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Improvement of the bridge curvature method to assess residual stresses in selective laser melting

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ABSTRACT

In the Selective Laser Melting (SLM) process, residual stresses are a major problem because they impact the dimensional accuracy and mechanical properties of the manufactured parts. A new methodology, based on distortion measurements using the bridge curvature method (BCM), is developed for the quantitative assessment of residual stresses. The bending of the surface of the released specimen is approximated by a quadratic polynomial and quantitative criteria are determined on both profiles and surface topographies measured by non-contact 3D optical microscopy. The accuracy of the method is evaluated by a statistical analysis using repeatability tests. Focus variation microscopy (FVM) measurements show better repeatability than extended field confocal microscopy. Compared to the 2D measurements generally reported in the literature, 3D characterization provides relevant information as the orientation of the main distortion, which may help to highlight the effect of SLM process parameters. In fact, the flatness parameters and curvature attributes measured on surface topographies are much more robust and repeatable than the distortion magnitude measured on isolated profiles. In particular, 3D analysis helps to show that the distortions are maximum perpendicular to the path of the laser.

1. Introduction

Additive manufacturing (AM) processes, and in particular selective laser melting (SLM), are recognized as a promising technology due to its ability to produce complex and lightweight customized components. These are directly fabricated from a sliced 3D-CAD model, without requiring expensive part-specific tooling [1]. Despite its many advantages, the SLM process is still under development, especially for aeronautical applications. Among the current challenging research topics, most studies focus on the material densification, microstructure and mechanical properties [2–7], while some others are dedicated to process monitoring, improving surface quality and reducing residual stresses [1,3,8–10]. The SLM process belongs to the family of powder-bed fusion (PBF) technologies [11], whereby a thin layer of powder spread on a substrate is selectively melted by a computer controlled laser beam and consolidates by heat diffusion. The part is built layer by layer, by repetition of these steps for successive powder beds [12,13]. During production, the material experiences large localized temperature gradients due to rapid heating and cooling within a short time associated to the scan pattern of the high energy focused laser beam. Due to the layered build-up, the latter melting layer may re-melt or reheat the underlying layers. This results in high thermally-induced internal stresses which can detrimentally affect the mechanical performances and thus the reliability and life of the components in service [14]. When removing the part from the base plate, the residual stresses are released by shrinkage and bending deformation, causing dimensional inaccuracies [7,9,10,15,16]. The distortion or even cracking of the part can sometimes happen during the process when the stresses reach critical levels. Understanding and controlling the development of the residual stresses inducing the component distortion is a critical issue and one of the current challenging research topics in SLM manufacturing [1].

Residual stresses can be generated in many structures and components during various thermal or thermo-mechanical manufacturing processes such as welding, forming, heat treatment, machining, etc. [17–21]. Over the years, various techniques have been developed to evaluate residual stresses, such as X-ray and neutron diffraction, ultrasonic velocity, magneto-acoustic emission, hole drilling, instrumented sharp indentation, crack compliance, layer removal, etc. [22–24]. These methods can be classified depending on their characterization scale and their destructive or non-destructive nature. Mechanical methods (e.g., sectioning, contour, hole-drilling, ring-core, curvature) are used to characterize type I macro-stresses which vary over large distances (namely the dimensions of the part). These

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destructive techniques are based on the deformation measurement during or after complete or partial release of the residual stresses upon disturbing the mechanical equilibrium of the part. Non-destructive "physical" methods, such as diffraction analysis, are more relevant for assessing residual stresses of type II and type III, which occur respectively at the grain level or on the atomic scale [9,22]. However, the measurement uncertainties obtained by these methods depend on the material being analyzed. In particular, the correct evaluation of residual stresses in titanium alloys is difficult due to the overlap of the diffraction peaks associated with their poorly defined shape [25,26].

The curvature method, which consists in measuring the deflection or curvature of a part caused by the addition or removal of material containing residual stresses, is generally used to determine post-process thermal stresses within coatings and layers [22,23,27]. It can be applied to SLM components since the additive manufacturing is based on melting of successive layers, for example to optimize process parameters (such as laser power, scan speed and strategy, layer thickness, preheating, etc.) known to have a significant effect on the residual stresses [22,28]. Thus, several studies [13,29–32] were performed using an overhang "cantilever" test geometry selected to cause significant distortions, to investigate the influence of process parameters or to validate distortion prediction models. The method consists in determining the difference between the height of the specimen arms before and after separation from the support structure, on few points (usually about ten) along the longitudinal axis of the specimen. However, the measurement accuracy is limited to a hundred or a few hundred micrometers, due to the method of cutting the supports, and to the high surface roughness which is not filtered in the profile [30]. In-situ measurements can be useful to monitor the PBF process during the part build [3,33,34]. Thus, Denlinger et al [35] used a laser displacement sensor to measure in situ deflection of a rectangular parallelepiped substrate material free to distort at one extremity, in order to investigate the residual stresses accumulated during the building of Ti-6Al-4 V and Inconel 625 parts by laser-based directed energy deposition. In addition, the authors determined the pre- and post-process plate profiles at ten points along the top of the substrate using a coordinate-measurement machine.

The changes in the plate profile and out-of-plane distortion of the substrate were then calculated by subtracting the pre-process from the post-process measurements. But this asymmetric geometry, as the cantilever, enables to assess the residual stress only in one direction, because it concentrates the stresses along the specimen axis. For their part, Kruth et al [15] investigated the amount of residual stresses in Ti-6Al-4 V parts produced by SLM using a bridge-shaped geometry specifically designed. Their so-called "bridge curvature method" (BCM) consists in determining the residual stress by finite elements simulation using on the curling angle α. This parameter is defined as the deviation from the normal position of the planes at the bottom of the pillars cut off from the base plate by wire EDM. It is determined using a 3D-CNC vision measuring machine. However, the measurement accuracy of the curling angle may be affected by a poor quality of the specimen cut, whereas the value of the calculated stress is very sensitive to the accuracy of this measure.

In the present study, an improved methodology derived from the BCM is proposed to accurately assess the part distortion of Ti-6Al-4 V bridge-shaped specimens produced by SLM. Profile and 3D surface measurements are performed on the upper surface using optical microscopy before and after removing the specimen from the base plate. The surface topographies are filtered and analyzed to determine the magnitude of distortion and additional parameters expressing the shape of the curvature. The repeatability of the method is assessed by statistical analysis, and the results of 2D and 3D measurements are compared.

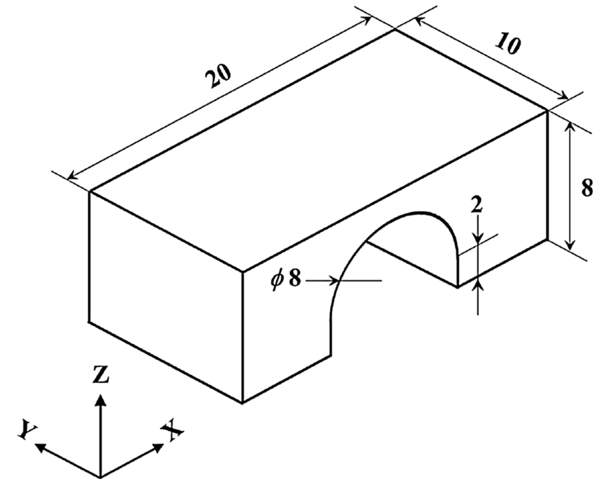

Fig. 1. Geometry and dimensions (in mm) of the SLM bridge-shaped specimen.

2. Experimental procedure

2.1. Material and specimens

SLM experiments were performed on a ProX® DMP 200 machine from PHENIX SYSTEMS. Titanium alloy Ti–6Al–4 V was used as powder material, chosen for many applications as aerospace and biomedical industries owing to its good strength-to-weight ratio, high fatigue and corrosion resistance, good bio-compatibility associated to a good formability and heat treatability [5,24]. The powder was plasma-atomized, resulting in a particle size ranging from 15 μm to 70 μm and a median diameter d_{50} of about 35 μm. A parallelepiped bridge shape, shown in Fig. 1, was selected to emphasize residual stresses during and after the manufacturing [15]. Specimens were manufactured in a protective argon atmosphere to prevent oxidation, using a non-preheated Ti–6Al–4 V base plate and without supporting structures. The invariant manufacturing parameters are reported in Table 1. Various laser scan strategies were investigated, as indicated in Fig. 2.

2.2. Measurement of distortions

2.2.1. Non-contact optical measurement techniques

The specimens were removed from the SLM support plate by electro-erosion. The distortions due to residual stresses that developed during the building process were released during the cutting. The surface of the specimen was measured using an Extended Field Confocal Microscope (EFCM, Altimet AltiSurf 520), based on the principle of chromatic coding (Fig. 3a):

- focusing of a white light source reflected on the surface of the sample,

- beam splitting of the polychromatic light source into its constituent wavelengths by an accurate distance-measuring sensor incorporating special chromatic lenses (each wavelength being able to focus only on a point situated at a specific distance from the sensor, thus creating a continuum of monochromatic imaging points),

- activating the distance-sensing ability of the sensor by matching the central wavelength of the reflected beam to the exact height of the

Table 1
Manufacturing parameters kept constant on the SLM machine.

Laser spot diameter (mm)	Laser power (W)	Scan speed (mm/s)	Hatch spacing (mm)	Layer thickness (mm)	Number of layers	Contour scan
0.07	300	1800	0.085	0.06	233	none