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Structural Optimization and Additive Manufacturing

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Abstract

Additive Manufacturing technology offers almost unlimited capacity when manufacturing parts with complex geometries which could be impossible to get with conventional manufacturing processes. This paper is based on the study of a particular real part which has been redesigned and manufactured using an AM process. The challenge consists of redesigning the geometry of an originally aluminium made part, in order to get a new stainless steel made model with same mechanical properties but with less weight. The new design is the result of a structural optimization process based on Finite Element simulations which is carried out bearing in mind the facilities that an AM process offers. The results of the structural optimization showed that the mechanical properties can be achieved but a lighter model made of stainless steel instead of aluminium was not possible to produce.

1. Introduction

Additive Manufacturing technology is considered to be one of the leading manufacturing technologies for the future. Although it seems to be a relatively new technology, it has been present over the last twenty years, but it is in the late decade when a big development has taken place [1].

It is a fact that in the last decade, the pure manufacturing industry has been moved to countries in development process due to the cost reduction involved for the companies. In line with this, Additive Manufacturing is seen by many experts as a way of bringing the manufacturing sector back to developed countries. The reason is that it is a clean technology that does not produce large waste and requires a low labour cost. One of the main advantages of additive manufacturing is the possibility of structural optimization of components to achieve unique products with excellent properties [2, 3, 4, 5].

2. Description of the model

The part chosen for the study is the sprocket of a racing competition kart (Fig. 1). The sprocket is part of the transmission system of the kart. It is attached to the rear shaft of the kart and it transmits the power of the engine through the chain to the wheels.

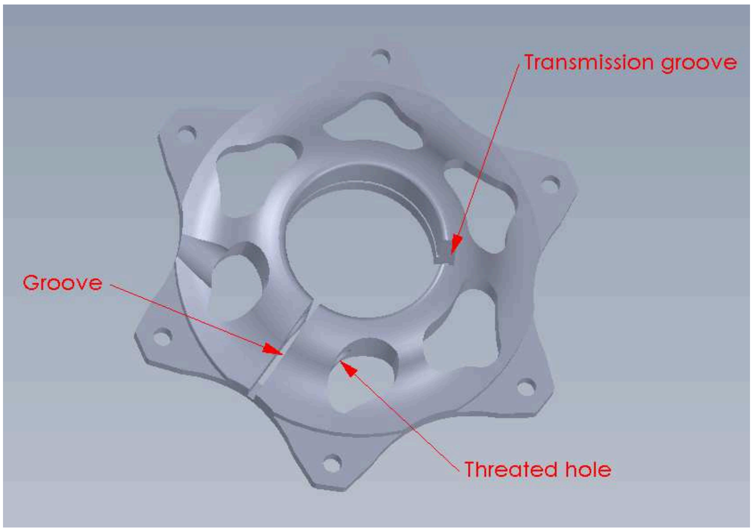

Fig. 1, Sprocket of a racing competition kart.

As a result, the sprocket has to be able to withstand the torque of the engine when accelerating the kart. Being the part subjected to a torque effort, the most required mechanical property is the stiffness, to avoid an excessive deformation which carries a loss of power. Apart from the mechanic properties required, the theme of lightness also comes into play as the sprocket is used in a racing competition kart.

The most important features that the new model must include regarding the geometry are the ones shown in (Fig. **1**). The big hole in the centre is where the shaft is located. In order to fix the sprocket to the shaft a screw is used, so a threaded hole and a groove are added to the piece. The function of the grove is to provide elasticity to the sprocket so that it is easy to enter it through the shaft. The transmission groove is the one who handles the power transmission from the sprocket to the rear shaft of the kart and the six small holes in the outer diameter of the disk are used to position and fix the gear. These are the restrictions when designing the geometry of the new model, indeed the dimensions of these features must also meet the original ones.

3. Goals of the new design

As mentioned before there are two main properties that the new model must fulfil: stiffness and weight. The challenge of this project is to achieve a new design for the sprocket with as high stiffness/weight ratio as possible. The design process is carried out by a structural optimization process based on finite element calculations that will provide information about the two key parameters in every step.

In order to measure the stiffness, input data for the efforts has to be defined. The information in this case is the maximum torque that the engine can offer. This is the torque that the sprocket must be able to support with the smallest deformation possible. According to the technical data provided by the engine manufacturer the maximum torque is 17Nm when the engine runs at 8500rpm.

The weight of the part is directly related to the material it is made of. The original sprocket is made of aluminium which seems to be a suitable material for this application due to its light weight. However, aluminium was not used in this case because of the limitations of the manufacturing device EOSINT M 270, which can’t sinter aluminium. Thus, stainless steel is used.

4. The AM process

The AM process that is used for manufacturing the redesigned sprocket is Selective Laser Sintering (SLS). Taking into account the features of the part and its size, it is a suitable process for this application.

The SLS process is included within the so called powder bed based additive manufacturing processes. The basic concept of this process is shown in the diagram. (Fig. 2)

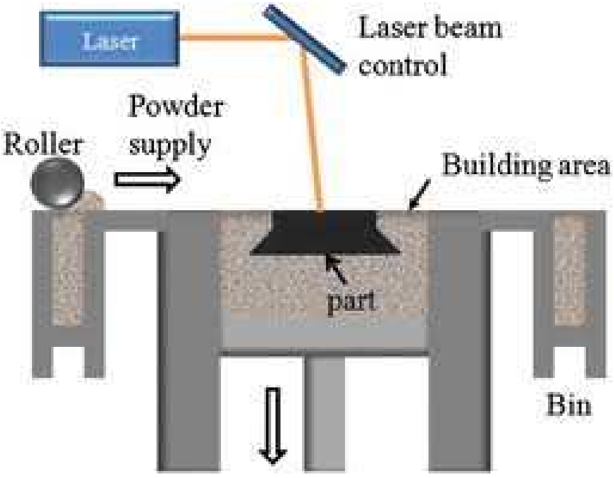

Fig. 2, Schematic basic concept of SLS. [6]

5. Design process

5.1. Original sprocket. The first task of the design process is to get the 3D model of the original sprocket in order to test it using finite element simulation and get data of its mechanical properties. This information is used to compare further new designs with the original model and decide whether they are better or not and how they can be improved.

It is critical that the 3D model of the part is as accurate as possible, so that the results of the finite element calculations are as close as possible to the reality. For that reason, a 3D scanning machine is used to analyse an object to collect data on its shape and create the digital 3D model. The dimensional accuracy that this laser scanning machine offers is ±0,81mm with a repeatability of ±35µm and can scan up to 19200points/s, which makes possible to scan the whole piece in a relatively short period of time.

Once the original 3D model is ready and the input data for the effort and boundary conditions is known, the first simulation is launched. Take note that a n=1.2 safety factor is used for the calculations to be safer. The total deformation map is shown in the (Fig. 3). As it can be seen, the maximum deformation is $1,57 \times 10^{-3}$mm. However, the biggest deformation for the surface of the inner hole is around $1,40 \times 10^{-3}$mm. So this is the value to take into account when making the comparison between the original sprocket and the new designs.

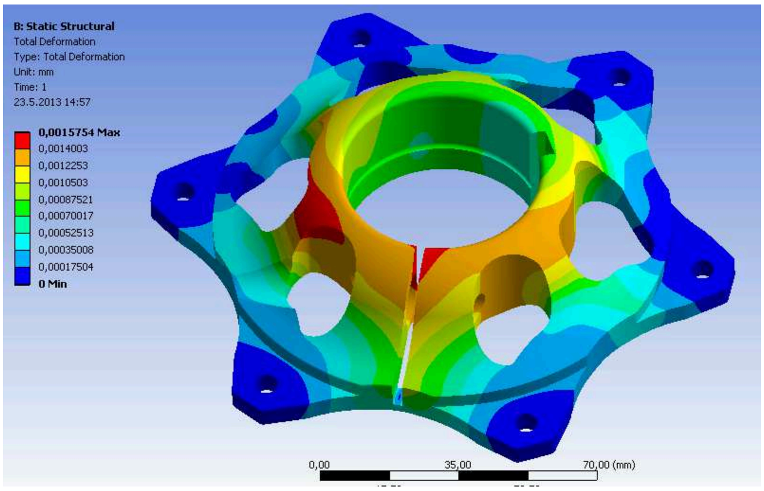

Fig. 3, Total deformation map for the original sprocket.

The other parameter to take into account is the mass of the component. In this case, the aluminium made original sprocket has a mass of 0,253Kg. (Table 1)

Table 1, Values for original sprocket.

	Original sprocket
Mass	0,253 Kg
Maximum deformation	$1{,}4\text{x}10^{-3}$ mm

5.2. New model. The next step is to get a new model starting from zero and following a structural optimization process. The structural optimization process roughly consists of removing material little by little starting from a particular initial shape. So a 3D model with the initial shape that will be the starting point of the structural optimization process has to be created. This model is imported to the software and the simulation is launched with the same input data used for the original model. When the simulation is ready, an analysis of the results is made with an emphasis on the deformation map and the weight of the model. These two parameters are compared to the original sprocket results and if the value of the deformation is smaller, an analysis of shape optimization for the model is launched.

The shape optimization analysis mode will provide some clues for removing material. So according to the information obtained from this analysis, the initial 3D model is modified removing as much material as possible. Once the second version of the model is ready, it is again imported to the software and the process is repeated once and again until, being the deformation smaller, the mass of the new model is lighter than the original sprocket.

During this project many different models have been tested, the model that is shown in this article is considered the best one though. The initial shape can be appreciated in (Fig. 4) and the first thing that jumps out is that in spite of six as in the original model, it has three spokes and as a result three small holes to attach the gear. This is a strategy adopted since the beginning of the design process in order to get a innovative and lighter design.

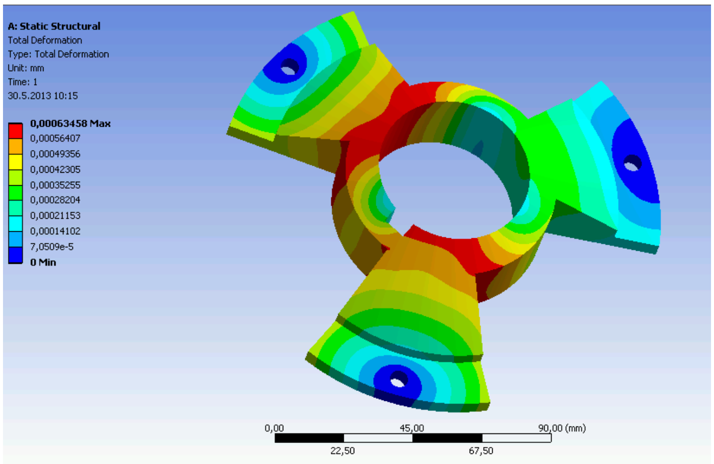

Fig. 4, Total deformation map for the initial model.

Table 2. Values for the initial model.

	Initial model	Original sprocket
Mass	0,875 Kg	0,253 Kg
Maximum deformation	$0{,}6\text{x}10^{-3}$ mm	$1{,}40\text{x}10^{-3}$ mm

For the initial shape the deformation is much smaller than in the case of the original sprocket, but obviously the mass is still almost four times bigger as the comparison (Table 2) shows. Therefore, the shape optimization calculation is launched and the results are presented in (Fig. 5).

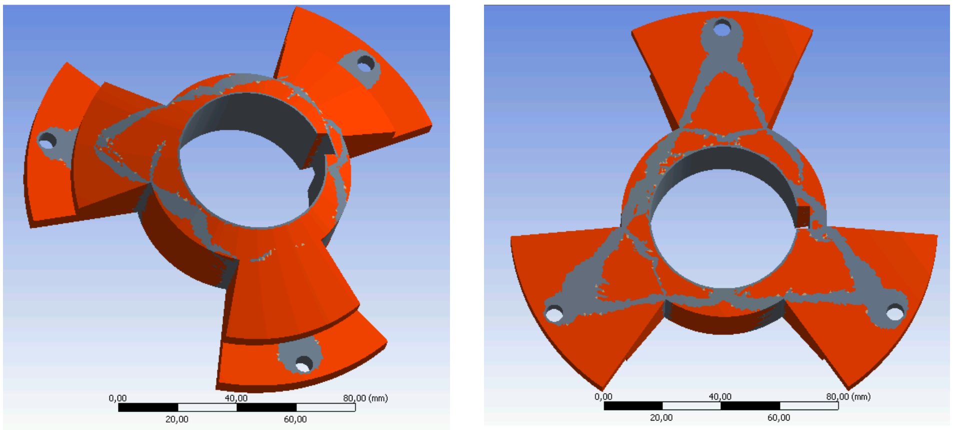

Fig. 5, Shape optimization result for the initial model.

The shape optimization tool gives a clue about where the material should be removed. Basically, it will highlight the areas of the piece that suffer lower stress so that they could be somehow useless.

Several calculations and material removals are made during the shape optimization process until the final design is ready. In spite of showing all the intermediate steps which would be too long, the final model is shown directly (Fig. 6) and then the main improvements are explained below.

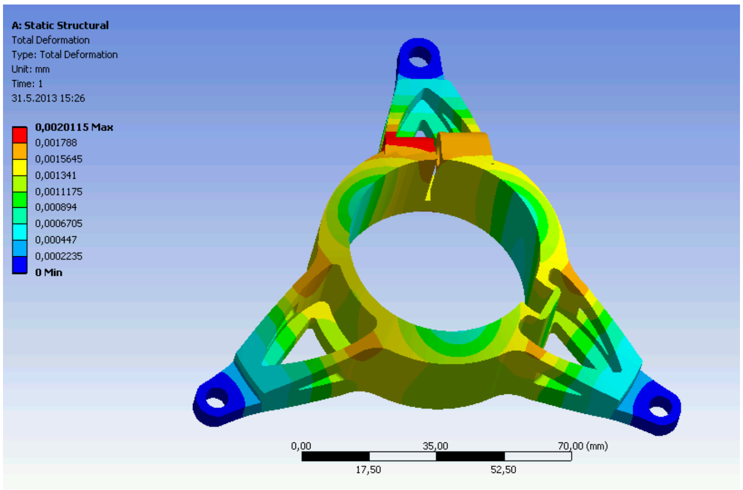

Fig. 6, Total deformation map for the final model.

Although the general appearance has not changed excessively since the initial design, there are many improvements to take into account. The reduction of material is mainly focused on the spokes which are now much more thinner and with lots of holes on them. The wall thickness of the inner ring has also been reduced. Besides, some features are added for the correct functioning of the component, such as the threaded hole for tightening the sprocket to the shaft and the groove that will carry out the power transmission to the shaft. In addition, there is also another small detail that can not be appreciated in the image above but is shown in (Fig. 7).

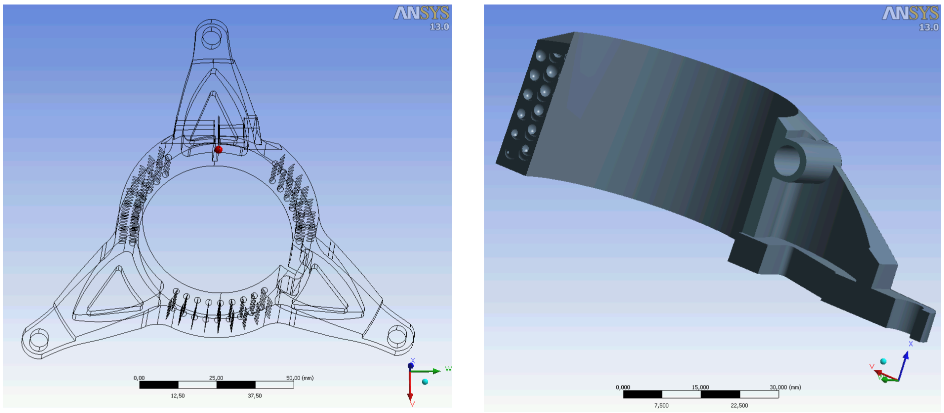

Fig. 7, Detailed view of the inner holes.

Being the removable material very limited in advanced stages of the design, a new strategy has been adopted to improve even more the design. The new strategy consists of making the walls somehow hollow. Due to the facilities that AM processes offer, there is almost no limit in the design and hollow structures can be easily manufactured. Taking advantage of this aspect, some holes have been designed inside the thickest walls of the piece. Owing to the use of selective laser sintering technology as the manufacturing process, there will be loose powder inside the holes. As a result, the actual weight of the sprocket will be a little bit higher than the one showed by the software, where the holes are defined as hollow. In any case, there is the possibility to drill some small holes which will allow emptying the loose powder from the hollows. This possibility will be considered and analysed in the end of the process.

The final properties of the new design are presented in (Table 3). The stiffness of the final model is pretty similar to the original sprocket. The deformation is a little bit bigger but the difference is completely negligible. In both cases, the deformation is minuscule so it does not imply any problem for the proper functioning of the component.

Table 3. Results for the final model.

	Final model	**Original sprocket**
Mass	0,359 Kg	0,253 Kg
Maximum deformation	1,5x10^{-3} mm	1,40x10^{-3} mm

A bigger problem comes when talking about the weight of the component. The result is not very good, the weight of the new model is about 40% bigger comparing to the weight of the original sprocket. Further material removals and simulations have been performed, but not with better results. In all cases the deformation suffered by the part increases a lot. Obviously, the stainless steel weights about three times more than aluminium and even if its mechanical resistance is much higher, it is not easy in this case to make a lighter design.

Considering the situation and all the failed attempts to make the part lighter, the analysis has come to the conclusion that this is the final design. Although the initial objective of trying to design a lighter sprocket with better, or at least similar stiffness has not been reached, all the process carried out has been very useful to get the knowledge for future structural optimization applications. Besides, the designed model is complex enough to justify its manufacture by an additive manufacturing process, so it is considered valid for this project. Specially, the inner holes are an unattainable challenge for a conventional manufacturing process so definitely it is a nice opportunity to take advantage of the unique capacities of the additive manufacturing process.

6. Manufacturing the new model

Once the 3D CAD model is completely defined, the new sprocket is manufactured using the previously mentioned SLS machine, Fig. 8.

In the end of the process a heat treatment is applied to the part for hardening. The heat treatment is defined by the material supplier, in this case EOS, and it is designated as H900. Although it is defined as H900 heat treatment, it is slightly modified to make it more suitable for the laser sintered material. The heat treatment consisted of the following process. The part was slowly heated up to precipitation hardening temperature (482°C) and soaked 4 hours in a vacuum atmosphere. After that a slow cooling inside the furnace was followed. The heat treatment increased the strength and hardness of the material.

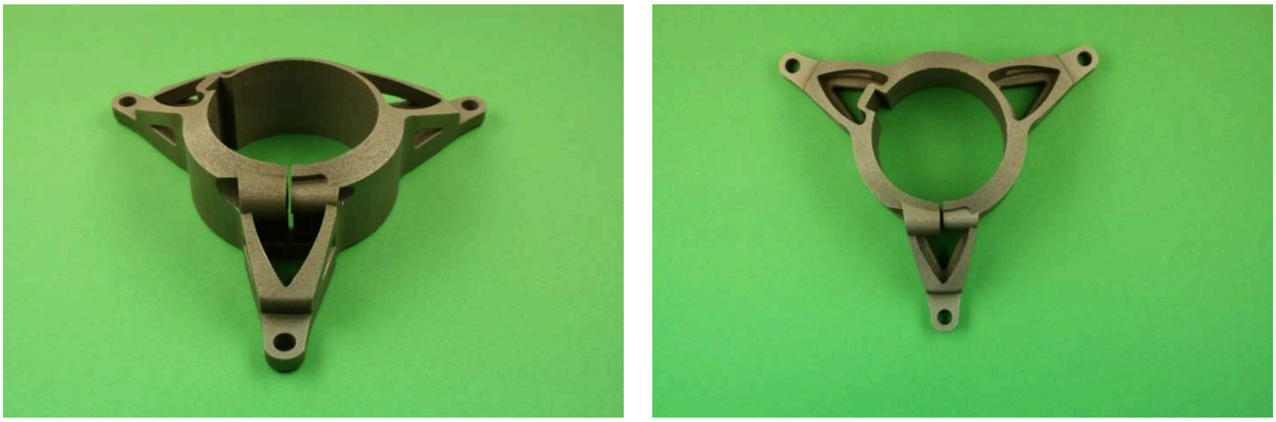

Fig. 8, Photograph of the final design of the sprocket.

7. Conclusions

Regarding the designing stage of the project, the main conclusions are that the mechanical properties can be achieved but a lighter model made of stainless steel instead of aluminium was not possible to produce. Original component was well optimized with hollow structure and lightening. However, the designed model was satisfactory and suitable for manufacturing with the SLS process.

As future ideas to carry on and continue the research, it could be interesting to proceed with the structural optimization of the model and try to improve it in weight and stiffness. At the same time, studying different materials to improve the performance of the component could also be a working line. Besides, some testing could also be made to the part with the objective of comparing the mechanical properties of the laser sintered material to those of original one.

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