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DESIGNING AND MANUFACTURING OF AN INTERNAL COMBUSTION ENGINE CONNECTING ROD MADE OF ALSI10MG MATERIAL USING SELECTIVE LASER MELTING TECHNOLOGY

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Abstract: *The article emphasize how the Selective Laser Melting (SLM) technology can be used to improve the design process of a connecting rod of an internal combustion engine by enabling the use of complex lattice structures and/or bionic design to enhance to reduce weight of the part, but by keeping the mechanical properties in admissible limits. One comprehensive analysis was made using the finite element analysis method in order to prove the efficiency of using lattice structures in the designing process of the connecting rod, this part being made of AlSi10Mg material by SLM technology in the end.*

Key words: *connecting rod, Selective Laser Melting, AlSi10Mg, finite element analysis, automotive*

1. INTRODUCTION

In the automotive industry, Selective Laser Melting (SLM) is still considered to be a new manufacturing technology of parts [1]. Few manufacturers have introduced this technology in their manufacturing process, most of them using SLM for its design advantages over conventional technologies [2]. SLM allows the automotive industry to develop more complicated parts with an intricate design, allow for better heat transfer properties thanks to the integration of functional channels used for cooling, reduce weight as a result of topology optimization that allows the introduction of lattice structures and overall improve the quality of the parts [3]. Connecting rods of internal combustion engines (ICE) are a crucial component that converts the linear motion of the piston, created by the combustion of the air and fuel mixture, into rotational motion of the crankshaft that ultimately transfers the power to the wheels [4]. Materials used in the manufacturing process of the connecting rods can be either steel alloys, aluminum alloys or titanium alloys [5]. These are the most used options in the automotive industry, with steel alloys being the most common choice of material for mass-production, because they can be easily manufactured, are cheap and have great mechanical properties [6]. Aluminum alloys are a great choice for this type of engines due to the material's property to be lighter than steel, conveniently strong and have great heat dissipation [7]. Furthermore, the use of lighter materials such as aluminum alloys increases the internal combustion engine's performance by enabling the use of higher rotations per minute (rpms) [8]. The most used aluminum alloys for this purpose are the alloys from the 7075 and 2024 series. Considering the given choices, the material for the manufacturing of the part using SLM is AlSi10Mg [9], due to its good mechanical properties, lightness given by the low density, and a fair price. The reduced weight of a connecting rod manufactured from AlSi10Mg improves the performance of the internal combustion engine, because the part consumes less power, and thus experiences less stresses. Moreover, the material's chemical composition of this type of material that is suitable to be used in the SLM process allows better heat transfer within the structures of the realized parts thanks to its high Silicon percentage (10% Si) [10].

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2. 3D DESIGNING OF THE CONNECTING ROD

The first step in the designing of the connecting rod was to study the possibilities that the selective laser melting technology has to offer. With the geometric possibilities being almost unlimited, lattice structures have to be taken into consideration. A lattice is a type of structure based on a unit-cell that is of a repeating nature, has a minimalistic surface and presents advantages in the additive manufacturing process. (see Figure 1) Some of the advantages are reduced material use, reduced manufacturing time, reduced energy consumption and optimized strength to weight ratio. There are a lot of types of lattice structures that can be categorized into two main groups: stochastic type and periodic type. The periodic lattice structures are the ones where their topology is repeatable and can easily be recreated, due to their function nature. By being able to repeat the unit cell, the size, angle, quantity and geometry can be controlled. Such structures include Body Center Cubic (BCC), Face Center Cubic (FCC), Kelvin Truss, Honeycomb and so on. The stochastic lattice structures are of random distribution and cannot be recreated precisely and are random structures that are present in wood, bone structure or collagen from cartilages.

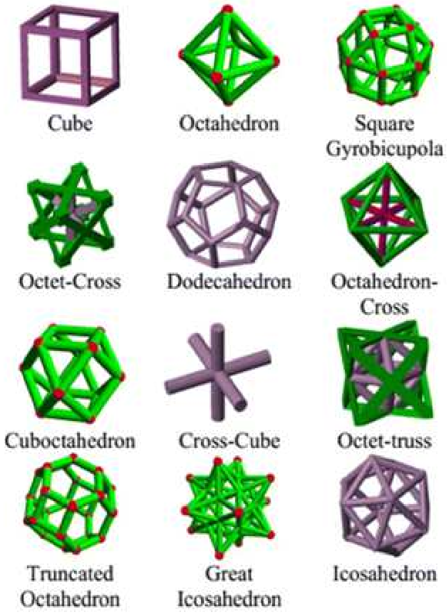
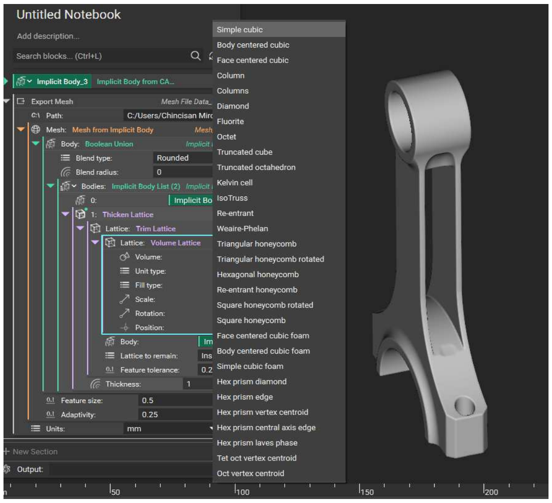


Fig. 1. Various types of periodic lattice structures [11]

The first designing approach was therefore to introduce the lattice structures in the core of the connecting rod. Thus, using the SolidWorks software, the core of the part was removed and the part was imported in the nTopology software, where it was meshed and prepared for lattice structure introduction. This software allows for complex modelling of the part and offers a large number of lattice structures, as shown in Figure 2.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Mesh: Mesh from Implicit Body Mesh

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1: Thicken Lattice

Lattice: Trim Lattice

Lattice: Volume Lattice

Volume:

Unit type:

Fill type:

Scale:

Rotation:

Position:

Body: Im

Lattice to remain: Ins

Feature tolerance: 0.2

Thickness: 1

Feature size: 0.5

Adaptivity: 0.25

Units: mm

Output:

Fig. 2. Removed core of the connecting rod in the nTopology software and lattice structures available

The first lattice chosen was a hexagonal honeycomb structure, with a 5x5x5 mm scale, with a thickness of 1 mm and with a feature recognition tolerance of 0.2 mm as it is shown in Figure 3.

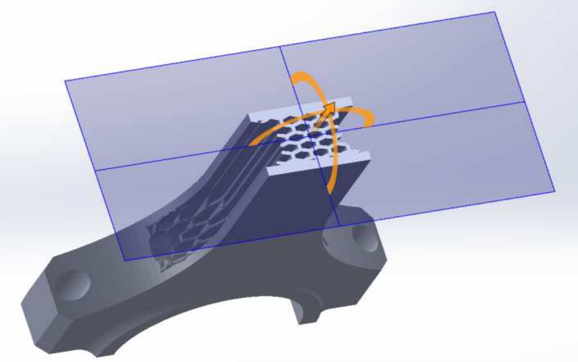


Fig. 3. Section of the connecting rod including hexagonal honeycomb structure

This designing of the connecting rod that includes a hexagonal honeycomb structure is very good because the structure is linear along the part and presents a reduced mass, however, because of the SLM technology's use of powder, the powder inside of the structures cannot be removed, thus making it non-reliable option. A possible solution to this issue is to rotate the structure with 90° on the entire axis. By using the same lattice structure parameters and rotating it on all axes, the connecting rod re-design shown in the first image of Figure 4 was obtained, being a good option taken into consideration.

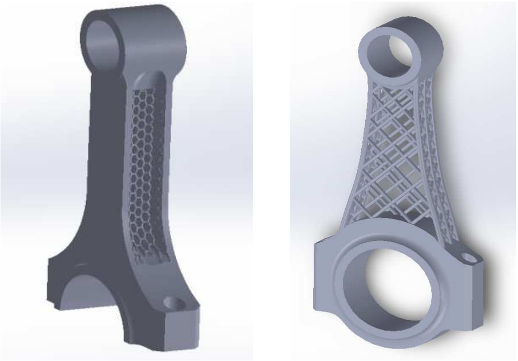


Fig. 4. Rotated hexagonal honeycomb structure included in the connecting rod. Structure of the connecting rod based on bionic design concept

As one may notice, the structure is not linear, being perpendicular to the normal direction and thus larger stresses can appear within. For this reason, to achieve even more mass reduction, bionic design has to be taken into consideration. Bionic design, also known as biomimicry, is the type of design inspired from nature and based on analogies from biology. Furthermore, by implementing a bionic design to the part, less material is used, making the manufacturing process cheaper, the part lighter, and the overall process of manufacturing easier, being considered a way to achieve the best results with the minimum amount of resources.

Considering a bionic design approach, shown in the second image of Figure 4 is the re-designed version of the connecting rod done in SolidWorks, resulting in a stochastic type of lattice structure. This designing variant includes linear beams that follow the initial shape of the connecting rod, having the purpose of ensuring the strength of the part to normal forces, and diagonally placed beams that further improve part's strength and bending resistance. The 6 outer beams have a diameter of 3 mm, while de smaller beams have 2 mm in diameter.

3. FINITE ELEMENT ANALYSIS TO ESTIMATE THE MECHANICAL BEHAVIOR OF THE CONNECTING ROD

In order to run a finite element analysis (FEA) on the connecting rod model, the boundary conditions were established. In the case of the connecting rod, the main boundary conditions that need to be taken into consideration are the compressive forces, the bending moment and the inertia forces tension presented in Figure 5.

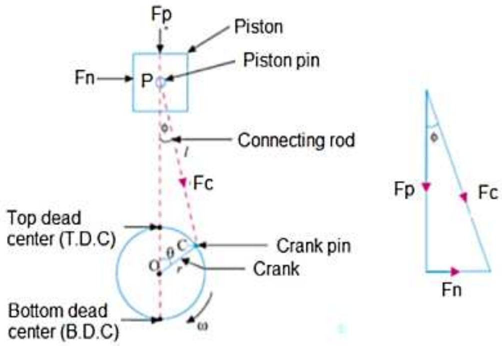


Fig. 5. Forces and angles taken into consideration for the boundary conditions [12]

As one may notice in Figure 5, in the calculus of the boundary conditions, there are a multitude of angles that have to be taken into consideration. Furthermore, the main boundary conditions aforementioned are dependent on the stroke phase that the internal combustion engine is in, thus, the angular velocities for the two forces and moment have to be determined for two rotations per minute (RPM) values: 6500 RPM (peak cylinder pressure) and 4300 RPM (Top Dead Center, peak performance output). These values have been determined using the Engine Analyzer Pro software. First, the values of the connecting rod, piston size and stroke have been converted in inches and a number of 4 cylinders have been introduced in the analyzing software. Then, using the performance simulator function of the program, a graphic representation of the cylinder pressures and their occurrence has been established, taking RPMs into consideration as it is illustrated in Figure 6. The compressive force acting on the connecting rod during the explosion phase of the ICE has been calculated at peak performance shown in Figure 6 (at 4300 RPM, when the gas pressure has been considered as the main force acting upon the piston-connecting rod assembly.

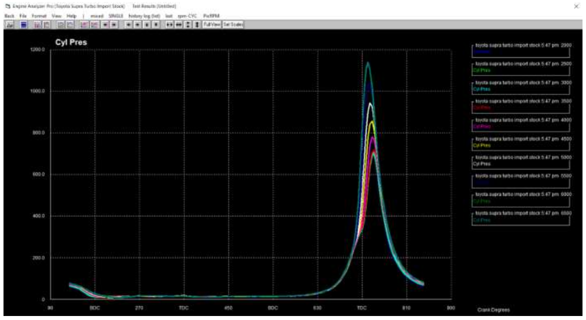
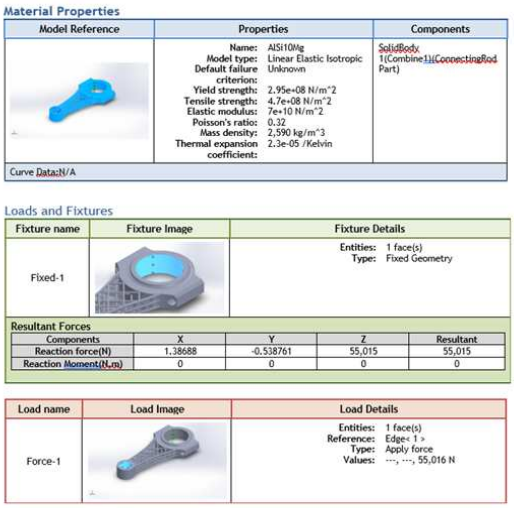


Fig.6. Graphical representation of the stroke phase-cylinder pressure dependence

After boundary conditions have been set, the materials' characteristics were defined and technological constraints were imposed as shown in Figure 7. The finite element analysis' purpose was to study the stress and displacement that the connecting rod is subjected to these technological constraints. Regarding the kinematical constraints, the big end of the part was considered to be fixed and the force was applied in the normal direction at the small end of the part.



Material Properties

Model Reference	Properties	Components
	Name: AlSi10Mg Model type: Linear Elastic Isotropic Default failure criterion: Unknown Yield strength: 2.95e+08 N/m^2 Tensile strength: 4.7e+08 N/m^2 Elastic modulus: 7e+10 N/m^2 Poisson's ratio: 0.32 Mass density: 2,590 kg/m^3 Thermal expansion coefficient: 2.3e-05 /Kelvin	SolidBody 1(Combine1)(ConnectingRod Part)
Curve Data:N/A		

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-1		Entities: 1 face(s) Type: Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	1.38688	-0.538761	55,015	55,015
Reaction Moment(N.m)	0	0	0	0

Load name	Load Image	Load Details
Force-1		Entities: 1 face(s) Reference: Edge< 1 > Type: Apply force Values: ---, ---, 55,016 N

Fig.7. Material properties, Loads and Fixtures for Bionic Connecting Rod

After generating the mesh and running the analysis, the von Mises stress and displacement have been determined. The first FEA was done for a compressive force calculated of 55016,56 N. As one may notice in Figure 8, the maximum von Mises value in this case appears at the joints between the wider beams and the narrow beams, with the maximum value being 4.728e+09 N/m². The maximum displacement caused by the compressive force is of 1.663e+00 mm and appears at the top of the small end as illustrated in Figure 9.

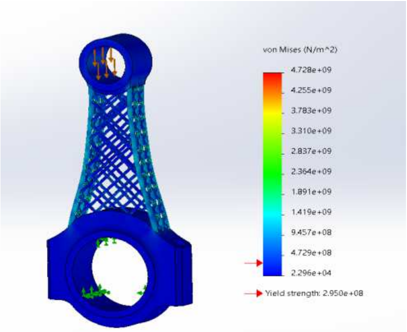


Fig.8. Compressive force applied to the designed connecting rod

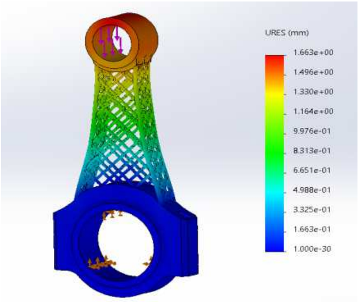


Fig.9. Displacement caused by the compressive force

For the second boundary condition, the force has been considered being applied in the opposite direction of the compressive force, with a value of 20015 N. As one may notice in Figure 10, the maximum Yield strength of the part is present, still, at the joints between the wider beams and the narrow beams, having a von Mises value of 1.891e+09 N/m². The displacement (see Figure 11) caused by the inertia forces is at the top of the small end, with a value of 6.648e-01 mm.

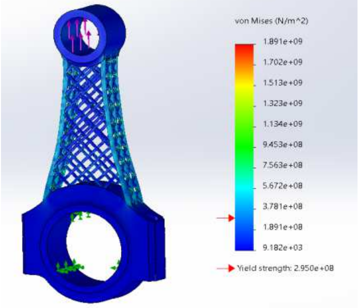


Fig.10. Inertia force acting on the designed connecting rod

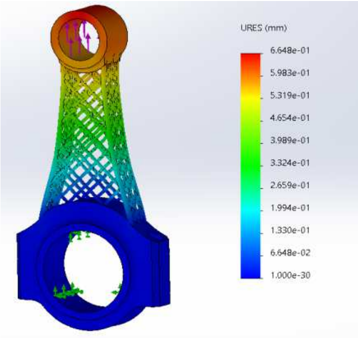


Fig.11. Displacement caused by the inertia forces upon the designed connecting rod

The last boundary condition taken into consideration for the FEA analysis was the bending moment occurring in the rod area of the connecting rod, calculated to be 22978 Nm. As one may notice in Fig.12, the maximum bending moment occurs at the joint of the wider beams about halfway on the side of where the bending moment was applied, having a maximum value of 5.3e+09 N/m^2. The displacement caused by the bending moment (see Fig.13) was once again, at the top of the small end, with a value of 1.02e +01 mm.

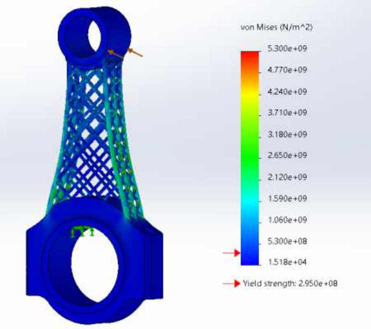


Fig.12. Bending moment applied to the re-designed connecting rod

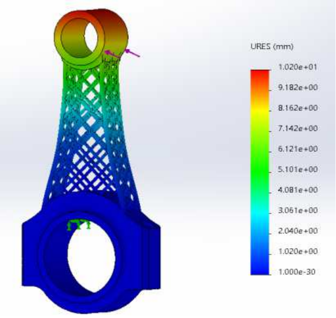


Fig.13. Displacement caused by the bending moment

As one may notice, the stress distribution throughout the designed connecting rod appears to be uniform in all cases, with only the joints between the wider beams and narrow beams being subjected to greater stresses. The displacement of the part remains the same, with the largest displacement occurring at the top of the small end.

4. MANUFACTURING OF THE CONNECTING ROD BY SLM

The connecting rod was made of Al10SiMg material using Sisma SLM Evemet 200 equipment. The part was printed vertically as shown in Fig. 14 in order to reduce the need of support structures and in order to keep the lattice structures unaltered. In terms of technological parameters, the slice thickness for the connecting rod was set at 0.02 mm due to the complex structures. The laser scanning speed was set at 1400 mm/s and laser power that was used has been set at 175 W.

Fig.14. Theoretical vertical build orientation and use of supports. Connecting rod manufactured using SLM technology

For the support structures that were needed in the 3D printing process a scanning speed of 2000 mm/s was used and laser power was set to a value of 150 W. The part was printed in Nitrogen atmosphere, the admissible level of oxygen in the working chamber of the machine being set to a level of 0.3%. After the manufacturing process was finished on the SLM machine, the support structures were removed and the areas where supports were in contact with the part were hand polished using sandpaper after the supports were removed. The final part made of AlSi10Mg material by SLM is presented in the second image of Figure 14.

5. CONCLUSIONS

By using 3D modelling software such as nTopology and SolidWorks, it was possible to improve the design of the connecting rod by introducing lattice structures and bionic design principles, with the purpose of light weighting and reducing the weight of material in this case. Using finite element analysis method it was proved that the stresses values in this case were not at very high levels and they are well and uniformly distributed within the structure of the part. Furthermore, the displacements caused by the forces acting upon the bionic connecting rod are in the limits. This has proved that the bionic design of the connecting rod can be used and thus, the part was realized in this variant by 3D printing. The SLM technology has proven to be suitable to realize the connecting rod from AlSi10Mg material, with an innovative design and good overall specifications.

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Proiectarea si fabricarea unei biele din cadrul unui motor cu ardere internă, realizată din AlSi10Mg prin SLM

Abstract: *Articolul curent evidenţiază modul în care tehnologia de topire selectivă cu laser SLM poate fi utilizată pentru îmbunătăţirea procesului de proiectare a unei biele din cadrul unui motor cu ardere internă prin posibilitatea materializării unor structuri complexe de tip celular şi a unor structuri de natură bionică ce sunt menite să scadă greutatea pieselor realizate, fără a influenţa în mod semnificativ comportamentul mecanic al piesei proiectate în final. O analiză aprofundată a fost realizată folosind metoda analizei cu elemente finite în vederea evidenţierii avantajelor utilizării structurilor de tip celular în procesul de proiectare al bielelor din structura motoarelor cu ardere internă, piesa proiectată astfel fiind fabricată dintr-un material de tip AlSi10Mg prin SLM în final.*

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