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Surface Analysis and Digitization of Components Manufactured by SLM and ADAM Additive Technologies

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The presented article focuses on the analysis of the components manufactured by different additive technologies and their reverse digitization. Sintered components were manufactured by Selective Laser Melting (SLM) and Atomic Diffusion Additive Manufacturing (ADAM) technologies. ADAM can be classified as indirect additive production using fibre of metal powder bound in a plastic matrix. SLM method works on the basis of selective bonding of metal powder using the thermal energy of the laser beam. The components were manufactured from anti-corrosion materials 17-4 PH and 316L–0407. In the experiment, parameters such as dimensional and shape accuracy were verified using laser scanning. Next, the roughness of the printed surfaces was measured on an Alicona Infinite Focus 5G optical measuring device. The dimensional accuracy of the ADAM process was evaluated using ISO IT grades. The accuracy of ADAM technology achieves the IT13 grade that is comparable to that of traditional processes for the production of semi-finished metal parts.

Keywords: Additive manufacturing, Sintering, Optical scanning, 17-4 PH, 316L-0407, SLM, Surface texture

1 Introduction

Additive manufacturing is a progressive way of manufacturing components with guaranteed design freedom. Dr. Carl Deckard from the University of Texas developed the first laser sintering 3D printer for plastics [1] in the 1980s [2], which marks the beginning of additive manufacturing. As a result of this invention, the additive metal printing process was facilitated. In 1995, the first patent application for laser metal melting was filed in Germany. Many companies and universities have begun to research and develop this process. In 1991, Dr. Ely Sachs initially developed the additive printing method that is currently known as Binder Jetting. ExOne was the first company to get a licence to print metal using Binder Jetting technology in the year 1995. In the 2000s, there was a gradual but consistent increase in the use of additive metal printing. It is estimated that the market for metal printing is currently worth $720 million and is expanding quickly. Just in 2018, there was an eighty per cent rise in the number of metal printers sold [3]. The key areas for the use of metal additive printing are the aerospace and automotive industries, biomedicine, industrial tool manufacturing, and product development [4].

Additive manufacturing methods have in common that they rely on computer-aided design (CAD) to design the object. Subsequently, this virtual object is oriented in a way that enables its production by the selected method. The 3D model is divided into several 2D layers and then assembled layer by layer. Additive manufacturing technologies have the advantage of being able to produce objects with extreme geometric complexity and complex details in a relatively fast and simple way [5]. Therefore, among the main benefits, we may list low shape and design limitations of printed components, a wide range of materials that can be used, and often materials of high quality [6, 7]. In addition, printed components achieve an IT accuracy equivalent to the components manufactured by conventional methods.

Rapid Prototyping (RP) technologies are mostly used in the aerospace and automotive industries because they rely heavily on prototyping during the development phase. Currently, the emphasis is being placed on the mass production of customized products [8].

It is essential to carry out an initial cost analysis before deciding between conventional technologies and metal additive printing. In general, the costs are mainly related to the volume of production. The fundamental advantage of metal additive printing is the ability to create components with complex and optimized geometries. Therefore, sintering is suitable for the production of high performance components. On the other hand, CNC machining or metal casting technology are more worthwhile investments for the production of larger quantities [3].

Reverse engineering (RE) is a technological process by means of which it is possible to create a reverse CAD model of an existing product or the drawing documentation according to specific customer requirements. The goal is to analyze the system so that it is possible to create a model of the system in a different form or at a higher level of the procedure or to identify the components of the system and their interdependencies. RE includes all activities that determine the functional principle of the product or the technology that was originally used in the development of the product. In general, it helps to accelerate innovation or development time. Thus, it is feasible to incorporate positive properties and good ideas into the next generation of products and avoid any potential risks. RE is widespread in the computer, electronics, chemical, and automotive industries. Additionally, it is utilized in the fields of software and mechanical engineering. In most cases, reverse engineering is economically beneficial only if the developed products guarantee a high return on investment or if there is a high probability of using the given technologies for reverse engineering. If the particular product is completely essential to the operation of the system, then this rule may have an exception. Digitizing objects is the main activity in the process of reverse engineering for engineering production. This process is possible due to scanning devices, known as 3D scanners, which enable the conversion of real three-dimensional objects into the digital form [9], [10].

2 Methodology and Experiment Design

The main task of the experiment was to digitize and compare the surface quality of two additive metal printing methods. The first manufacturing method was SLM. The second method used was ADAM. With SLM technology, two components were printed due to print orientation.

Component (P) was printed in only one direction using ADAM technology. The component (XY) was printed supine, horizontally to the print bed, and the component (Z) was printed perpendicular to the print bed.

Samples were printed from 316L-0407 (SLM) on a Renishaw AM500M and from 17-4 PH (ADAM) on a Markforged Metal X. The second goal of the experiment was to test the viability of Reverse Engineering on the printed components, as the additively manufactured components were quite lustrous, which can cause a problem during the optical scanning of the components.

2.1 The design of the structural component of the samples

To meet the requirements of the experiment, the component model was designed with more complex shapes to compare these two additive printing technologies appropriately. As a result, we can determine which technology coped better with printing. The component contains six threads, each with a different size and pitch. Figure 1 displays the model of the component created in the PTC Creo program.

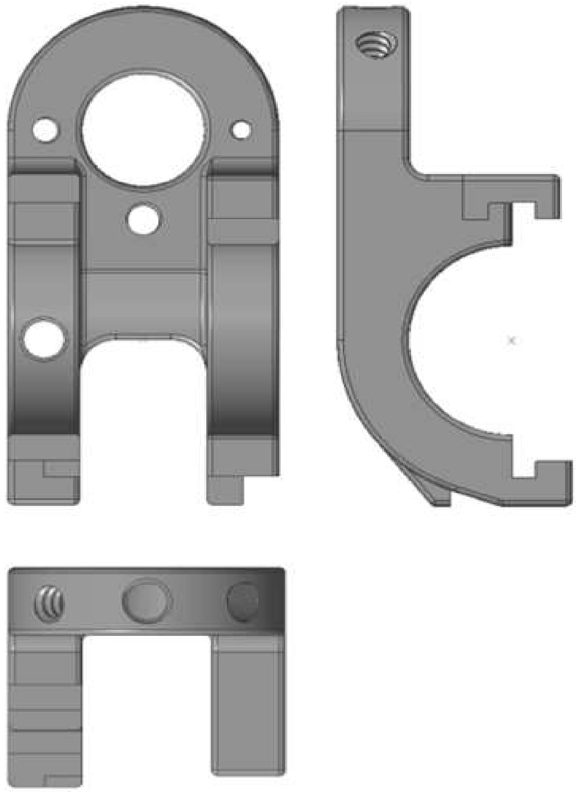

Fig. 1 *CAD model of the component and the sample*

2.2 SLM Technology

Selective Laser Melting is a technology based on the sintering of metal powders. The printed components are almost completely dense. With this technology, no binders are required, furthermore, the mechanical properties and accuracy are better compared to SLS [11], [12]. The melting process occurs within a highly controlled atmosphere. Prior to the beginning of the process, the build box is deprived of moisture and air, and the space is almost 100% vacuum. Then the chamber is filled with an inert gas such as argon or nitrogen. After preparing and calibrating the print bed for 3D printing, metal powder is released from the reservoir onto the print bed, where a silicone strip spreads it evenly. This layer of metal powder is sintered with a high-power laser beam. After the fusion is completed, the print bed is lowered by one layer and another layer of powder is applied. After the sintering process is complete, we obtain a three-dimensional component that was manufactured layer by layer. The thickness of the layer varies between 20-100 μm depending on the powder material used. The heat source for melting the powder is a high-power laser, or an electron beam, which melts the applied powder evenly on the print bed [12].

Once the part is finished, it can be removed from the machine (using a band saw). Subsequently, the supporting structures are removed. Since the support material is identical to the material used to print the component, removing the supports can be difficult and time-consuming. The surface remains rough after melting, which requires additional machining.

2.2.1 Renishaw AM500M (SLM)

The Renishaw AM500M device works based on the selective bonding of metal powder using thermal energy (PBF) in a stable controlled atmosphere. The laser device is equipped with automated powder and waste manipulation systems that enable consistent process quality. Powder sifting recycling processes are performed automatically within the compact system, reducing the need for manipulation with the material. The intelligent control system actively senses the condition of the filter and automatically redirects the gas circuit to a clean filter before process conditions deteriorate. The device can process a wide range of metal materials such as stainless or tool steels or superalloys [13], [14]. The finished component is shown in Figure 2.

2.2.2 Material 316L – 0407

It is a material with high hardness and toughness from austenitic stainless steel which comprises iron alloyed with chromium of mass fraction up to 18%, nickel up to 14%, and molybdenum up to 3%, along with other minor elements. Due to its low carbon content, this alloy is resistant to sensitization (carbide precipitation at grain boundaries) At the same time, it is an extra-low carbon variation on the standard 316L alloy. Furthermore, this material displays good welding characteristics, and it is machinable. It also has good tensile strength at high temperatures. From a design perspective, the material can be highly polished [15]. The chemical composition of the material is shown in Table 1.

Tab. 1 *The chemical composition of the material 316L-0407 (mass fraction %) [15].*

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

2.3 ADAM Technology

The component is printed from metal powder with a temporary thermoplastic binder. It is a filament of metal powder encased in a plastic fiber. The component is printed in layers in the shape of the future print. The model is adequately enlarged to compensate for its shrinkage during the sintering process. The printed part, which comprised the binder and metal materials, was named the “green part”. This part needs to be washed in a special solution that removes the binder and leaves the print with certain residual porosity. This allows the rest of the plastic carrier to be burned in the next step. Burning ensures the purity of the final metal model and keeps the sintering furnace clean. The strengthening of the component is carried out by sintering in a furnace at a high temperature and in an inert atmosphere. In this stage, the cleaned print is transformed into a solid, all-metal component with the required dimensions. As with other 3D printing methods, it is possible to do post-machining if necessary (grinding, sandblasting, etc.) ADAM technology allows the creation of metal parts relatively quickly and precisely and allows the creation of enclosed structures without an escape hole for powder. ADAM technology is up to five to ten times less expensive than alternative metal printing processes, as well as significantly cheaper than traditional machining or casting methods [16].

2.3.1 Markforged Metal X (ADAM)

Markforged Metal X consists of three parts, Metal X printer, washing station, and sintering furnace. The quality of printed components is mainly influenced by the printing accuracy, the composition of the input material, the temperature of the sintering process, and the sintering atmosphere in the furnace. This device (technology) has significantly lower maintenance and operating costs than all other types of 3D metal printers. It requires minimum updating and neither a powder management system nor a professional employee. Markforged Metal X is approximately 5 to 10 times more affordable than other systems. Furthermore, it can process a wide range of materials such as stainless steel, tool steel, or aluminium alloys [17]. The finished component is shown in Figure 2.

2.3.2 Material 17-4 PH

It is a stainless steel powder hardened by the precipitation of chromium and copper. Type 17-4 PH is a martensitic precipitation hardening stainless steel that provides an excellent combination of high strength-to-weight ratio. This alloy has moderate corrosion resistance and good mechanical properties at temperatures up to 316 °C. Different heat treatment temperatures can optimize mechanical properties. It is also possible to reach high yield strength at 1100 – 1300MPa [17]. The chemical composition of the material is shown in Table 2.

Tab. 2 *The chemical composition of the material 17-4 PH (mass fraction %) [18].*

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

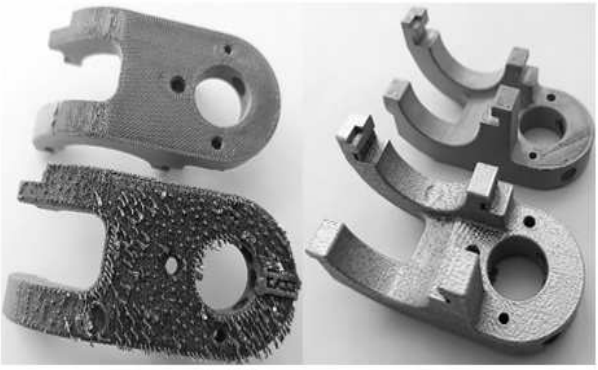

Fig. 2 *Finished additively manufactured components. In the picture, the component placed above was created by ADAM technology, and the component placed below was created by SLM technology*

3 Results of the experiment

The topography of the surfaces of additively manufactured samples was evaluated at the Department of Machining and Production Technology, on the optical measuring device Alicona Infinite Focus 5G. This non-contact measuring device is used to check surfaces at the micro and nano levels with a resolution of up to 10 nm. It is possible to evaluate curved surface roughness, and at the same time, we can monitor and evaluate surface defects and the character of surfaces [19].

The Focus variation method is utilized by the device that performs the evaluation. With the use of focusing, the operating concept combines a shallow depth with vertical scanning to gain topographical information. The surface is illuminated by white coaxial LED light.

The operation of a calibrated microscope is fundamentally based on the focus variation method. The basis of the system is an optical microscope that employs a white light source to illuminate the sample being studied. The light from the sample is reflected into the lens of the objective and the CCD sensor analyses the light captured by the lens. To capture a large amount of data, it is necessary to move the device along the vertical axis. Due to the shallow depth of focus, each region must be focused on a vertical position. Subsequently, the algorithms convert the gained data into 3D information and images in real colour [19].

The measurement occurs directly within the optical image. With the use of focusing, the operating concept combines shallow depth with vertical scanning to gain topographical information. The surface is illuminated by white coaxial LED light. With the device, it is possible to measure surface defects and the character of the surface.

The surface structures of the samples, which were manufactured by SLM and ADAM additive technologies, were evaluated at a 100-fold magnification. When evaluating the roughness parameters, the limiting wavelength of the filter λc= 0.8 mm was chosen. Figure 3 depicts the structure of surfaces manufactured by SLM technology (XY and Z samples). For these samples, the orientation of the print was changed. Figure 4 illustrates the surface structure manufactured by ADAM technology (sample P). The two photos are present because one measurement was taken from above and the other was taken from the side of the component (individual layers).

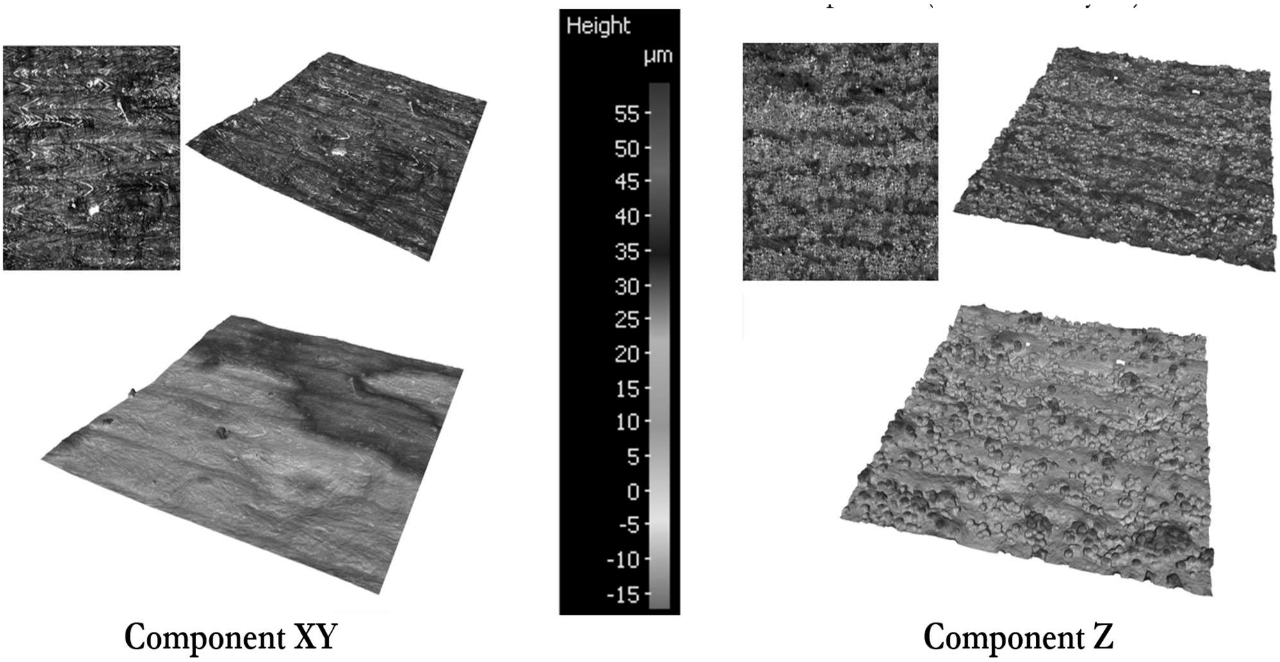

Fig. 3 *Surface topography of samples manufactured by SLM technology*

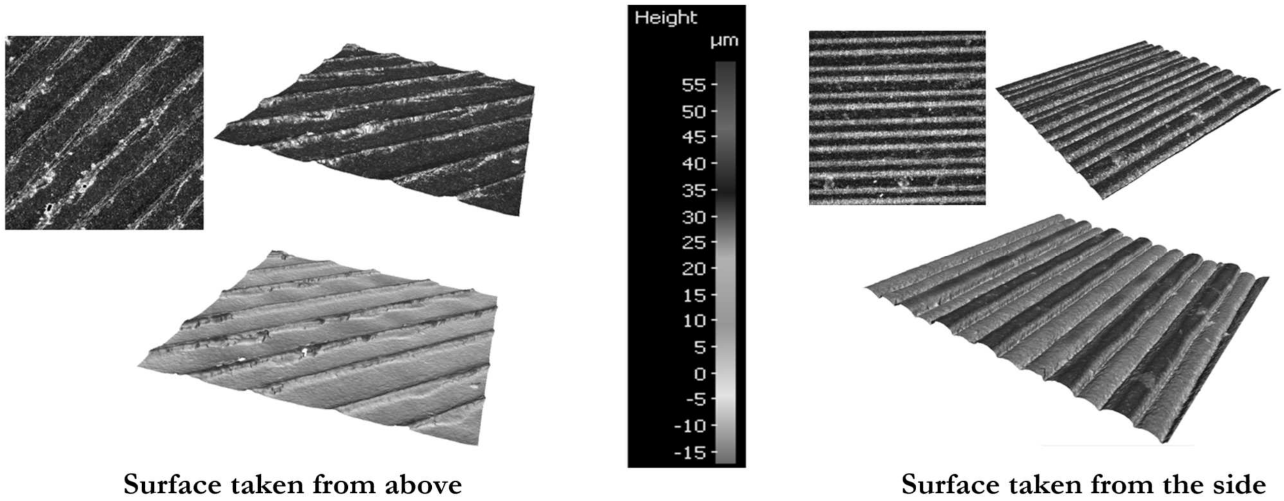

Fig. 4 *Surface topography of samples manufactured by ADAM technology – Component P*

Figure 5 depicts a graphical evaluation of surface roughness that was evaluated using the implementation of the ISO 25178 or ISO 12781 standards. Surface roughness parameters such as Sa, Sz, Sv, etc. were evaluated.

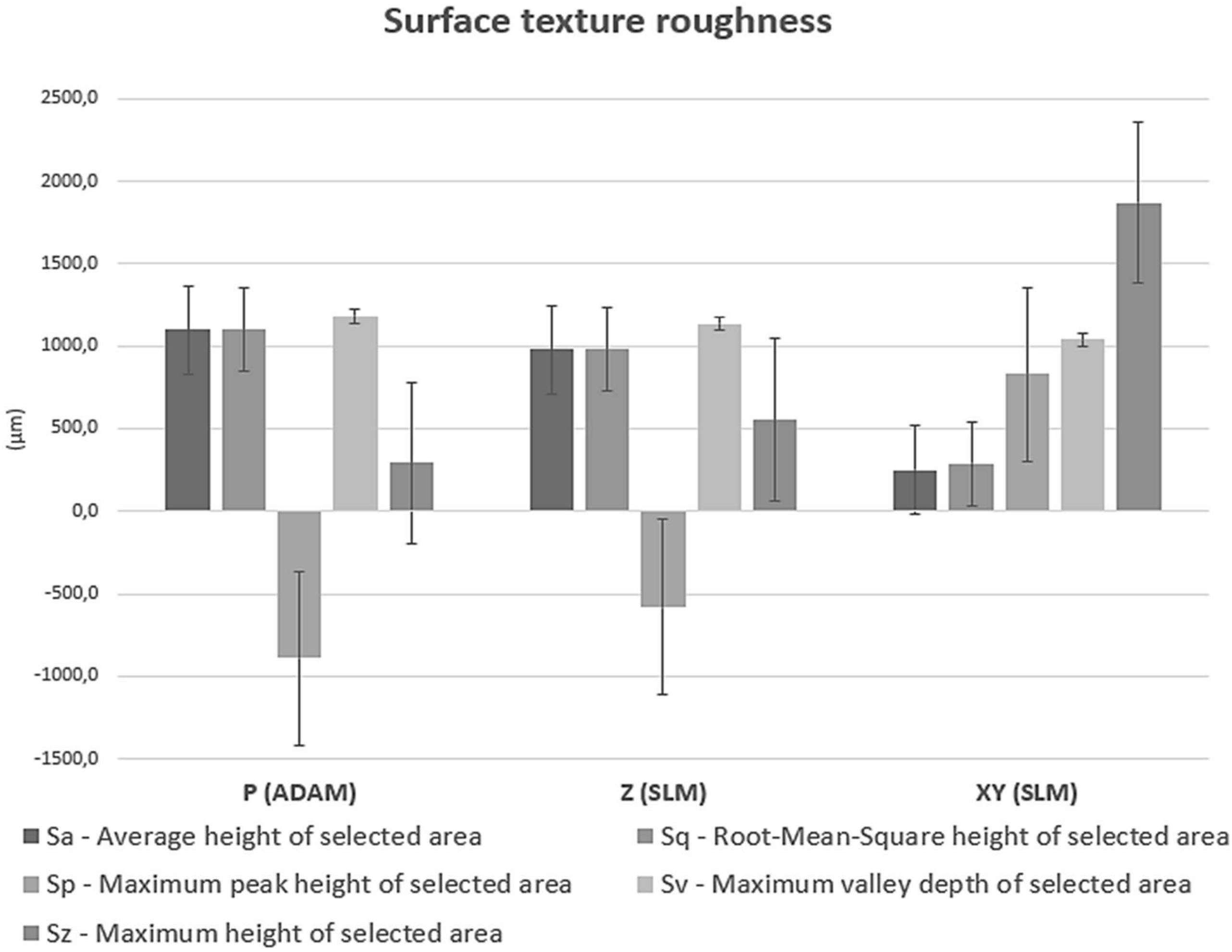

Fig. 5 *Surface texture roughness of samples P, Z and XY*

3.1 Analysis of reverse engineering possibilities for additively manufactured components

The main purpose of an optical scanner is to create a 3D model that is derived from the point clouds of geometric patterns. These points can be used to reconstruct the shape of the subject. A significant limitation of the scanners is that they are only able to acquire data from surfaces that are visible to the lens.

In contrast to conventional cameras, which obtain colour information about surfaces inside their range of view, 3D scanners obtain distance information. The distance on the surface at each point describes the image that is created by the three-dimensional scanner. For a complete model of an object, a single scan is insufficient; consequently, numerous scans are performed in different directions to gather data about all surfaces of the object. Structured light 3D scanners create a pattern of light on an object and track the deformation of the object. The pattern can be unidirectional or bidirectional [9]. A straight line projected onto an object by use of an Aquilon laser scanner is an example of a unidirectional pattern (Figure 6).

3.1.1 Aquilon 3D laser scanner

The 3D optical laser scanner Aquilon is among the most powerful scanners manufactured by Kreon. This scanner is designed for applications that require high measurement accuracy and high density of scanned data. Due to the existence of two built-in cameras, it is also feasible to quickly scan the surface of complex shapes. Some parameters of the optical scanner [20]:

- Accuracy ±5 μm,
- Beam resolution – 25 μm
- Laser beam width – 50 mm,
- Shutter speed–1 million points per second,
- Scanning distance – 60 mm.

Scanning of the surfaces of individual components took place at the University of Žilina. Using the scanner, point clouds were generated in Figure 7, which were then used to create a model of the real component. The real model was compared to the optimal CAD model in Figure 8 and 9 for both additive technologies.

Fig. 6 *Aquilon optical laser scanner on an ACE 7-axis measuring arm and the example of scanning the component*

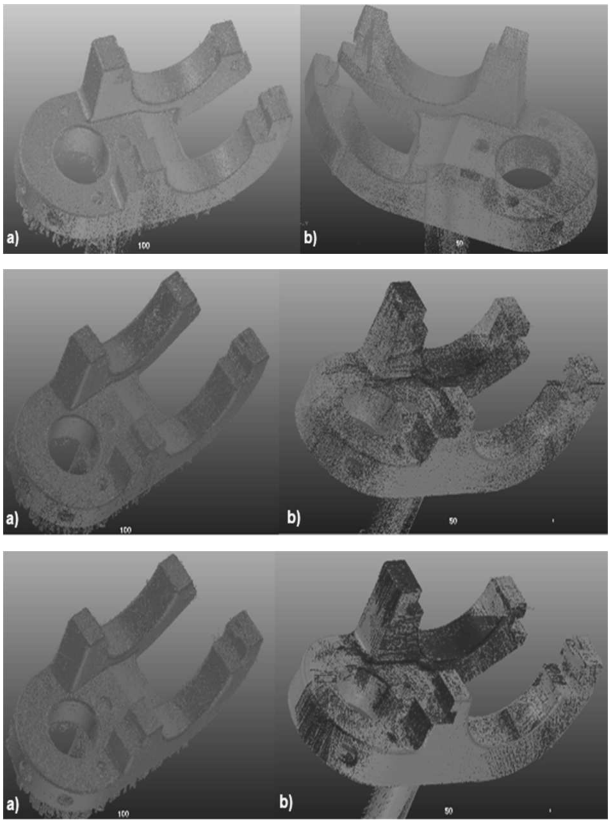

Fig. 7 *The process of performing a first, second, and third scan (top-down) of the component to generate point clouds, from which a model of the component is subsequently created. In the third scanning process, bundle adjustment on the cloud of points was also used. Component a) manufactured by SLM technology (distinguishable building supports) and b) by ADAM technology*

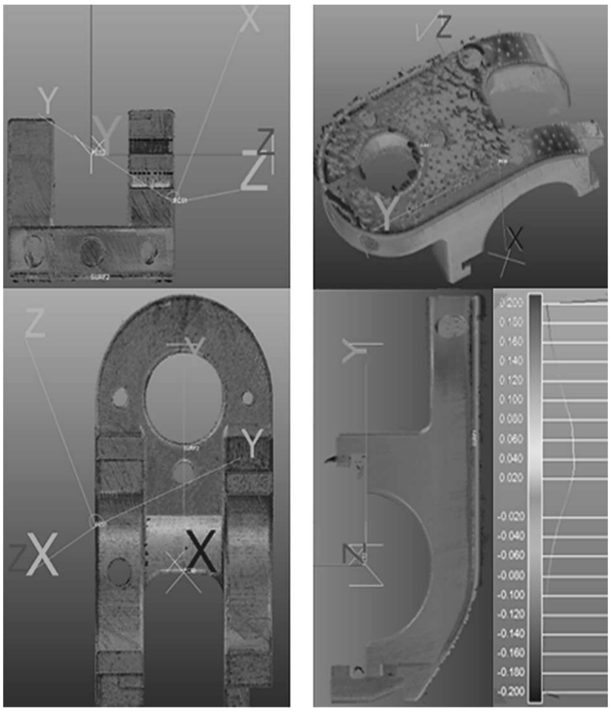

Fig. 8 *Comparison of the real model with the nominal model. The component was printed using SLM technology*

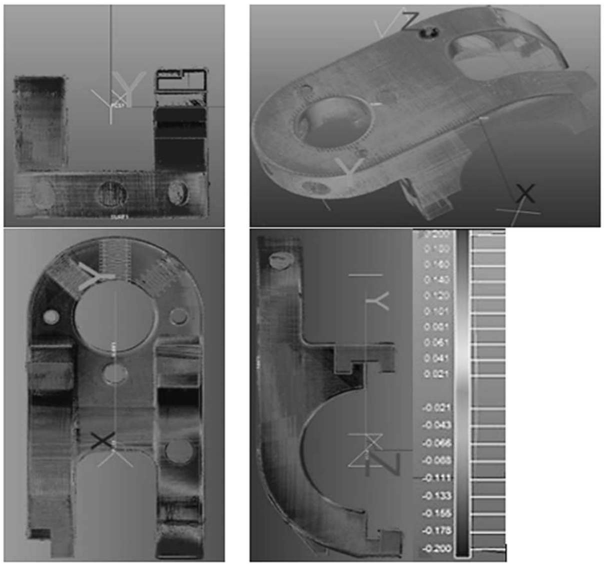

Fig. 9 *Comparison of the real model with the nominal model. The component was printed using ADAM technology*

4 Conclusion

The presented research aimed to compare two prospective technologies of metal additive printing, namely SLM and ADAM technology. The SLM technology produces metal components via sintered metal powders. The ADAM technology is based on metal-plastic fibres. Based on the results of the research, it was decided which of these technologies is more appropriate, accurate, and cost-effective.

- In terms of analysing surface roughness, ADAM technology proved superior. The surface structure of the sample printed by SLM technology is almost six times more curved than the sample printed by ADAM technology.
- The surface roughness of the samples is not so significant, the best surface was achieved by sample P (ADAM).
- The print speed with SLM technology is faster than ADAM technology (approx. 34% less production time) - mainly because SLM technology does not require sintering.
- Scanning the components with a laser scanner has shown that even sintered parts have potential in reverse engineering. However, it is necessary to note that the scanning of sintered components is accompanied by certain ailments. Optical methods of verification often have a problem, especially with shiny (metal) surfaces. Therefore, it is recommended to use darkening sprays, which also roughen the surface structure. Such sprays include special chalk sprays (which must be washed off), or disappearing ones based on titanium dioxide ($TiO2$).
- Scanning real components and comparing their models with the nominal model served to evaluate the IT grade of accuracy. For component P, the level of accuracy was grade IT 13, for component Z it was grade IT 14, and for component XY to grade IT 15.
- In terms of dimensional parameters, deviations of up to 0.154 mm were achieved by printing the P (ADAM) sample. For the Z(SLM) component, the maximum dimensional deviation was -0.506 mm. For sample XY (SLM), the maximum dimensional deviation was up to -0.633 mm.
- From economic point of view ADAM technology shows a better outcome. Because the product costs was almost two times cheaper than SLM technology.

The mentioned results of experiments comparing components produced by individual additive technologies shows the advantage of ADAM technology. This technology is capable of producing complex components with high accuracy, hardness, and structure at a competitive price. The production process has already been so developed that the accuracy of the components is comparable to those produced by conventional technologies.

Furthermore, it is possible to further increase the attained dimensional accuracy and surface roughness of sintered surfaces using conventional post-additive-production machining methods.

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