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Additively manufactured metallic compliant structures, a focus on manufacturing strategy and material performances verification

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Abstract

Additive Manufacturing (AM) processes is a constantly growing topic of interest in sectors such as space, astrophysics, medical and watch making industries. While the largest part of the R&D work presently reported is focused on developing and optimizing designs of "structural or massive parts", little work has been published to determine the limits related to the manufacturing of flexible structures used in compliant mechanisms. In this context, usual weaknesses attributed to AM processes – surface roughness, material porosity & mechanical anisotropy – may become major showstoppers. It is worthwhile to mention that designing compliant mechanisms also implies the association of these elementary flexible structures to the stiff structural segments of the mechanical part. Associating these very heterogeneous geometries into a single monolithic part built by AM is a challenge in itself.

Compliant mechanisms, Additive Manufacturing, Selective Laser Melting, fatigue testing, tensile testing, material analysis

1. Introduction

Compliant mechanisms can achieve macroscopic linear and rotary motion without friction, wear, backlash, and with extremely high fatigue performance thanks to the elastic deformation of flexible structures. To date, their very high complexity has required highly sophisticated and expensive manufacturing methods, the gold standard being the Wire Electro-Discharge Machining (WEDM) from a bulk material block with consecutive large material losses and very long and delicate machining procedures.

Today, this paradigm is questioned by the new possibilities offered by AM technologies. In the field of compliant mechanisms, the potential of AM for innovation is already proven [1]. Nevertheless, implementing innovation into cutting-edge applications first requires in-depth process mastering, especially when space applications are targeted. The present paper describes how CSEM tackled the challenge of producing AM-based compliant structures targeting such applications. This endeavor started in 2014 with the production of an SLM-based (Selective Laser Melting) compliant structure demonstrator, and continued with the development of an end-to-end production strategy, addressing the key aspect of optimizing material properties and its tensile and bending fatigue mechanical performances.

2. SLM-based compliant structures feasibility study

The case-study of Figure 1. – a 6 mm × 8 mm stroke 2DoF compliant linear stage – gathers simple & double parallelogram arrangement. It was defined and sized to be typical of compliant structures encountered in real applications. SLM was chosen for its high TRL and subsequent ease of access at industrial level.

The preliminary results revealed that the thermal gradients occurring during the SLM process were generating internal stresses and a consecutive macroscopic warpage as the part was manufactured on low density material support. Manufacturing the final part on a fully dense substrate and implementing an annealing step prior to separating the part from its substrate successfully addressed the warpage issue.

The research for the optimum SLM parameters showed that those had to be accurately tuned and optimized depending on the type of segment in presence – i.e. structural or flexural. Preliminary inspection and material analysis revealed poor surface quality compared to WEDM processed surfaces, visible material porosity and rather irregular microstructure, which were all suspected to affect the tensile and fatigue properties. These observations were used as inputs for the next phase.

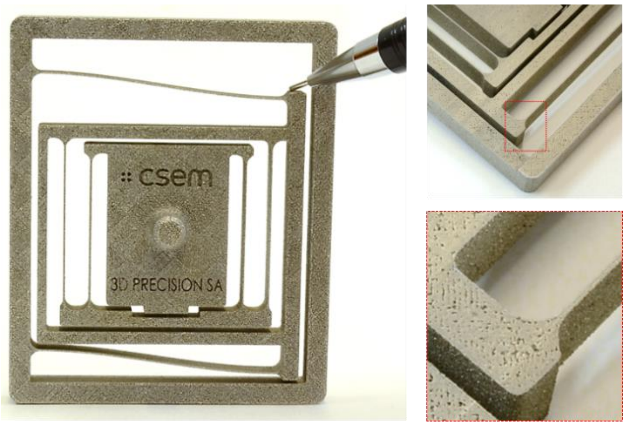

Figure 1. AM-SLM produced 316L stainless steel 2DoF linear stage

3. SLM-based production of optimized compliant structures

3.1. General philosophy

The samples were manufactured from a CL92PH powder alloy, a chemical equivalent of the widely used and studied 17-4PH precipitation hardening stainless steel. The study consisted in the optimization of the SLM parameters and in the definition of the best post-process approach. Both steps were driven by continuous material analysis and the final validation was achieved through tensile and alternate bending fatigue testing.

3.2. SLM process and post process parameters optimization

The optimization of the SLM parameters was performed in an iterative manner with the aim to get minimized and homogenized porosity, micro-structure and surface roughness. The fatigue samples were chosen as reference geometry, since they were gathering both structural and flexure areas. The parameters being tuned were the layer thickness, laser beam power, focus point, scan speed and the laser patterns applied to different areas of the samples. The laser pattern was confirmed to be the key parameter leading to homogenous material quality on both massive and thin geometries, as shown on Figure 2. After SLM manufacturing, the thin sections were showing thickness variations of ±18 µm at 3σ, with an average thickness of 380 µm, whereas the reference value was 350 µm.

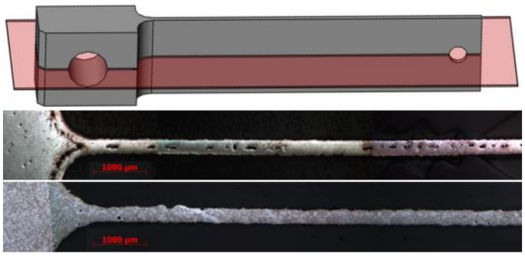

Figure 2. Fatigue sample cuts before and after SLM optimization

The post-processing optimization consisted in assessing the benefits of Hot Isostatic Pressing (HIPing). The analysis confirmed the removal of the residual porosity and the improvement of the microstructure in terms of homogeneity and grains size, as depicted by Figure 3. Although the dimensional accuracy of the flexures was not affected, a visible warpage of the base plate holding the samples was observed.

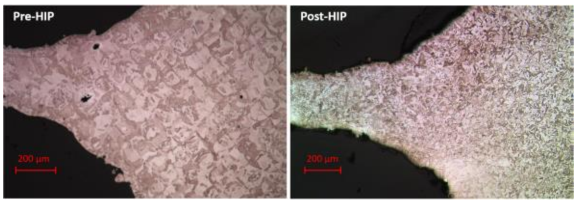

Figure 3. Sample cuts before and after HIPing treatment.

3.3. Tensile testing

The tests were conducted for HIPed and non-HIPed material condition with a total of thirty samples produced according to the 3 manufacturing directions (five samples per direction). The samples were designed according to the ASTM E8/E8M – 15a standard. Raw rods were produced, heat treated, machined to their final geometry and finally tested.

The results of Table 1 show that for both heat conditions, the SLM produced samples show similar or higher R_m and $Rp_{0.2}$ compared to the commercial grade *17-4PH.* The elongation at break for non-HIPed samples tend to show a fragile behavior which is confirmed by the fracture inspection (see Figure 4). The fracture inspection proves that HIPing also improves the intergranular cohesion, leading to enhanced tensile properties.

Table 1. Tensile test results and comparison with commercial 17-4PH.

TENSILE TESTS RESULTS			17-4PH Böhler	CL92PH X-Y-Z mean values ±1σ	
Material heat condition - Solution Annealed (*SA*) - Age Hardened (*AH*)			*SA / AH*	*SLM/ SA/AH*	*SLM/HIP/ SA/AH*
UTS	Rm	N/mm²	1170	1412±32	1415±18
Yield strength	*Rp0.2*	N/mm²	1070	1034±43	1335±21
Elongation	A_5	%	8	3.1	9

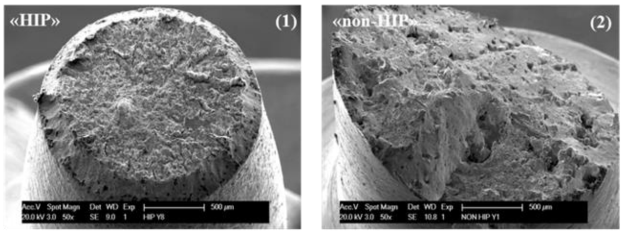

Figure 4. SEM fracture surface inspection for HIP and non-HIP groups.

3.4. Alternate bending fatigue tests

HIPed and non-HIPed flexure samples were produced by SLM, each group consisting of at least 10 samples, with 5 samples per stress level. A third group was machined by WEDM from 17-4PH, applying the standard protocol followed for the MTG space program the CSEM is involved in. To benefit from comparative data, the geometry of the samples (see Figure 2) and of the test apparatus were kept identical to those used in MTG. Under standard lab conditions, the samples were applied a ±1 mm shuttle motion at 15 Hz. The *S-N* curve and fatigue limit S_f estimates show that SLM produced flexures performances remain in the same order of magnitude, with decrease limited to 15 % for HIPed samples and 30 % for the non-HIPed samples.

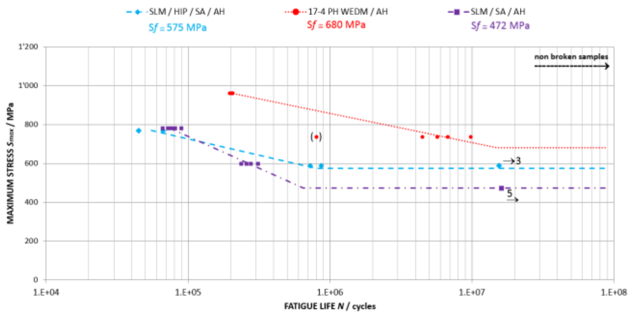

Figure 5. S-N curves from R=-1 alternate bending fatigue test campaign.

4. Conclusions

In this study, an end-to-end SLM-based manufacturing and post-processing protocol for a high strength stainless steel comparable to 17-4PH steel was successfully developed. The beneficial effects of HIPing on material performances were confirmed, with a tensile yield strength comparable to that of the commercial grade 17-4PH. This study shows that compliant structures offering lifetime above fifteen million cycles under realistic load cases can be produced, proving the potential eligibility of SLM-based compliant structures for space applications. Nevertheless, the geometry of the SLM manufactured samples was less accurate than those produced by WEDM. It was also observed that HIPing may affect the geometrical accuracy of larger parts, which might be a real challenge when it comes to producing more complex shapes whilst preserving high accuracies. These aspects clearly indicate that using SLM to manufacture high quality flexure assemblies is not a straightforward approach.

Future work will focus on verifying whether the increased design freedom promised by SLM specialists is applicable to compliant structures. This point will be essential to get a clear overview of the pros and cons of this technology which could enable interesting new perspectives for compliant mechanisms.

References

[1] Merriam, Ezekiel G., Stiffness Reduction Strategies for Additively Manufactured Compliant Mechanisms, *All Theses and Dissertations.* Paper 5873, 2016