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Experimental analysis of residual stresses on AlSi10Mg parts produced by means of Selective Laser Melting (SLM)

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Abstract

During the Selective Laser Melting (SLM) process, the scanned layers are subjected to rapid thermal cycles. Steep temperature gradients generate residual stresses. Residual stresses can be detrimental to the proper functioning and the structural integrity of built parts. In this paper, the semi-destructive hole-drilling method has been used to measure the residual stresses on AISi10Mg parts after building, stress relieving and shot-peening, respectively. The outcomes have shown the presence, on the as-built components, of high tensile stresses that the usual post-processing operations are not able to minimize. The adopted method has proved to be a suitable tool to identify optimal process parameters for each step of the production cycle.

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Keywords: Residual stresses; Selective Laser Melting; AlSi10Mg; Hole-drilling method; Stress relieving; Shot-peening

1. Introduction

The selective laser melting process (SLM) utilizes a laser-beam to melt metal powder and produce components of elevated geometrical complexity. The powder absorbs a fraction of the laser's energy flow. This is converted into heat through electronic interactions with the atoms on the surface of the powder, which in turn causes the fusion of the powder and elevated thermal gradients. Production processes that utilize a laser as an energy source, such as soldering and laser bending, are known to induce large quantities of residual stresses because of the high temperature gradients that are generated on the components [1, 2]. In the case of the SLM process, the residual stresses can cause distortions, cracks and delamination between the subsequent layers of the components [3-6]. There are a great many similarities between the residual stresses that develop during a multi-pass welding process and those that develop during the SLM process; both processes in fact lead to the heating of the material that is deposited layer-by-layer. Although the welding process has been studied in great detail, the same cannot be said about the study of the stresses that develop during the SLM process of metal powder. In fact, very few experimental or numerical research papers are available in the literature concerning the study of residual stresses associated with the components produced by means of the SLM process.

The residual stresses created during the SLM process are the sum of the effects of hardening derived from the rapid solidification of the sections and of the volumetric changes caused by both the temperature gradients and by the phase transformations, including the solidification and the phase changes to a solid state between crystalline structures [7]. The differences in temperature in the irradiated region produce transient thermal deformations on the surface and at a depth. When the source of heat is removed, the material cools down and contracts more than the material that is present in the surrounding zone and residual stresses are thus created. The work by Mercelis and Kruth [7] supplies descriptions of the development of the residual stresses that seem to be generated by a similar process to that of the Temperature Gradient Mechanism (TGM), in which the thermal expansion and contraction of the material during the heating and cooling phases that follow the laser interaction induce step-like temperature gradients in all of the irradiated region. The heated

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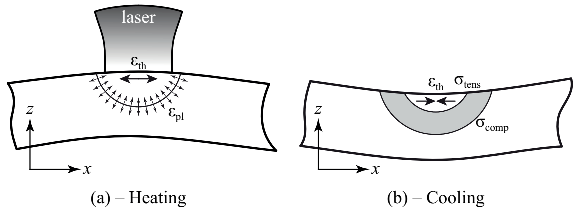

Fig. 1. Temperature gradient mechanism (TGM) in laser-based additive manufacturing systems [8].

material and the solid surrounding material can be assimilated to a structural unbalance that effectively restrains the movement of the heated metallic material when the latter changes in state. During the cooling, a complex contraction of the irradiated region takes place, that is a tension state, while the material that surrounds the irradiated zone undergoes an expansion that results in a compression state. The volumetric shrinking of the material melted during the cooling induces compression stresses in the surrounding material, which is under the influence of the temperature gradient, as illustrated in Figure 1 [8]. Gusarov, Pavlov and Smurov [9] proposed a thermos-elastic model, which showed that longitudinal tensile stresses are on average two times greater than transversal ones. The model explains the formation of two longitudinal and transversal crack systems that were observed during experiments. The *island scanning* strategy of some SLM machines can reduce residual stresses by shortening the scan tracks [10]; the rotation of the scan pattern between layers is another adopted solution that is able to create a more uniform stress distribution by compensating for directional anisotropy.

Some studies can be found in the literature that have had the aim of evaluating the distribution of the stresses in the different longitudinal, transversal and normal directions, with reference to parallelepiped samples of thin walls in order to simplify the analysis. The results show that the stresses in the longitudinal direction are greater and that they reduce as they come closer to the base of the component. Compression states are generally observed in the center of the samples, which then become traction states as they approach the surface [11-13]. Other studies on residual stresses are of a qualitative or semi-quantitative type and are based on the evaluation of the deformations of bridge or cantilever structures [10]. Furthermore, the forecasting of the residual stresses and distortions induced during laser melting have proved to be a hard task because of the high localized temperatures, of the rapid temperature cycles and of the source of heat in movement, due to the use of a laser.

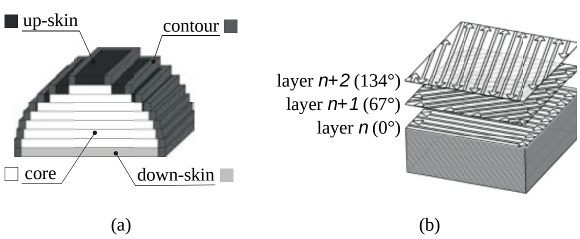

Fig. 2. (a) Schematization of the structure of the downskin, upskin and core parts; (b) exposition of each layer to the laser [14].

This work describes an experimental activity that has made it possible to draw the trend of the residual stresses on the upper layers of samples produced in AlSi10Mg aluminum alloy by means of an SLM process in order to evaluate how such stresses are altered by the different phases of the production process, starting from the production to the thermal treatment and going on to removal of the supports and the final shot-peening treatment.

2. Materials and Methods

Eight parallelepiped 30 × 20 × 10 mm³ samples in EOS AlSi10Mg aluminum alloy were produced in a single job using an SLM EOSINT M 270 eXtended machine. The layer was 30 µm thick and the building platform was kept at 35° C. The components were constructed while blowing argon into the work chamber in order to avoid oxidation of the material. A standard construction strategy, which foresees different exposition parameters for the core, the skin, and the contour was adopted. The first two layers of the base of the components have been termed *downskin*, while the last three at the top have been termed *upskin*. The layers compressed between the downskin and the upskin represent the *core*. A schematization of the structure is shown in Figure 2a with the downskin, upskin and core parts. After the contouring phase of the core region has been completed, the contour of each layer is exposed to a low power laser in order to improve the surface finishing of the part [14]. The pattern of the exposition to the laser beam is shown in Figure 2b. The scan lines of each layer within the core area have been rotated by 67° to the scan line of the preceding layer. Table 1 reports the values of the parameters utilized during the construction of the components [14].

Immediately after the construction, the table (Figure 3a) was removed from the machine and the residual stresses on the first two samples, indicated with the letters A and B, were evaluated. Sample A was prepared without supports, while sample B was prepared with supports. After the measurement, the platform with the samples was subjected to a stress relieving thermal treatment at 300° C for 3 hours. Other evaluations of the residual stresses were conducted on samples C and D, without and with supports, respectively, in order to evaluate the release of the stresses generated by the thermal treatment. Subsequently, samples E and F were removed from the platform and the shot-peening process of the surface was conducted. A NORBLAST SD9 shot-peening machine was used for the shot-peening treatment, utilizing 200 µm diameter zirconia beads and a pressure of 3 bar. A 6 mm nozzle was kept inclined at 45° to the treated surface. After the finishing operation, the samples were again measured in order to evaluate the final residual stress state.

Table 1. Process parameters utilized for the production of the samples [14].

Parameters	Skin	Core	Contour
Scan speed [mm/s]	900	800	900
Laser power [W]	120	195	80
Hatch distance [mm]	0.10	0.17	–
Layer thickness [µm]	30		
Laser spot diameter [µm]	10		