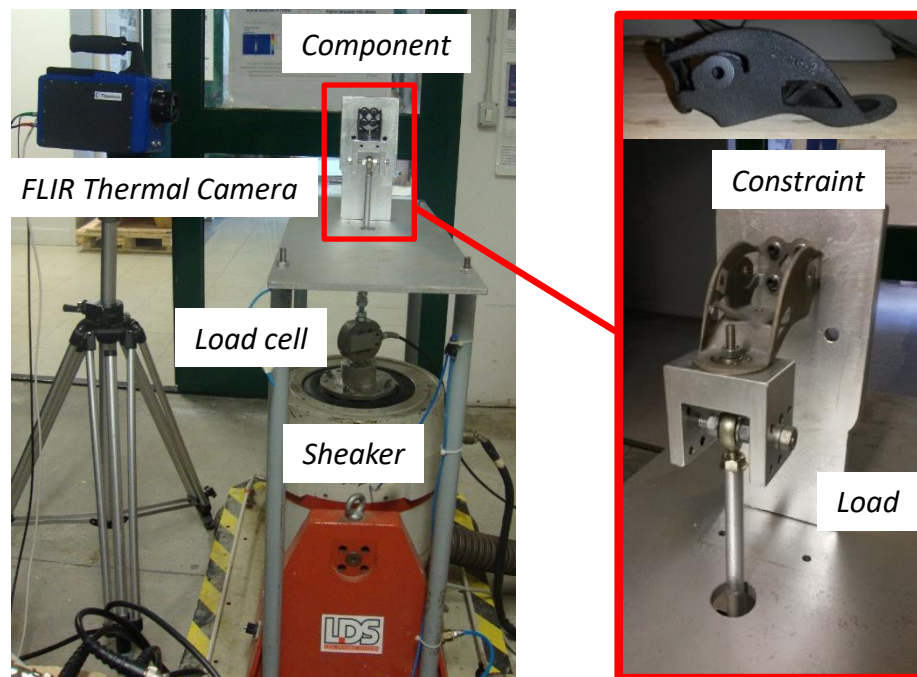


Figure 3. Test bench

3.2. Comparison between experimental and expected results

In order to define possible deviations between the expected and the actual mechanical behavior, we compared TSA results with a Finite Element Analysis evaluated on the CAD model.

4. Results and discussion

In this section, we will show and discuss the results obtained by the method described in the previous sections. We focused our attention on the regions where the evaluated FEM predicts higher stress concentrations, i.e. the curvatures near the rigid body constraint (see figure 3), and we observed them both from the outer side and from the inner one. Results shown in figure 4 are associated with the test conditions reported in Tab.1. In figure 4 (a), the stress localization is in accordance with the predicted one, confirming the feasibility of TSA investigation for the examined component. On the other side, figure 4(b) shows another result in accordance with the physics of the problem: the upper and the lower curvatures work oppositely in terms of stress: when the ones are stretched, the others are compressed and vice-versa. This can be deduced by the opposition of color levels in figure 4 (b), as the color level is associated to phase values between -180° and 180° . Moreover, in figure 5 the comparison between experimental and theoretical results is reported. We extracted significant interrogation lines in order to gain more sensitivity about the stress trends. Therefore, it is remarkable that the stress trend relative to the FEM analysis conducted on the CAD model (figure 5(b)) is much smoother than the trends in the actual component. This is an unexpected datum, since it generally happens the opposite due to the fact that a small amount of heat exchange always occurs during a Thermoelastic test, smoothing the curves, and providing a small loss of resolution. On the contrary, our test campaign reveals that the particular micro/macro structure and the surface roughness provided by the Additive Manufacturing process, lead to localized stress peaks, not predictable a-priori.

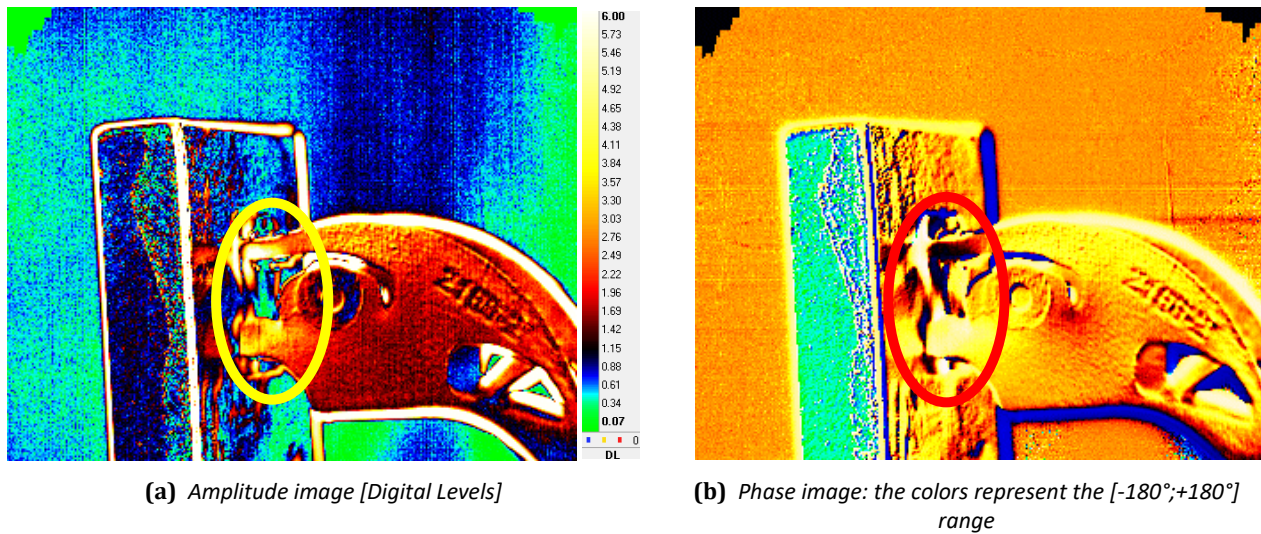


Figure 4. TSA results revealing the location and the sign of the stress concentrations

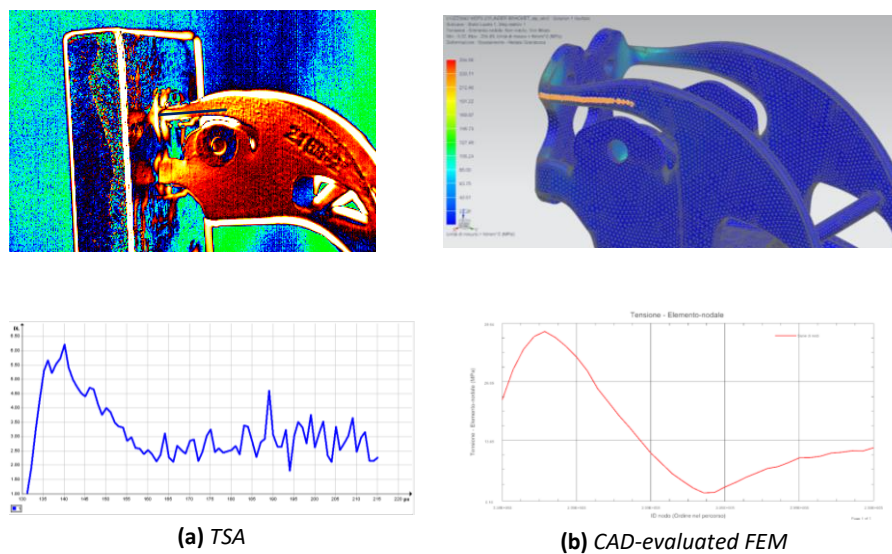


Figure 5. Comparison between experimental results and theoretical ones

5. Conclusions

A feasibility study about the possibility of applying Thermoelastic Stress Analysis (TSA) on an additively manufactured aerospace bracket made in a titanium based-alloy is presented. A TSA test bench has been equipped, in order to dynamically load the structure and to perform the Lock-In technique. Results show the same trends at larger scales, but smaller unexpected peaks in the TSA data and in the evaluated FEM, due to the particular micro and macro conformation given by the Additive Manufacturing process. Hence, our measurement technique, in conjunction with usual morphological and dimensional investigation, could make available a more complete Non- Destructive qualification process for AM made aerospace brackets, giving information about the effective mechanical behavior of these structures.

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