Aerospace actuator manufactured by Selective Laser Melting

Borja Lizarribar (1), Borja Prieto (1), Miguel Martínez-Iturralde (1), Miren Aristizabal (1), Jose Manuel Martín (1), Javier García (1), Mikel Aitor Flores (1), Ione Golvano (2), Ekain San José (2) and Yannick-Ghislain Attrazic (3)

1 : Ceit-BRTA, San Sebastián, Spain
2 : Egile AeroTransmissions
3. : Safran Electronics & Defense

Abstract

This paper presents a case study of an aerospace actuator manufactured by Selective Laser Melting (SLM) in which the design, the material selection and the topological optimization of the actuator are performed to take advantage of the possibilities given by the AM process. First, different electromagnetic configurations are studied for the application of the actuator, and between the options analysed, the configurations that best fulfil the specifications are selected to analyse an initial mechanical layout. With these mechanical layouts, one machine topology is chosen regarding the weight and the complexity of fabrication of the preliminary mechanical solutions presented for each motor configuration. Then, different materials are analysed, and the material which best suits the requirements is selected, considering that this material is thought to have mechanical and electromagnetic function, so its properties must be good enough for both functions. Finally, the mechanical pre-design is done and the mechanical topological optimization method is applied to this pre-design to obtain the final solution. With the method described, a simpler mounting structure is achieved, reducing the assembly parts to only 4, and, losing 25.67 % of the weight in the final design comparing with the previous design that is in use.

Introduction

Due to the growing interest in the electrification of different sectors, the additive manufacturing (AM) of electrical machines is gaining strength over traditional manufacturing techniques. Some of the advantages offered by the AM compared to other methods are the reduction of mounting parts due to the versatility of geometric shapes that can be achieved [1], the improvement in fabrication time, material savings and the efficiency improvement by taking advantage of the 3-dimensional flux lines with the complex geometric shapes that can be manufactured [2, 3, 4].

A case study for the additive manufacturing of an aerospace actuator is presented in this article. Specifically, the manufacturing of the soft magnetic and main structural parts by Selective Laser Melting (SLM) is addressed in this work. The conducted work shows promising results regarding weight and volume reduction, power consumption and mechanical integration and demonstrates the applicability of AM techniques for the design and manufacturing of low speed electrical machines.

This article is arranged as follows: first, the requirements for the case study actuator are briefly summarized in Section 2. Then, potential motor topologies for the actuator are evaluated and discussed in Section 3. Section 4 reviews the work conducted related to the processing and assessment of the magnetic and mechanical properties of a number of materials processed by SLM. A first mechanical concept and a later refinement in terms of Topology Optimization (TO) of the structural parts is conducted in Section 5. Finally, a few limitations of the additive manufacturing of magnetic cores are discussed and some considerations are given regarding future work and the conclusions extracted from this work in Section 6.

Requirements of the actuator application

The designed actuator is part of an active sidestick system, in which the connection with the wings is not made with a hydraulic circuit but it is done electronically. With the new electronic control, there is not any feedback obtained at the sidestick, so in order to imitate this feedback, the actuator will make the force at the sidestick to emulate the force done by a hydraulic circuit.

The concept for the active inceptor system is shown in Fig. 1, as illustrated in the figure, the main elements of the system are a grip, a kinematic joint that connects the 2-axis movement of the grip to two motors/actuators and a set of brakes and resolver for each motor. Both motors share the same specifications, which are summarized in Table 1.

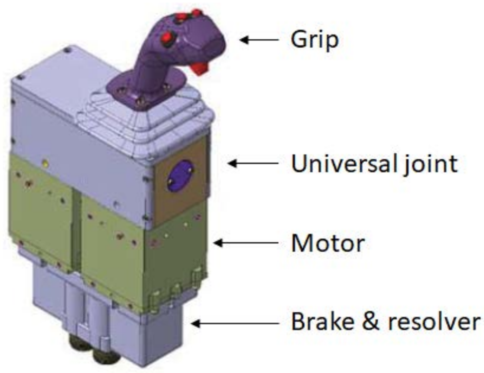

Fig. 1 Concept for Smart Active Inceptor [5].

Requirements	
Envelope	100 x 100 x 100 mm
Max. weight	3 kg
Torque	8 Nm
Voltage	40 V_{DC}
Max. speed	833.33 rpm
DC consumption	< 150 W
Cogging torque	< 0.01 Nm

Table 1 Main requirements for the designed actuator.

There is a previous version of the actuator that is currently in use in the application of Fig. 1. The main motivation for the work, therefore, has been to investigate the potential of additive manufacturing to achieve improvements in terms of weight, consumption and cost.

Additionally, a key requirement for the actuator is the limit on the cogging torque (max.-min.), as any uncontrolled force feedback is transferred to the user and negatively impacts the ergonomics of the Active Inceptor System.

Evaluation of motor topology candidates

In this section, different machine topologies (Double rotor, axial, inner rotor and outer rotor) are evaluated to identify the more advantageous in terms of consumption, weight and mechanic integration. To take advantage of the AM process, the proposed electric machine topologies differ from usual ones. At this first approach, the material used at the FEM simulation is a M800-65A grade electrical steel, as the material that will be used is not yet characterized. The results obtained for the most promising machines are the ones in Table 2.

	Torque [Nm]	***Weight [kg]***	***Current density [A/mm²]***
Double Rotor	8.69	3.14	12.5
Inner Rotor	9.29	2.13	11.6
Outer Rotor	11.2	2.45	12.2

Table 2 Results for machine configurations analysed.

An initial analysis of the three configurations has been done and the initial conclusions about each configuration's mechanical design are that the double rotor Halbach configuration is the heaviest solution and it has the highest number of machined parts, so this configuration will be discarded. Between the two remaining configurations, it must be said that the lightest configuration and the one with least number of machined parts is the inner rotor one. However, in the inner rotor topology is much harder to present an automatic winding process for the small diameters that are being considered, then, the outer rotor solution will be selected for the final design. In order to make the wind operation easier the slot will be opened.

Assessment of materials processed by SLM

As the topology of the machine has been selected, the next step will be to select the materials. In the traditional design, the active parts of the machine need to have good electromagnetic and the support part must have good mechanical characteristics. It is not important for the active parts to have excellent mechanical properties, and it is not important neither for the support part to have good magnetic properties. However, while the parts are manufactured by AM, they will be designed to have structural and magnetic function, trying to reduce the number of parts of the machine, so the material used must have good magnetic and structural properties as well. Having said that, three materials are studied for this application.

Gas atomization of soft magnetic materials

Before starting manufacturing testers, a study in terms of atomization of material is done. For this study, 3 materials are considered, Supermalloy, FeCoV (permendur) and Fe6.5Si. In this first study, it is seen that due to the high torque density required by the prototype, Supermalloy suitable for the application, however, Fe6.5Si and FeCoV are used in fabrication of testers and are analysed deeply.

- **Fe6.5Si**

This option is very interesting in terms of price as it has the lowest price between both options. Not only the price, but this material has also shown promising structural and magnetic properties [6] and also has already been used in AM [7]. However, while manufacturing this material several cracks have appeared in all the testers, in Fig. 2 an example of these cracks can be seen, so this material will be discarded for this project.

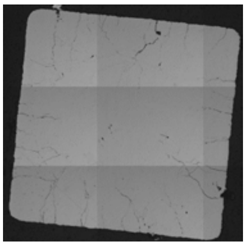

Fig. 2 Cracks appeared while manufacturing tester.

- **Permendur (FeCoV)**

Despite the price of this option is higher comparing to the one analysed before, it has been proven satisfactory in terms of cracks and porosity.

However, it is seen that the magnetic and mechanical properties are highly dependent on the heat treatment applied. For example, in Fig. 3 can be seen the change in microstructure of the material depending the heat treatment applied.

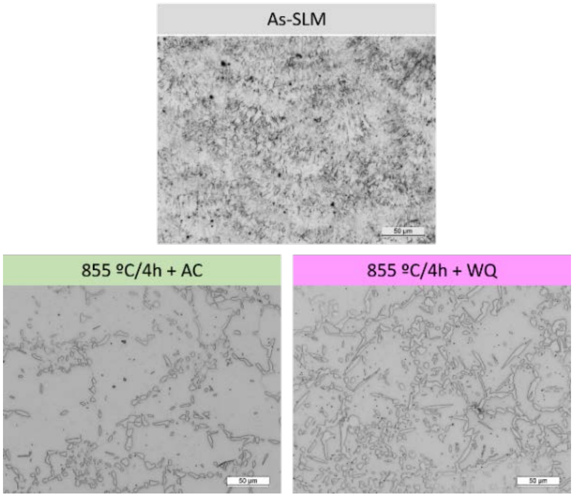

Fig. 3 : Microstructure for different heat treatments (As-SLM is the sample without any heat treatment).

Having seen the effect of the heat treatment in the microstructure, the following heat treatments have been applied to Permendur test samples manufactured by SLM: Water Quench (WQ), Air Cooling (AC), Furnace Cooling (FC), MRF. Then, to find the heat treatment that suits best the application, a more intensive study about the relation between the magnetic and mechanical properties is carried out. The results for structural properties can be seen in Table 3 and the magnetic results in Fig. 4.

Treatment	***Cooling rate (ºC/min)***	***UTS (MPa)***	***YS (MPa)***	***El (%)***
As-build	-	924	852	16.5
855 ºC/Ar/4h + WQ	1000	854	543	20.0
855 ºC/Ar/4h + AC	> 150	645	296	10.0
855 ºC/Ar/4h + FC	150	659	332	6.0
855 ºC/Ar/4h + MRF	71	449	302	3.6
855 ºC/Ar/4h + 18ºC/min	150	538	286	3.9

Table 3 Permendur mechanical characteristics.

Results analysis

It can be noticed from Table 3 and from Fig. 4, that there is a balance between magnetic and structural properties, if a heat treatment improves the magnetic properties, the mechanical properties decrease. Then, a heat treatment must be selected that does not decrease the performance of the machine, but also assures the structural stability. For the study of this document, the selected heat treatment is the 855ºC 4h Ar + Furnace Cooled. The mechanical properties are the ones seen in Table 3, and the magnetic properties are the saturation magnetization of 2.27 T and the coercivity field strength of 275 A/m

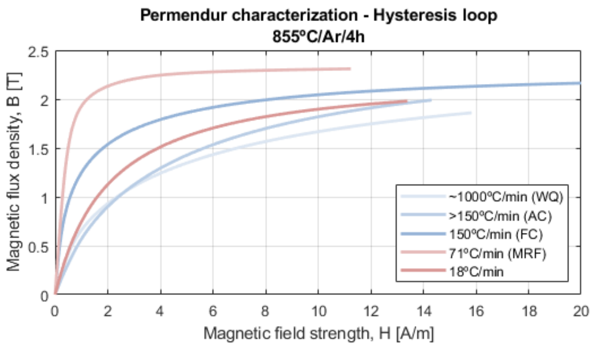

Fig. 4 Magnetic properties of SLM-processed Permendur depending on the heat treatment.

Mechanical design

Preliminary mechanical design

As it has been said in Section 1, one of the AM advantage is the reduction of manufacturing parts. For this purpose, the importance of the mechanical design to assure the structural reliability of the machine and to minimize the material used is critical. On the study case, the manufacturing parts are reduced to 4, of which 2 have structural and magnetic function. In Fig. 5 the initial machine layout can be seen, where the parts with structural and magnetic function are the ones named rotor and stator, which are manufactured with permendur, and the other 2 parts as they do not have any magnetic function can be made with only structural material such as stainless steel.

Once the layout of the machine has been defined, a mechanical topological optimization is applied in the next subsection to reduce weight.

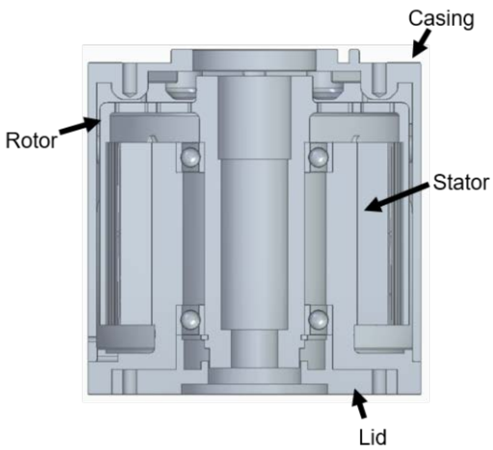

Fig. 5 Initial mechanical design layout.

Mechanical TO

Once the Topological Optimization (TO) is performed the results are interpreted and considering the constrains of the AM, such as not having "*flying*" parts or not changing the amount of material abruptly between layers, the final design is presented in Fig. 6.

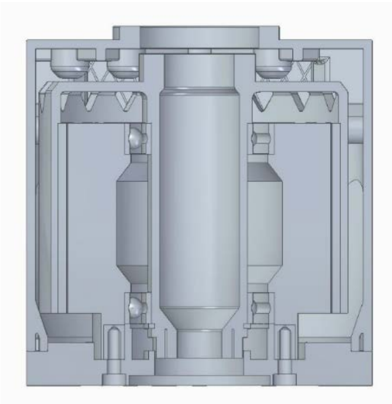

Fig. 6 Final mechanical design.

With the mechanical TO of all parts comprising the machine and making some material reduction by experience, the reduction in weight of the final design is of a **25.68 %** comparing to the design that is in use at this moment. Despite the reduction in weight achieved, the reference weight defined in Table 1 has not been reached yet, however, the results obtained in weight are much better than the machine that is being used, manufactured with traditional methods.

Future work and conclusions

Despite the work that has been done in this study case, there are several possibilities that has not been analysed for this case study, however, these features of the AM method may be analysed in more detail. In this document, these features will be presented but not studied in detail.

Fabrication with AM

The first thing to consider is that the prototype has not been manufactured yet, so the problems while manufacturing with AM the magnetic material are not analysed in this document, however, it is planned to be done by the end of 2021.

Eddy current losses

In the nominal operation of the machine the actuator is working at 0 speed conditions, however, there are some punctual operating points in which the actuator must give 8 Nm at the maximum speed of 833 rpm. The problem appears when the AM motor is operating at high frequencies, in the operating point of 8 Nm with maximum speed, as the iron losses increases exponentially with the excitation current frequency, because the material used, which is manufactured by AM, is not laminated as it is in conventional manufacturing [8].

Conclusions

Regarding the conclusions of this research work, the Additive Manufacturing of soft magnetic materials has been proven effective for low speed electrical machines, having studied two different materials and different heat treatments to fulfil the requirements. Moreover, a mechanical design has been presented in which the advantages of AM in terms of combining magnetic and structural functions for the parts have been considered and the number of motor parts has been reduced to only 4, with little amount of joining pieces. Future work to deal with eddy-current losses at high frequencies has been outlined as well.

Finally, it has to be mentioned that this project is due to finish at the end of 2021, and more results are expected in terms of fabrication by the end of 2021.

Acknowledgements

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