THE POSSIBILITIES OF STUDYING THE LIFETIME OF ADDITIVELY MANUFACTURED SHAPED MOLD PARTS

[1,2]Martin PINTA, [1]Ladislav SOCHA, [1]Karel GRYC, [1]Jana SVIŽELOVÁ, [1]Adnan MOHAMED, [3]Martin DVOŘÁK, [3]Miloslav ROH

[1]Institute of Technology and Business in České Budějovice, České Budějovice, Czech Republic, EU, pinta@vste.cz, socha@vste.cz, gryc@vste.cz, svizelova@vste.cz, mohamed@vste.cz

[2]University of West Bohemia, Pilsen, Czech Republic, EU, mpinta@kmm.zcu.cz

[3]MOTOR JIKOV Fostron (Tools) a.s., Tool Shop Division, České Budějovice, Czech Republic, EU, martindvorak@fostron.cz; milroh@fostron.cz

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Abstract

This article aims to obtain new and unique knowledge in the field of additively manufactured shaped mold parts within their operational application in high-pressure casting of aluminum alloy castings. Part of the work is the mapping of the service life of conventional and additively produced shapes parts of molds. The evaluation of operational experiments was focused on mapping the life cycle with the help of 3D measurements and contactless scanning. Within the text, attention is also paid to the implementation of a multidisciplinary approach related to quality control, material, and metallographic analysis to verify the application possibilities of additively manufactured shaped parts of molds in the operating conditions of a die-casting foundry.

Keywords: 3D scanning, 3D CNC CMM, additive printing, dimensional and shape analysis, material and metallographic analysis

1. INTRODUCTION

Shaped parts of molds for high-pressure aluminum casting can be manufactured by 3D printing. Materials with high thermal conductivity and resistance to high temperatures, such as tool steels, are most commonly used to produce shaped mold parts [1]. Heat treatment of additively manufactured steel is a vital part of the whole manufacturing process [2]. When manufacturing shaped mold parts for high-pressure die casting of aluminum using 3D printing, it is important to ensure sufficient accuracy and surface quality to achieve the required dimensions and quality of the castings. Components that are produced using additive manufacturing exhibit heterogeneous properties [3]. Additive manufacturing is a technology that enables the production of fully functional and geometrically complex parts [4]. Commonly used additive 3D printing technologies for mold manufacturing include selective laser sintering (SLS), electron beam melting (EBM), and selective laser melting (SLM) [5]. Each of these technologies has advantages and disadvantages and the choice of a particular technology depends on the desired properties of the mold parts as well as the material used [6]. The advantage of using 3D printing to manufacture molds for high-pressure aluminum die casting is the manufacturing speed and flexibility. Thanks to 3D printing, even complex geometric shapes such as comfort cooling channels, which would otherwise be difficult to achieve with traditional production methods, can be manufactured very quickly and easily [7,8]. Another advantage of 3D printing is the possibility of producing small batches of components that form a working tool in high-pressure aluminum casting. In contrast, high-pressure casting is usually only cost-effective when manufacturing large batches of castings [9]. The use of 3D printing can reduce the cost of manufacturing molds for small and medium batches while increasing the speed of product delivery. The disadvantage of 3D printing is the limitation of the size of the product that can be manufactured. In addition, the materials used for 3D printing are often more expensive than the conventional manufacturing materials used for mold production [10,11]. Therefore, the costs and benefits need to be considered when choosing this technology for the production of molds for high-pressure die casting of aluminum. In any case, 3D printing offers an interesting alternative to traditional methods of producing molds with complex geometries, and if the technology and material are chosen correctly, it can be a very successful and efficient production method for high-pressure aluminum die casting [12,13]. In terms of operational testing, it is important to monitor the internal structure, mechanical properties and wear history of additively printed components [14]. Compared to conventionally produced and heat-treated H13 tool steel, the values of additively manufactured H13 are comparable or better [15]. Tool steels that are additively manufactured need to be further heat treated as high residual stresses in the component can be problematic [16]. Mechanical properties should be analyzed for any effects on properties and shape, due to the orientation of the model and the different layering of the material [4,17].

The aim of this paper is to propose a methodology for monitoring the quality and lifetime of shaped mold parts for high-pressure die casting of aluminum castings. The proposed methodologies were used to carry out inspections during the manufacturing of mold components and it was also planned to carry out inspections after 20,000 cycles in the operating conditions of the foundry. The methodologies developed can be used to map the lifetime of the shaped mold parts and prevent any possible low-quality production of castings. The development of the methodology was carried out in cooperation with the die casting division of MOTOR JIKOV Slévárna a.s. The delivered components were continuously analyzed according to operational possibilities. The development of methodologies for the evaluation of the lifetime of the shaped mold parts will be presented on one piece of the A component, which was manufactured by additive technology from H13 material.

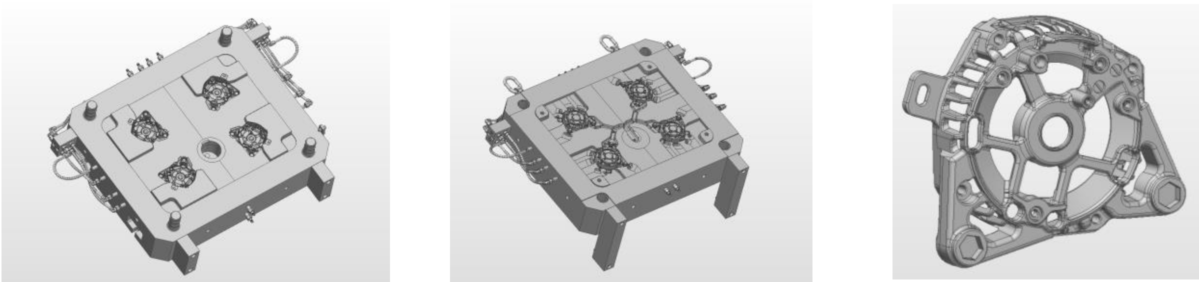
2. EXPERIMENTAL PROCEDURE

In terms of the possibilities of studying the lifetime of additively manufactured shaped mold parts, the focus was on the A component of H13 material, which is designed for the automotive industry. This component has a working surface on the so-called crown that comes in direct contact with the liquid aluminum alloy. Within the research, analyses were carried out on a total of four components that are manufactured by the additive SLM technology. Due to the large amount of data, only the A component is presented within this paper. **Figures 1a,b,c,d** shows the A component in the form of a 3D CAD model from printing to the final real component which is ready to be tested in the operating conditions of the foundry.

a) component after printing *b) component after machining* *c) final component for testing in manufacturing* *d) detail of crown representing the working part*

Figure 1 Shaped mold part – A component

The mold for the additively printed shaped parts is shown in **Figure 2a,b**. This mold is a quadruple mold consisting of a frame made of tool steel 1.2312, while the shaped inserts in contact with the aluminum alloy are made of Thermodur 2367 EFS Superclean, which is hardened and tempered to 46+2HRC. The mold is designed for casting four automotive castings. **Figure 2c** shows the resulting casting intended for the automotive industry.



a) mold assembly - fixed *b) mold assembly – movable* *c) resulting casting*

Figure 2 Example of mold for aluminum die casting and casting for automotive industry

In the study of additively manufactured mold parts, the aim was to map the lifetime of these parts under operating conditions. Therefore, continuous dimensional measurement of the accuracy of the A component was proposed. The component mapping was planned after 20,000 cycles, but currently, the mapping has been carried out according to the operational capabilities of the foundry. Specifically, the measurement methods include measurement on a 3D laser scanner on a ROMER ABSOLUTE ARM 7525SI arm, measurement on a THOME PRÄZISION GmbH coordinate measuring machine, and surface roughness measurement on a MITUTOYO SURFTEST SJ – 410 device.

2.1 Measurements on a 3D laser scanner

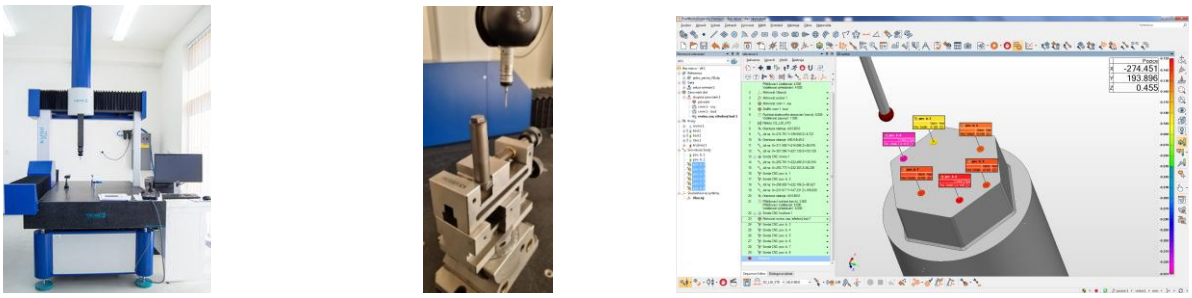
In terms of measurements on the 3D laser scanner, geometric deviations were detected. In **Figure 3a**, the scanning arm that was used for the measurement of the A component can be seen. Furthermore, **Figures 3b,c** shows the measurement method, the clamping of the component, and the evaluation of the data. The reason for the use of this instrument is due to the principle of the ROMER ABSOLUT ARM scanner, which consists of a combination of touch measurement and optical scanning. The scanner is equipped with a touch probe that allows the user to measure geometric properties of physical objects such as dimensions, shape, distances, etc. The probe is attached to an arm that can be easily moved in different directions, allowing the operator to measure objects from different angles and positions. In addition to the touch probe, the scanner is also equipped with an optical sensor that allows the surface of objects to be scanned using a laser beam. This laser beam quickly and accurately scans the surface of objects and furthermore generates a number of points that are used to create a polygonal model of the object. The 3D measuring laser scanner is suitable for measuring complex shapes and quick verification of dimensions during production, where the accuracy of the device reaches 50 µm.

a) ROMER ABSOLUTE ARM 7525SI *b) component clamping* *c) measured data evaluation*

Figure 3 Example of measurement on the ROMER ABSOLUTE ARM 7525SI 3D laser scanner

2.2 Measurement on the coordinate measuring machine THOME PRÄZISION GmbH

The second device used to study dimensional accuracy is the measurement on the coordinate measuring machine THOME PRÄZISION GmbH. **Figure 4a** shows the machine for illustration. This equipment enables precise measurement of the geometrical characteristics of objects. **Figure 4b**, c shows the measurement method, component mounting, and data evaluation. The coordinate machine consists of a movable arm and a work plate on which the measured A component is clamped by means of a vice. The arm of the machine is equipped with movable axes enabling the arm to move in different directions. The arm moves by means of motors and guide rods, allowing the user to measure objects from different angles and positions. A touch probe is used for the measurement, placed at the end of the arm and touching the surface of the object. The probe has several different types of tips and can measure different characteristics of the object such as length, width, height, radius, angle, and more. The probe records the measured values and transmits them to a computer for evaluation. The THOME PRÄZISION GmbH coordinate machine is ideal for precise and repeated component measurements. The accuracy of this measurement method is 5 μm and the uncertainty is 2.2+(L/350) 2.5 microns.



a) coordinate measuring machine *b) component clamping* *c) measured data evaluation*

Figure 4 Example of measurement on the THOME PRÄZISION GmbH coordinate measuring machine

2.3 Surface roughness measurement on the MITUTOYOU SURFTEST SJ – 410 device

The third device used is intended to check the surface roughness of the A component. **Figure 5a** shows the MITUTOYO SURFTEST SJ - 410 roughness tester for illustration. **Figure 5b**, c shows the clamping of the component and the evaluation of the measured data in the form of a diagram. Due to the direct contact with the molten alloy, the surface quality is reduced. Subsequently, small metal particles get into the shaped mold parts and dimensional deviations occur, which can be detected by previous measurement methods. The roughness measurement aims to detect geometric surface roughness deviations from the ideal shape.

a) Mitutoyo roughness gauge *b) component clamping* *c) measured data evaluation*

Figure 5 Example of roughness measurement on the MITUTOYO SURFTEST SJ – 410 device

3. RESULTS AND DISCUSSION

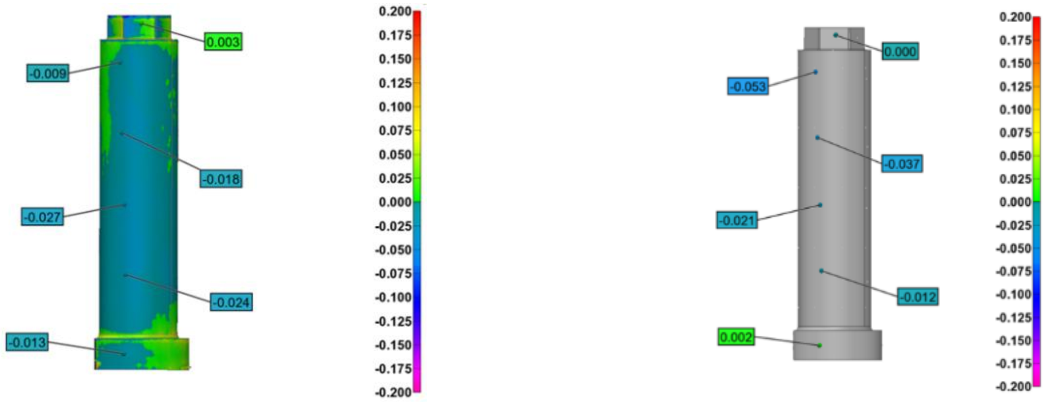
The mapping of the lifetime of the A component was carried out after individual technological operations of production and subsequent continuous measurement according to the capabilities of operating conditions.

These operations are shown in **Figure 6** and are accompanied by images. In the measurements on a 3D laser scanner, a CNC CMM coordinate measuring machine, and a roughness gauge, one component labeled A was selected for this paper out of a total of four pieces monitored. The dimensional accuracy mapping of the shaped mold parts was scheduled after 20,000 cycles, while in reality the mapping was performed according to the operational capabilities.

Additive printing	Heat treatment	Machining	Coating	Operation of 11,500 cycles	Operation of 52, 000 cycles	Operation of 61,000 cycles after repair	Operation of 77,000 cycles
							

Figure 6 Illustration of the individual technological manufacturing operations and the measurement process under manufacturing conditions

Figure 7a, b shows the fixed measurement points on the 3D laser scanner and CNC CMM, where the measurements are taken after each operation or after a certain number of cycles according to the operating capabilities of the foundry. Both methodologies have their advantages and disadvantages, and it depends on the specific application and the needs of the user which approach is more suitable for their situation. Figure 7a, b shows that the scanning and measurement on the CNC CMM are in accordance with the requirements.

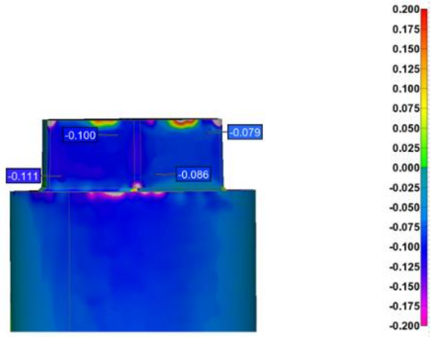


a) measurement on a 3D laser scanner *b) measurement on CNC CMM*

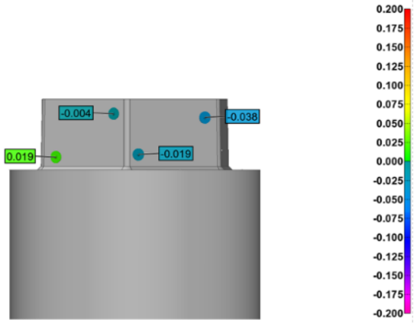
Figure 7 Comparison of body measurements -> scanner and CNC CMM measurements

The disadvantages of measuring the A component with a laser scanner include the lower accuracy of the measurement and the impossibility of repeatability of the measurement with the same result. The advantage of the measurement is the creation of an area map called a point cloud, which creates a color map. From the data obtained from the measurements on the 3D measuring laser scanner, it can be seen that additive technology -> 3D printing achieves lower accuracy, so it is necessary to further modify the components, such as heat treatment, machining, and coating. The advantage of a coordinate machine is the high measurement accuracy and the possibility of repeatability of measurements. The disadvantage is the measurement of only single points without a color map.

In **Figure 8** a, b the measurement of the so-called crown can be seen, with the component within the tolerance according to ISO 1101. [18] The use of a scanner provides us with the advantage of creating a color area map that shows the trend of the component movement and its deviations. In contrast, when using a CNC CMM, only comparative planar points are created, which only show us the deviation on the component, but do not show the exact trend.



a) points on crown measured by laser scanner



b) points on crown measured by CNC CMM

Figure 8 Comparison of measurements on the working part, the so-called crown -> by scanner and CNC CMM

For the surface roughness measurement, the A component was measured at predetermined points that are fixed. From the values measured on the body and the crown, the average value of the two parts was then calculated after each operation. In **Table 1** and **Table 2** it can be seen that for the application it is necessary to perform the operations after 3D printing and the values do not change substantially during the actual application. It is necessary to continue this production mapping, since a failure may occur in operation, which will be reflected in the surface roughness of the component.

Table 1 Measurement of surface roughness before application in operation (μm)

Position	3D printing			Heat treatment			After machining			After coating		
	Ra	Rq	Rz	Ra	Rq	Rz	Ra	Rq	Rz	Ra	Rq	Rz
ø body	5.729	7.247	37.947	5.015	6.224	26.426	0.351	0.450	3.483	0.362	0.471	3.264
ø crown	4.455	5.567	24.171	5.474	6.913	29.725	0.460	0.594	2.832	0.370	0.469	2.260

Table 2 Measurement of surface roughness after application in operation (μm)

Position	Operation 11,500 cycles			Operation 52,000 cycles			After repair			Operation 77,000 cycles		
	Ra	Rq	Rz	Ra	Rq	Rz	Ra	Rq	Rz	Ra	Rq	Rz
ø body	0.371	0.477	3.379	0.345	0.454	2.300	0.310	0.401	1.984	0.373	0.482	2.193
ø crown	0.256	0.332	1.535	0.335	0.435	1.951	0.338	0.447	2.145	0.555	0.716	2.941

It is worth noting that the plan was to carry out the inspection following 20,000 cycles after being put into the mold, which is designed for high-pressure die casting and works in the operating conditions of the foundry. The inspection was carried out according to the operational capabilities, but a cycle after 20,000 cycles will be further maintained.

4. CONCLUSIONS

This paper has described three methodologies used to map the dimensional accuracy and lifetime of the A component used as the shaped part of a mold for high-pressure die casting of aluminum. From the results obtained, the following findings can be defined.

- In terms of application in the operating conditions, the following operations - heat treatment, machining, and coating - must be carried out after printing the shaped part of the insert due to the material properties required by the foundry.
- The results obtained by the 3D measuring laser scanner and CNC CMM conform to the required standard, which is verified by the dimensional stability of not only the A component but also all four components.
- Another method used was the measurement of surface roughness, with this method showing no influence of the operating conditions either. The surface roughness has been within the standard of the component surface quality since the machining operation.
- Based on the continuous measurements, it was found that there is no significant wear.
- The methodologies that were proposed by the research team are used for the initial assessment of the component's lifetime. In addressing this issue, the research team will further focus on material properties, internal structure, and mapping of potential defects.
- It should be noted that the interim results (measurements after 77,000 cycles) have confirmed that there is no significant degradation of the additively printed component A. It can also be noted that the selected methodologies allow the shaped mold parts to be mapped and measurements will continue to be taken in the selected cycles.

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