EXPERIMENTAL VERIFICATION OF PROCESS PARAMETERS INFLUENCING THE MECHANICAL PROPERTIES OF M300 IN THE SLM PROCESS

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The main goal of this paper is to present the results of experimental verification of process parameters affecting mechanical properties of M300 material in the Selective Laser Melting (SLM) process. To obtain the values of mechanical properties, the samples were subjected to tensile testing, where the force, and elongation values were obtained. Therefore, from these values, the values of yield strength, elastic modulus, force and stress at the interface, tensile strength were then derived. It was also possible to construct tensile test F - ΔL: force-elongation diagrams for all specimens, and to construct an R – Ɛ: stress-strain dependency diagram using the calculation of the original area and original length of the specimen. As a result of this work, mechanical property diagram was produced as a function of the process parameters used, showing which parameters most appropriate for the desired properties on the Renishaw AM400 printer.

KEYWORDS

ADDITIVE MANUFACTURING, SELECTIVE LASER MELTING, TENSILE TEST, MECHANICAL PROPERTIES, M300

1 INTRODUCTION

Constant technical progress leads to creation of new production technologies and processes. One of those technologies are additive manufacturing. This particular technology uses the principle of manufacturing layer-by-layer and in recent years many of industry sectors adapting additive manufacturing machines and processes to their own systems and structures. In the near future, there is the great promise of additive manufacturing technologies to create new structures or use bionic-like structures while keeping the specified mechanical properties, or even improve them, but with the advantage of less used material. To achieve this, we need to fully understand the technology, know its strengths and weaknesess during the manufacturing process and adjust the process to get the best results every time. [Yanping]. To describe all the parameters directly influencing the manufacturing process is impossible in a one, single article. As Yadroitsev states in his publication, there is over 100 parameters in Selective Laser Melting technology (SLM), which directly influence the printed part, but most important of those are laser power, scanning strategy, scanning speed, hatching distance, layer thickness, powder bed temperature, morphology of the powder and atmosphere present in the chamber when printing [Yadroitsev 2009].

The main objective of this article is to prepare and realize experiments leading to verify mechanical properties with various settings of certain process parameters. The process parameters which were set out to investigate were laser power and scanning speed, for 1.2709 (M300) Maraging steel powder on the Renishaw AM400 SLM 3D printer. Research of this type of steel, with similar 3D printing machine has been already tackled. Research where focus was to better understand the Direct Metal Laser Sintering (DMLS) process, which is identical to SLM, and the effects of scanning strategies. This research was done by Bhardwaj [Bhardwaj 2018] where they used bi-directional (X) and cross-directional (XY) scanning strategy. From those samples the density, surface finish, texture, residual stress, and mechanical properties were investigated. They discovered that that there is not significant difference in relative density, however presence of high concentration of pores and voids resulting in higher surface roughness was on X scan strategy sample. Also, higher %El was found for X scan strategy, since XY strategy being perpendicular to the loading direction. In this case the scan strategy has strong influence on the ductility or elongation of the manufactured parts by the DMLS method. They recommend using XY scan strategy for fabrication of higher quality parts from M300 steel, since using this strategy and alike one leads to reduction of anisotropy in AM parts. Reduced anisotropy in those manufactured parts by this method provide more homogenous mechanical behaviour along all geometric axes.

Another paper done by Vishwakarma [Vishwakarma 2020] and his team was more aiming on effect of build orientation on microstructure and tensile behaviour of samples made from M300 maraging steel. The orientation of plates was set to 0°, 45° and 90°. After additional postprocessing, the properties such as density, hardness, surface roughness and residual stress and character of microstructure were carried out. In this case, the Renishaw AM 250 SLM machine was used to manufacture the specimens. Other process parameters were set same for all three orientations, where namely laser power was set to 400 W, and scan speed to 2000 mm/s with energy density of 62.5 J/mm^3 and strip hatch pattern scanning strategy. They mentioned that due to stair step effect, specimens created in 45° angle had highest surface roughness, and found out that compressive residual stresses varied with build orientation. Increase in stress were present with increase in degree of orientation. Those stresses were relieved with heath treatment applied afterwards.

In the research done by Suzuki [Suzuki 2019] they targeted to investigate effects of laser power and scan speed on relative density, melt poll depth and Vickers hardness of selectively laser melted (SLM) maraging steel. For manufacturing specimens, the 3D Systems ProX 200 AM system were used. Applied scanning pattern was a hexagonal grid with constant volumetric energy density of approximately 68 J/mm^3, Twenty-five cuboidal samples, each with different laser powers and scan speeds. However, due to uneven surface caused by excessively high laser energy and slow scan speed, samples were not completely built. Laser power applied (85 W – 230 W) and scanning speed used (1250 mm/s – 2500 mm/s) led to results, when low laser conditions were present (low laser power and high scanning speed) the samples included many pores, and the morphology of the raw material powder was partially retained. Under high laser conditions (high laser power and low scanning speeds) dense material were obtained reaching approximately 99.4% compared to 78.0% relative density reached under low laser conditions.

2 EXPERIMENTAL METHODOLOGY

When preparing to print specific parts, it is important to carefully consider which scanning strategy to use to ensure the resulting parts are high quality, accurate and efficient. There are many scanning strategies, each suited to different situations and part types, and it is important to carefully consider all factors and select the scanning strategy that best suits the part type and desired characteristics. The correct choice of scanning strategy can have a significant impact on the quality and efficiency of the printed part.

The scanning method known as "meander" works on the principle of successive layers, where each new layer is applied after a 67° rotation. After 180 layers have been applied, the print direction returns to its initial direction. This strategy allows for less porosity, which means that the resulting parts are less likely to have voids or gaps. However, a disadvantage of this method is the uneven heat distribution during the laying of the layers, which can affect the quality of the final product. The scanning method, called "chessboard", creates square fields on a printed surface in the shape of a chessboard, with the individual fields rotated 90°. [Hajnys 2019]. The main advantage of this strategy lies in the distribution when printing a given component, as the thermal energy is not concentrated at one point. This printing method allows for better heat distribution, which can lead to a better result. On the other hand, this method is often considered slower compared to other printing strategies, see Fig. 1. The scanning method known as "stripes" works with the principle of hatching, where the hatching style of adjacent layers shifts by half the hatching distance. After every two layers, a 90° rotation is performed. This process allows for good heat distribution during printing while minimizing porosity. [Giganto 2022]

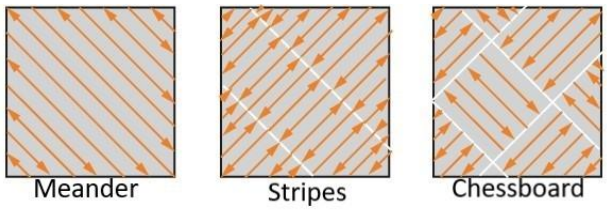

Figure 1. Scanning strategies

Research focuses on the combination of different factors that influence the characteristic of interest. However, testing all combinations can be challenging, so shortcut methods are used that focus on only some combinations. The Design of Experiments (DOE) method uses a systematic approach to design the factors and conditions of an experiment to achieve results at minimum cost. These methods are recommended by QS 9000 and ISO/TS 16949 and are used when testing complex problems where the outcome involves a combination of many factors.) However, our experiment will focus only on the samples listed in Table 1.

Table 1. Setting of Printing Parameters

No. Sample	Power of Laser	Scanning Speed
-	**[W]**	**[mm/s]**
1	250	700
2	300	800
3	300	700
4	350	800
5	300	500
6	250	800
7	350	600
8	250	600
9	250	500
10	400	600
11	350	500
12	300	600
13	400	500
14	400	700
15	350	700
16	400	800

For this research, the stripes scanning method was chosen, which is one of the most commonly used methods for printing 3D objects. The stripes scanning strategy was chosen for this research because of the small area of the printed sample. This type of geometric components requires a special printing strategy that allows printing even complex geometries with high precision. The orientation of the samples on the printing platform was chosen in the XY axis, see Fig. 2. This orientation allows the creation of strong and durable samples by depositing layers of material in this axis. However, this orientation also requires the application of supports on the printing platform to minimise the risk of deformation during printing. Hatch distance between vectors was set to 0.095 mm. Layer height is one of the key factors in manufacturing a part using SLM technology. This height is usually in the range of 30-50 µm, which means that each layer of metal powder has this thickness. However, to achieve even better product quality and a finer surface, a layer height of 40 µm was used. Composition of used powder is listed in Table 2.

Table 2. Composition of powder

Element	Mass (%)
Iron	Balance
Nickel	17.00 to 19.00
Cobalt	7.00 to 10.00
Molybdenum	4.50 to 5.20
Titanium	0.30-1.20
Manganese	≤ 0.15
Carbon	≤ 0.03
Phosphorous	≤ 0.01
Sulphur	≤ 0.01

Figure 2. Orientation of samples

3 RESULTS AND DISCUSSION

After 3D printing, the samples were prepared and then processed and tensile tested, the results are listed in Table 3 and 4. During the test, the specimens were loaded and the force waveforms required to rupture the specimens, the elongation waveforms of the specimens, the test time and the mechanical properties such as yield strength, modulus of elasticity, ultimate strength and ductility were measured. The values of these properties were generated by the machine program, so it was not necessary to calculate them. The tensile test is the relationship between force and elongation, which allowed the creation of a tensile test (F-ΔL) diagram.

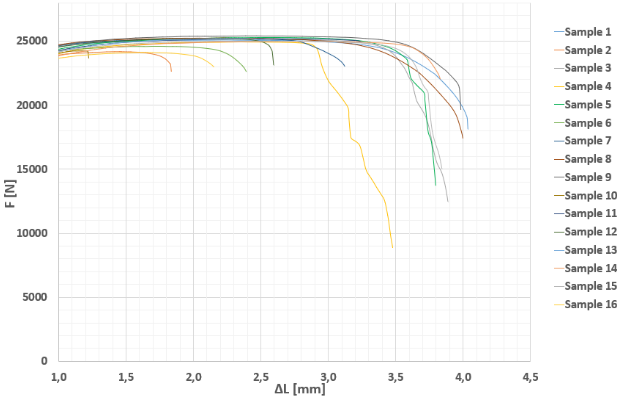

Figure 3. Tensile test diagram (F-ΔL)

To better visualize the effect of the printing parameters on the specimens, the values of all specimens were entered into the graph. This graph was further converted to a contracted stress-strain diagram (R - Ɛ) obtained from the tensile testing machine program.

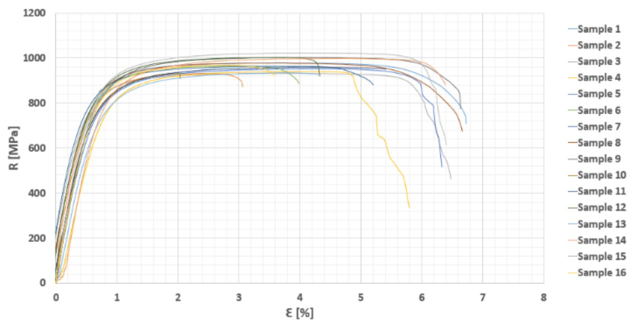

Figure 4. Tensile test diagram (R - Ɛ)

Table 3. Results of tensile test

No. Specimen	Power of laser	Scaninng speed	Yield strength	Elastic modulus
-	[W]	[mm/s]	[MPa]	[GPa]
1	250	700	792	173
2	300	800	792	170
3	300	700	757	168
4	350	800	794	119
5	300	500	727	165
6	250	800	763	174
7	350	600	761	189
8	250	600	793	159
9	250	500	808	153
10	400	600	767	149
11	350	500	773	138
12	300	600	807	157
13	400	500	732	143
14	400	700	719	185
15	350	700	808	183
16	400	800	820	142

Table 4. Results of tensile test 2

No. Specimen	Tensile strength	Tensile strength	Dusctility
-	[MPa]	[kN]	[%]
1	978	25.09	6.7
2	932	24.18	3.1
3	932	25.16	6.6
4	741	24,95	5.7
5	952	25.29	6.3
6	965	24.6	4.1
7	964	25.21	5.3
8	978	25.25	6.8
9	1002	25.42	6.6
10	931	24.24	2.1
11	959	25.19	5.5
12	1002	25.19	4.4
13	935	25.21	4.3
14	998	24.99	6.3
15	1022	25.01	6.4
16	968	24.12	3.6

3.1 Yield Strength

Plotting of Figure 5. showed that the highest value, i.e., more than 790 MPa, reaches the yield strength in two regions, the first region is bounded by a curve at laser power from 250 to 266 W and scanning speed from 500 to 580 mm/s, indicating that low settings of these variable parameters increase the yield strength values. The second region is the opposite of the first. The yield strength reaches its high values at the parameter settings of 321 W and 800 mm/s scanning speed up to 400 W and 765 mm/s scanning speed.

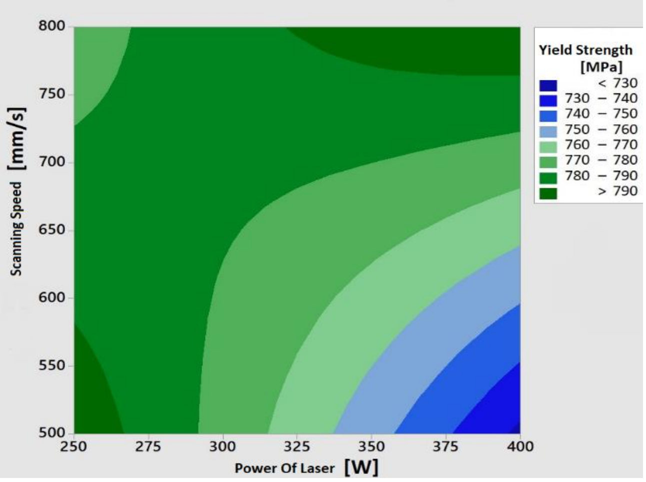

Figure 5. Yield Strength graph 1

Figure 5. also revealed areas of very low yield stress that were created by using high power and low scanning speed. The lowest value of the yield stress, which was less than 730 MPa, was recorded at a power between 395 and 400 W and a scanning speed between 500 and 510 mm/s. From figure 5., it can also be expected that at low power and high scanning speed, the yield strength would also be low. This phenomenon can be seen in the upper left part of the graph where the limiting slip starts to decrease towards the middle of the graph. Therefore, it can be assumed that a scanning speed greater than 800 mm/s at a low power setting (≤250 W) will reduce the limiting slip value. The highest yield stress value was measured for sample 16 (820 MPa) using a laser power of 400 W and a scanning speed of 800 mm/s. On the other hand, the lowest yield stress value was obtained for sample 14 (719 MPa) with a laser power of 400 W and a scanning speed of 700 mm/s. To better visualize the behavior of the yield stress as the parameters are varied, a 3D plot is also shown in Figure 6.

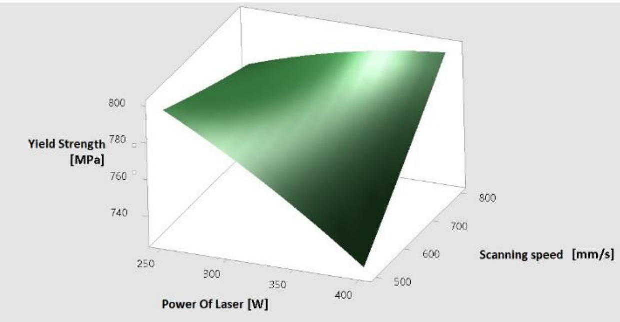

Figure 6. Yield Strength graph 2

3.2 Elastic Modulus

The elastic modulus graph shows that the most elastic material, which has an elastic modulus greater than 175 GPa, is achieved at laser powers between 250 and 300 W and scanning speeds between 615 and 735 mm/s. Conversely, the material with the lowest elastic modulus is obtained at the highest parameter setting, i.e. at a laser power of 400 W and a scanning speed of 800 mm/s. The graph also shows that low elastic modulus values are obtained at the lowest scanning speed setting (approximately 500-505 mm/s) and that in this case the laser power has no effect on the elastic modulus.

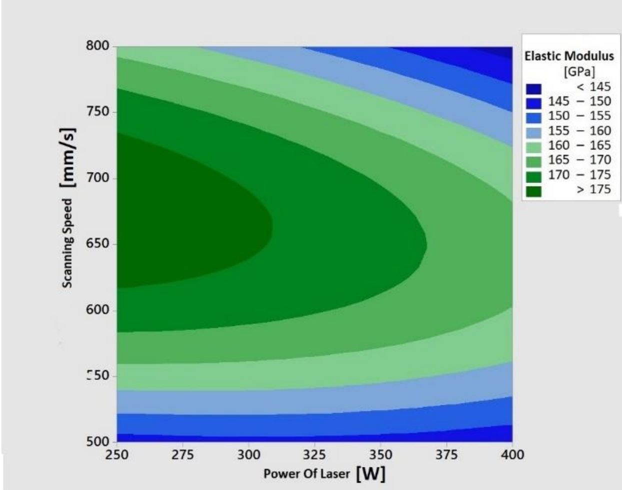

Figure 7. Elastic Modulus graph 1

The highest value of elastic modulus (189 GPa) was obtained for sample 7 with a laser power of 350 W and a scanning speed of 600 mm/s. On the other hand, the lowest values (119 GPa) were recorded for sample 4 with the parameters: laser power 350 W and scanning speed 800 mm/s.

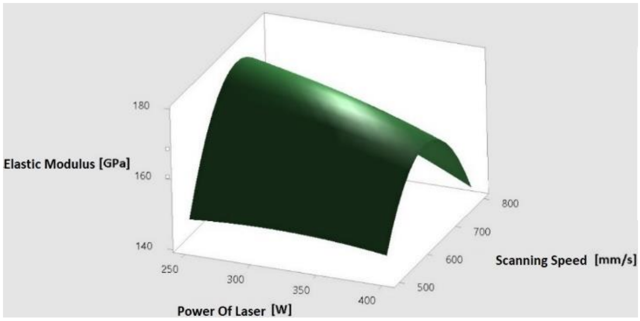

Figure 8. Elastic Modulus graph 2

3.3 Tensile Strength

The values obtained from the tensile test for the ultimate strength are recorded both in terms of force and tensile stress. Figure 9. shows the behaviour of the force at the strength limit when the printing parameters are varied. Figure 9 in turn shows the tensile stress on the interstress at varying parameters.

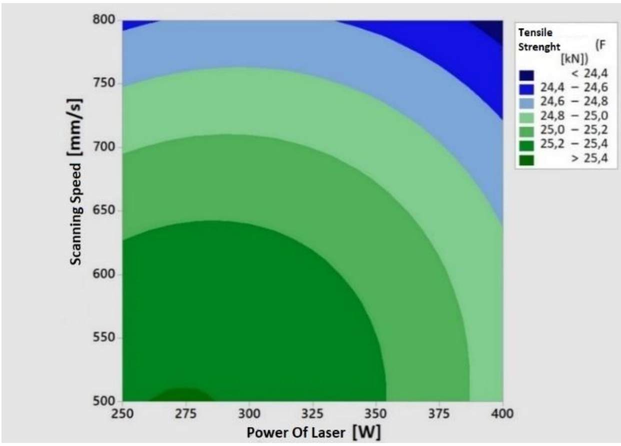

Figure 9. Tensile Strength graph 1

Figure 9 shows that the highest strength at the interfacial is achieved at laser power ranges from 260 to 285 W and at scanning speeds from 500 to 510 mm/s. The lowest measured interfacial strength was achieved at the maximum parameter settings, i.e., at laser powers of 385 to 400 W and scan speeds of

780 to 800 mm/s. The measured values for the strength at the interface are also shown in 3D Figure 10.

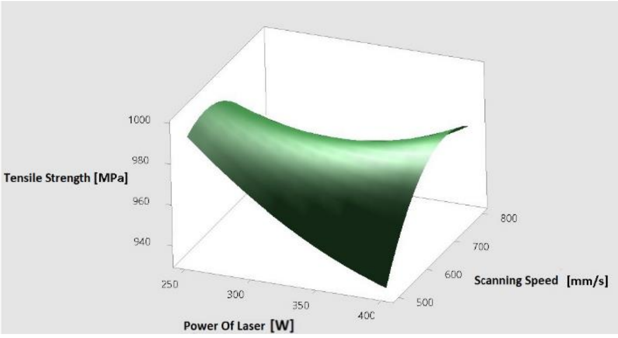

Figure 10. Tensile Strength graph 2

The values of the cutoff voltage varied depending on the laser power setting and scanning speed. The highest values, greater than 990 MPa, were recorded at laser powers of 250-260 W and scan speeds of 500-640 mm/s. On the other hand, the lowest stresses, less than 940 MPa, were measured at laser powers of 375-400 W and scan speeds of 500-520 mm/s. The highest interface force was recorded for sample 9 with a laser power of 250 W and a scan speed of 500 mm/s, while the lowest force was recorded for sample 16 with a laser power of 400 W and a scan speed of 800 mm/s. The interfacial voltage reached its highest value for sample 15 with a laser power of 350 W and a scan speed of 700 mm/s, while the lowest value was recorded for sample 10 with a laser power of 400 W and a scan speed of 600 mm/s.

3.4 Ductility

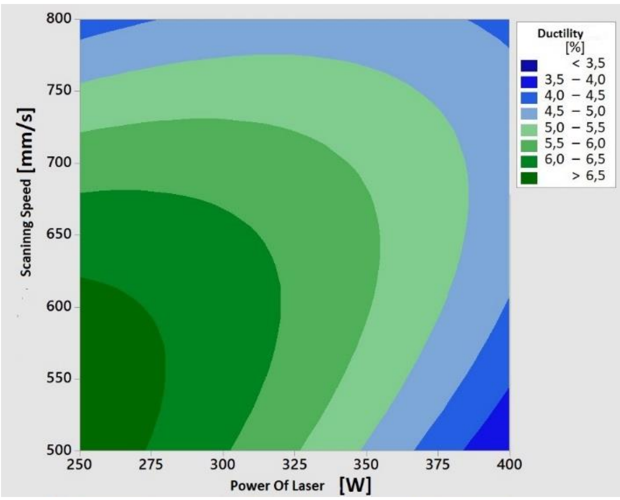

Figure 11. Ductility graph 1

According to contour plot 11, the highest tensile strength values were obtained for the samples at low laser power settings (250-280 W) and scanning speed (500-620 mm/s), while the highest value (more than 6.5%) was recorded at the lowest settings. Conversely, the lowest value of ductility was recorded at the maximum settings of laser power (3.5-4%), scan speed (4-4.5%) or both parameters simultaneously (4-4.5%). Specimen 8 achieved the highest tensile strength value (6.8%) at a laser power of 250 W and a scanning speed of 600 mm/s, while the lowest ductility value was recorded for specimen 10 (2.1%) with a laser power of 400 W and a scanning speed of 600 mm/s.

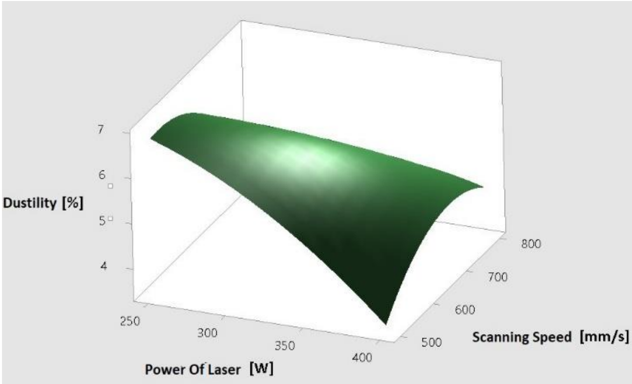

Figure 12. Ductility graph 2

4 CONCLUSION

An important step of the experiment was to determine the number of samples according to the agreed process parameters using the DOE method. Using the Taguchi distribution it was possible to reduce the number of samples to 16 applied, all samples, were subjected to tensile test and then diagrams and graphs were created from them. After successfully breaking all the specimens, the values of forces, elongation and values of mechanical properties such as yield strength, modulus of elasticity, interfacial tension, ultimate tension were obtained. Using the measured forces and elongations during the course of the test, it was possible to create a tensile test F - ΔL diagram for all specimens (Fig. 3). By calculating the original area and knowing the original length, it was further possible to transform the tensile test diagram into an R - Ɛ dependence (Fig. 4).

The evaluation of the mechanical properties is based on the generated graphs (Fig. 5 - 12), It is from these graphs that the parameter settings for the desired property can be clearly determined. The highest yield strength value was achieved by specimen 16 (820 MPa) and the lowest by specimen 14 (719 MPa). For the modulus of elasticity, the highest value was achieved by specimen 7 (189 GPa) and the lowest by specimen 4 (119 GPa). The highest yield stress was measured on specimen 15 (1022 MPa) and the lowest on specimen 10 (931 MPa). Specimen 9 (25.42 kN) had the highest intergranular strength achieved and specimen 16 (24.12 kN) had the lowest. The highest percentage of ductility was achieved by specimen 8 (6.8%) and on the contrary, the lowest value was achieved by specimen 10 (2.1%). Further research focus on M300 material can be directed in the proposed three directions. The first is to investigate the mechanical properties of the material at 3 factors with the addition of preheating. The second type of research may focus on the fracture surface of the samples and obtain the dependence of fracture on changes in laser power parameters and scanning speed. A third type of follow-up research may be to investigate the porosity of the material as the parameters are changed.

M300 steel is a high-quality material that has many advantages and applications in various industries such as engineering, metalworking, and construction. One of the interesting applications of this steel is the production of punches where very high-quality mechanical properties are required. The production of punches is a process where the punch is processed to produce a sharp edge that is used for cutting. In order to produce quality punches, a material with high wear resistance and durability must be used, as these tools work under high forces, all these properties are met by the M300 material. [Li 2019] This steel also has one vulnerability - it is very susceptible to corrosion cracking, which can reduce its mechanical properties. Corrosion cracking in steel can be caused by many factors such as stress, water, chlorides and other aggressive chemicals. However, there are solutions to reduce this vulnerability. One possible solution is the use of HIP technology (Hot Isostatic Pressing). This technology involves exposing steel components to high temperatures and pressures. The advantage of this technology is that it not only reduces the susceptibility to corrosion cracking, but also reduces the pore density and increases the austenite content of M300 steel. Austenite is a phase component of steel that plays a significant role in improving corrosion resistance [Anoop 2021].

For further research, the team recommends to apply and test the obtained results using HIP technology, which should further improve the mechanical properties.

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