Compliant Mechanisms Re-Design based on Additive Manufacturing and Topology Optimization

Lionel Kiener*, Hervé Saudan*, Gérald Perruchoud* and Johan Kruis*

Abstract

The use of Additive Manufacturing (AM) processes for cutting-edge applications is a constantly growing topic of interest in various sectors such as space, astrophysics, medical and watchmaking industries. While the largest part of the research presently reported is focused on developing and optimizing designs of what could be described as “structural or massive parts”, little work has been published up to now to determine the limits related to the manufacturing of thin, flexible structures used in compliant mechanisms [1].

While the common thinking is that everything can be done by AM - which is only partially true - it can be added that it cannot be done haphazardly. The Additive Manufacturing process needs to be well mastered as it introduces several new challenges which need to be taken into account in the design phase. In parallel, reproducing by Additive Manufacturing the same parts that are currently produced by traditional methods such as machining is usually of no interest. To ensure the highest added value, the entire device - and not only the individual parts - need to be reconsidered under a process-oriented design perspective, the whole being driven according to a system engineering mindset. CSEM is investigating the new capabilities of AM with the aim to help industries to redesign their products according to this holistic approach.

This paper exposes the status of the Research & Development activities carried out at CSEM with the aim to produce novel designs of mechanisms, including compliant structures based on AM. The general development strategy is presented, followed by material & process characterization and testing results. The re-design, including topology optimization of space products and compliant mechanisms are presented as well.

Introduction

CSEM is active in the design and development of very high performance flexural elements and mechanisms for more than 30 years. Notable examples for space applications are the HAFHA flexural pivot and the Corner Cube Mechanism which is currently operated in the IASI instrument on board MetOp satellites, to date with more than 800 million cycles (linear stroke of ±15 mm) achieved in 10 years. Other mechanisms (e.g. Slit Mask, tip-tilt and chopper) have been developed and produced for ground-based telescopes as well as for the airborne SOFIA telescope.

In the same philosophy, the elaboration of new products made by additive manufacturing has been investigated at CSEM over several years targeting the general goals of assessing the benefits and weaknesses of the AM fabrication process for compliant mechanisms and getting a sufficient level of expertise on AM-produced compliant mechanisms for future projects.

Development Strategy

For future development projects, CSEM tackled the challenge of producing compliant structures by Selective Laser Melting (SLM). The first chapter of this endeavour started in 2014 with the development

* CSEM SA, Neuchâtel, Switzerland

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of a 2-DoF linear stage demonstrator and continued with a second chapter consisting in the development of an end-to-end production strategy addressing the optimization of the material properties. The main conclusions derived from the characterization of these samples were that - in their optimized version - their tensile properties were similar to those of the commercial grade alloy, while their alternate bending fatigue lifetime was greater than 15 million cycles under cyclic loads near to 50% of their Yield Strength. Based on these encouraging results, a third chapter was opened in 2017 with the aim to design, produce and test several topologically optimized parts and mechanisms.

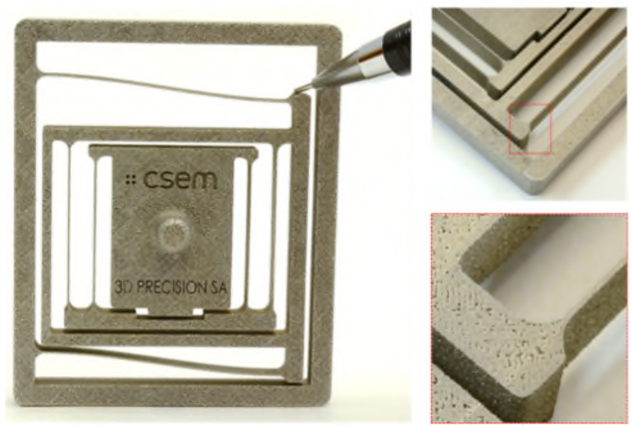

Figure 1. AM-SLM produced 316L stainless steel 2-DoF linear stage. Flexures thickness = 300 µm, aspect ratio respectively 80 and 123 for the blades of the double and simple parallelograms

Materials Selection, Development and Validation

The material choice was oriented toward high-strength stainless steel alloys available in powder form, with the aim of approaching the exceptional mechanical properties and stress corrosion cracking (SCC) resistance of MARVAL X12, the material usually chosen by CSEM for demanding applications. This high-strength precipitation-hardened stainless steel offers both high SCC resistance [2] and high fatigue resistance when it is submitted to alternate bending deformation, a parameter which was experimentally verified through several internal fatigue test campaigns. The alloy chosen – Concept Laser's CL92PH – is an equivalent of the widely used and studied 17-4PH martensitic precipitation-hardening stainless steel [3, 4]. Recently, the AM process for titanium alloy has been optimized following the same procedure. Other prototypes have been made of aluminium AlSi10Mg and copper by SLM.

SLM Process Optimization

The optimization of the SLM parameters was performed in an iterative manner with the aim to minimize porosity and surface roughness, whilst seeking to optimize micro-structure for high mechanical performances.

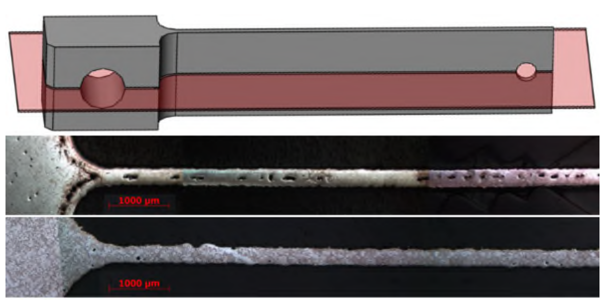

Figure 2. Fatigue sample cross-sections before and after SLM parameters optimization. The thickness of the blade is 350 µm.

Among the process parameters evaluated, such as layer thickness, laser beam power, focus point or scan speed, the laser pattern was confirmed to be the key parameter leading to homogenous material quality on both massive and thin geometries, as shown in Figure 2.

The impact of the manufacturing direction was also investigated. The only notable differences were found on the transverse cut where Y samples showed a finer micro-structure compared to X. These visual differences were all suppressed after the Hot Isostatic Pressing (HIP) treatment, which removed all porosity and improved the micro-structure, such that X and Y could no longer be distinguished (see Figure 3). The analysis confirmed that the HIP treatment permits the removal of the residual porosity and the improvement of the microstructure in terms of homogeneity and grain size.

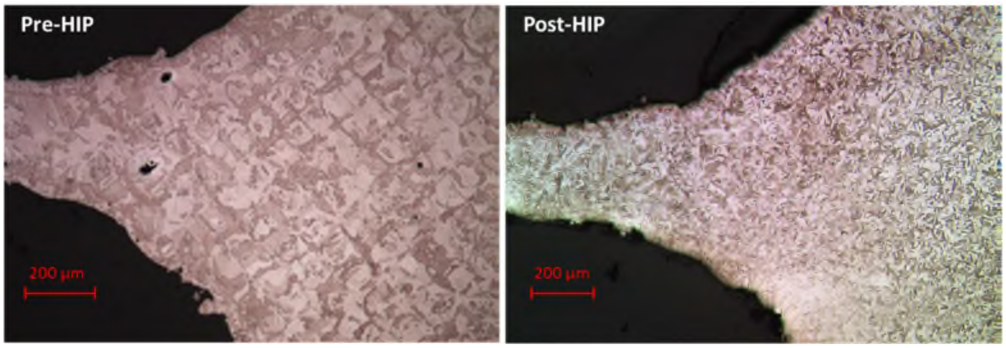

Figure 3. Sample cross-sections before and after HIP processing.

Tensile Test Results

The tensile tests were conducted for two groups of samples representing two plausible final heat conditions for mechanical parts of a compliant mechanism. The samples were produced according to the three manufacturing directions, X-Y-Z, to highlight potential anisotropies in the final heat condition states. The second objective was to quantify the difference expected between HIP and non-HIP material. The tensile test samples were designed according to the ASTM E8/E8M − 15a standard. Raw rods were produced and submitted to the heat treatment sequences. Finally, the rods were machined to their final geometry and tested.

The results show that for both heat treatment conditions, the SLM produced samples show similar or higher Rm and Rp 0.2 compared to the commercial grade 17-4PH. The elongation at break for non-HIP samples tend to show a fragile behavior which is confirmed by the fracture inspection. The tensile tests revealed minor anisotropy according to the manufacturing directions, X showing the highest *Rm* & *Rp0.2*, followed by Z and Y. The overall relative variations of *Rm* & *Rp0.2* versus the manufacturing directions are below 5% for the HIP samples and 10% for non-HIP samples, which tends to show a slight improvement on anisotropy induced by the HIP treatment.

Fatigue Test Campaign

The graph of Figure 4 compares the approximated S-N curves and fatigue limit estimations Sf of each fatigue test sample (FTS) group. As expected, the group C whose FTS were manufactured from commercial grade 17-4PH and machined according to the best WEDM-based protocol shows the highest fatigue performance with Sf_C estimated at 680 MPa. This group is to be compared with group B, where FTS were machined according to the same WEDM-based protocol, but from additively manufactured and HIP raw material. The subsequent loss in fatigue performance is around 25% with Sf_B estimated at 510 MPa.

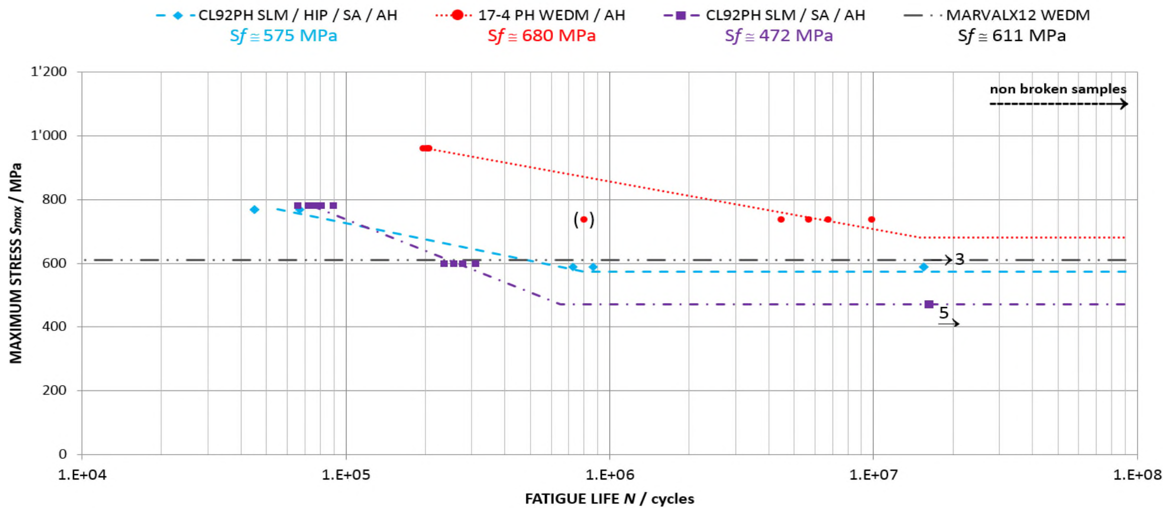

Figure 4. S-N curves estimates for SLM (CL92PH) and WEDM (17-4PH) samples. The fatigue limit of MARVALX12 was determined experimentally during the MTG-CCM test campaign.

Design for Additive Manufacturing

Using AM technologies to reproduce a part whose design was driven by a conventional manufacturing strategy such as turning and milling is often not pertinent, since it does not take into account most of the advantages given by AM. For example, the complexity of the assembly can be reduced by designing a monolithic mechanism or by decreasing the number of parts and combining functions.

To ensure an optimized redesign for AM, a system engineering vision will allow understanding all parameters pertaining to the mechanism and therefore being aware of all key requirements to be considered during the design phase. On the other hand, the design constraints associated with AM are to be well understood.

A major limitation of the current AM technologies (e.g. SLM) is the need of support structures when the part comprises overhanging areas with an angle of usually less than 45 degrees with respect to the horizontal plane. Therefore, keeping in mind the following strategies during the redesign will contribute to obtain better results and will ease the removal of the part from the baseplate:

- redesign with overhanging angles greater than 45 degrees from horizontal
- changing the part orientation to minimize support structures
- allowing support material in dedicated areas

<u>Examples of parts and compliant structures redesigned for Additive Manufacturing</u>

A successful product redesign for AM is the rotor of a slipring performed in partnership with RUAG Space Switzerland Nyon, where the support material could be avoided. The production of complex geometries by AM-SLM allowed us to integrate the electrical conductors within the rotor structure leading to a drastic reduction in the number of parts – from 36 to 1 for a 12-track rotor – and therefore a significant reduction of the manufacturing and assembly time.

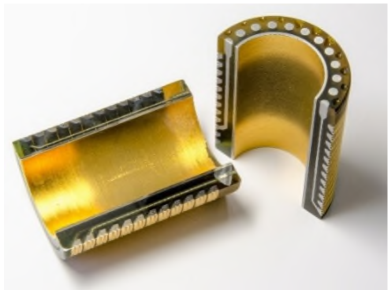

Figure 5. Slipring rotor made by Additive Manufacturing

For compliant mechanisms, the redesign is more challenging since the design guidelines of most of the AM processes recommend avoiding thin structures and abrupt thickness variations, which are characteristic of flexible structures. CSEM's approach is therefore to work on several aspects of AM in parallel, such as redesign, thin structures manufacturing and testing, mechanical and thermal post-processes, Finite Element Modelling (FEM) and topology/parametric optimization.

Topology Optimization is actually the most efficient approach to improve various properties of structural parts designed for AM, such as mass reduction, eigen-frequency tuning, thermal transfer, thin-wall thickness optimization, etc. Unfortunately, the use of commercial software is currently limited to the optimization of structural geometries, since the algorithms are not able to handle flexible structures. Due to their own nature, the algorithms try to *decrease* the compliance of the structure (see example in Figure 6), which is the opposite of what is requested for flexible structures. To optimize those, we need to determine where and how to locally increase the compliance in order to provide the requested movement. Since commercial software solutions were not able to fulfil this need, some particular tools have been developed internally to be able to generate the geometry for compliant mechanisms.

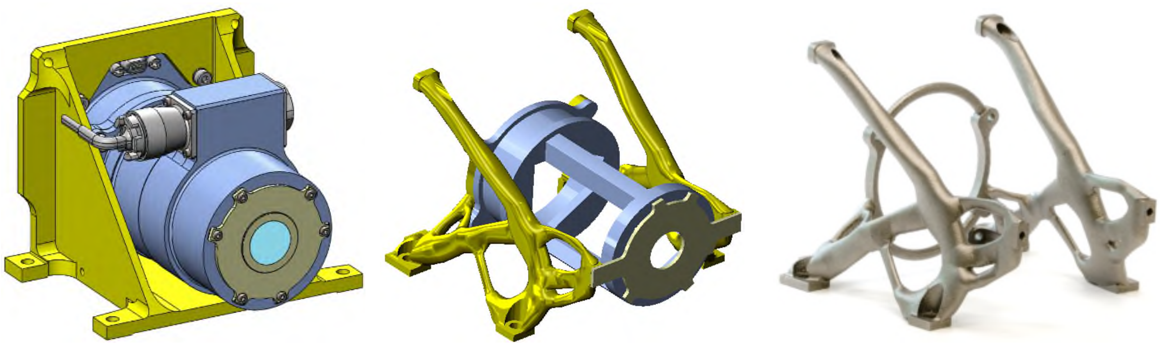

Figure 6. Example of CLUPI (EXO MARS Mission) bracket redesigned with topology optimization. Left: classical bracket, middle: geometry optimized to maximize the stiffness with a given mass diminution, right: part additively manufactured in titanium alloy.

An intermediate approach currently under investigation at CSEM is to improve the rigid parts of the mechanism, keeping conventional flexure geometries as they have been used successfully up to now. This concept is currently under investigation at CSEM with the redesign of first, the HAFHA pivot alone, before integrating the result in a more complex scanning mechanism using two such pivots. Some pictures of the preliminary concepts are shown in Figure 7 and 8.

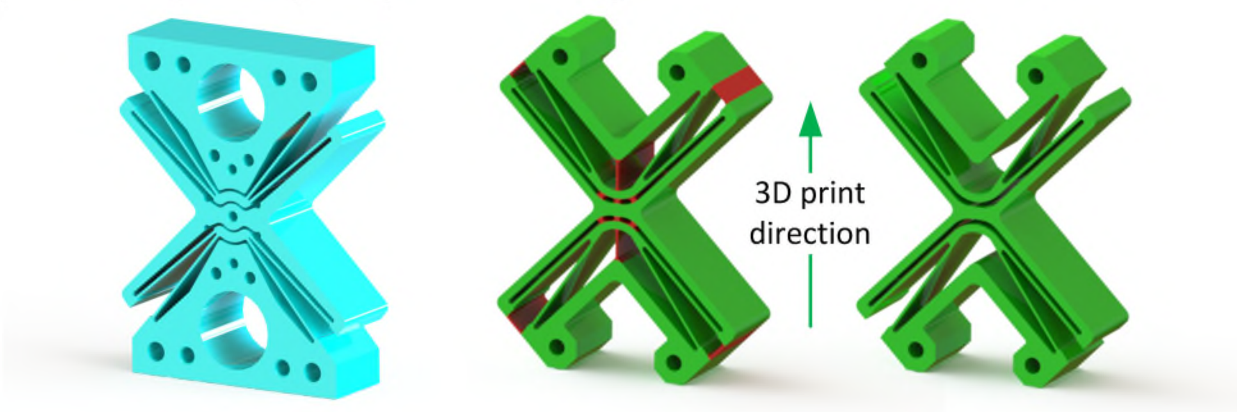

Figure 7. Example of HAFHA pivot redesigned for monolithic AM with a given print direction. Left: classical pivot, middle: optimized for AM with support bridges in red, right: AM pivot after bridge removal.

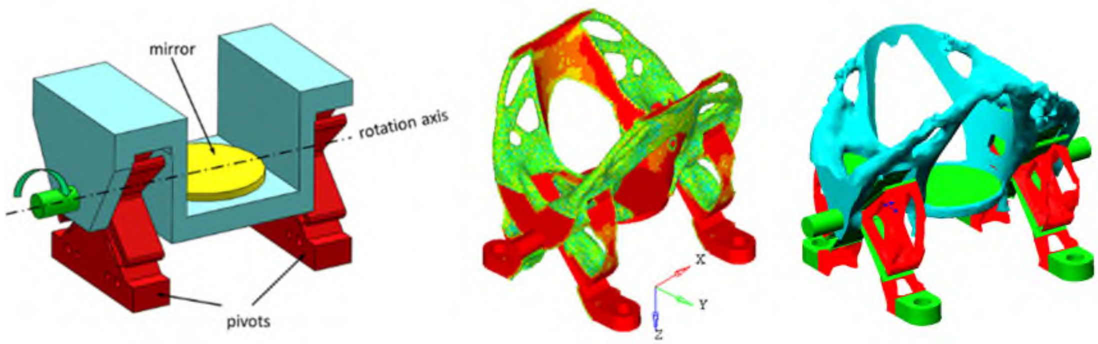

Figure 8. Example of scanning compliant mechanism designed and optimized for monolithic additive manufacturing. Left: architecture overview, middle: first results without support material considerations, right: raw result with constrained parameters to avoid overhanging structure of less than 45° from horizontal plane.

Conclusions

After showing in 2014 the feasibility of manufacturing an elementary compliant structure made of stainless steel with AM-SLM, CSEM successfully developed – jointly with the company 3D PRECISION – a comprehensive end-to-end SLM-based manufacturing and post-processing production method for a high-strength precipitation-hardened stainless steel comparable to the widely known and used 17-4PH.

The tensile properties of the material were tested for the three manufacturing directions and for two thermal post-processing conditions, highlighting the tremendous improvement of the performances after HIP treatment, with the conclusion that the SLM manufacturing of CL92PH powder material can lead to tensile performance similar to a commercial grade 17-4 PH stainless steel, provided the appropriate post-processing strategy is applied. The positive influence of the HIP treatment was also investigated at a microscopic scale through detailed metallographic analysis which revealed the successful suppression of macro porosity and the improvement of the microstructure for both structural and flexural segments.

The fatigue performance of the flexural segments was investigated in detail through a comprehensive alternate bending fatigue test campaign covering four different sample groups. The collected fatigue test data helped to highlight the contribution of the key material and surface defects on the final fatigue performance. The beneficial effect of the HIP treatment on fatigue performance was demonstrated, with further investigations to be carried out on the impact of the geometry of the parts versus HIP and subsequent thermal post-processing efficiency and side effects. The percent replication of the fatigue data collected allows us to affirm that from a lifetime point of view, SLM-manufactured compliant structures have the potential to be eligible for demanding applications. Despite the loss in fatigue performance, it is possible to design – provided a well-adapted sizing – a compliant structure offering lifetime above 15 million cycles.

Similarly, the AM process for a titanium alloy has been recently optimized following the same procedure. From the mechanical design point of view, SLM manufacturing is acknowledged to have the potential to enable new design strategies, leading to high mass/stiffness optimized parts and simplified assemblies. The present study demonstrates that even thin structures can offer sufficient fatigue performance and geometrical accuracy to be foreseen for space applications. Nevertheless, it must be stressed that SLM also brings some challenges which need to be addressed. The use of material support and the subsequent need for material removal is foreseen to be the main source of design restrictions and needs some additional creativity.

Another critical issue encountered during this study is the accumulation of internal mechanical stresses during the SLM process and the necessity for annealing post-processing which avoids the emergence of macroscopic warpage during the delicate step of separating the part from its manufacturing substrate.

From the design point of view, new generation design tools such as topology optimization software could lead to interesting results. With their capacity to minimize or control the effects associated with the thermal history of the parts, the emergence of AM process simulation tools should also contribute to improve the design of the parts. But all these software tools are only complementary to the understanding of the designer which needs to be aware of the possibilities and limitations offered by Additive Manufacturing.

The present study demonstrates how the most critical steps related to Additive Manufacturing of high-precision and compliant mechanisms were addressed, starting from the specific mechanical design, followed by the definition of the Additive Manufacturing and post-processing strategies and concluded with the validation strategy. This approach has led to the successful redesign of a space slipring rotor and will continue with other products.

The near future work is to design and built more demonstrators integrating all the developments achieved over these last few years, especially in the frame of a development project for the European Space Agency.

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