Mechanical properties of 3D printed metals

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Abstract: *The new challenges in the aerospace field lead to the need to develop new materials with complex shapes, without major intervention in their definition. Thus, laser 3D printing technologies have been developed for both composite and metallic materials. This paper presents a study of characterization and testing of a 3D printed metal material (Maraging steel 1.2709) in three different directions (x, y and z) to observe, from a mechanical point of view, the behavior depending on the printing direction and the structural changes that intervene following the tensile stress. Mechanical tests consisted of tensile testing in accordance with current international standards, and morphostructural analyzes consisted of investigation of the failure area using optical microscopy and scanning electron microscopy (SEM), respectively.*

Key Words: *3D printing, tensile testing, optical investigation, SEM analysis*

1. INTRODUCTION

Among the metallic materials used in aerospace and defense applications such as aircraft, missiles, missiles and ammunition components there are also Maraging steels. These steels are part of a special class of steels that have high mechanical properties, excellent tensile strength, excellent thermal properties with high temperature resistance, corrosion resistance and a high ratio tensile strength over density [1].

The automated process by which objects with complex three-dimensional shapes can be obtained by the successive addition of material by digital control, is called additive manufacturing (AM). This technology is increasingly used because it is one of the most important emerging processing technologies with low material consumption and costs [2].

Additive technologies allow building of complex shapes and structures not only from paper or plastic, but also from composite or metal materials, with the same or even better properties than their predecessors, obtained by thermoforming or other processing technologies such as casting in mold, extrusion and machining processes [3].

Additive manufacturing processes are technologically ideal for industrial production and they are becoming economically feasible for a growing number of aerospace applications [2]. In general, the raw material for additive fabrication of metals is powder [3] with specific particle size depending on the manufacturing process. For laser sintering the dimensions are in the range of 15 - 45 µm, and for electron beam sintering the dimensions can vary in the range of 45–106 µm [4].

Selective laser melting (SLM) of powders to build 3D metallic parts is fast gaining acceptance as a way to manufacture structural components that are highly optimized for load bearing and hence have a complex shape [5]. Considering the demanding aerospace requirements for production technologies, it is necessary to know, as much as possible, the properties of the new material for each produced component.

The mechanical properties may differ from one metallic material to another, and especially depending on the manufacturing technology used. The figure below illustrates the hardness and yield strength of materials in additive technology, as reference points for the use of materials suitable for the desired applications.

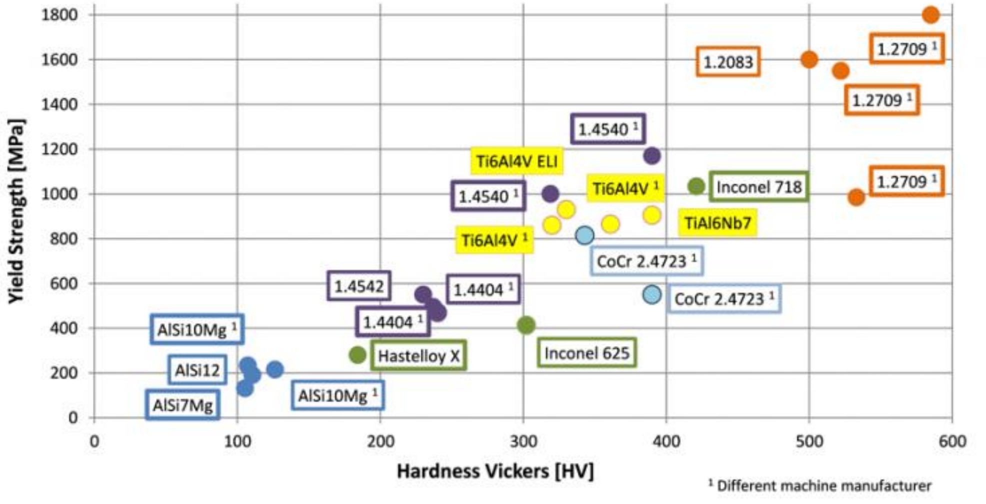

Fig. 1 Mechanical properties of metallic materials – minimum values from data sheets [6]

The quality of the products will depend on the processing parameters used [1, 5]. The metallic parts produced using the SLM technique are characterized by various advantages such as substantial microstructural refinement, reduction in phase segregation and extended solid solubility [2, 3, 5], all these properties being due to the rapid melting and cooling rates that the alloys undergo during the SLM process [5].

European Maraging Steel 1.2709 is part of a class of steels with high mechanical strength, good weldability, high temperature resistance, corrosion resistance, dimensional stability during aging and a high ratio tensile strength over density [1, 2].

Maraging steel 1.2709 is a steel with low carbon content [7] that contains iron and nickel steel and it is often used in applications where high breaking strength is required. One of the fastest additive manufacturing technologies for the production of complex shape samples is selective laser melting (SLM) [8]. This technique uses the laser to selectively melt the metal powder by laser melting a bed of metal powder layer by layer until a fully formed metal part is achieved [9] according to 3-D digital description of the final component. The SLM process has proven to be ideal for the manufacture of tool hard steels, stainless steels, various metal composites, Ni, Ti and Mg alloys [8]. Due to the few existing studies in the literature on the effects produced by the printing direction on the mechanical properties of Maraging steel, it was desired to study this factor by printing two types of specimens with specific shapes of the tensile test (cylindrical and dog bone).

2. EXPERIMENTAL

The metallic material used in laser 3D printing was Maraging steel (material 1.2709) having the technical specifications presented in table 1.

Table 1. Maraging steel – technical specifications [10]

Thermal conductivity	14,2 W/mK at 20 °C
Coefficient of thermal expansion	10,3 x 10-6 m/mK at 20°C to 100°C
Surface roughness	min. Rz 40-60 μm
Density	in average 99,9 % (8,1 kg/dm³)
Max. operating temperature	400°C

Maraging is a martensite hardening steel with a high limit of extension and low deformation.

Two sets of samples (cylindrical and dog bone) with specific shapes and sizes according to the international standard ASTM E8 / E8M Standard Test Methods for Tension Testing of Metallic Materials [11], were printed in three distinct directions (x, y and z), as seen in figure 2, to observe from a mechanical point of view the behavior depending on the printing direction, and the structural changes that they intervene following the tensile stress solicitation.

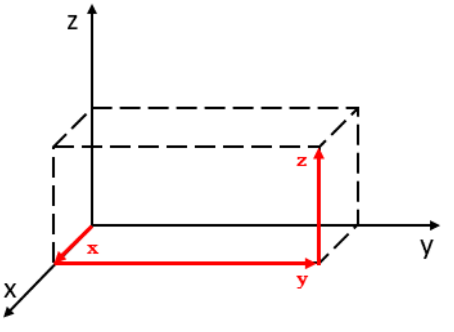

Fig. 2 Printing directions for metallic samples with shapes specific to tensile tests

3. RESULTS AND DISCUSSIONS

3.1 Mechanical tensile testing

The mechanical tensile test was performed at room temperature using INSTRON 5982 mechanical test facility, equipped with a 100 kN force cell, in accordance with the international standard ASTM E8/ E8M ("Standard Test Methods for Tension Testing of Metallic") at speeds of 5 mm/ mm for both sets of samples (cylindrical and dog bone) (fig. 3).

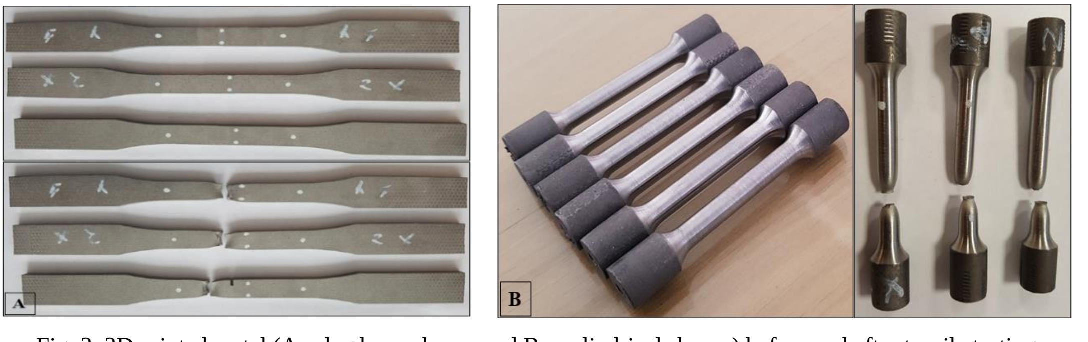

Fig. 3 3D printed metal (A - dog bone shapes and B - cylindrical shapes) before and after tensile testing

As it can be seen in the stress-strain curves in figure 4, the cylindrical specimens printed in the three directions (x, y and z) show a similar behavior in the tensile test.

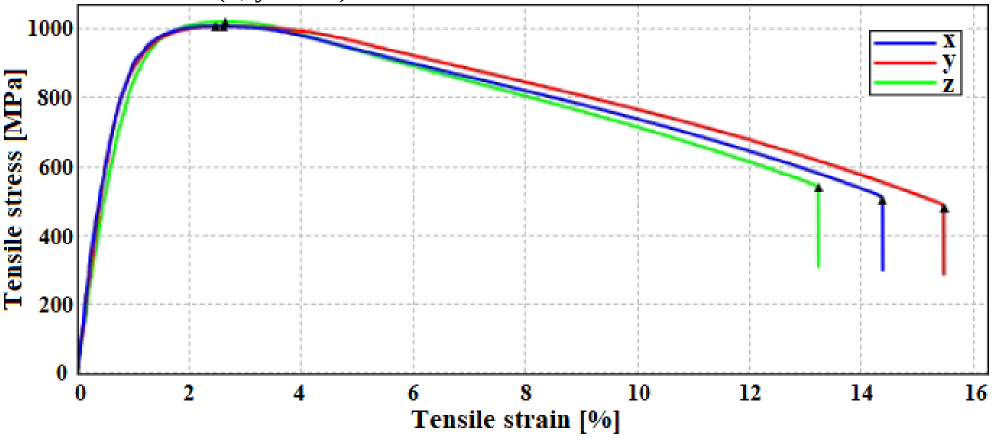

Fig. 4 Stress-strain curvesof cylindrical 3D printed metallic materials after tensile tests

The average results of the Young modulus of elasticity, bending strength and elongation were added in table 2 for 3D printed cylindrical samples and table 3 for 3D printed dog bone samples, respectively.

Table 2. Tensile mechanical properties of 3D printed cylindrical samples

Printing direction	**Modulus [GPa]**	**Strength [MPa]**	**Elongation [%]**
x	104.60	1007.11	2.48
y	110.02	1006.44	2.61
z	92.54	1019.72	2.63

The results obtained after the tensile testing of the 3D printed samples in cylindrical shape, showed clearly higher values of the tensile strength for the samples printed on the z-direction compared to the other samples printed on the x and y directions, respectively. From the point of view of the elasticity mode, the samples printed on the y-direction present superior values to the other samples printed on x and z-directions.

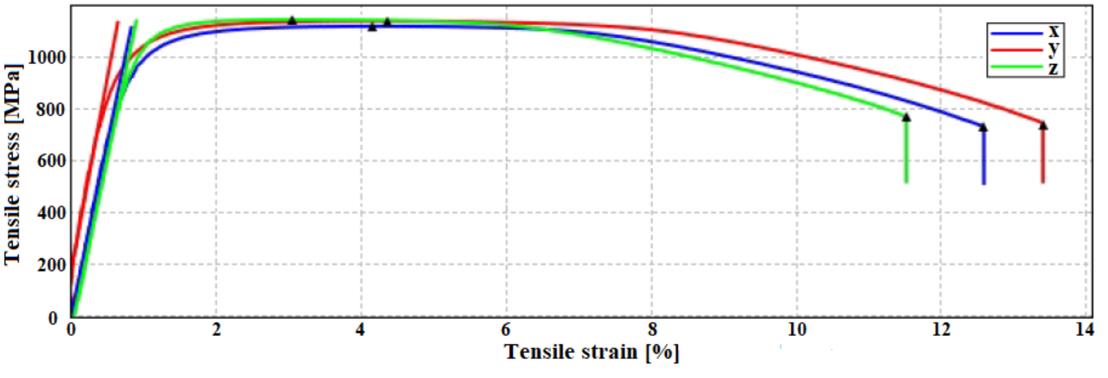

Fig. 5 Stress-strain curvesof dog bone 3D printed metallic materials after tensile tests

In figure 5, stress-strain curves during tensile testing of the 3D printed metallic materials on the three directions (x, y and z) of the dog bone geometry are illustrated.

Table 3. Tensile mechanical properties of 3D printed dog bone samples

Printing direction	Modulus [GPa]	Strength [MPa]	Elongation [%]
x	133.24	1116.92	4.16
y	148.53	1137.35	4.36
z	132.39	1142.46	3.05

Also, in the case of 3D printed samples dog bone geometry, the results indicate high resistance values for samples printed in the z-direction, compared to the other two directions (x and y) and higher modulus values for samples printed in the y- direction compared to those printed in the x and z-directions.

These results will be correlated with the information given by the morphostructural analyzes that will highlight the failure of the samples for the three printing directions.

3.2 Morphostructural analysis

From a morphostructural point of view, the laser printed samples were analyzed by optical microscopy and scanning electron microscopy (SEM), respectively. In both morphostructural analyzes techniques, the images were acquired in the failure area of sample after mechanical tensile testing. The MEIJI 8520 microscope equipped with a 100x magnification video camera was used to record optical microscopy images for both cylindrical and dog bone samples, as shown in figure 6.

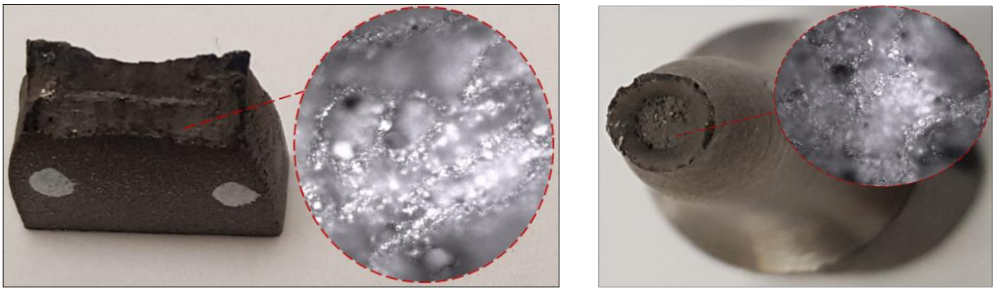

Fig. 6 Optical microscopy images registered in the failure area of 3D printed metal samples (left- dog bone shapes and right- cylindrical shapes)

Optical analysis highlights the failure mode, that occurred by breaking the layers overlapped by 3D printing. For a better comprehension of the failure mechanism of these layers, SEM analysis was performed, as the high magnifications offered by this technique provide supplementary information. Both types of samples (cylindrical and dog bone) were investigated with the aid of scanning electron microscopy (SEM), using SEM Quanta 250 electron microscope, which allows much more advanced magnifications than optical microscopes. In figure 7, the cylindrical samples show a morphology with inhomogeneous spongy architecture, with structural features, without discontinuities.

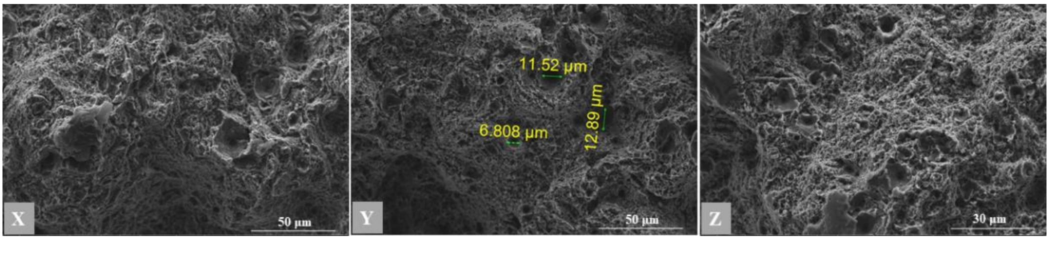

Fig. 7 SEM images registered in the failure area of 3D printed cylindrical methal samples

After the mechanical tensile test, for all three cylindrical samples, a plastic deformation can be observed, in the printing direction, which indicates a ductile rupture of the material.

It is identified the existence of modular particles embedded in the structure (2-4 microns diameter), which follow the flow direction of the material.

The dog bone shape samples, presented in figure 8, illustrate a morphology with porous architecture in the fracture cross section.

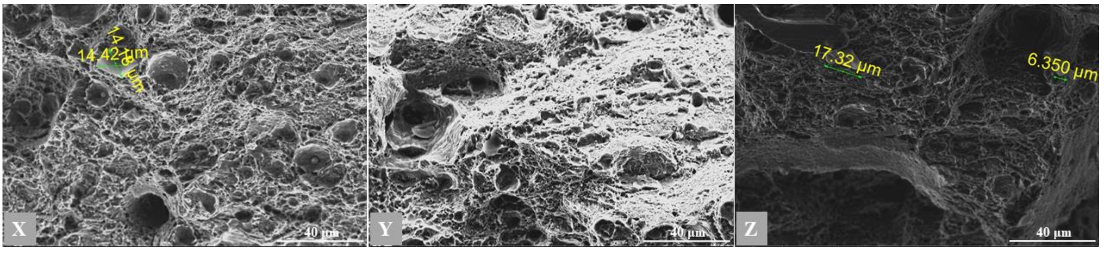

Fig. 8 SEM images registered in the failure area of 3D printed dog bone methal samples

For all three 3D printing sections, it can be observed (figure 8) the formation of a convex cavity after tensile testing. Also, in the case of samples printed in cylindrical shape, the morphological aspect indicates a ductile rupture with the plane oriented in the printing direction for each sample.

4. CONCLUSIONS

The paper investigates the influence of the printing direction on the mechanical tensile properties of Maraging steel samples (material 1.2709) produced by additive manufacturing.

Thus, two sets of specimens consisting of the same material but with different geometric shapes (dog bone and cylindrical) made by 3D printing in three distinct directions (x, y and z) were tested from a mechanical point of view.

The results obtained indicated a small difference consisting of a slight increase in the values of both the modulus of elasticity and the tensile strength for the samples printed in the y-direction compared to those printed in the x and z-directions.

The specimens were investigated from a morphostructural point of view by optical microscopy and scanning electron microscopy investigation techniques to analyze the fracture surfaces obtained after the tensile test.

For both sets of test specimens (dog bone and cylindrical), the images illustrated structures with spongy architecture, without discontinuities, which showed plastic deformations in the direction of 3D printing, which indicates a ductile rupture of the material.

Overall, it can be said that due to the insignificant differences between the values of mechanical results in the 3 directions and the behavior of the specimens after testing, the material does not have an anisotropic character.

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