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# Assessment of the Mechanical Properties of AlSi10Mg Parts Produced through Selective Laser Melting Under Different Conditions

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**Abstract**

Additive manufacturing technologies of metals are gaining increasing interest due to several advantages; among these processes the selective laser melting (SLM) is of particular interest for industrial applications. Despite the clear advantages related to this technique, there are some issues that still hamper a mainstream industrial application of SLM, one is the repeatability of the process. It is well known that varying, for instance, the building direction or the position in the building chamber the components obtained show different microstructures and mechanical properties, several authors are trying to develop processing routes aiming to increase the repeatability of the process. Another issue is the fact that different SLM equipment, produced by different manufacturers, even if the process parameters adopted are the same will lead to the production of components with slightly different properties. These differences are due to small differences among the different equipment, for instance the gas used in the chamber or the way the laser is delivered. The scope of this work is to investigate the mechanical properties of AlSi10Mg components produced with different SLM machines: EOS M400, SLM 280 and RENISHAW AM400. Aiming to assess which are the differences and try to find a range of properties that can be assumed for SLMelted parts. Tensile specimens, designed according to ASTM standard, were printed with the above-mentioned equipment and tensile tests were carried out. The results obtained showed that slight differences can be outlined among the different samples and a range of tensile properties has been also proposed.



*Keywords:* Additive Manufacturing; Selective Laser Melting; Tensile Properties; Building Angle.

## 1. Introduction

Additive manufacturing (AM) of metals is gaining increasing interest due to several advantages and to its intriguing potentialities but, on the other hand, some more research is needed to fill some gaps of knowledge and widen the application field of these techniques [1, 2]. AM is the formalized term for what used to be called rapid prototyping and what is popularly called 3D Printing. The basic principle of this technology is that a model, initially generated using a three-dimensional Computer-Aided Design (3D CAD) system, can be fabricated directly without the need for process planning [3].

Among the additive techniques, powder-based ones are the most promising for metals, in particular the process that uses a laser as a source of energy to melt the powder, i.e. Selective Laser Melting (SLM), is of great interest for industrial applications. Nevertheless, despite the clear advantages related to this technique, there are some issues that still hamper a mainstream industrial application of SLM, one is the repeatability of the process. Premising that the building

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direction is defined as an acute angle between the longitudinal axis of a given sample and the vertical axis, it was showed that the position of the workpiece within the building chamber and also the building direction will affect the final properties of the component [4, 5]. What is more relevant, two different parts produced with the same equipment, under the same conditions but in two different jobs, can show different properties (such as mechanical, of surface and microstructural) [6,7]. Under this light, it can be easily supposed that parts produced with nominally the same process parameters but through different SLM equipment may show different properties. The aim of this work is to (i) clarify this point by testing AlSi10Mg specimens produced through different equipment and (ii) better assess the influence of the building direction on the mechanical properties of the specimens. To this aims tensile specimens were produced with three different equipment and in three different building directions and then tested by using an universal testing machine.

## 2. Experimental

Three different commercial equipment were used in this experimentation, the details are given in table 1.

Table 1. Details of the equipment used as declared by the manufacturers [8, 9, 10].

| | EOS M400 | SLM 280 | RENISHAW AM400 |
|---|---|---|---|
| Effective building volume | 400x400x400 | 280x280x365 | 250x250x300 |
| Laser Type | Yb-fibre laser (continuos wave laser) | IPG - fiber laser (continuos wave laser) | Yb-fibre laser (pulsed wave laser) |
| Focus diameter | 90 µm | 80-225 µm | 70 µm |
| Laser power | 1kW | 400W-1kW | 400W |
| Inert gas | Nitrogen | Argon | Argon (after vacuum) |

The samples were printed according to the process parameters suggested by the manufacturers of each machine, these are based on previous studies and experiences of the constructor on the optimization of the process parameters to guarantee the highest dimensional accuracy and precision for the three different machines: EOS M400, SLM 280 and RENISHAW AM400. As a consequence, it is important to consider that the building processes were carried out under slightly different conditions, but each process is run under its best conditions.

The samples to be tested were produced according to ASTM standard for general tensile test [11], whose dimensions are shown in table 2. The dimensions were chosen considering the dimensions of effective building volume and so a Gauge length with a minimum value of 50 mm.

Table 2. Dimensions of the samples set in the standard file used to print the specimens.

| | mm |
|---|---|
| G-Gauge length | 51 |
| W-Width | 12.5 |
| T-Thickness | 4.8 |
| R-Radius of fillet | 12.5 |
| L-Overall length | 134.8 |
| A-Length of reduced section | 57 |
| B-Length of grip section | 30 |
| C-Width of grip section | 20 |

Three samples, for each machine, were printed in three building directions. These angles were chosen considering the principal building directions and other simple configurations taking into account also the role of the support structures. On these bases, the angles chosen respect to the position of the building plate are 0°, 60° and 90°. For specimens printed in the vertical direction (90°), the area of the support structure is smaller than the one necessary to support samples printed in horizontal direction (0°). A possible good trade-off is given with and inclination of the samples, in this work the angle investigated is 60°. The following combinations were investigated, for each sample three valid specimens were built and tested, the different samples are summarized in table 3.

Table 3. List of the samples under investigation in this experimental campaign, each sample is defined by the equipment used and the building angle adopted.

| Building Angles | Equipment |
|---|---|
| 0° | EOS M400 |
| 60° | EOS M400 |
| 90° | EOS M400 |
| 0° | SLM 280 |
| 60° | SLM 280 |
| 90° | SLM 280 |
| 0° | RENISHAW AM400 |
| 60° | RENISHAW AM400 |
| 90° | RENISHAW AM400 |

The used material was an aluminum alloy: AlSi10Mg, one of the most common alloys used in additive manufacturing chosen for its low weight and excellent mechanical properties [12, 13].

The AlSi10Mg powder was provided by EOS, SLM Solutions and RENISHAW, the composition of which is the same and shown in Table 4. The chemical composition of the powder corresponds to the standard DIN EN 1706. [7, 8, 9]

Table 4. Chemical composition of the AlSi10Mg powder used for the additive manufacturing industry supplied by EOS, SLM Solutions and RENISHAW.

| Material composition (weight%) | | |
|---|---|---|
| Element | Minimum | Maximum |
| Al | Rest | |
| Si | 9.0 | 11.0 |
| Fe | - | 0.55 |
| Cu | - | 0.05 |
| Mn | - | 0.45 |
| Mg | 0.20 | 0.45 |
| Ni | - | 0.05 |
| Zn | - | 0.10 |
| Pb | - | 0.05 |
| Sn | - | 0.05 |
| Ti | - | 0.15 |

To study the mechanical properties of the specimens, uniaxial tensile tests were carried out through a Zwick Roell testing machine equipped with a MakroXtens P extensimeter and a 250kN load cell, at room temperature and with a testing speed set to 1.3 mm/min. The software associated with the Zwick Roell machine, testXpert iii, provides the stress-strain curves.

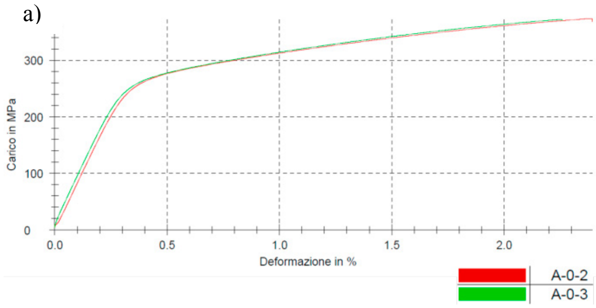
## 2.1. Results and discussion

All the different printed samples are shown in figure 1.

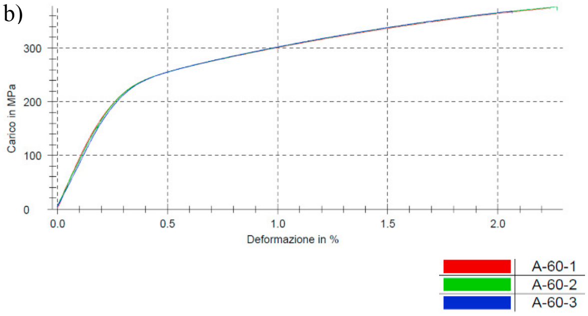

Fig. 1. Additively manufactured samples, printed with three different equipment: EOS M400, SLM 280 and RENISHAW AM400 (from left to right). A ruler is also depicted to provide a dimensional reference for the samples

True stress- true strain curves for all the tested samples are reported below in the following images. It is possible to appreciate that all the samples showed the typical behavior of aluminum alloys, the good quality of the specimens is also attested by the well developed ductile region of the curves that suggests that no fragile failure occurs. Furthermore, the values of the ultimate tensile strength and of the yield stress are well higher than the ones of castings of the same alloy.

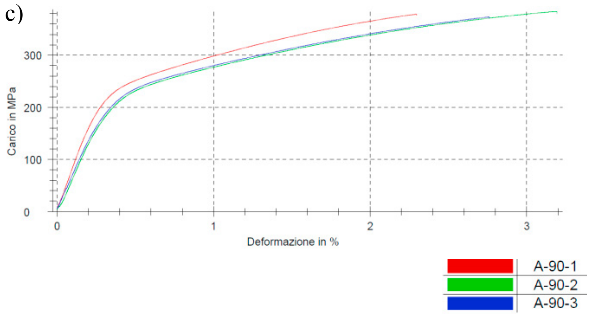
a)



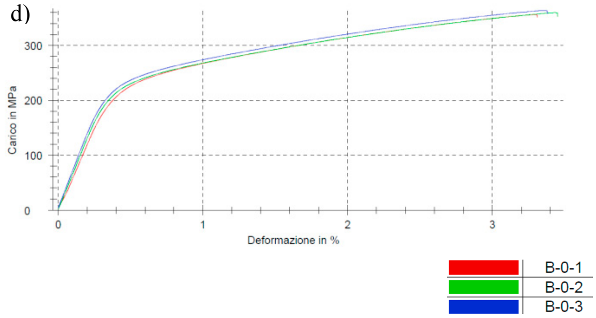

b)



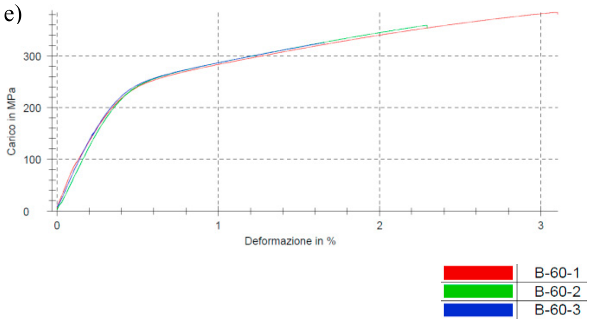

c)




d)




e)



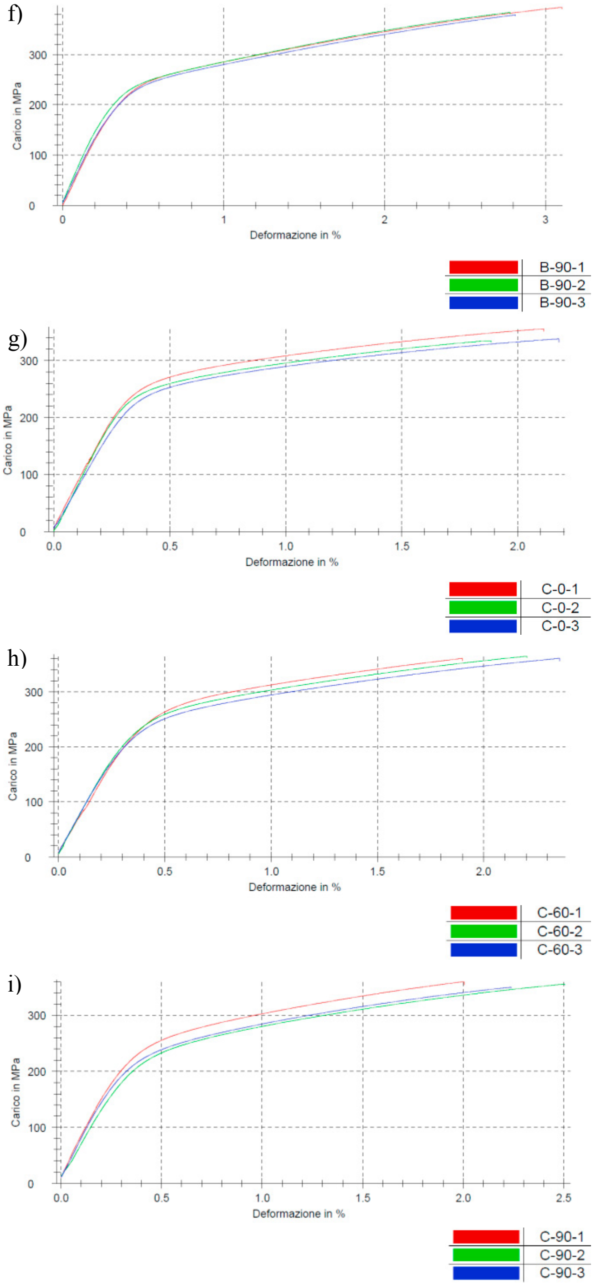



Fig. 2. Stress-strain curves of the additively manufactured samples in AlSi10Mg, produced through powder bed fusion technology. a, b, c) 0°,60° ,90° EOS M400; d, e, f) 0°,60° ,90°SLM 280; g, h, i) 0°,60° ,90° RENISHAW AM400

It can be observed that plastic deformation happens in almost all the cases at 1%, with a maximum value of deformation of 2.5%.

Through the observation of the tested samples, it is also possible to note in figure 3 (a, d, g) that, as concerns samples printed at 0°, the fracture happens in the middle of the gauge length, regardless of the machine used. The same happens also for samples printed at 60° in the EOS 400 and RENIISHAW AM400. Instead, for samples produced with the SLM 280 at 60°, the fracture was detected before the radius of fillet. The last case is also the one detected for specimens printed at 90°, in all the machines used.

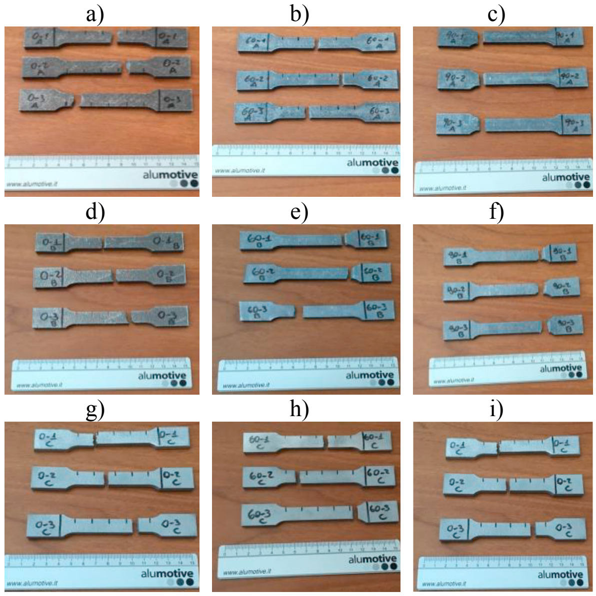
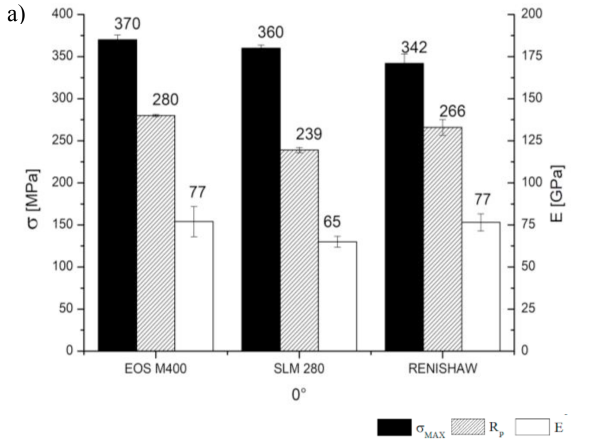
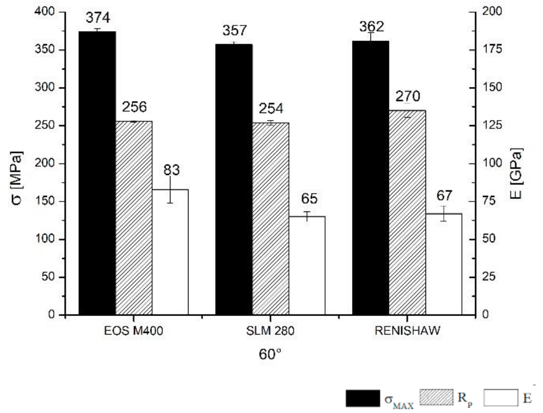



Fig. 3. Images of the two fractured parts after the tensile tests that compose samples in AlSi10Mg. a, b, c) 0°,60° ,90° EOS M400, d, e, f) 0°,60° ,90°SLM 280; g, h, i) 0°,60° ,90° RENISHAW AM400

To better understand the influence of the equipment used and of the building angle, the results of the tensile tests are summarized in figures 4.



b)




c)

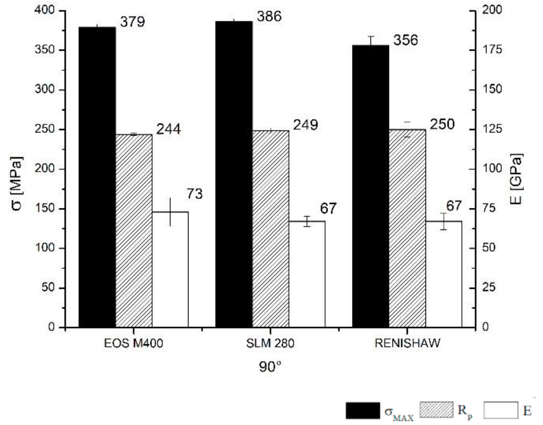
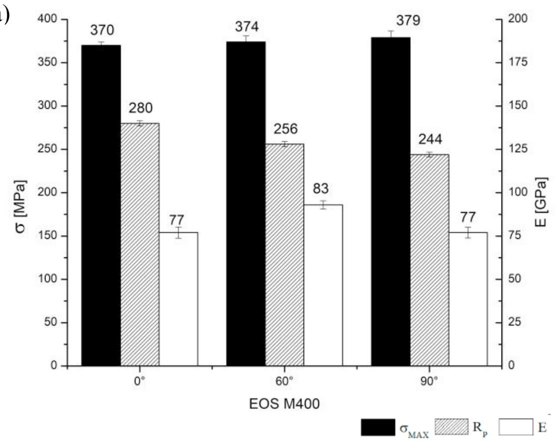


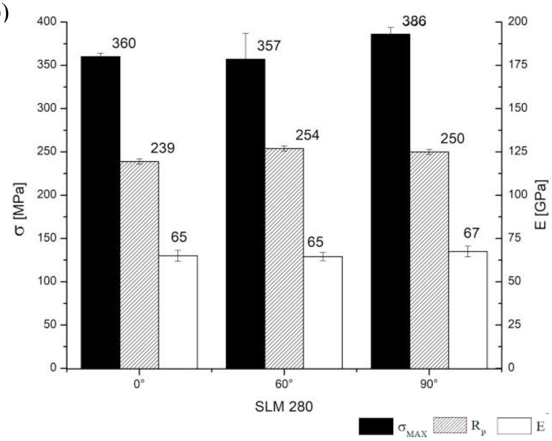

Fig. 4. Ultimate Tensile Stress, Yield Strength and Young's Modulus depicted with a fixed equipment and a different building angle: a) 0°; b) 60°; c) 90°.

In figure 4 the data are presented aiming to highlight the influence of the building direction while in figure 5 the same data are arranged to highlight the influence of the different equipment used.

a)




b)




c)

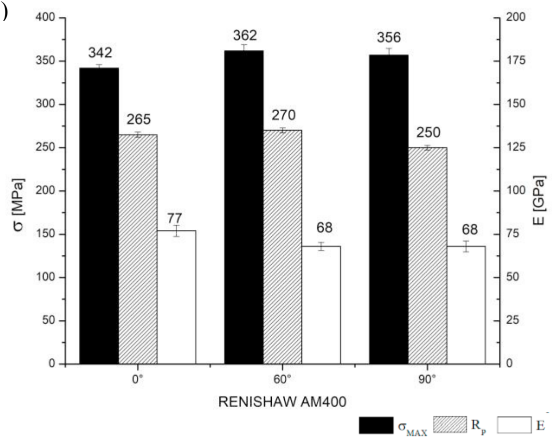



Figure 5. Ultimate Tensile Stress, Yield Strength and Young's Modulus depicted with a fixed building angle and different equipment: a) EOS M400; b) SLM 280; c) RENISHAW AM400.

The first comparison is possible varying the building angles fixing the equipment. It can be observed that the value of the Ultimate Tensile Stress is dissimilar for the various set-up.

The absolute lowest value of the UTS among the different machines is detected in the RENISHAW machine at 0° (342 MPa), in this case the UTS is comparable with the one obtained with a die casting AlSi10Mg parts [14]. Therefore, in the other cases we have better results, indeed in the EOS M400 the lowest value is 370 MPa and is it an output of the samples printed at 0°, in the SLM 280 The lowest value of $\sigma_{max}$ is 357 (at 60°).

The absolute highest value of the UTS among the different equipment is detected in the SLM machine at 90° (386 MPa). The maximum stress also in the EOS M400 is obtained for an inclination of the building angle of 90° (379 MPa), while in the RENISHAW machine this maximum value is obtained for an inclination of 60° (362 MPa). The maximum deviation is 2% in EOS, 6.7% in SLM 280, and 5.3% in RENISHAW.

It is important to highlight that there is not a correlation between the building direction and the value of the UTS in the selective laser melting process using the above-mentioned equipment.

The yield strength, in the EOS M400 has a decreasing trend with the increasing of the building angle and assumes the highest value at 0° (280 MPa); while in the SLM and RENISHAW the yield strength does not follow a trend and assumes, in both cases, the maximum value for inclination of 60 ° (respectively 254 MPa and 270 MPa). The lowest values are at 90 ° for EOS and RENISHAW, and at 0 ° for SLM. The maximum deviation is 12.5% in the EOS, 5.8% in the SLM, and 7.4% in the RENISHAW.

Also in this case, no correlation is possible to highlight for the building angle and the machine used

The Young's modulus or modulus of elasticity E, in each machine has similar values among the different inclination. However, there is a higher value at 60 ° in the EOS M400, a higher value at 90 ° in the SLM 280 and a higher value at 0 ° in the RENISHAW AM400: respectively 83 GPa, 67 GPa and 76 GPa.

Lower values are obtained at 0° and 90 ° for EOS, at 0° and 60 ° for SLM and at 60° and 90° for RENISHAW: respectively 76 GPa, 65 GPa and 67 GPa.

It is interesting to note that, in the case of the SLM 280, the modulus of elasticity is almost the same, regardless of the building direction.

On the other hand, referring to figure 5, the same values can be analyzed from another point of view: the building angle is fixes and the equipment changes.

For inclinations of 0° and 60° respect to the building plate, the highest value of UTS is obtained in the EOS M400, respectively 370 MPa and 374 MPa; at an inclination of 90°, it occurs in the SLM 280 (386 MPa).

The lowest values of UTS are obtained in the RENISHAW at 0° and at 90°, while at 60° in the SLM 280: respectively 342 GPa, 356 GPa and 357 GPa.

In any case, there are not very significant variations when the machine changes. The maximum deviation is 7.4% at 0°, 4.5% at 60°, and 7.8% at 90°. The difference between the different machines is not so excessive.

The yield point, for a 90° construction angle, is very similar in all three machines while it has a higher value in RENISHAW in the case of inclination of 60 ° and a higher value in the EOS in the case of inclination of 0°. The maximum deviation is 14% at 0°, 6% at 60°, and 2.4% at 90°. Hence, it is possible to observe comparable values at 60° and 90°, while slightly further at 0°.

The Young's modulus is similar for the specimens printed with SLM and RENISHAW while changes in the EOS, in which it achieves the highest value. Instead, the value for SLM and RENISHAW are similar, regardless of the building angles in almost all the cases except for 0° in the RENISHAW, in this case Young's modulus E has the same value obtained with the EOS. At 0° there is a maximum deviation of 15%; at 60° there is a maximum deviation of 21%, and at 90° there is a maximum deviation of 7%.

It is relevant to highlight that Young's modulus has a wide difference from the minimum to the maximum value: it means that printing with an EOS M400 machine rather than a RENISHAW AM400 leads producing AlSi10Mg samples with a modulus of elasticity of about 10 GPa of difference.

## 3. Conclusions

In this work, specimens were produced through the same powder bed fusion manufacturing technology, i.e. selective laser melting process, but using different equipment. The repeatability of the process was studied to increase its industrialization starting from the analysis of the mechanical behavior of the samples printed with EOS M400, SLM 280 and RENISHAW AM400 and, then, from their comparison. Moreover, also the influence of the printing direction is investigated, considering the influence of the building angle respect to the horizontal plate in the chamber. For this aim, tensile tests were carried out and on the basis of the experimental outcomes, it is possible to answer the open questions designed in the introduction. Hence, the following conclusions can be drawn:

- At first, it is possible to observe that defining the material, AlSi10Mg, and using different equipment for the same manufacturing technology with the same condition, i.e. the optimum suggested by the manufacturer in terms of process parameters, the mechanical properties of workpieces are different. They show different values according to the printing machine employed in terms of Ultimate Tensile Stress, Yield Strength and modulus of elasticity, with an exception of the elongation at break that is almost the same for the several set-ups. In any case, the properties of the printed AlSi10Mg samples are better or, at the most comparable, with the one produced with conventional technologies.
- The influence of the building angle and of the equipment is confirmed by the results shown following several set-ups, but at the same time, although it is evident in the diagrams, it is not possible to design a clear and specific trend, in any illustrated case by the experimental work. On the other hand, it is possible obtaining products with a maximized mechanical behavior rather than another, with the use of a particular machine or of the building angle.

## References

[1] Sames VWJ, List FA, Pannala S, Dehoff R R, Babu SS. The metallurgy and processing science of metal, International Materials review, 2016.

[2] Biffi CA, Tuissi A, Stato dell'arte sulle tecniche di produzione additiva sui metalli, 2017. Strunk Jr W, White EB. The elements of style. 3rd ed. New York: Macmillan; 1979.

[3] Gibson I, Rosen D, Stucker B. Additive Manufacturing Technologies Springer, New York 2015; 30–41.

[4] Hanzl P, Zetek M, Bakša T, Kroupa T. The Influence of Processing Parameters on the Mechanical Properties of SLM Parts, Procedia Engineering 2015; 100: 1405 – 1413.

[5] Barile C, Casavola C, Vincenzo M, Vimalathithan PK. A comprehensive study of mechanical and acoustic properties of selective laser melting material, Archiv.Civ.Mech.Eng 2020; 20:3.

[6] Hassanin EA, Troiano M, Silvestri AT, Contaldi V, Scherillo F, Solimene R, Scala F, Squillace A, Salatino P. Fluidised bed machining of metal additive manufactured parts. AIP Conf. Proc. 2019; 2113: 6.

[7] El Hassanin A, Troiano M, Silvestri AT, Contaldi V, Scherillo F, Solimene R, Scala F, Squillace A, Salatino P. Influence of Abrasive Materials in Fluidised Bed Machining of AlSi10Mg Parts Made through Selective Laser Melting Technology. KEM 2019;813: 129-134.

[8] www.SLM-Solutions.com.

[9] www.eos.info/en.

[10] www.RENISHAW.com/en.
[11] ASTM (2016) E8/E8M-16a standard test methods for tension testing of metallic materials. ASTM International.
[12] Brandl E, Heckenberger U, Holzinger V, Buchbinder D. Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behavior 2011.
[13] Romano S, Brückner-Foit A, Brandão A, Gumpinger J, Ghidini T, Beretta S. Fatigue properties of AlSi10Mg obtained by additive manufacturing: Defect-based modelling and prediction of fatigue strength, Engineering Fracture Mechanics 2018;187: 165-189.
[14] Matweb materials data, Web-Based Data, Matweb, UK http://www.matweb.com/, as on 08.12.2019.