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Structural integrity of direct metal laser sintered parts subjected to thermal and finishing treatments

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ABSTRACT

Direct Metal Laser Sintering (DMLS) is a rapid manufacturing technology that is starting to be used for the manufacturing of functional components. Therefore, properties of DMLS manufactured parts must be carefully analyzed to determine if they satisfy technical requirements under fatigue conditions.

In this work, the structural integrity of Maraging Steel, Inconel 718 and CoCr alloy DMLS parts subjected to different thermal and finishing (shot peening and surface polishing) treatments has been characterized in order to determine the optimum stabilization treatment with regard to structural integrity. For this characterization, surface residual stresses, microstructure, porosity and hardness of the parts have been studied.

In general, DMLS process origins detrimental surface tensile stresses in Inconel 718 and CoCr alloy components whereas in Maraging Steel parts DMLS results in light surface compressive stresses that improve in general with the application of subsequent thermal and mechanical treatments. Moreover, surface polishing homogenizes the final stresses resulting, besides, in very compressive surface residual stresses.

1. Introduction

Additive manufacturing or rapid prototyping is an advanced manufacturing technology based on layer-by-layer deposition that has been developed subsequent to conventional machining. The first additive technologies were patented on 1971 by Ciraud (1971), but the first applications of these technologies did not appear until 1979 in the case of stereo-lithography process with the patent of Hull (1979), and, as Shellabear and Nyrhilä (2004) gather in their review of the development history and state of the art of DMLS (Direct Metal Laser Sintering), applications for polymer sintering were not developed until 1985 and specific applications of metal sintering were not achieved until 1990. The main advantages of additive manufacturing are that can be used to manufacture plastic, ceramic and/or metal components, with nearly any kind of geometry, completely automatically and without the need of tooling, thereby reducing production time and cost.

At the beginning, layer manufacturing techniques were used for the fabrication of prototypes (this is the origin of the name rapid prototyping) but nowadays, with the introduction of new metallic alloys and equipment improvement, additive manufacturing techniques are moving from rapid prototyping to direct fabrication of functional or structural end-use products, i.e. rapid manufacturing of functional components.

Different rapid manufacturing technologies can be distinguished regarding the way in which the layers of material are made to grow up until the generation of the final component. Direct Metal Laser Sintering (DMLS) is a rapid manufacturing technology where a high power laser is used to fuse metallic powder particles, doing a scan of the transversal cross sections of the final component generated from a CAD model. After each scan a new powder layer is deposited and is subsequently laser sintered, until the entire component is manufactured.

DMLS is based on a sintering mechanism involving a partial or total (depending on the laser energy density employed) melting of the powder, i.e. DMLS is a semisolid consolidation mechanism. Therefore, DMLS products could show characteristic cast structure, with high superficial roughness, presence of porosity (in certain cases even lack of densification), heterogeneous microstructure and residual stresses (thermal residual stresses), resulting in poor mechanical properties which can be improved to certain extent by additional treatments (post-processing). Since DMLS can be used to manufacture functional components, it is essential a good characterization of the sintered parts, with and without post-processing treatments, to control the effect that each treatment causes on the final integrity of the parts, and this way being able to warranty that the DMLS components fulfill final functional requirements.

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Some works can be found in the literature related to the study of some properties of DMLS parts (of different materials) without any subsequent treatment: Wang et al. (2006) have found that Fe-Ni-Cu-P DMLS parts present surface roughness R_a of around 18 μm and porosity values of approximately 2.6%, with location and morphology of pores sensitive to the laser building direction. They also observed a very heterogeneous microstructure. Gu and Shen (2008) have studied the densification of DMLS 316L stainless steel, observing porosities between 21 and 55% that increase as laser power is reduced or scan speed, scan line spacing and powder layer thickness are increased. More recently Gu et al. (2012) have done a similar study in pure titanium, and have concluded that there is a narrow, feasible process window of scan speed where DMLS parts can be manufactured without defects and with full densification. Dinda et al. (2009) have concluded that Inconel 625 is an attractive material for laser deposition as DMLS samples of this alloy are free from relevant defects such as cracks and porosity. Tang et al. (2003) have observed that final density of DMLS Cu-based alloy parts increases when the laser power increases and scan speed and scan spacing decreases, just the opposite to the conclusions of Gu and Shen (2008) in their study of DMLS of 316 stainless steel. Tang et al. (2003) have also observed that in DMLS Cu-based alloy samples the tensile strength increases with increasing laser power and decreasing scan spacing, scan speed and layer thickness; on the other hand surface roughness increases with laser power, scan spacing and layer thickness but decreases when scan speed increases. Simchi and Pohl (2003) and more recently Simchi (2006) have performed similar studies on the effect of processing parameters on densification, but in this case on iron and steel powders, respectively. Their conclusions regarding porosity coincide with those of Tang et al. (2003): final density of DMLS parts increases with laser power and decreases with scan speed and scan spacing. Simchi and Pohl (2003) have also observed that density is slightly affected by the atmosphere if the oxygen potential remains constant.

Other bibliographical references are focused on the study of the effect of post-processing treatments on DMLS parts: Brinksmeier et al. (2010) have studied the surface integrity (roughness, residual stresses and hardness) of selective-laser-melted (SLM) components after being machined to assure final accuracy in shape and dimension. They have observed that SLM samples present lower compressive surface stresses and higher surface roughness than conventionally manufactured samples, but this surface state can be comparable if a final machining (milling and grinding) is applied to the SLM parts. Rossi et al. (2004) have observed that shot peening and emery polishing followed by coating deposition improves surface roughness and corrosion of DMLS polymeric components. Surtarsic et al. (2009) also found that wear resistance can be improved by decreasing porosity of the up-skin layer and surface roughness by appropriate surface finishing and hard coating after DMLS. Brandl et al. (2012) have studied the morphology, microstructure and hardness of Ti6Al4V deposited by wire-feed additive layer manufacturing and subsequently heat treated. They have observed that hardness is influenced by the post heat treatments rather than by the deposition process parameters. The as-built morphology and microstructure can be completely changed with heat treatments at appropriate temperatures.

Most of the works found in literature are studies of microstructure, porosity, roughness, and hardness of DMLS components with and without post-processing treatments, as described in previous paragraphs. Nevertheless, very few studies focus their attention on the residual stresses generated during the DMLS process or their release by the post-processing treatments or link residual stress state with microstructure. However the control of residual stresses is foremost in aeronautical applications since they could affect the component life: residual stresses are added to the external stress fields leading to a real stress in the component higher (in the case of tensile residual stresses) than the nominal stress applied and therefore fatigue strength of the component is reduced, what can result in premature failure of the components in use.

The aim of the present work has been to cover this lack of works in bibliography about residual stresses in DMLS parts, especially in materials of interest in the aeronautical industry, where residual stresses are of relevant importance. Hence, in this work, the residual stresses and other aspects of structural integrity (such as microstructure, porosity and hardness) of Maraging Steel, Inconel 718 and CoCr alloy DMLS parts subjected to different thermal and finishing (shot peening and surface polishing) treatments has been studied. The study of surface integrity of DMLS parts after different post-processing treatments has allowed the determination of the optimum stress relieving treatment.

2. Experimental procedure

2.1. Materials

Three different materials have been employed in this research: Maraging Steel, Inconel 718 and CoCr alloy. The chemical composition of these materials, provided by the powder supplier (EOS e-Manufacturing Solutions), is gathered in Table 1.

EOS Maraging Steel MS1 is a pre-alloyed ultra high strength steel, characterized by having very good mechanical properties, and being easily heat-treatable using a simple thermal age-hardening process to obtain excellent hardness and strength. This material is ideal for many tooling applications and also for high performance industrial and engineering parts.

EOS Nickel Alloy IN718 is a heat and corrosion resistant precipitation-hardening nickel-chromium alloy, characterized by having good tensile, fatigue, creep and rupture strength at temperatures up to 700 °C. This material is ideal for many high temperature applications.

EOS Cobalt Chrome MP1 is a high carbon CoCrMo alloy, characterized by having excellent mechanical properties, corrosion resistance and temperature resistance. Such alloys are commonly used in biomedical applications and also for high-temperature engineering applications.

2.2. Manufacturing of the parts and stabilization treatments

Two different geometries of DMLS samples have been used in this work: Maraging Steel, Inconel 718 and CoCr H-geometry samples (Fig. 1(a)) and Maraging Steel prototype vanes (Fig. 1(b)). A commercial DMLS system with a 200 W Yttrium laser has been employed by Pole Européen de Plasturgie in France for the manufacturing of the samples. The parameters associated to the deposition process are the thickness of the deposited layer and the average laser spot speed. These parameters are different for each material:

- Maraging Steel: layer thickness = 40 μm; average laser spot speed = 750 mm/s,
- Inconel 718: layer thickness = 40 μm; average laser spot speed = 1200 mm/s,
- CoCr alloy: layer thickness = 20 μm; average laser spot speed = 800 mm/s.

This work is focused on the study of the effect of post-sintering treatments, being the sintering parameters the same in all the samples where the effect of different post treatments has been compared. Therefore, for each material studied, the initial state