Chapter 1
Rapid Fatigue Characterisation of AlSi10Mg-AM using Energy-based approaches

Rosa De Finis, Davide Palumbo, and Umberto Galietti

Abstract The advent of additive manufacturing has transformed the manner in which structural and non-structural materials and components are designed and manufactured. This technology offers the flexibility of manufacturing but also presents a number of challenges concerning the performance of the material itself.

One such challenge is the lack of data regarding the structural aspects of the material, including fatigue resistance. This information is crucial for understanding the behaviour of a component under operating loads.

A valuable support in such activities aimed at shedding light on dynamic behaviour is provided by the techniques provided by the experimental mechanics. In particular, Infrared thermography is a valuable tool for detecting anomalies in the thermal map of a material or component subjected to cyclic loading. This is achieved using certain indices linked to reversible and irreversible physical processes that characterise the nature of heat sources. Furthermore, conducting rapid fatigue tests allows for the study of material behaviour through the examination of material self-heating.

The aim of this study is to present the challenging aspects of studying the fatigue behaviour of aluminium alloys produced by Additive Manufacturing. This is regarding both the behaviour of aluminium from a thermal point of view (it is a highly diffusive material, so temperature variations are very low) and the behaviour from a mechanical point of view (the fatigue limit of some alloys does not present the characteristic "knee" point). The goal is to demonstrate how thermography can support structural evaluations on this material.

Introduction

Additive manufacturing is a new material production technique that combines several technological advantages such as the ability to build complex-shaped components in a relatively short time using a relatively circular process and, in some cases, no material rework is required [1]. However, there are still many challenges to face like induced anisotropy, residual stresses, surface finish that affect structural integrity and mechanical material properties. Indeed, the characterization of heterogeneous or anisotropic microstructures, along with the presence of residual stresses and induced defects, and the dependence of material properties on building direction and orientation, requires the development of ad-hoc testing and analysis procedures. Specifically, the whole comprehension of the fatigue behavior in these materials remain not fully achieved. This push the research toward new methodologies for studying the fatigue behavior [1–2].

The experimental mechanics provides invaluable support for both structural integrity inspections and material characterization [3–9]. In particular, in the past different thermography-based techniques were developed to carry out the rapid characterization of materials and the early damage detection. These techniques present the advantage of assessing the damage information in relatively short time. Such techniques are mainly adopted during rapid fatigue tests that exploit the self-heating effect of the material. In these tests by fatigue loading the material first at very low and then at very high load levels until failure, the transition between damage regimes can be studied [3–5]. In fact, if a thermal imaging camera monitors the test, it is possible to derive a range of information related to the energy involved in dissipative processes that serve

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Garrett Pataky et al. (eds.), *Fracture, Fatigue, Failure, Damage Evolution and Thermomechanics & Infrared Imaging, Vol. 4*,
Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.13052/97887-438-0830-5_1

as a sentinel for early and local detection of damage. This has enabled the development of energy-based approaches and methodologies [10–18].

Energy-based methodologies [6–9], founded upon the evaluation of quantifiable variables such as temperature and strain, have exhibited their efficacy in the identification of damage, even in the presence of small surface defects, and in the separation of inelastic from anelastic material behavior [10, 12, 17]. More in detail, in recent years, the estimation of energy dissipated during fatigue processes through the assessment of temperature fluctuations (second amplitude harmonics, or SAH [7–9]) has demonstrated considerable potential for the precise analysis of material behavior through the assessment of a parameter that is resistant to the influence of numerous disturbing noise factors.

This paper presents preliminary results of fatigue characterization of the AlSi10Mg-AM alloy produced by selective laser melting, using rapid methods. The SAH and the area under hysteresis loop are used as damage indices and to study the material behavior.

The results will also be analyzed in terms of material specificity: SAH will represent not only dissipative but also thermoelastic effects [11, 18]. This significantly complicates the assessment of material behavior.

Moreover, an ad-hoc procedure for the evaluation of material fatigue strength taking into account the specific thermal behavior of the material is also provided.

Materials and Methods

The present study dealt with AlSi10Mg alloy produced by selective laser melting additive manufacturing process [2]. The samples were built in vertically direction and heat-treated (age-hardening for 6 hours-T6). Moreover, the surface of the samples was matt black coated to enhance and uniform the surface emissivity.

All fatigue tests were performed on a servo-hydraulic MTS 647 loading machine with a 100kN load cell. The samples were addressed to a stepwise loading procedure in order to study the self-heating material behaviour [3–10]. It consists of a sequence of load blocks, each with the same duration of load cycles and fixed values for load frequency and stress ratio. The sequence of blocks is defined by incrementally increasing the applied stress level. Three acquisitions were carried out at each load step at 1000 and 15000 cycles respectively at a loading frequency of 15hz which is sufficiently high to avoid loss of adiabatic conditions. To acquire thermal data the Flir X6540SC Infrared camera was adopted. In particular, this camera has a cooled detector with 640×512 pixels matrix and a NETD lower than 25 mK. The adopted frame rate to obtain IR sequences was 200Hz. An extensometer MTS 634 (clip-on type with 25 mm gage length) acquired the strain data at 500 frame per second.

The setup and equipment are reported in Fig. 1.

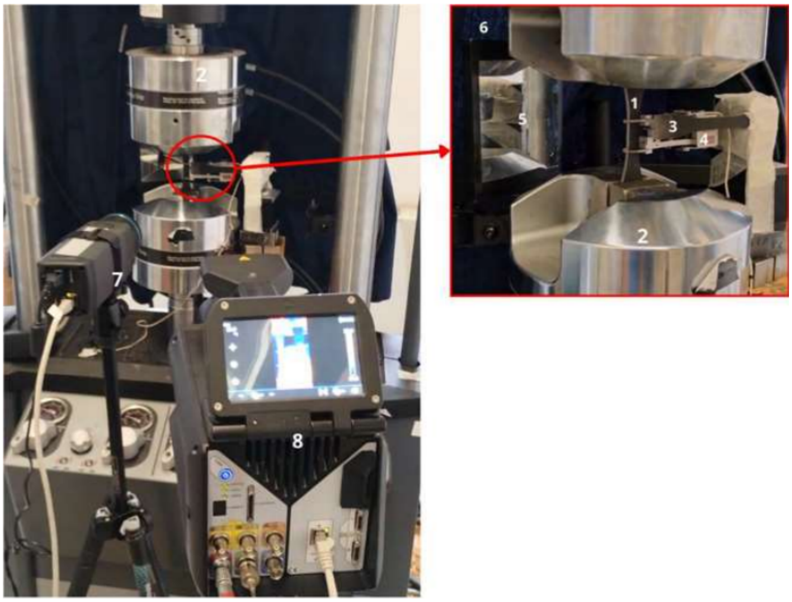


Fig. 1 Experimental setup (1:sample, 2:clamps, 3:dummy specimen;4: extensometer, 5:mirror, 6: cover sheet; 7:microbolometer camera; 8:cooled camera FLIR X6540SC).

Referring to the signal processing a signal reconstruction algorithm based on the least squares method [7] is adopted. The algorithms are implemented in the software IRTA®. The mathematical model describing the temeprature evolution and fluctuation is:

$$T\,(t) = T_0 + a \times t + T_1 \times \sin\left[2\pi f_{\mathrm{L}}\, t + \varphi_1\right] + T_2 \times \sin\left[4\pi f_{\mathrm{L}}\, t + \varphi_2\right] \tag{1}$$

where T_0 is the mean value, a is the mean rate, T_1 and T_2 the two amplitudes, and φ_1 and φ_2 the two phases and f_{L} is the loading frequency.

The processing was performed pixel by pixel but the identified indicator for the damage was the 95° percentile value in a region of interest (ROI) coinciding with the gage volume of the sample, was considered to represent the T_2 field.

The T_2 maps were addressed to a double-dimension filter using a gaussian kernel in order to filter out the noise.

The strain data from extensometer were used to study the hysteresis loop behaviour and in general the energy involved in fatigue processes.

Results

Fig. 2 shows the maps of assessed second amplitude harmonics (SAH) referring to the gage volume. The analysis of the SAH maps reveals an increase in signal from the first load levels to the last for all specimens. The damage appears to be widespread, affecting the entire useful section. However, it is only in the final loading steps that circumscribed areas with a markedly higher signal can be identified, which are indicative of the damage sites.

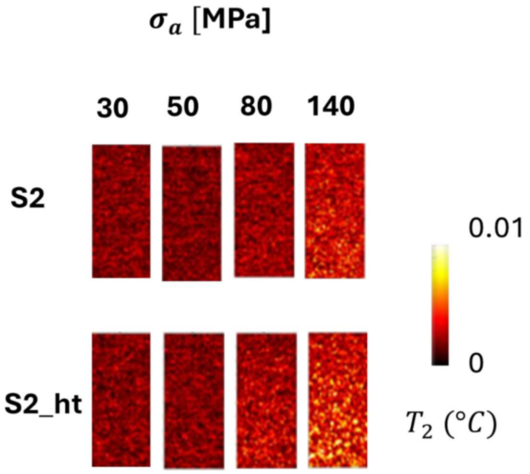


Fig. 2 Maps of SAH for samples as provided (right) and heat-treated (left).

Fig. 3 shows two exemplary charts with the hysteresis loops related to a sample in ‘as provided’ condition and a sample after heat treatment. The curves show that in both conditions the material behaviour is characterized by limited plastic

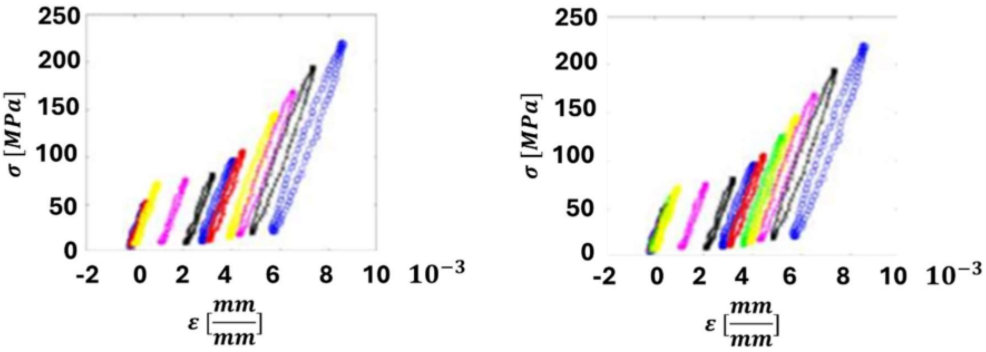
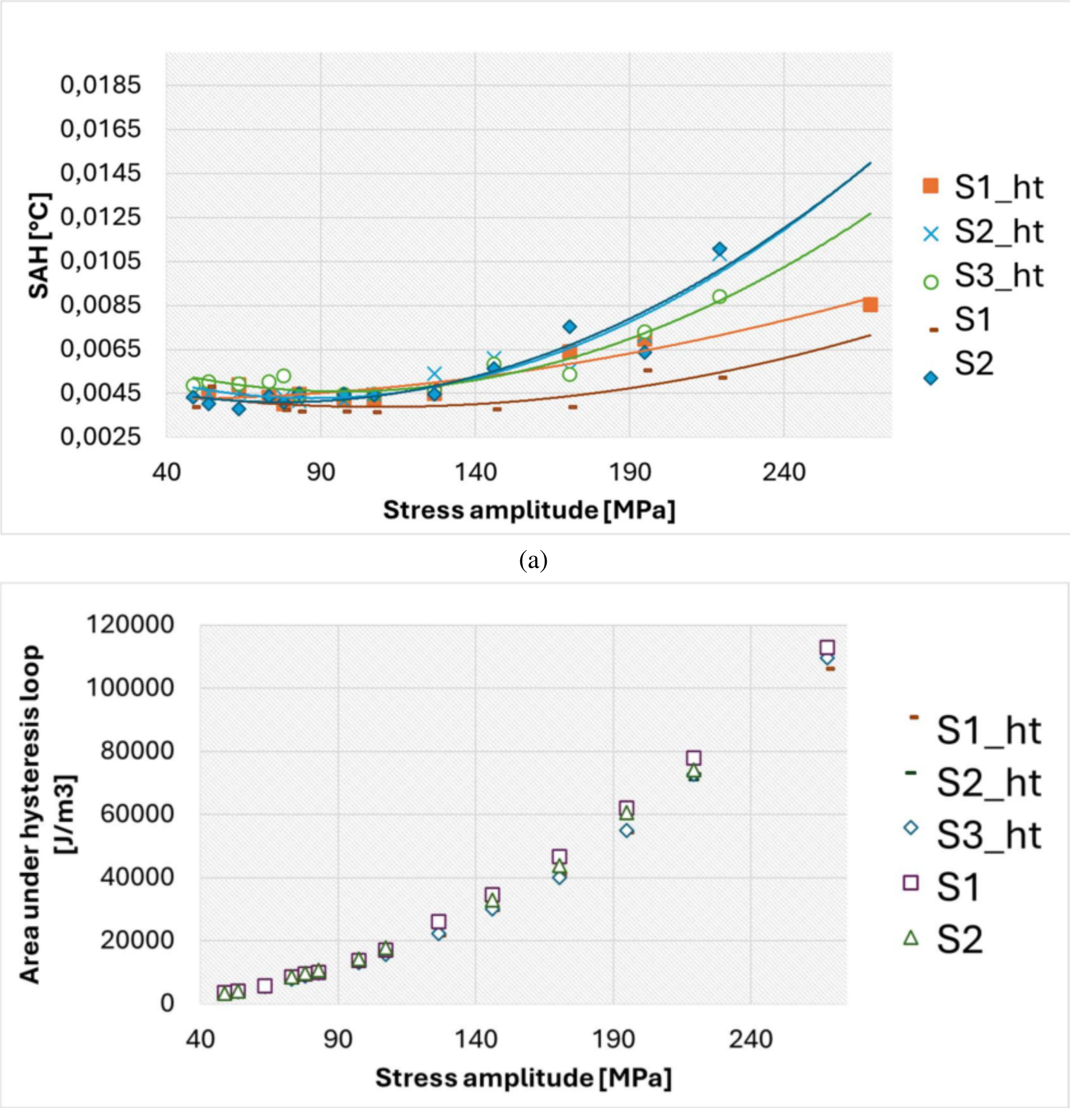


Fig. 3 Hysteresis loops curves for sample 3, as provided (right) and heat treated (left).

deformation and general brittle behaviour. The dissipation increases markedly only in the last loading levels where the hysteresis loops are wider than those at the beginning of the test.

Fig. 4 shows the curves of SAH (Fig. 4a) and the area under the hysteresis loop-Wp (Fig. 4b) for the specimens built in the vertical direction.



(a)

(b)

Fig. 4 Curves for samples realized in z-direction with and without heat treatment (ht=heat treatment), (a) SAH , (b) area under hysteresis loop (Wp).

As can be seen from Fig. 4a, there is no real cut-off point in the thermal behaviour of the material as would be expected from the reference parameter (Fig. 4b). This may be due to the superposition of reversible and irreversible effects in the thermal behaviour of the material. It should also be noted that aluminum does not have a knee point [16], but rather it is necessary to refer to fatigue strength at a given number of cycles. This will require future testing to better understand how to separate the two reversible and irreversible thermal contributions, as well as ad hoc processing procedures.

To estimate the material fatigue strength, a new procedure was identified to be applied to each specimen to select the stress level at which the series trend deviates significantly from the initial trend representing undamaged material.

The procedure is summarized as follows:

- Starting from the SAH values of the last 3 stress levels, consider the (stress amplitudes, SAH) pairs and calculate the R^2 coefficient;

- Adding another pair of data (stress amplitudes, SAH) and calculate the R^2 coefficient;
- Continuing until the value of R^2 differs by more than 5% from the previous values.

The methodology has been applied to SAH data and produced an estimation of the fatigue limit of 97±10 MPa without much difference between heat treated specimens and 'as provided' specimens.

Conclusions

In this paper, a comparison between SAH and hysteresis loop area has been presented to study the fatigue behaviour of AlSi10Mg -AM alloy subjected to stepwise testing.

The thermal method proves to be a comprehensive technique, allowing not only the detection of damage from its onset, but also the study of its evolution. All this has the advantage of consistently reducing the duration of the experimental campaign.

An additional advantage is the ability to better understand any differences between heat-treated and 'as provided' material, which is relevant for the purpose of providing guidelines for the technological process.

From the obtained results, there is in fact no difference between the fatigue strength of the material in the two configurations, but the data are certainly less noisy after heat treatment.

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