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Dimensional and Shape Analysis of Additively Manufactured Shaped Parts of DIEVAR Steel Moulds

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Abstract

The paper presents the results of dimensional and shape analysis of additively manufactured shaped parts of foundry moulds; specifically, shaped gate valve inserts made of DIEVAR steel used in the die-casting process of aluminium alloys. The paper aims to provide a comprehensive overview of dimensional and shape analysis during the manufacturing of shaped mould parts before their use in foundry operating conditions. The manufacturing operations include additive manufacturing, heat treatment, machining, and applying a protective coating. Based on these technological operations, the required component accuracy is achieved before application in the operating conditions. The dimensional and shape analysis was measured by 3D scanning and 3D measuring methodology on a coordinate measuring machine. The ROMER ABSOLUTE ARM 3D scanning arm and the THOME PRÄZISION coordinate measuring machine were used for the measurements. The paper presents findings in the development and application of additive manufacturing technologies in engineering metallurgy.

Keywords: Additive manufacturing, DIEVAR steel, Dimensional analysis, Shape analysis

1. Introduction

In the engineering sector, it is necessary to conduct quality control of shaped mould parts. This is done to guarantee their dimensional and shape accuracy, which is crucial for the functionality and reliability of the individual components during operation. The potential risk of component failure during manufacturing is reduced based on the measurements used to verify the correctness of manufacturing. This leads to an increase in the efficiency of the manufacturing process of shaped foundry mould parts. Currently, these analyses use Various 3D measurement methodologies that provide accurate and detailed information about the geometry of the components [1].

One of these 3D measurement methods is 3D scanning, which offers detailed shape analysis of the measured components. The measurement uses scanning equipment and MS Polyworks software to convert the component's physical form into digital form. The acquired data is converted into polygonal models in the form of a point cloud, which can be easily shared in standard CAD formats. 3D scanning technology has a wide range of applications and is most commonly used in the engineering, automotive, and aviation industries [2, 3, 4].

Another method used for dimensional analysis is point measurement using a 3D coordinate measuring table, referred to as 3D CNC CMM (3D computer numerical control coordinate-measuring machine). This is a device used in engineering to verify the dimensional accuracy of components quickly and accurately. The principle of measurement is to determine points in three-dimensional space relative to a selected starting point, with the data also being processed using MS Polyworks software. Compared to 3D scanning, the coordinate machine offers greater accuracy and consistency, especially for more complex geometries and critical applications [5, 6, 7].

A state-of-the-art technology used across the industry additive manufacturing is based on applying component materials layer by layer. Its numerous benefits include the possibility of rapid component prototyping, the ability to manufacture components of complex geometry with the required mechanical properties, and savings on material due to producing minimal waste. A longer lifetime of the individual components under operating conditions is also likely [8, 9].

This paper focuses on an additively manufactured shaped component that is part of a mould for die-casting aluminium alloys. It is a gate valve insert made of additively manufactured DIEVAR steel. The mould includes two identical gate valves. The paper focuses on monitoring the lifetime of a single piece, designated 06D, on which the entire manufacturing process of the component is mapped using dimensional and shape analysis, before being deployed into service. Geometric analysis plays an important role, especially in assessing the correctness of manufacturing to ensure the dimensional and shape quality of the component.

2. Measurement methodology

This paper describes the individual aspects of the research, including the characterisation of the material, manufacturing of the gate valve insert, and measurement methodology. The paper outlines the overall dimensional and shape analysis during the manufacturing process, which comprises additive manufacturing, heat treatment, machining, and component coating.

2.1. Material properties

DIEVAR steel is a state-of-the-art tool steel used in the engineering industry for components exposed to higher-temperature environments. This steel is alloyed with chromium, molybdenum, and vanadium, giving it excellent properties for many different applications. One of its key attributes is its outstanding resistance to thermal stress, which means it maintains stability at high temperatures. Another advantage of this steel is its ability to resist cracking, making it an ideal material for demanding industrial processes. The steel also has excellent mechanical properties, including good ductility and high material purity, which improves its usability and processability. The best-known supplier is the Uddelholm company. The very good hardenability of this material allows for a variety of heat treatments and coatings according to application requirements. In practice, the steel is mainly used to manufacture foundry moulds for high-pressure casting of aluminium alloys and individual mould parts. DIEVAR steel is very suitable for nitriding and offers good dimensional stability throughout the entire range of heat treatment and coating. The chemical composition of the steel used is given in Table 1 [10].

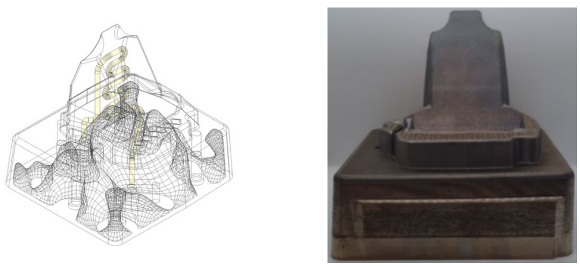
Table 1.
Chemical composition of DIEVAR steel

Element	C	Si	Mn	Cr	Mo	V
Hm %	0.35	0.20	0.50	5.00	2.30	0.60

2.2. Component manufacturing characteristics

The shaped part of the mould was manufactured in the tool shop of MOTOR JIKOV Fostron a.s. (Tools). At the end of the manufacturing process, the component had to meet all dimensional requirements to be deployed under operating conditions. The manufacturing process was conducted in the following steps:

Additive manufacturing: due to the complex design of the component, hybrid additive manufacturing of the mould part of the gate valve insert was used. The insert base was made of conventional DIEVAR steel, with an allowance of 3 mm on this part for further technological operations such as machining. The complex shaped part was then 3D printed on the base using the SLM 208 HL with an allowance of 1 mm. SLM (Selective Laser Melting) was used for the printing, by means of which the individual parts of the gate valve insert were joined together. The additively manufactured functional part of the gate valve included a conformal cooling channel, which ensured optimised cooling of the gate valve insert, thus also extending the service life and improving the mechanical properties of the component. A diagram of the conformal cooling channel is shown in Figure 1a. DIEVAR metal powder was used for the additive manufacturing. The actual form of the component is shown in Figure 1b.



a) Conformal cooling channel b) Component after printing

Fig. 1. Gate valve insert

Heat treatment: heat treatment provides the required mechanical properties such as material strength, heat resistance, and toughness, but the required hardness of the component must also be achieved, specified here as 46 +2 HRC. Due to high temperatures during heat treatment, the dimensions of the component may be affected.

Machining: the component was machined in its entire cross-section to obtain the required dimensions of the gate valve insert. The conventional base was machined, removing the allowance, which was 3 mm here. The machining also included milling the reliefs on the underside of the conventional base. The additive part, i.e. the form-function part, was also machined in its entirety, with the allowance of a 1 mm thick layer being removed here.

Coating: the last stage of the technological process is the coating of the component. Specifically, it is a surface treatment called Ferritic nitrocarburizing (FNC), mainly used to increase the corrosion and wear resistance of metal components. This chemical process is characterised primarily by leaving a grey coating on the component surface, which improves the overall mechanical properties [11].

At this stage, the component conformed to the production dimensions, with a required tolerance of ±0.200 mm. The component produced in this way is shown in Figure 2 and can be tested in the operating conditions of the MOTOR JIKOV Slévárna a.s. (Die-Casting Division) foundry for high-pressure casting of aluminium alloys.

Fig. 2. Gate valve insert at the end of the manufacturing process

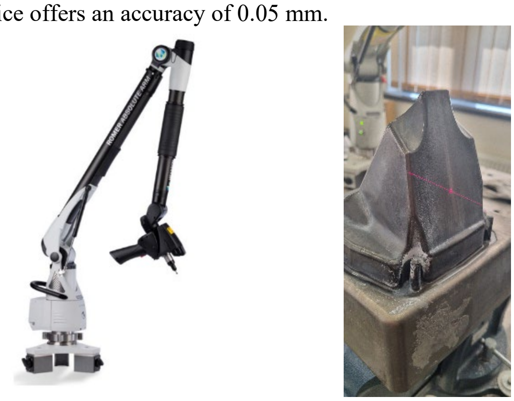
2.3. Definition of measurement

The check of the dimensional and shape analysis was conducted in two phases by two different methods. Firstly, the check was carried out using a 3D measuring laser scanner on a ROMER Absolute Arm 7525SI. The scanning is performed with a limited gauge accuracy of 0.05 mm. It allows for fast data acquisition and provides an overall view of the dimensional and shape accuracy of the component across the entire cross-section. The result is a colour map based on a colour scale that determines the tolerance of the component.

The second phase involved measurements on a coordinate measuring machine by Thome Präzision GmbH, referred to as a 3D CNC CMM. This is a measurement method with a higher gauge accuracy of 0.005 mm. Unlike scanning, there is no measurement across the entire cross-section but only spot measurements at predefined locations. The measurement is more time-consuming but provides highly accurate results that are crucial for dimensional and shape analysis. The measurements result in values that are processed in the form of a table.

The evaluation for both methods was carried out in the professional measurement and evaluation software MS Polyworks. For scanning and measurement, one component representing the gate valve insert marked 06D was monitored. The aim was to map the dimensional and shape variations after each operation of the manufacturing process including additive manufacturing, heat treatment, machining, and coating of the component.

3D laser scanning arm: a non-contact 3D laser scanner, working on the principle of laser triangulation, was used to measure components across the entire cross-section. The ROMER Absolute Arm 7525SI, shown in Figure 3a, was used. This device allows measurements to be made by moving the scanning head relative to the component. The scanning is based on the principle that the laser light emitted from the scanner hits the component surface and is reflected back from the surface into the scanner where the measurement information is captured by the scanning head. The sensor then determines the position of the measured points in relation to the scanner position. The whole evaluation process is based on the principle of triangulation, where the exact positions of the points in space (X, Y and Z coordinates) are determined. This methodical approach ensures that the data obtained is not only accurate, but also a reliable representation of the actual shape and dimensions of the measured object. The optimal scanning distance is reached when the laser beam and the laser point perfectly intersect, as illustrated in Fig. 3b. The standard scanning head of this device offers an accuracy of 0.05 mm.

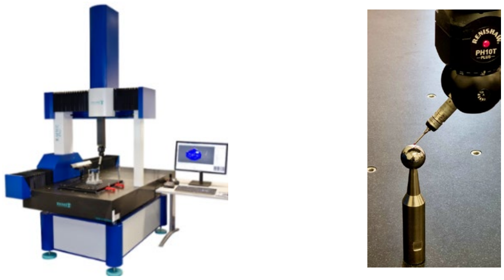


a) 3D scanning laser arm b) scanning distance

Fig. 3. Scanning process

Coordinate measuring machine: A 3D CNC CMM coordinate measuring machine by Thome Präzision GmbH shown in Figure 4a was used to perform point measurements of individual components. It is a contact device using the contact between the measuring tool and the analysed component. This machine is designed to provide a high level of accuracy, specifically within 0.005 mm, which allows measurements to be made with high precision and reliability.

Before starting the measurement process, calibration of the required contacts used during the measurement was performed using a calibration sphere, shown in Figure 4b. The calibration involved setting up and verifying the measurement system to ensure maximum accuracy and reliability of the results.



a) Coordinate measuring machine Thome Präzision GmbH

b) Calibration

Fig. 4. Process of measurement on 3D CNC CMM

At the moment of contact between the ruby ball and the measured part, the contact position is recorded through the movements of the measuring head. This information is then sent to the evaluation station where it is processed and converted into results of deviation from the nominal dimensions. This procedure allows the dimensions, features, and surface characteristics of the measured component to be accurately determined, which is key to ensuring quality and accuracy in the manufacturing process.

Alignment method: using a 3D scanner and a 3D CNC CMM, the component was aligned on 3 planes. In 3D scanning, the entire component was first scanned, then a polygonal model was created from which the necessary elements for alignment (in this case 3 planes) could be extracted, on which the 3D CAD model was then aligned.

Coordinate measuring machine, where point measurements are made rather than measuring across the entire cross-section of the component, alignment to a grid of points is impossible. First, elements used for the alignment are determined on the 3D CAD model. In this case, three planes were involved. These planes are then defined, measured, and evaluated. Subsequently, the actual alignment of the component in space takes place.

Evaluation method: two methods were used for the components to evaluate the overall results. For 3D scanning, the results were evaluated using a 3D colour map capturing the overall dimensional analysis across the entire cross-section of the component. The 3D CAD model and the scanned component surface had to be interlaced to obtain this colour map. Based on a predetermined colour scale, which determined a manufacturing tolerance of ±0.200 mm, the overall condition of the component was assessed. This assessment method is shown in Figure 5.

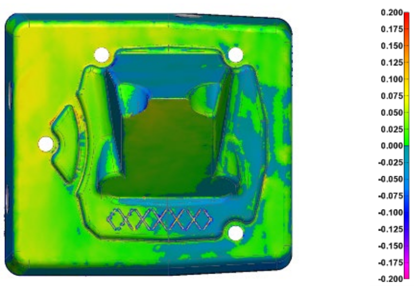


Fig. 5. Example of a colour map from 3D scanning

In the case of the dimensional analysis verification methodology using a 3D coordinate measuring machine, the method of evaluation had to be changed, as this method cannot assess the condition of the component in the entire cross-section. Here, only spot measurements on the surface of the component are taken. Based on the different measurement methodology, key points on the functional (printed) part were defined, for which the development of the dimensional analysis was observed depending on the manufacturing process. A diagram of the defined points for the 3D CNC CMM measurement methodology is shown in Figure 6.

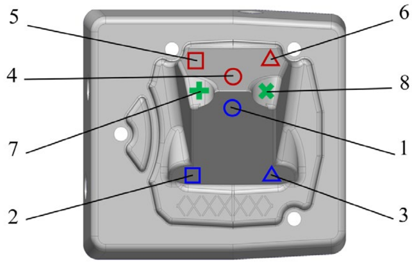


Fig. 6. Sample of selected points for 3D CNC CMM

3. Experimental part

The experimental part describes the individual results obtained from the different measurement methodologies. Finally, the current status of the additively manufactured gate valve insert is assessed.

3.1. Characteristics of the results

All results obtained for the 06D gate valve insert are based on the tolerance required at the end of the production cycle, which is set at ±0.200 mm.

For the 3D scanning, the points shown in Figure 7 where the measurement was taken using the 3D coordinate measuring machine were highlighted on the colour map. It is not appropriate to compare these methodologies due to the different accuracies of the various devices.

- The scan results are used to determine the overall shape analysis status over the entire range of the component, with a limited gauge accuracy of 0.05 mm. They provide a quick overview of the dimensions in the form of a colour map, based on a colour scale indicating the tolerance.
- 3D CNC CMM results verify dimensional accuracy by spot measurement at predefined measurement points with a very high gauge accuracy of 0.005 mm.

From the above information, it can be concluded that it is not appropriate to compare these methodologies due to the different accuracies of the individual gauges and the evaluation methods. Scanning sets the trend for dimensional and shape analysis across the component, whereas 3D CNC CMM provides the local precise data key to the evaluation.

3.2. Evaluation of results – 3D scan

Figure 7a shows the 06D gate valve insert after additive manufacturing and as can be seen, most of the dimensions are outside the required colour scale spectrum (±0.200 mm), which corresponds to the grey areas on the component. This deviation is due to the effect of the SLM technology and thermal exposure.

The following step is the heat treatment shown in Figure 7b. Due to the effect of the high temperatures, there is a dimensional change and the base and back side of the functional part of the 06D component are better than after additive manufacturing, but the rest of the component is still outside the required dimensions. The non-conforming dimensions are again shown by the grey area of the 3D CAD model.

In the next stage of manufacturing, machining was carried out, removing 3 mm of allowance on the conventional base and 1 mm of material on the printed part of the component.

Figure 7c shows the component after machining and it can be concluded at this point that all the results obtained are within tolerance. The variance of the measured values ranged from +0.05 mm to -0.15 mm across the component, depending on the colour map. There are no grey areas on the component that would indicate machining inaccuracy.

A coating was applied to the component in the last stage of manufacturing. At this stage, the final manufacturing dimensions were achieved conforming to the drawing documentation. The measurements after coating are shown in Figure 7d, where results ranging from ±0.10 mm were measured and are therefore consistent with the required dimensions.

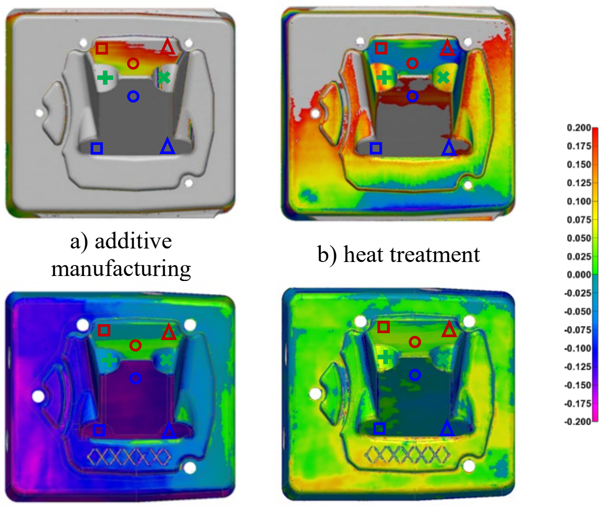


Fig.7. Dimensional and shape analysis for scanning

3.3. Evaluation of results – 3D CNC CMM

Table 2 shows the results obtained by spot measurement using 3D CNC CMM. These values represent the recorded deviation from the nominal (i.e. zero) value. Figure 8 shows the entire evolution of the individual points within the manufacturing process involving additive manufacturing, heat treatment, machining, and coating of the component. The labelling of the individual points in Figure 8 is based on the original design of the evaluation method, which was presented in Figure 6 and on which the measurement points are also individually numbered.

Table 2.
Measurement results achieved using 3D CNC CMM (mm)

Component 06D				
Measurement spot	Additive manufacturing	Heat treatment	Machining	Coating
1	0.017	-0.075	-0.016	-0.018
2	0.036	0.256	-0.017	-0.010
3	-0.006	0.168	-0.026	-0.009
4	-0.336	0.090	0.004	0.042
5	-0.316	-0.043	-0.003	0.036
6	-0.295	-0.024	0.002	0.039
7	-0.284	0.044	0.001	0.022
8	-0.352	-0.015	-0.004	0.022

From Figure 8, a very similar trend can be seen in the development of dimensional and shape analysis as in the scanning, where initially, i.e. after additive manufacturing of the insert, dimensions outside the required tolerance of ±0.200 mm were found.

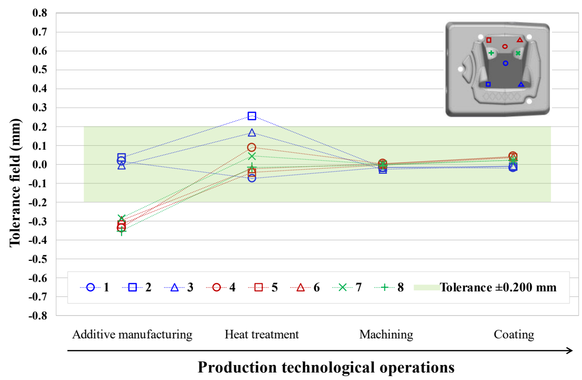


Fig.8. Dimensional and shape analysis for 3D CNC CMM

At the spots surveyed, the deviation of individual dimensions was found to range from -0.284 mm to -0.352 mm. The other monitored spots were within the required tolerance. These deviations were eliminated during the manufacturing process.

The post-heat treatment measurements showed values within tolerance at most of the measured spots. The dimensions corresponded to a range of +0.168 mm to -0.075 mm. Only at one measurement point a value of +0.256 mm was found that exceeded the permissible limit of the stated tolerance.

After machining, the production dimensions of the component were achieved and met the required tolerance. Their values ranged from +0.004 mm to -0.026 mm.

At the end of the manufacturing process, i.e. after the coating has been applied to the component, all observed values are in accordance with the required manufacturing dimensions. The range of measured results was from +0.042 mm to -0.018 mm.

It is worth mentioning that this measurement methodology achieves more accurate results than scanning and is therefore crucial when considering dimensional analysis.

The gate valve insert produced in this way meets all the requirements for shape and dimensional analysis. All dimensions are within the required tolerance of ±0.200 mm. The additively manufactured DIEVAR steel mould insert can be used for operational testing where the life cycle of the component will continue to be monitored. Dimensional and shape analysis will be carried out until the very end of the service life or until the insert is dimensionally insufficient as a result of the operational testing. In this case, the functionality and reliability of the casting production may be compromised. The expected life of the component is 120,000 operating cycles.

4. Conclusion

The paper examined the additively manufactured part of a mould, a gate valve insert, with the aim of mapping the dimensional and shape analysis of the manufacturing process, which included additive manufacturing, heat treatment, machining, and coating operations on the component.

- Two measurement methodologies were used to verify the geometry of the component. 3D scanning with a gauge accuracy of 0.05 mm, where the output was a colour map showing the component dimensions in the entire cross-section depending on a predefined colour scale, where the manufacturing tolerance was determined to be ±0.200 mm.
- Another method used was point measurement using a 3D CNC CMM with a gauge accuracy of 0.005 mm, where the output was a table of measured values of individual measurement points, from which a graph was subsequently created showing the development of dimensional analysis across the production process. This methodology is more accurate than scanning and is therefore crucial for component evaluation.
- After additive manufacturing, the scanning detected deviations on the component outside the required tolerance, caused by the SLM printing technology and the thermal effect on the material during printing. These deviations were also confirmed by the 3D CNC CMM spot measurement methodology where most of the observed dimensions were outside the required tolerance.
- The component's dimensions changed with the heat treatment due to the high temperatures. The scanning showed an improvement within the cross-section. Point measurement on the coordinate table verified the dimensional improvement to the additive manufacturing; a deviation not meeting the required tolerance was measured at only one of the monitored points.
- After machining, almost final production dimensions of the component were obtained, which resulted in a noticeable change in individual dimensions. The scanning process produced a colour map consistent with the component's colour scale throughout the cross-section. The 3D CNC CMM verified the accuracy of the machining and all the values on the component at each measurement spot were within the required tolerance.
- The moment the protective coating was applied to the component, the final dimensions of the production itself were obtained. After the component was remeasured, both methods produced satisfactory dimensions meeting the tolerance requirements. It can be concluded that the component can be subjected to operational testing in the foundry.
- Subsequently, attention will be paid to monitoring the lifetime in operational testing until the component is at the end of its life cycle, which should correspond to approximately 120,000 operational cycles, or until the gate valve insert is dimensionally inadequate due to operational testing and its functionality and reliability of casting production may be compromised.

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