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Influence of the Orientation of Parts Produced by Additive Manufacturing on Mechanical Properties

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Binder Jetting technology works on the principle of line injection moulding, using metal powder and liquid binder as input material, which is uniformly applied by print heads to the previous layer using a nozzle. By successively applying each layer, the desired shape of the designed component is obtained. The technology offers a large number of advantages which include the possibility of using any printing powder that may contain functional graded materials. Furthermore, it is a green manufacturing technology where we can reuse unused metal powder in the next printing cycle after following the prescribed process. As a result, we characterize this technology as a near-waste-free production of metal parts. The research aims to analyse the impact of different orientations of printed parts within the workspace on the mechanical properties of the resultant components. Additionally, the study aims to compare these mechanical properties with the specifications recommended by the metal powder manufacturer and findings from previous research studies. Based on the experimental measurements carried out, we can conclude that the influence of the orientation of the parts in the workspace has only a minimal effect on the mechanical properties of the manufactured parts.

Keywords: Additive Manufacturing, Binder Jetting, Sintering, Mechanical properties, Tensile test

1 Introduction

Additive manufacturing is one of the progressive production methods of plastic or metal components. This production method works on the principle of layering material in the form of powder or filament. The process involves the initial design of the component using CAD software. Subsequently, the design is exported as an STL file and directly applied to the additive manufacturing production equipment. This model can be created either by scanning a physical object or by creating a structural design in a CAD system. The setup of the export process itself is very important to ensure the desired quality of the 3D model. Failure to meet the quality requirements of the model has a significant impact on the accuracy of the final component. Important parameters in the actual setup of the equipment are the orientation of the parts, nozzle temperature, thickness of the layer to be deposited, shape of the internal filler, and others. These parameters have an impact on the mechanical properties of the produced parts as well as on the quality indicators. [1,2,3,4,5,6,7,8]

Binder Jetting technology uses powder as the input material, which is applied in individual layers that are bonded together by a liquid-applied binder. The technology was developed at Massachusetts Institute of Technology (MIT), with the origins of the technology dating back to the early 1990s. Binder Jetting currently uses a variety of materials, including 316L and 17-4 PH stainless steel, M2 tool steel, Inconel 718, silver, and others. [9,10,11,12]

Kumar et al. dealt with the mechanical properties of specimens fabricated by SLM and Binder Jetting technology from 316L stainless steel material. The experimental results indicate that the specimens fabricated by SLM technology are significantly stronger and with smaller pores than the specimens fabricated by Binder Jetting technology. [13]

Lv. et al. worked out a practical analysis where they concluded that the mechanical properties are influenced by the shape and size distribution of the powder particles. The material in powder form is currently produced in irregular shapes, while the trend in the next developments will be the production and application of rod-shaped powders, which represent a suitable alternative also in relation to the positive influence on the mechanical properties. The mechanical properties of parts produced by the additive process are influenced by the shape of the powder and the particle size distribution. [14]

Mao et al. investigated the effect of sintering temperature on the mechanical properties of the fabricated parts. The results of the research showed that the sintering temperature significantly affects the properties of the sintered parts. [15]

2 Materials and methods

The aim of the experiment was to compare the mechanical properties of samples produced by Binder Jetting technology, which works on the principle of layering powder layer by layer, which are bonded together by a liquid binder. Based on the ASTM E8M method, which is the most common test method for determining mechanical properties, test specimen were designed. The number of specimens fabricated was nine, and three specimens were produced from each orientation in the X-axis, Y-axis, and Z-axis (Fig. 1). The aim of the study was to provide new insights into the effect of orientation on the mechanical properties of parts produced by the additive process. For each orientation, the parameters strength (Rm), yield strength (Rp), and ductility (A) were evaluated.

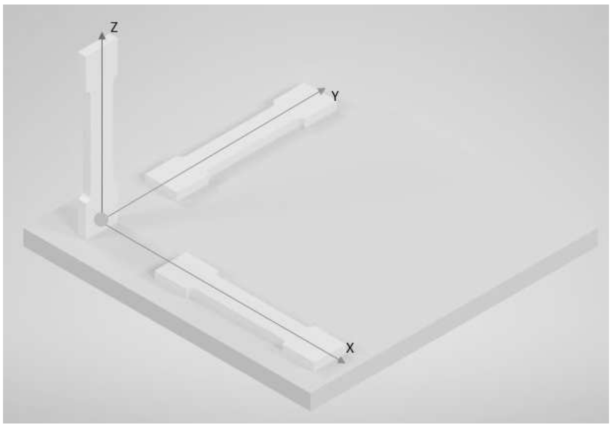

Fig. 1 *Orientation of test samples in the printing box*

2.1 Design of experiment (DoE)

The experimental specimen for mechanical testing of additively manufactured parts was designed based on ASTM E8M (Fig. 2). This specimen shape is mainly intended for homogeneous materials because the failure of the specimen occurs in the narrowest part of the specimen. This is due to the highest stress at this location, which exceeds the strength of the material and causes the specimen to rupture.

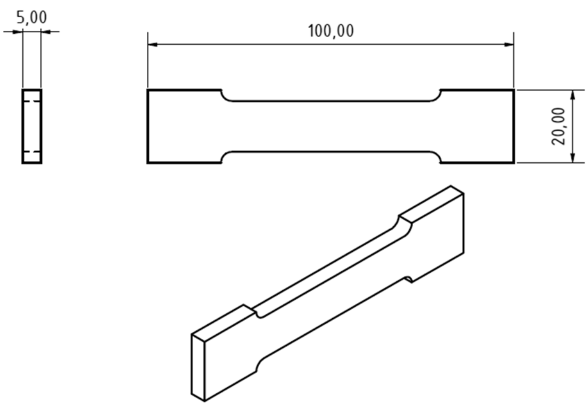

Fig. 2 *Specimen shape according to standard ASTM E8M*

2.2 Applied technology

Binder Jetting technology consists of a process in which an industrial print head applies a liquid binder to a thin layer of powder particles made from materials such as composites, metals, ceramics, and sand to create full-size and functional parts for industry. [16] The production of metal parts by the additive process of Binder Jetting consists of the following workflow: metal powder is applied uniformly to a thin layer (50 μm), and then the industrial print head selectively applies the liquid binder. For each layer, a short drying process takes place and then the layer is finished. The process is repeated layer by layer based on the digital design in STL format, (Fig. 3) [17,18,19,20,21] After the actual production is completed, the print box is moved to the curing oven for 4-6 hours where the liquid binder solidifies at a temperature of 200 °C to form the so-called green part, which is fragile and is printed roughly 20% larger to compensate for the shrinkage of the part during the sintering process. The green parts, composed of metal powder and binder, are removed from the printing box. They are then cleaned of the surrounding metal powder. The unused metal powder is returned to the work equipment for reuse in the next printing cycle. As a result, Binder Jetting technology can be considered as an almost waste-free production of metal parts. The last stage consists of binder removal and sintering. Both of these processes are carried out in the sintering furnace during one cycle. The binder is removed from the part at about 400 °C and then the free pore closure occurs at temperatures just below the melting point of the metal, resulting in densities above 97-98%. [22,23,24,25]

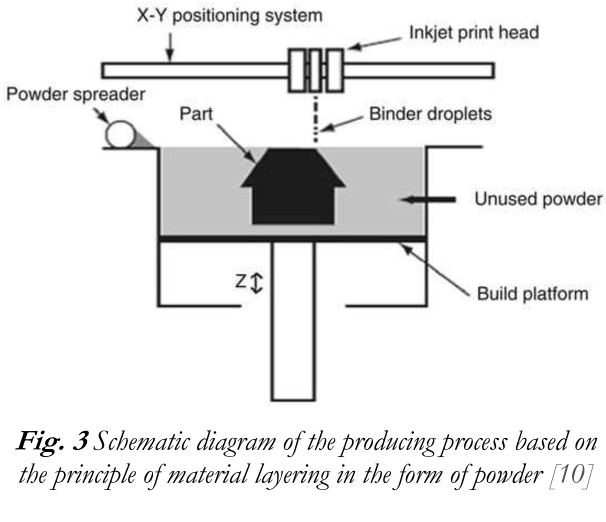

Fig. 3 *Schematic diagram of the producing process based on the principle of material layering in the form of powder [10]*

2.3 Used device

The experimental samples for mechanical tests were produced on the ExOne X160 Pro additive manufacturing machine (Tab. 1, Fig. 4), which operates on the Binder Jetting technological principle. The device is used for producing samples from materials loaded into it in powder form, encompassing metals, sands, ceramics, and specialized materials.. It is a high-volume production, which has a working chamber with a volume of 160 l. The benefit of this equipment is its ability to easily produce shape-complex parts in one operation without the need for additional technology.

***Tab. 1** Technical parameters of the ExOne 160L Pro*

Machine parameters	Parameter Description/Value
Producing technology	Binder Jetting
Direction of production	Universal (X, Y, Z)
Print head type	4-chamber (4096 nozzles)
Production speed	3120 cm3/h
Layer thickness	50 μm
Powder bed dimensions	500 x 800 x 400 mm
Production volume	160 l
Materials	Stainless steels (316L, 17-4 PH), Tool steels (M2, H13), Inconel, Cooper

***Fig. 4** Additive device ExOne 160L Pro working on the technological principle of Binder Jetting*

2.4 Used material

The material used in the experimental part was 316L stainless steel in powder form (Tab. 2). It is a low carbon alloy which has high corrosion resistance with relatively good strength and suitable mechanical properties. In additive manufacturing, it exhibits good ductility, thermal properties, high hardness, and toughness, while it can be welded and machined. Due to these properties, 316L stainless steel is widespread in several industries such as aerospace, energy, medicine, automotive, and many others. [26]

***Tab. 2** Chemical composition of 316L metal powder based on attestation certificate (wt. %)*

Cr	Cu	Fe	Mn	Mo	N	Ni	O	S	Si	P
16.9	0.01	Bal.	0.01	2.52	0.00	11.60	0.02	0.003	0.59	0.006

2.5 Test principle

Tensile tests belong to the static class of tests, where the principle (Fig. 5) involves gradual and controlled pulling of test specimens of prescribed shapes and dimensions until they break. In order to achieve the correct orientation, the specimen must be correctly fixed in the jaws of the test rig so that the axis of the specimen coincides with the axis of the applied load. During the test, a force-displacement graph is recorded to visualize the correlation between the specimen and the applied pressure. [27]

The tensile tests were carried out on an Instron 5985 test device (Fig. 6) in the Mechanical Testing Laboratory of the Department of Materials Engineering. The test device has a maximum tensile load of 250 kN with a vertical test area of 1930 mm.

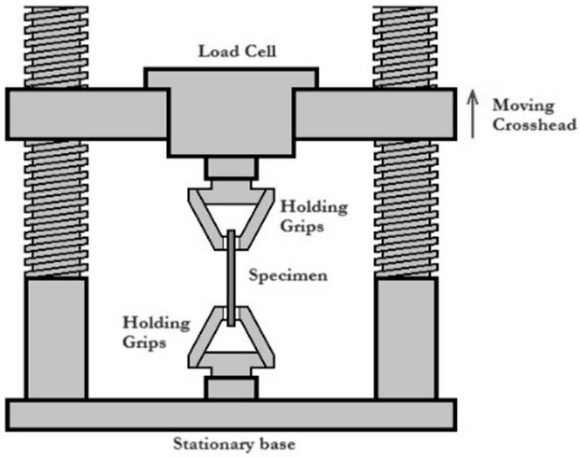

***Fig. 5** Tensile test principle [26]*

Fig. 6 *Testing device Instron 5985 for realization of tensile tests*

2.6 Mechanical properties guarantee by producer

The mechanical properties of the powder used generally vary with the use of additive manufacturing technology, but also with the orientation of the printed parts themselves. In the table (Tab. 3) we can see the guaranteed mechanical properties given by the manufacturer of the metal powder used for the experiments carried out.

Tab. 3 *Mechanical properties guaranteed by the metal powder manufacturer*

Parameter	Parameter value
Tensile strength (Rm)	500±15 MPa
Proof strength (Rp0.2)	200±5 MPa
Elongation (A)	60±3 %

3 Results

Based on the ASTM E8M method, test specimens were designed to test and verify the mechanical properties of the fabricated specimens. The number of specimens fabricated was nine, three specimens were fabricated from each orientation in the X-axis, Y-axis, and Z-axis. Static tensile testing, which is one of the basic mechanical tests, was used to determine the mechanical properties. The tensile tests were carried out on an Instrom testing machine. Fractures in specimens occurred uniformly across all orientations, predominantly within the middle third of their length. This indicates a ductile fracture pattern, attributed to the homogeneous deformation resulting from the powder metallurgy process.

Standardized specimens were produced with different orientations along the X, Y, and Z axes, with each orientation comprising three specimens. Tensile diagrams for these standardized test specimens are presented in Figure 8, while the mechanical characteristics of each specimen are graphically compared in Figure 9. The values depicted in the graphs represent the averaged results of the three specimens fabricated for each axis.

In the graphical representation (Fig. 7), a comparison of mechanical properties as a function of orientation is evident across all three axes. The specimen in the Y orientation attains the highest stresses, followed by the X-oriented specimen with the second-highest stress, and the Z-oriented specimen with the lowest stress. Notably, the graph illustrates a continuous increase in elongation in all three orientations, reaching a maximum length of 38.40 mm.

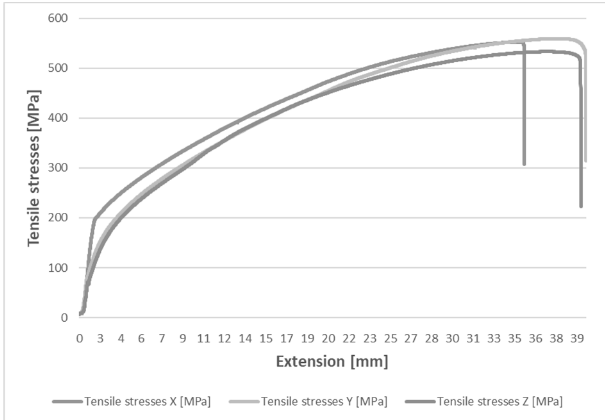

Fig. 7 *Results of experimental tests*

The following graph presents a comparison of strength, yield strength, and ductility. It is evident from the graph that the highest values were attained by specimens produced in the X orientation, followed by specimens in the Y and Z orientations.

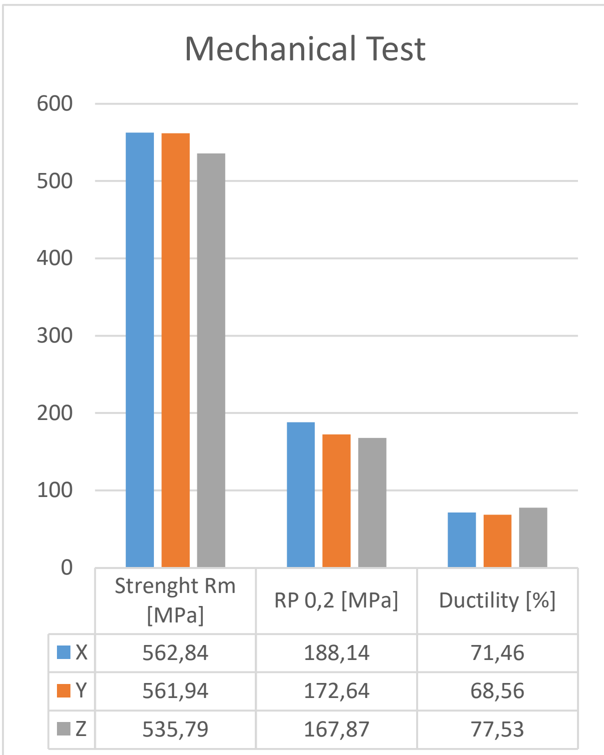

Fig. 8 *Mechanical test results*

4 Conclusion

A series of experimental tests were conducted using Instron equipment to verify the mechanical properties specified by the powder manufacturer. These experimental measurements aimed to compare and validate the mechanical properties assured by the material manufacturer through actual mechanical tests. The experiments also included a comparison of specimens produced in different orientations, encompassing multiple directions.

Based on the experimental results and measurements, we can summarize the following:

- The mechanical properties specified by the manufacturer of the material correspond to the experimental results obtained. Notably, our experimental measurements yielded significantly better results compared to those prescribed by the manufacturer of the metal powder itself.
- The mechanical properties vary depending on the orientation of the parts in the additive process itself. However, these variations are minimal, signifying that the printing orientation of the parts does not significantly impact the mechanical properties.
- The best mechanical properties were obtained for the specimen oriented in the X-axis, where the average value of ultimate strength reached Rm = 562.842 MPa, yield strength Rp0.2 = 188.138 MPa and elongation A = 71.46 %
- Manufacturers of metal parts by additive processes are recommended to use X-axis orientation

Binder Jetting technology is a suitable choice of additive technology presenting itself as an optimal alternative to conventional manufacturing methods like CNC machining or metal part casting. It holds the potential to supplant or complement current technologies across various industrial sectors, particularly in the production of smaller product batches.

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