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The Fatigue of Additive Manufacturing Metal Parts

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Abstract
Additive manufacturing (AM, also called 3D printing or rapid prototyping) is radically changing the production of the technology industry globally. According to the manufacturers of AM machines the materials are very well comparable to those used with traditional manufacturing methods. However the layer based structure has made many of us concerned about the fatigue properties of AM materials. This research was focused on the fatigue properties of AM parts and limited to examine two types of stainless steels. The tests conducted during this study show that the material properties of AM steels were well comparable and even better than those of traditional materials.

Keywords:*Additive manufacturing, Fatigue, Stainless steels, Strength.*

1. Introduction

Additive manufacturing (AM, also called 3D printing or rapid prototyping) is radically changing the production of technology industry globally. The technology develops fast to be more accurate and effective. There are also completely new technologies under development.

Additive Manufacturing (AM) is a manufacturing method in which the material is added instead of removing or forming it. In it the 3D computer model of the part is divided into layers which are then used to add the material needed to form the part. This makes it possible to produce complex parts without limitations of traditional manufacturing methods.

One of the main benefits of this technology is the optimization of the use of material. The material can be used only there where it is needed. The amount of scrap is also minimal.

The typical targets for AM are customized parts like concept models, molds and prototypes. At the moment AM is also used to manufacture small batches of parts. [1]

According to the manufacturers of AM machines the materials are very well comparable to those used with traditional manufacturing methods. However the layer based structure has made many of us concerned with the fatigue properties of AM materials.

This paper present the preliminary research of the fatigue properties of AM parts made of stainless steel.

2. Additive Manufacturing Methods Used to Produce Metallic Parts

This research is limited to examine two common methods to produce metallic parts. These are called DMLS (Direct Metal Laser Sintering) and 3DP (3D Inkjet Powder Printing).

DMLS is an additive manufacturing method developed by EOS e-Manufacturing Solutions. DMLS method uses the powder bed process and a high power laser beam to produce the material layers. The working chamber is filled with protective gas during the 3D printing process. The 3D printing machine will add a layer of metal powder on the working area after what the laser melts the powder to solid metal and forms one layer. The accuracy of DMLS method is between ±0,05 - ±0,25 mm. The roughness of the part surface is between 7-10 µm Ra. The layer thicknesses begin from 0,02 mm. [2]

Another alternative to produce metallic parts is 3DP (3D Inkjet Powder Printing) developed by MIT. In it there is a powder bed same way as in DMLS. Instead of a laser beam there is a printing head that uses glue to bind the metallic powder layer by layer. After the gluing process the glue is vaporized in an oven followed by a sintering phase and remaining pores are finally filled with infiltration metal. The infiltration metal is normally bronze. The reason to use bronze is that the melting temperature of the infiltration material must be lower than the one of the sintered metal. The typical mix of base and infiltration metals is 50%/50%. The accuracy of 3DP is between ±0,1 - ±0,5 mm and the surface roughness is about 60 µm Ra. [2]

The mechanical properties of two commonly used AM steel materials provided by the manufacturers are presented in the table 1. The horizontal direction is parallel to the layers. The EOS 316 L is used with DMLS and 420 SS+ Bronze with 3DP method. The properties of 420 SS + Bronze were not provided to different directions.

Table 1: THE MECHANICAL PROPERTIES OF SOME AM STAINLESS STEELS.

Property	***EOS 316 L***	***420 SS+Bronze***
Ultimate strength in horizontal direction [MPa]	640	682
Ultimate strength in vertical direction [MPa]	540	682
Yield strength in horizontal direction [MPa]	530	455
Yield strength in vertical direction [MPa]	470	455
Elongation at break in horizontal direction [%]	40	2
Elongation at break in vertical direction [%]	50	2

3. Fatigue

Fatigue is a phenomenon that occurs when a repeatedly varying load influences the structure. Up to 90 % of fractures of metal parts result from fatigue. The final fracture is surprising and fast. [3]

The evolution of fatigue is divided into three phases: nucleation, progress and fracture. The nucleation phase will take about 90 % of the time needed to break the part. In it a microscopic crack will be born in the material. The typical starting points of cracks are the discontinuation points of parts.

After the nucleation phase the growth of the fracture accelerates in the progress phase. In it every cycle of stress will grow the crack fast until the stress in the remaining area of the material reaches the ultimate strength causing the part to break. If we are talking about steels, the maximum stress that will cause no crack growth at all is about half of the ultimate strength (see also the Fig. 1). This stress is called the fatigue strength (σ_w).

The traditional steel is quite homogenous and normally don't have many potential starting points for fatigue. The steel produced by AM instead has a rough surface and layer based structure that might offer much more possibilities for cracking.

Rimeira et al [4] have been studying the fatigue properties of AM parts manufactured from stainless steel 316L. It looks, that direction of manufacturing has an effect on the route of crack. The crack may grow faster in the parallel direction with the printed layers and shorter way in the perpendicular direction with the layers. That would have been expected. However, after heat treatment of the AM part this phenomenon is not as clear.

4. Fatigue Tests

The main methods used in fatigue tests are based on tensile, bend or torsion stresses. Normally the stress is varying in the form of sine curve. The stress cycles that will cause the part to break are counted and used to draw the stress-cycle curve. A simplified version of such curve is presented in Fig 1.

If no other data is available the limit stresses for an ordinary steel parts can be roughly estimated as presented in Fig 1. The stress that will cause the part to break around 1000 stress cycles (σ_{1000}) can be estimated to be 0,9 times the ultimate strength of material. As well the fatigue strength (the maximum stress that for unlimited lifetime) can be estimated to be 0,5 times the ultimate strength of the material.

In the research presented in this paper the testing method was based on tensile stresses. The AM test parts were manufactured from EOS 316 L and 420 SS + Bronze materials. The comparative material was an ordinary 316 L stainless steel. The tests were based on standard ISO-SFS-1099. The shape of the test parts is presented in Figs.2, 3 and 4. The tests were made by using the equipment provided by Walter + Bai, model LFV 500-HH.

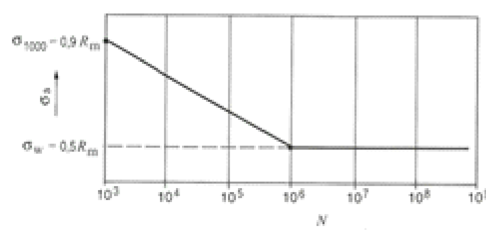

Fig. 1 The stress-cycle curve.

The measured static mechanical properties can be seen in Table 2. [5] The comparison material is an ordinary stainless steel 316 L. The measured values are different from those that the manufacturers have given what would be expected. The differences are not very large however. The 420 SS + Bronze material seems to be very brittle while the EOS 316 L is almost as elastic as the comparison material.

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Fig. 2The 3D computer model of the fatigue test part.

Fig. 3The test parts made of EOS 316 L.

Fig. 4. The test parts made of SS 420 + Bronze

Table 2: THE MEASURED MECHANICAL PROPERTIES.

Property	*EOS 316 L*	*420 SS+Bronze*	*316L*
Ultimate strength in horizontal direction [MPa]		554	609
Ultimate strength in vertical direction [MPa]	654		609
Elongation at break in horizontal direction [%]		0	49
Elongation at break in vertical direction [%]	32		49

Fig. 5.The results of tensile tests of SS420 + Bronze (left) and EOS 316 L (right)..

The results of the fatigue tests are presented in tables 3,4 and 5. The results of the fatigue tests of the comparative material 316 L are presented in table 6. The results of EOS 316 L fatigue tests are also presented as graphs in Figs. 6 and 7. The blue line is a theoretical stress-cycle curve and the red dots are test results. The fracture started always from the change part of material thickness.

The hardness of the test parts was also measured and it varied from 179 to 222 HB30. The heat treatment of 0,5 hours in 600 degrees Celsius had effect only to the 420 SS + Bronze test part that had a hardness change from 222 HB30 to 167 HB30.

Table 3: THE RESULTS OF THE FATIGUE TESTS OF SS420 + BRONZE.

Property	*Test1*	*Test2*	*Test3*
F(N)	16000	17000	17000
σ(MPa)	318,3	338,2	338,2
N	56692	62700	91500
f(Hz)	10,50,25,15	10	10
R_a(µm)	~60	~60	~60

Table 4: THE RESULTS OF THE FATIGUE TESTS OF SS420 + BRONZE.

Property	***Test1***	***Test2***	***Test3***	***Test 4***	***Test5***	***Test6***
F(N)	16000	20000	18000	18000	18000	18000
σ(MPa)	318,3	397,9	358,1	358,1	358,1	358,1
N	64817	5389	39128	37020	42930	35320
f(Hz)	10	10	10	10	10	10
R_a(μm)	7-12	7-12	7-12	7-12	7-12	7-12

Table 5: THE RESULTS OF THE FATIGUE TESTS OF EOS316L MACHINED.

Property	***Test1***	***Test2***	***Test3***	***Test 4***	***Test5***	***Test6***
F(	16000	20000	18000	18000	18000	18000
σ(MPa)	318,3	397,9	358,1	358,1	358,1	358,1
N	422709	23216	107000	177440	332947	198340
f(H	10	10	10	10	10	10
R_a(μm)	0,8	0,8	0,8	0,8	0,8	0,8

Table 6: THE RESULTS OF THE FATIGUE TESTS OF COMPARATIVE MATERIAL ORDINARY 316L MACHINED.

Property	***Test1***	***Test2***	***Test3***
F(N)	16500	16000	16000
σ(MPa)	328,26	318,3	318,3
N	8800	17900	16000
f(Hz)	10	10	10
R_a(μm)	0,8	0,8	0,8

5. The Effect of Internal Structures

One of the focuses of the research was examine how the internal structures like honeycomb would affect the fatigue properties of AM parts.

The internal structures of AM parts are often made of honeycomb like or corresponding structures that will make the part lighter and reduce the use of material. In many cases the manufacturer of AM machines will give a minimum wall thickness that must be followed when designing the internal structures. It is also essential to notice, that the extra powder needs to be removed from the internal holes of AM parts. [2]

The hanging surfaces are not desirable in AM parts because they may demand the use of support structures. The hanging surfaces in stainless steel parts should be designed to be in 30 degrees angle or larger. This should be noticed as well when designing internal structures. [7]

The shapes of the internal structures are often resembled trusses or honeycombs. With these it is easy to put material there where it is needed. Some software solutions are meant to form this kind of structures based on the strength calculations.

The truss based structure is often one of the next: X, Grid, Star or Hexagon. In X structure the trusses are situated in crossing positions with each other. Grid looks like a traditional structure where trusses are situated in x-y directions. In star structure the ends of the trusses are collected together in one point from where they connect to other star points. Hexagon is a structure where the trusses will form hexagon like frames.

Normally the operation software of 3D printers will be asked to automatically generate an internal comp based structure. The stiffness of the comps may be selected between 0 and 100 %. If 0 is selected there will be no internal structure at all. In the case of 100 % the part will be solid. Examples of the comp structures can be found in Fig. 8.

The research question in this part of the study was could it be possible to stop the progress of fatigue crack with the help of internal structures. A shaft with complex internal truss structure was selected to be the test part (Figs. 9 and 10). The truss structure was supposed to stop the possibility for a crack to progress through whole part.

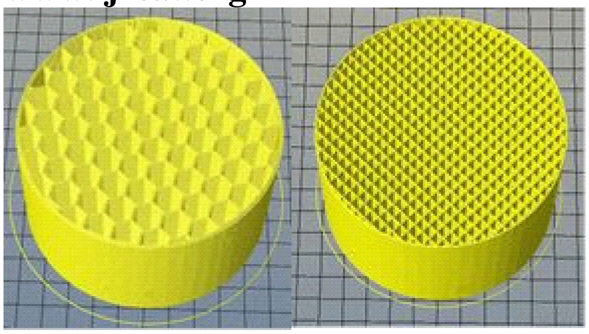

Fig. 8. Examples of the internal structure alternatives.

The theoretical examination was made by FEM-analysis. The analysis was used to find the limits for empirical tests and also to understand how the internal truss behaves in the case where the outer wall of the test part breaks.

The hypothesis was that if the outer wall would be completely broken the crack still will not approach to the core of the part. It was also supposed that in the case of the outer wall break the nucleation phase should have started all over again which would longer the life of the shaft remarkably.

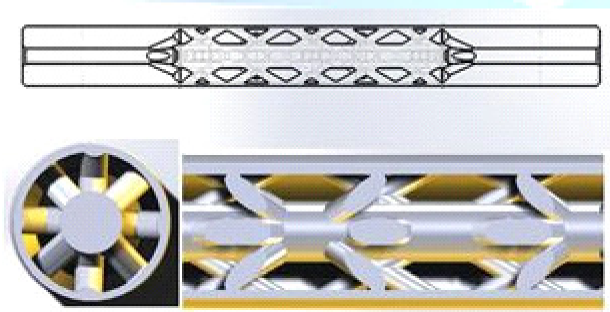

Fig. 9. The internal structure of the test part.

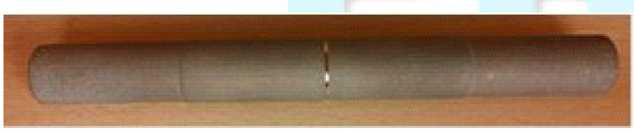

Fig. 10. The test part made of SS420+Bronze.

The FEM-analysis was divided in three cases. In the first case a 0,7 mm deep groove was modelled in the middle of the part from where the crack was supposed to start also in the empirical test. In the second case the outer wall was removed and the stress in the truss structure was examined. In the third case only half of the outer wall was removed which would cause a bending moment to the other side of the part. In all cases a tension of 3 kN acted as a load.[6]

The results of the FEM analyses can be seen in Figs. 11, 12 and 13.

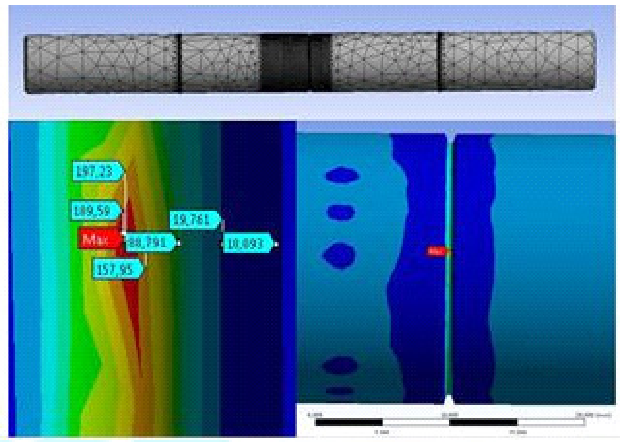

Fig. 11. The results of the FEM-analysis of the groove.

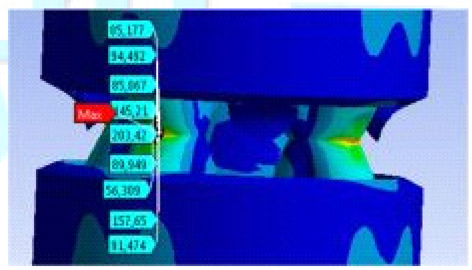

Fig. 12. The results of the FEM-analysis of the truss.

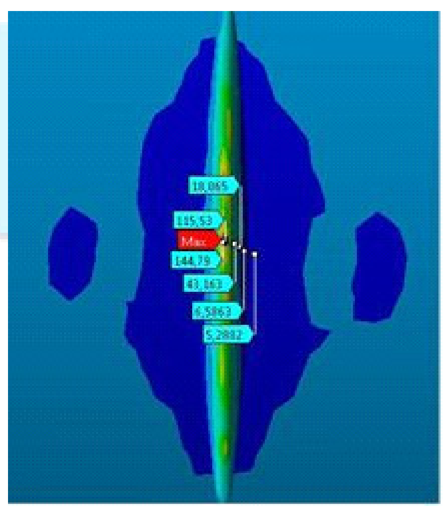

Fig. 13. The results of the FEM-analysis of the partial break of outer wall.

The empirical study of the fatigue of AM-part with internal truss was made with the same test equipment that was used to test the standard parts. Loads of 5 kN (10000 cycles) and 10 kN (10000 cycles) were applied to the test part. After that the part was examined to see if there were any cracks.

The examination was made with penetrating liquid. Only one clear crack (about 1,2 mm long) was noticed (Fig. 14). Also some beginnings of cracks were noticed but they were extremely small and difficult to see.

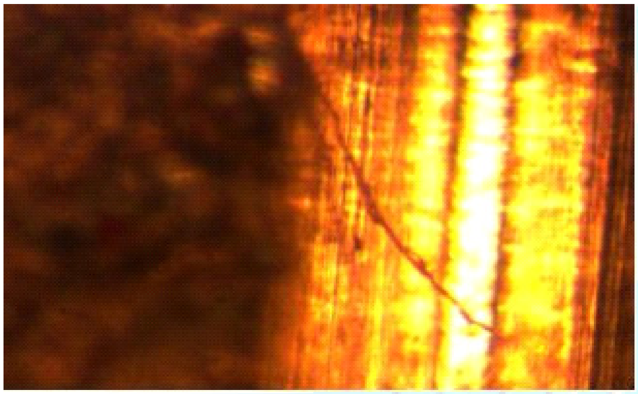

Fig. 14. The microscope picture of the largest crack.

Because of the limited possibility to make further tests the results cannot be generalized. However it was clear that the results of the FEM analysis and empirical test were well comparable.

6. Conclusions

The hypothesis before these tests was that the AM parts made of steel should have weaker fatigue strengths than traditional materials because of the layer based structure and surface quality. The tests show however that the material properties of AM steels were well comparable and even betterthan those of traditional materials.

It was also assumed that the stainless steel + bronze alloy would have worse properties than ordinary steel. The only difference was, however, that it was harder and brittle. These properties improved in heat treatment process.

The results of this research are only directional because of the limited number of test parts. The fatigue properties of AM stainless steels seems to be, however, well comparable to those of ordinary stainless steels.

Acknowledgments

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