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Analysis of Parameters of Sintered Metal Components Created by ADAM and SLM Technologies

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Atomic Diffusion Additive Manufacturing (ADAM) is a recent metal sintering process based on known composite printing technology. ADAM can be classified as indirect additive production using fibre of metal powder bound in a plastic matrix. The plastic binder allows the metal powder to remain in place when is printing. Thus, a "green part" is printed and then the plastic binder is removed by the post-washing and sintering process. The aim of this work is providing a brief description of the ADAM process patented by Markforged. Furthermore, the main task was to compare the technology with other sintering technology, namely SLM technology. It works on the basis of selective bonding of metal powder using the thermal energy of the laser beam. Parameters, such as dimensional and shape accuracy, roughness of printed surfaces or tensile strength of printed samples were examined and compared. Dimensional accuracy of the ADAM process was evaluated using ISO IT grades - determined on the basis of the reference standard. The observed accuracy of the sintering process was comparable to traditional production processes.

Keywords: Additive Production, Markforged, Sintering, SLM, 17-4 PH, 316L–0407, Roughness

1 Introduction

Additive manufacturing (AM) is a progressive way of making components while guaranteeing great design freedom. The origins of the additive production can be found in 1981, when Hideo Kodama of Nagoya published information concerning the production of a solid printed model [1]. From the first Rapid Prototyping systems to current AM machines, these technologies have undergone complex development, with particular emphasis on mass production of custumized products [2]. The beginning of the 20th century brought the first commercial selective laser sintering machine (SLS), which was built on the basis of sintering powder material. The development also continued and over time, in addition to sintering plastic powders, metal powders began to sinter - this is how Selective Laser Melting (SLM) technology was developed [3]. At the present, the additive production is on the rise, with interest in it is growing exponentially [4,5]. This is due to great advantages over conventional chipless and particleless methods of component production. Main advantages of the additive technologies include low shape and design limitations of printed parts [6,7], a wide range of used and often high-quality materials [8] and, last but not least, the IT accuracy of printed components is comparable to conventional production methods.

Atomic Diffusion Additive Manufacturing is a new progressive method of metal 3D printing, which is based on the known technology of composite printing, but instead of composite materials uses metal powder, which is bound in a plastic matrix. It is a rod made of metal powder built into a plastic filament. This is similar to conventional 3D printing technologies, such as FDM, when metal parts form layer by layer but align during the printing phase to account for shrinkage. The binder allows the metal powder to remain in place during printing and is subsequently removed during cleaning and sintering. ADAM technology allows the formation of metal parts relatively quickly and accurately and also allows the formation of closed structures without „an escape hole“ for powder [9,10]. ADAM technology is up to 5-10 times cheaper compared to alternative metal printing systems and is also significantly cheaper than traditional machining or casting methods [9].

2 Methodology and design of the experiment

The main task of the experiment is to compare two methods of metal additive 3D printing. The first method is selective laser melting (SLM), which is based on the sintering of metal powders, and the second method is Metal X technology (ADAM), which is based on metal-plastic filaments. Two components were printed from both technologies. One sample was printed for measuring of mechanical properties of the material (test sample) and the other for examining the geometrical specifications (test component). The samples for the SLM technology were printed from stainless steel 316L material on the device Renishaw AM500M. Adam technology samples will be printed from the stainless steel 17-4 PH material on the device Markforged Metal X.

2.1 Technology SLM

Selective Laser Melting is a technology which is based on the sintering of metal powders. It can directly create metal parts that are almost completely dense. No adhesives are needed during use of this technology. Mechanical properties and also shape accuracy are better in comparison to SLS [11]. The melting process takes place in a strictly controlled atmosphere. The working chamber is free of moisture and air before the start of the process, the space consists of almost 100% vacuum. Then it is filled with inert gas, such as argon or nitrogen. To achieve greater efficiency, it is better to use argon, which has a higher proton number and is heavier than nitrogen. After preparing and calibrating the plate before 3D printing, a metal powder is feeded from the powder hopper, which is evenly applicated on the platform with using a silicone rod. This layer of the metal powder is sintered with a high-efficient laser beam. At the end of the fusion, the operating platform reduces the distance by one layer and continues with processing of the next layer of powder. When melting is completed, there is created a three-dimensional mixture. Required products are accumulated by processing of the layer by layer. The thickness of the layer varies between 20-100 μm and it is chosen according to the powder metal used. The heat source for melting powder is a high-efficient laser (CO_2) or an electron beam, which melts the applied powder evenly on the base plate. The beam diameter is around 70 μm [11,12].

Once the part is finished, it can be removed from the machine. Finished parts at SLM need to be removed from the printing platform, which is often done with the help of a saw. Consequently, supporting structures are removed. When the supporting material is the same as the one from which the part is printed, removing the support can be difficult and time consuming. The surface remains rough after melting, which requires additional treatment [13,14].

The SLM system can process a sufficient range of metal materials, such as stainless steels, tool steels or super alloys [15]. The device, using an inert atmosphere of argon, also allows to work with reactive metal powders, such as aluminium and titanium alloys. The most common materials are aluminium alloys (AlSi10Mg, AlSi12), stainless steel 316L and titanium alloys (Ti6A14V). The production of metal powders with a defined shape and very small particle size is a complex and classified process [16,14].

2.2 Renishaw AM500M (SLM)

Renishaw AM500M is a laser device that works on the basis of selectively connecting metal powder using thermal energy (PBF). It is equipped with automated powder and waste handling systems that enable consistent process quality, reduces operator contact times and ensures high system safety standards. Recycling of the powder is carried out automatically in the compact system, reducing the need of manual handling of the material. This provides increased safety and sustained quality of metal powders [17,18, 19].

2.3 Material 316L-0407

It is a stainless-steel powder which contains iron alloyed with chromium (18%), nickel (14%), molybdena (3%) and other small elements. Due to its low carbon content, this alloy is resistant to sensitisation (precipitation of carbides at the grain boundaries). This material shows good welding properties and has good tensile strength at high temperatures. Fe ration (wt%) is balanced with respect to the production batch, as stated by the manufacturer in the material data sheet. The nominal composition of 316L-0407 material is reported in Tab. 1 [20, 21].

Tab. 1 *Chemical composition of material 316L-0407*

Cr	Ni	Mo	Si	Mn	N	C	P	S	Fe
16-18%	10-14%	2-3%	1% max	2% max	0.01% max	0.03% max	0.045% max	0.03% max	Balanced

2.4 Technology ADAM

The whole process of a component printing starts with designing a 3D model that is no difference from other 3D printing methods. A surface model from CAD program is in format .stl and it is designed by the Eiger application. Using this application it is easily prepared for additive production. This is followed by 3D printing itself, which prints a piece of metal powder with using a temporary thermoplastic binder. The part is printed in layers in the shape of a future component. The model is adequately enlarged to compensate for its shrinking in the next stage of production. The as-built-printed part or "green part" is next cleaned (debinding) in a special solution, which washes out the fasteners and leaves the component partially porous so that the rest of the plastic carrier can be burned in the next step. This step ensures the cleanliness of the final metal model and also maintains a clean sinter furnace. Reinforcement of the component is carried out by sintering in a sintering chamber. Sintering takes place at high temperature, in a protective atmosphere according to the prepared program. This step provides a cleaning of the component, a solid all-metal part of the required dimensions. If necessary, additional adjustments may follow at the end of the process, as in case of the other 3D printing methods (sandblasting, grinding, etc.). Temporary support can be easily removed thanks to a ceramic separation layer. The process of production of the part can be seen in Fig. 1.

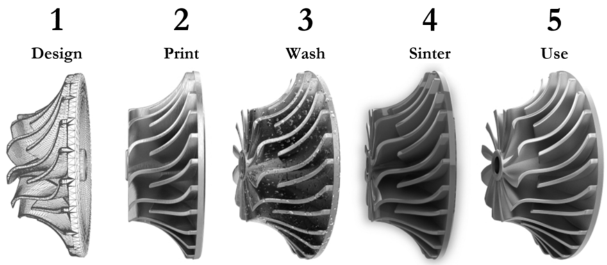

Fig. 1 *ADAM technology procedure*

2.5 Markforged Metal X (ADAM)

Markforged Metal X consists of three devices according to industrial standards. It is the Metal X printer itself, the cleaning station and the sinter furnace. The Metal X printer, which was introduced in 2017 for the first time, operates on the same principle as FDM printers, with the difference that Adam technology allows metal to print. Key parameters that affect the output of parts include print accuracy, input material composition and component size, sintering process temperature and chamber sintering atmosphere. Metal X has significantly lower acquisition and operating costs than all other types of metal 3D printers. It requires minimal modernization of equipment, does not need a powder management system or a specialized worker. The Markforged Metal X costs between \$150,000 and \$200,000, which is about from 5 to 10 times cheaper than other systems.

Markforged Metal X can process a wide range of materials such as stainless steel (H13 tool steel and 17-4 PH), Inconel (625), Ti-6Al-4V, A-2 and D-2 for tools and aluminium alloys (6061 and 7075) [22,18,23]. However, only tool steels H13 and 17-4 PH are today industrialized and ready for production.

Material 17-4 PH

It is a stainless steel powder cured by chromium and copper precipitation. Type 17-4 PH is a martensitic hardened stainless steel that provides excellent quality combination of high strength, good corrosion resistance and good mechanical properties at temperatures up to 316 °C. Mechanical properties can be optimized by heat treatment. It is possible to reach a very high slip limit of up to 1100-1300 MPa. Fe ration (wt%) is balanced with respect to the production batch, as stated by the manufacturer in the material data sheet. The nominal composition of 17-4 PH material is reported in Tab. 2 [24,25].

Tab. 2 *Chemical composition of material 17-4 PH*

Cr	Ni	Cu	Si	Mn	Nb	C	P	S	Fe
15-17.5%	3-5%	3-5%	1% max	1% max	0.15-0.45% max	0.07% max	0.04% max	0.03% max	Balanced

2.6 Design of the sample structural element

The component model that was printed and designed according to the demand of one unnamed company from the Netherlands. It is a complex component and is suitable for the needs of the experiment. Because of a complex shape, we can thoroughly compare both metal 3D printing technologies and determine which technology has dealt with printing better. In addition to more demanding geometry, the component contains six threads, each with a different size and a different thread pitch. In Fig. 2, there is shown a model of a given component created in Creo. In addition to component models, samples for mechanical properties of the material were also printed by using of both technologies. These simple samples have been designed for tensile tests. In Fig. 2 are shown the models of the given sample in CAD program Creo.

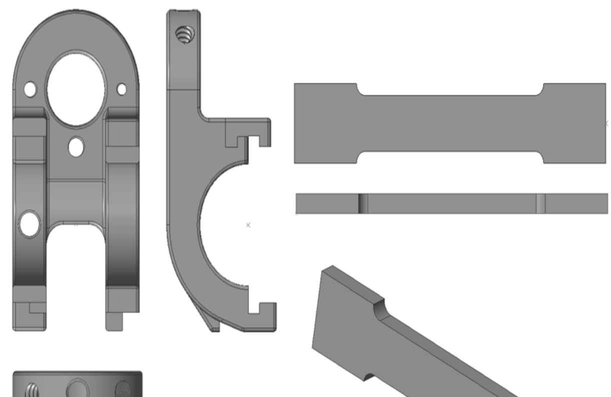

Fig. 2 *CAD part and test sample model*

3 Results of the experiment

The dimensional accuracy of the samples was measured to determine the achieved degree of IT accuracy according to the ISO scale. The accuracy of this scale is based on the extrusion-based AM system for polymers. For the second on the printed samples, was analysed achieved surface roughness. Furthermore, mechanical tests of the material were carried out, where the hardness of the material was determined and a static tensile test was also carried out. The results of these measurements are presented in the following subchapters. The experiments were continued for reverse engineering purposes, where samples were scanned with a laser scanner, a model was created, and this was compared with the nominal model. The microstructure of the printed material was also analysed. However, the last two experiments mentioned above are no longer the subject of this article.

3.1 Visual inspection of component and samples

On the Fig. 3 are detailed parts of models that have been printed by SLM and ADAM technologies. The difference between the two technologies is noticeable mainly on the surface caused by a presence of the supports.

Each test sample has been printed in the same way as components by SLM and ADAM technologies. Using of SLM technology, there are two kinds of samples for printing orientation. The XY samples, which were printed lying down horizontally with the pad, were slightly bent.

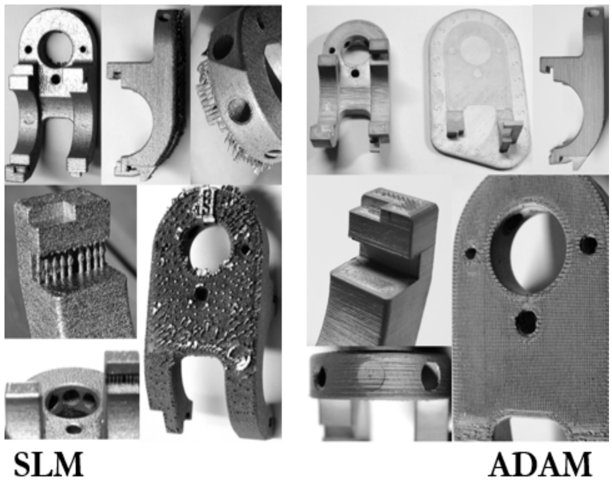

Fig. 3 *Component printed with SLM and ADAM technologies*

3.2 Control of internal dimensional and geometrical specifications

The inspection of internal dimensional and geometrical specifications on samples was measured optically by laser scanner and contact by digital micrometer. Based on the manufacturing drawing of the sample the dimesions have been measured. The measured dimensions are in Tab. 3, Tab. 4, Tab. 5 for each sample.

From the measured values of the sample, it was determined by the IT accuracy of SLM and ADAM technology, which can be seen in Fig. 4.

Tab. 3 *Sample XY (SLM)*

Nominal dimension [mm]	Measured value [mm]	Standard tolerance factor	IT range [μm]	Tolerance
3	3,633	0,652	-971	-0,633
5	5,121	0,774	-157	-0,121
14	14,131	1,099	-119	-0,131
20	20,158	1,241	-128	-0,158
20	20,124	1,241	-100	-0,124
60	60,07	1,822	-38	-0,070
100	99,878	2,189	56	0,122

Tab. 4 *Sample Z (SLM)*

Nominal dimension [mm]	Measured value [mm]	Standard tolerance factor	IT range [μm]	Tolerance
3	2,859	0,652	216	0,141
5	5,122	0,774	-158	-0,122
14	14,027	1,099	-25	-0,027
20	19,502	1,241	401	0,498
20	19,958	1,241	34	0,042
60	60,345	1,822	-189	-0,345
100	100,506	2,189	-231	-0,506

Tab. 5 *Sample P (ADAM)*

Nominal dimension [mm]	Measured value [mm]	Standard tolerance factor	IT range [μm]	Tolerance
3	2,846	0,652	236	0,154
5	5,074	0,774	-96	-0,074
14	14,128	1,099	-116	-0,128
20	20,076	1,241	-61	-0,076
20	20,061	1,241	-49	-0,061
60	59,952	1,822	27	0,048
100	100,116	2,189	-53	-0,116

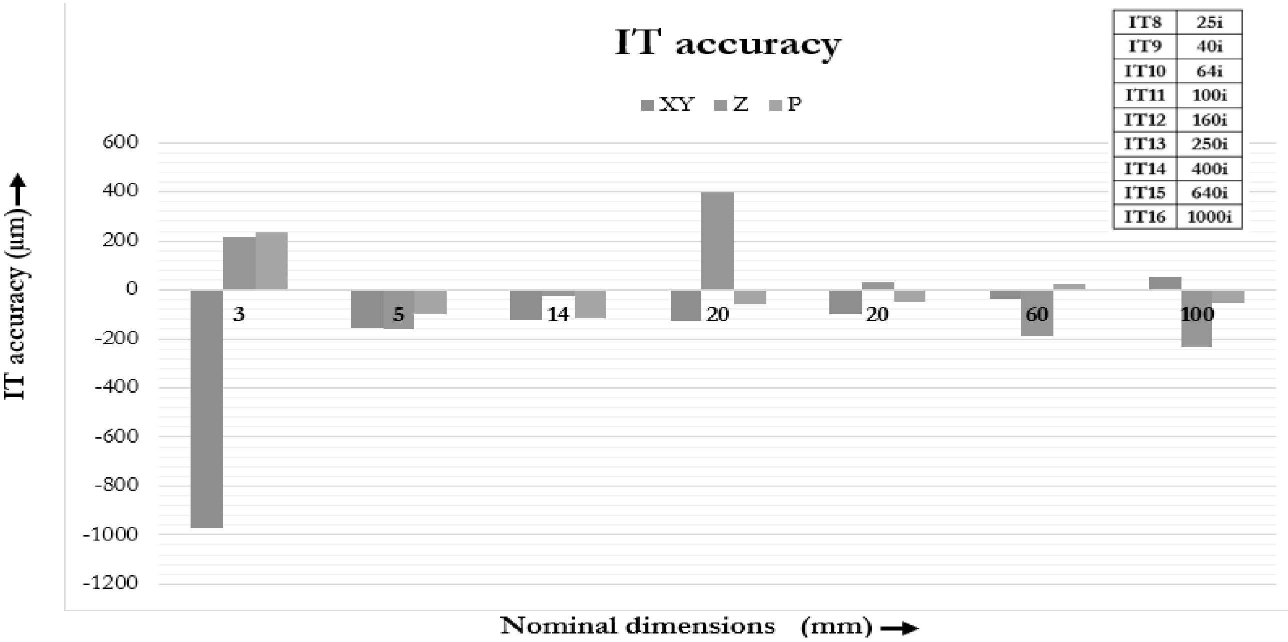

Fig. 4 *Graph of IT accuracy of samples XY, Z and P for individual nominal dimensions*

3.3 Scanned profile and surface roughness of samples

A profile and roughness scan of the surface was carried out on the Alicona InfiniteFocus measuring device.

The measurements of the profile and roughness were carried out on the surface of the samples XY, Z and P.

The measurement results are shown in Tab. 6.

Tab. 6 *Profile and roughness parameters of printed samples*

Profile and roughness parameters	XY (SLM)	Z (SLM)	P (ADAM)
P_a [μm]	157,839	9,171	7,739
P_q [μm]	187,156	11,710	10,345
P_z [μm]	333,283	71,158	58,365
R_a [μm]	14,799	7,482	6,072
R_q [μm]	19,309	9,629	8,207
R_z [μm]	118,353	64,062	49,758

3.4 Measurement of hardness on the surface of the component and test samples

The Leeb hardness test was performed on a portable TH-160 hardness tester. The measurement was carried out separately on the samples and on the models themselves. Using SLM technology, the samples XY and Z were produced. The samples XY were printed horizontally, horizontally with the bed, while samples Z were printed perpendicular to the bed. The hardness was evaluated in units of hardness HL (Leeb), which can optionally be converted to conventional hardness scales. The hardness tester was equipped with a type D sensor, with a measurement accuracy of ± 6HLD.

The hardness of the samples was measured at three locations (A, B, C), with three measurements took at each location and made into an arithmetic mean, Fig. 5. The hardness of the component was measured in only one location. The arithmetic mean was calculated from the five measurements. The results from hardness measurement are shown on Tab. 7 (Samples) and Tab. 8 (Part).

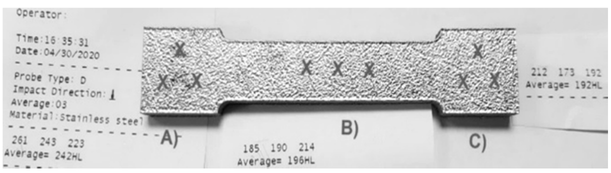

Fig. 5 *Sample XY, SLM technology*

Tab. 7 *Measurement of the hardness of samples by Leeb*

	Sample XY (SLM)	Sample Z (SLM)	Sample P (ADAM)
Place A	242 HL	230 HL	500 HL
Place B	196 HL	179 HL	266 HL
Place C	192 HL	173 HL	613 HL

Tab. 8 *Measurement of the hardness on the components*

	Part made by SLM	Part made by ADAM
Average value	297 HL	460 HL

3.5 The static tensile test on sintered samples

The static tensile test is one of the basic mechanical tests. In its principle, expediency and simplicity, it has become the most widespread test method for evaluating the mechanical properties of metal materials. The tensile test was carried out on the Zwick / Roell Z200 device at 20°C.

For XY (SLM) samples, a quarry occurred in the middle third of the length, Fig. 6. It is a classic quarry as after powder metallurgy. The sample was stretched by almost 20 mm and had good toughness and plasticity. The results of the tensile test from sample XY are shown on Tab. 9.

Tab. 9 *Result of tensile test of the sample XY (SLM)*

Sample	R_m [MPa]	R_{eH} [MPa]	A [%]	F_m [N]	A_t [%]
XY (SLM)	494,5	232,4	37,5	47771	38,6

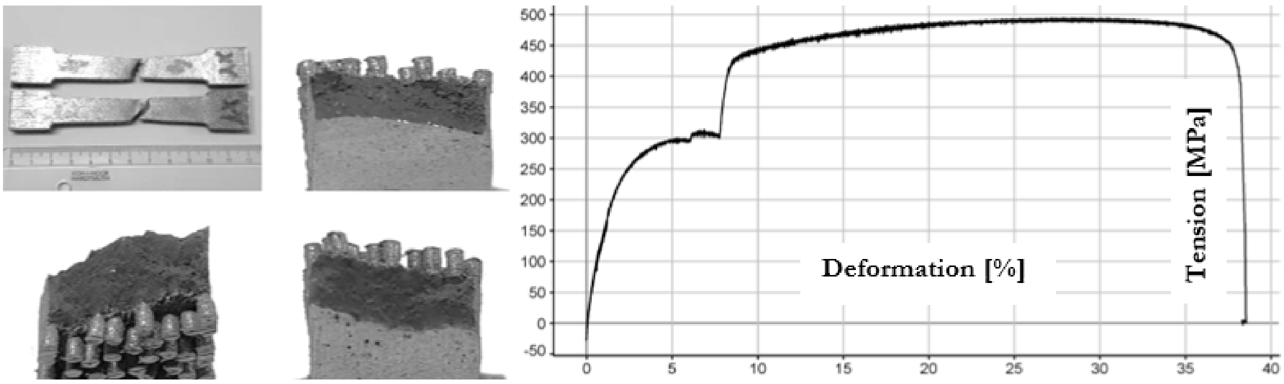

Fig. 6 *XY samples after static tensile test with working diagram*

For Z (SLM) samples, the quarry occurred equally in the middle third of the length, in the Fig. 7. It is a classic quarry as after powder metallurgy. The sample was stretched slightly more than the XY sample and had also good toughness and plasticity. The results of the tensile test from sample Z are shown on Tab. 10.

Tab. 10 *Result of tensile test of the sample Z (SLM)*

Sample	R_m [MPa]	R_{eH} [MPa]	A [%]	F_m [N]	A_t [%]
Z (SLM)	607,5	254,7	40,5	42525	41,4

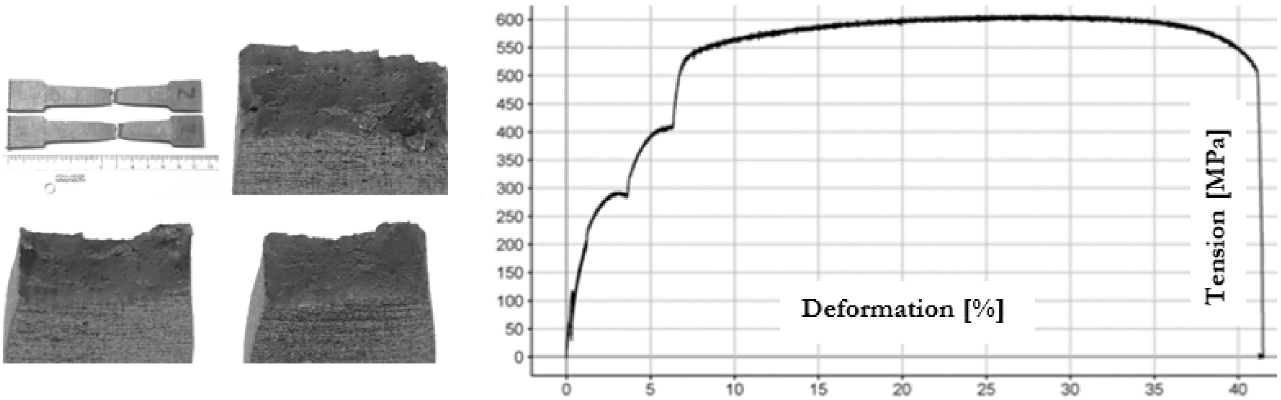

Fig. 7 *Z samples after static tensile test with working diagram*

For samples P (ADAM), the quarry occurred exactly at the location where the sample was mounted into the jaws, Fig. 8. The jaw grip degraded the wall of the reinforcement and thus the vault was damaged. A different sample shape or other clamping is required to perform a static tensile test. The results of the tensile test from sample P are shown on Tab. 11.

Tab. 11 *Result of tensile test of sample P (ADAM)*

Sample	R_m [MPa]	R_{eH} [MPa]	A [%]	F_m [N]	A_t [%]
P (ADAM)	327,6	191,5	3,9	22931	4,7

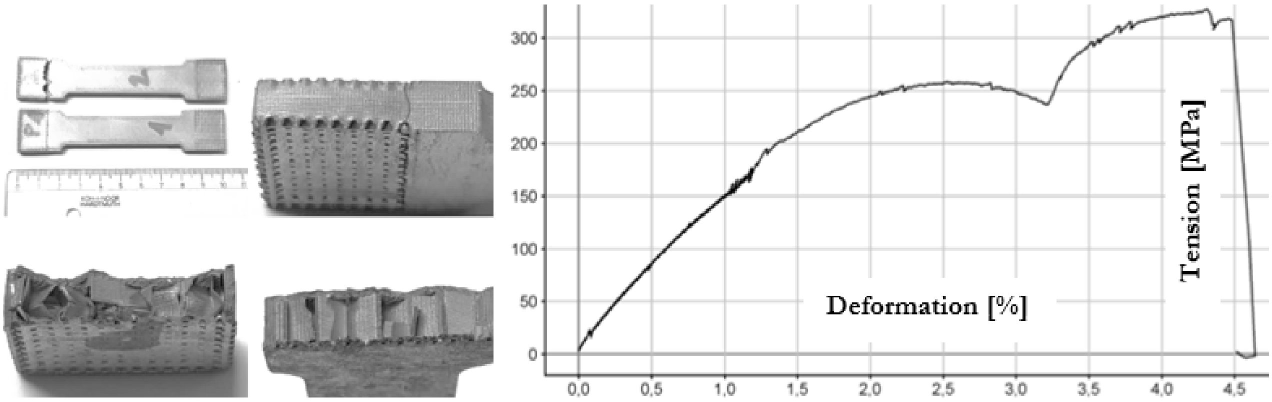

Fig. 8 *Samples P after static tensile test with working diagram*

3.6 Economic evaluation

Tab. 12 shows the material consumption for printing and the time cost of production. The samples in the
Z-axis from ADAM technology were not printed due to technological predispositions.

Tab. 13 compares the economic costs of printed samples by SLM and ADAM technologies. The cost of labour, materials and energy were included in the total price. The price of the device is not included in the total valued cost but is stated to give the reader an overview of the price of the device.

Tab. 12 *Measurement of the weight of applied material for construction and economical evaluation*

Weight of parts (g)		
Technology	SLM	ADAM
3D model	155,5	79,5
Support	-	48
Sample XY	79	32,5
Sample support XY	15	0
3pc. sample XY	227	100
Sample Z	66	not printed
Sample support Z	2	not printed
3pc. sample Z	199	not printed

Technology	SLM	ADAM
Layer thickness	0,05 mm	0,05 mm
Speed of construction	150 mm/s	120 mm/s
Total time of sample construction	8 h	9 h
Total component construction time	10 h	12 h
Minimum cleaning time	1 h	2 h
Sintering	0	9 h

Tab. 13 *SLM technology economy compared to ADAM technology*

Price appreciation (€)		
Technology	**SLM**	**ADAM**
Price of the device	650 000	200 000
Price per hour	45,14	13,89
Material price per component	17,81	11,36
Price of material per sample	27,01	11,63
Price of material	44,81	22,99
Energy	10,47	3,88
Labour cost of samples	361,11	125
Labour cost of components	451,39	166,67
Total price	**957,74**	**355,42**

4 Conclusion

The aim of the submitted research was to compare the two most perspective technologies of metal additive printing, namely SLM technology, which creates metal components through sintering of metal powders, and ADAM technology, which works on the basis of metal-plastic fibers. The second aim was to increase knowledge and awareness of ADAM technology, which represents a new and progressive layering process that has so far received little attention in literature. Based on the results obtained from individual experiments, it can be determined which of these technologies is more suitable, accurate and economical. The experiment compared the differences between dimensional errors of printed models from a real model and individual dimensional specifications of samples XY, Z and P. The measurements showed that ADAM technology is far more accurate than SLM technology. However, when the measurement the profile and roughness of the surface on individual samples was performed, the best ADAM technology was shown. The surface structure of the sample printed by SLM technology is almost 6 times more curved from the sample printed with ADAM technology. The comparison of duration of the measurement showed that SLM technology shows worse values in this regard as well. The hardness of samples printed by ADAM technology is two times higher. In conclusion, individual technologies were compared from an economic point of view. From an economic point of view, although there were three more samples have been printed by SLM technology, ADAM technology has come out almost 2 times cheaper. The print speed of SLM technology was slightly faster than ADAM technology – especially since SLM technology has not required sintering.

The results of experiments comparing components and samples printed by individual technologies showed that ADAM technology is more suitable in all ways for the production of metal components. This technology can produce complex metal components with excellent accuracy, hardness and structure at a reasonable price. The production process has already been so fine-tuned that the components compete with parts produced by traditional technologies, such as forming or casting. Additional space to improve the accuracy and roughness of the intered components can be seen in classic finishing operations. And so it is possible to anticipate further development of this technology in the field of microstructures of the interacted material.

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