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Design of an Injection Mould Utilizing Experimental Measurements and Reverse Engineering

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Casting with a disposable pattern is a method employed to produce intricate-shaped castings. This manufacturing technique falls into the near-net shape methods category, which ensures that the resulting castings closely resemble the final components. Its primary application lies in industries where precision and complex castings are of paramount importance. Typically, castings manufactured using this method utilize higher-cost materials. The focus of this study centres on the utilization of reverse engineering in the production, modification, and inspection of wax injection moulds during the casting process. Within the scope of this investigation, a non-contact method employing the Kreon arm with the Aqulion scanner was implemented. This method facilitated the generation of a digital scan, serving as the foundation for designing and validating the mould for subsequent practical application.

Keywords: Precision casting, Reverse engineering, 3D scanning, CT, Injection moulding

1 Introduction

Reverse engineering is used in almost all engineering fields, and its principle is to digitise a real part in order to create a virtual or numerical model. In general, this process can be defined as a process that extracts design information from a product. Final parts produced in various industries can thus be analysed in detail and in a comprehensive manner using reverse engineering, where we can comprehensively observe, disassemble, test and document the product based on scans, including in terms of functionality, shape, physical processes and manufacturability of the part. [1,2,3,4,5,6,19]

The study conducted by Kat'uch et al. explores the utilization of reverse engineering in the manufacturing and repair of injection moulds, specifically focusing on the measurement capabilities of a selected component using three different scanning systems. Two coordinate measuring machines (CMMs) were employed to scan the surface points of the component. The first device used was the Carl Zeiss SMS Contura G2, which featured both a contact and non-contact camera system. The second device employed was the industrial computed tomography (CT) Metrotom 1500, equipped with an X-ray scanning system. The study presents a comprehensive analysis of the key differences, intricacies, and similarities of these methods. Scanning with a contact probe stands out as one of the most widely used measurement techniques with CMMs. The geometry of the sensor, particularly its diameter, influences the effectiveness of the mechanical filter. A larger sphere diameter results in more filtered data. Computed tomography measurements are influenced by various factors, including the CT device itself (X-ray source, detector), parameters of the object being tested, measurement parameters, data analysis (software for data reconstruction and analysis), environmental conditions (temperature, humidity, vibrations, dust), and the operator (measurement strategy and implementation). CT scans are highly sensitive to errors related to the absolute scale/range (incorrect voxel size) and the proper determination of threshold values for surface extraction from point clouds. The study highlights the detrimental effects of material inclusions with varying densities. [7]

Gasparin et al. utilized an optical coordinate measuring machine (CMM) in their experiment to inspect micro-components produced by injection moulding [8]. The dimensions of the components ranged from 0.19 to 9.00 mm, and the maximum permissible error (MPE) of the measuring machine was 4.0 µm. The study brings attention to the issue of part deformation, as small plastic products can be distorted when measured using contact CMMs. However, optical measurements presented several drawbacks, including challenges in edge detection, contrast variation between dark and light areas, and component fixation during measurement. To overcome these limitations, Ontiveros et al. employed computed tomography (CT) for part inspection [9], offering an alternative approach that surpasses the constraints of touch probes and optical measurements.

Drbúl et al. conducted a study on normal vectors that must be taken into account when developing a measurement program. The selection of these vectors is crucial because an improper choice can significantly influence the measurement process, leading to inaccurate values for geometric features. [10]

Cioană et al. conducted an experiment using the Roland LPX-600 laser scanning machine to investigate the factors that affect the surface quality of virtual models obtained through scanning. The experiment involved plastic and aluminium parts with cylindrical and prismatic shapes, employing both rotational and planar scanning strategies while varying the scanning resolution. Additionally, the study aimed to determine the dimensional accuracy of the laser scanning machine and explore the integration of this technology into the quality control process for plastic parts. [11]

Soonhwang and Jongsun conducted an analysis of the plastic injection moulding process using the Autodesk Moldflow Insight 2018 application [12]. Current injection moulding analyses primarily focus on predicting qualitative outcomes, whereas quantitative analysis is required for computer-aided engineering (CAE) in reverse engineering. This discrepancy can result in inaccuracies when predicting injection moulding defects and, consequently, expensive mould modifications due to the complex design of the moulds. The simulation was employed to identify the surface sink mark on the component, and a predictive model was developed. The predictive model was compared to typical regression models such as polynomial regression, EDT, and RBF to determine the optimal approximation model. [13,14]

The aim of Sahla et al.'s experimental work was to design a mould cavity using a point cloud obtained from a measuring arm [15]. The CAD model derived from the point cloud was reconstructed, validated, and analyzed for any errors that occurred during the process. The significance of this study lies in the direct application of this scanning technique to complex objects. The work is divided into the following stages: 1) cleaning of the point cloud data, 2) alignment and decimation of the point cloud, 3) simplification of the point cloud, 4) generation of a 3D mesh, 5) error correction, 6) creation of the object's surface, 7) generation of a CAD model, 8) spectral analysis of deviations, and 9) design of the mould cavity. [16,17]

The study conducted by Stoklásek describes the application of optical digitization, reverse engineering, and rapid prototyping technology in the manufacturing process. The components were scanned using a non-contact 3D scanner, generating digitized 3D models that served as inputs for reverse engineering. Considering the technological limitations of vacuum forming, the shapes of the components were modified, reduced in size, and utilized for designing 3D-printed moulds specifically tailored for vacuum forming. The primary objective of this study is to examine the process of reverse engineering, with particular emphasis on the digitization phase, which entails scanning the moulds used for injection wax and casts produced through precision casting methods. The study involved a comparison between the actual geometry of the components and the corresponding CAD model geometry. Line laser scanning was employed for these measurements. [18] [20,21,22,23]

2 Materials and methods

The injection mould was manufactured from an Al-Cu4-Mg alloy (EN AW-2017A) and was initially measured after the production of 500 moulded pieces, and subsequently after the production of 20,000 moulded pieces.

2.1 Used Material

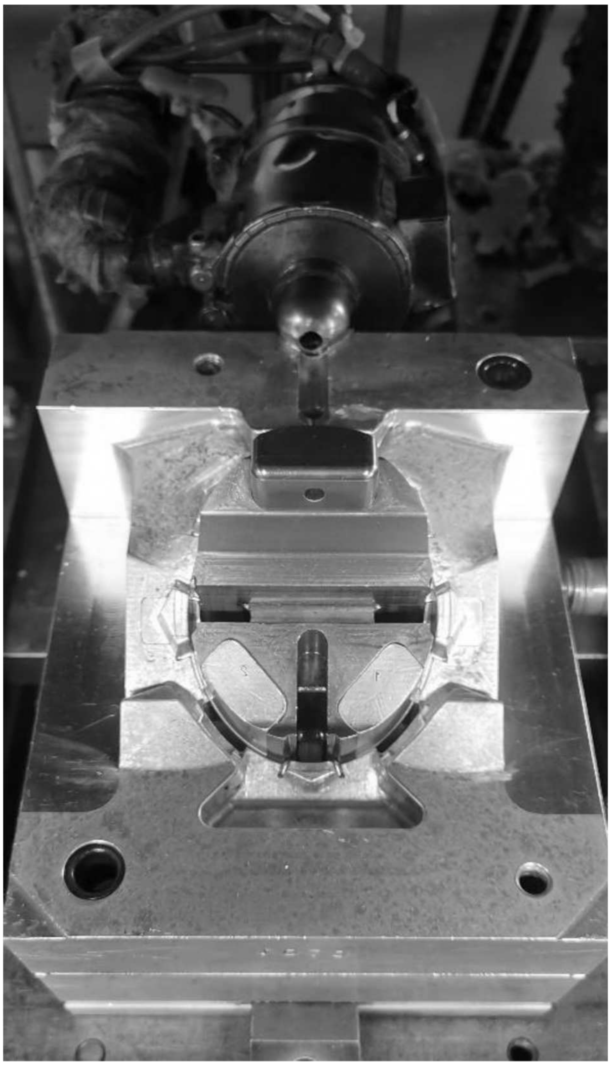

Fig. 1 *Injection wax mould used in the experiment*

The EN AW-2017A alloy has a high copper content, which leads to the formation of short chips and makes it suitable for machining. However, it has low corrosion resistance and is not suitable for welding due to its high copper content. Any necessary modifications to the moulds made from this material were addressed using shape inserts. These inserts were securely attached to the mould using ISO8734 cylindrical pins (6-20) and socket head cap screws with internal hexagons EN ISO 4762. Reference points and surfaces were established on the moulds, which were further evaluated for each individual injection mould.

Tab. 1 *Chemical composition of EN AW-2017A mould material*

SiI	Fe	Cu	Mn	Cr	Zn	Zr+Ti
0,2-0,8	0,7	3,5-4,5	0,4-1,0	0,1	0,25	0,25

2.2 Experimental methodology

The research focuses on investigating mould wear through the use of reverse engineering. A comparison was made between the actual geometry and the CAD model geometry. Points were identified on the produced casting to validate the final dimensions and ensure compliance with customer requirements. These points were subsequently transferred to the injection mould. The selection of these points was based on their ease of measurement and comparability. The positions of these points corresponded to functional points on the casting (Fig. 2), and their verification took place after aligning the mould to ensure precise positioning, considering that all dimensions were measured to the hundredth of a millimetre. The chosen points were determined by the final product, which, in this case, is the casting. However, it was also necessary to determine the points on the wax model, as additional dimensional changes occur during casting on the expendable model due to the solidification process and mould handling. All measurements included a tolerance range, which was narrower for the wax models than for the castings, as deviations from the nominal dimensions increased during production. This tighter tolerance range for the wax models helped prevent the production of non-conforming pieces. Multiple points were measured on the casting to accurately describe all deformations present. Point measurements were conducted using the Aquilion laser scanner.

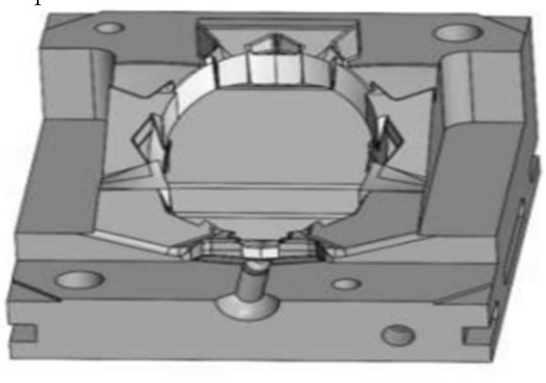

Fig. 2 *CAD model of the injection mould with functional surfaces*

To ensure stability during scanning, the mould was carefully positioned within the workspace. A line laser scanner was used to capture surface points on the top part of the mould. The scanning procedure was conducted under controlled laboratory conditions at a temperature of 20°C. As the mould surface was not coated with chalk spray to reduce reflections, it was necessary to apply filtering techniques to remove outlier points in relation to the CAD model. The resulting filtered spatial points are visually represented in grey colour in Fig. 3.

Due to the complex shape of the component, the Best-fit method was employed to align the CAD model with the scanned point cloud. For alignment, only 25% of the point cloud was utilized with a point-to-point search distance of 0.2mm. Subsequently, an additional filtering process was applied to remove outliers. The RGB map highlights vector deviations that indicate changes in the mould dimensions along the Z-axis. Fig. 4 illustrates the measured deviations, which predominantly ranged around -0.05mm. The majority of deviations fell within the range of -0.05mm to 0.05mm. The most significant wear was observed on the parting line. Inaccuracies resulting from wear cause a displacement of cavity shapes in relation to each other. Expanding deviations can lead to the production of non-conforming moulded components, underscoring the importance of controlling and addressing these deviations during adjustment and sampling processes. If dimensional discrepancies are detected, mould modifications, such as replacing specific sections, can be proposed and verified using the scanner.

During the experimental phase, modifications were implemented on the mould to simplify, accelerate, and enhance the alignment process, leading to improved control over the mould's geometry. The mould was originally made from tool steel and was subsequently modified with a shape insert (Fig. 5). The dimensions of the modified mould were verified using contact measurements, which allowed the determination of the wear limit after 20,000 pieces.

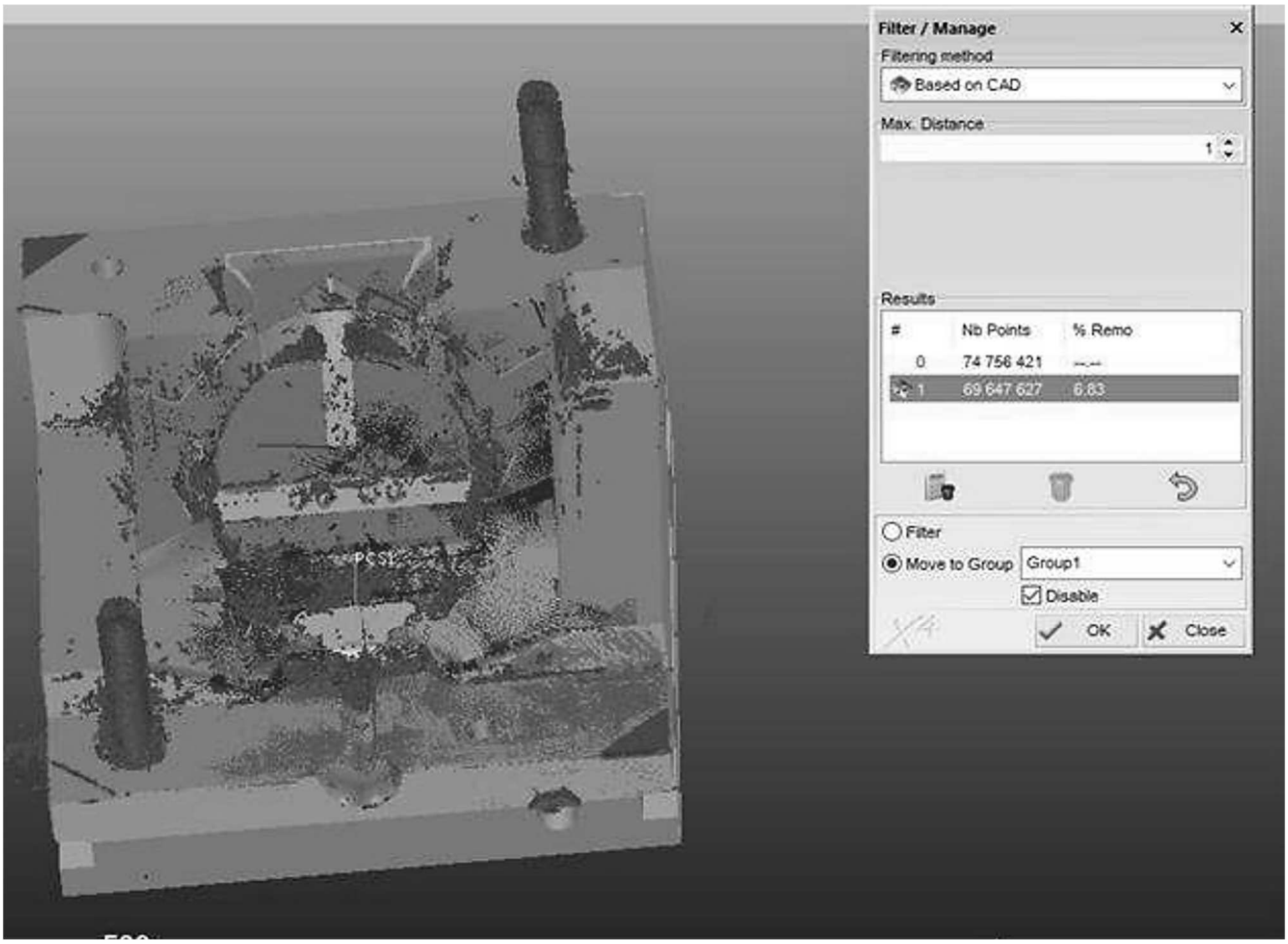

Fig. 3 *Removal of outliers*

Fig. 4 *RGB map of measured values*

The deviations on the functional surfaces exceed the maximum tolerances for castings, and for this reason, precise ISO 8018 guiding bushings were added to the mould to ensure proper spatial positioning of the component.

Tool steels, carbon steels, and alloy steels were utilized in the production of both the mould and its components. The mould base and core, for instance, were constructed using tool steel. Modifying the mould geometry became necessary due to increased wear in the parting plane area. Specifically, the draft angle in the parting plane was increased, resulting in reduced stress during mould closure.

Two precise holes were drilled into the upper and lower parts of the mould's side walls from the inside, ensuring that they do not hinder the mould's operation and do not interfere with the cooling system. A third hole was drilled from the rear side of the mould, where it connects to the injection unit of the device. Fig. 8 illustrates the guide bushings of the injection mould.

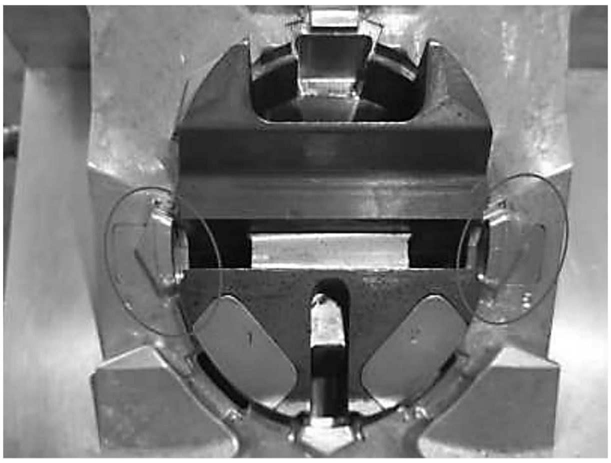

Fig. 5 *Shape inserts in the mould*

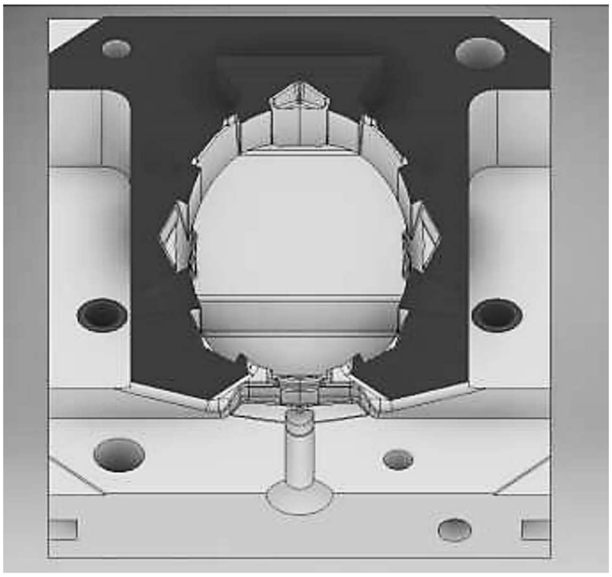

Fig. 6 *Original model reinforced with guiding bushings*

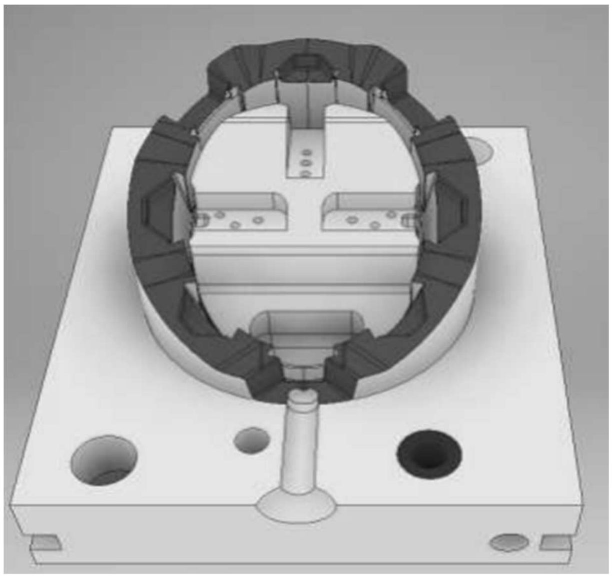

Fig. 7 *Modified mould with added bushings*

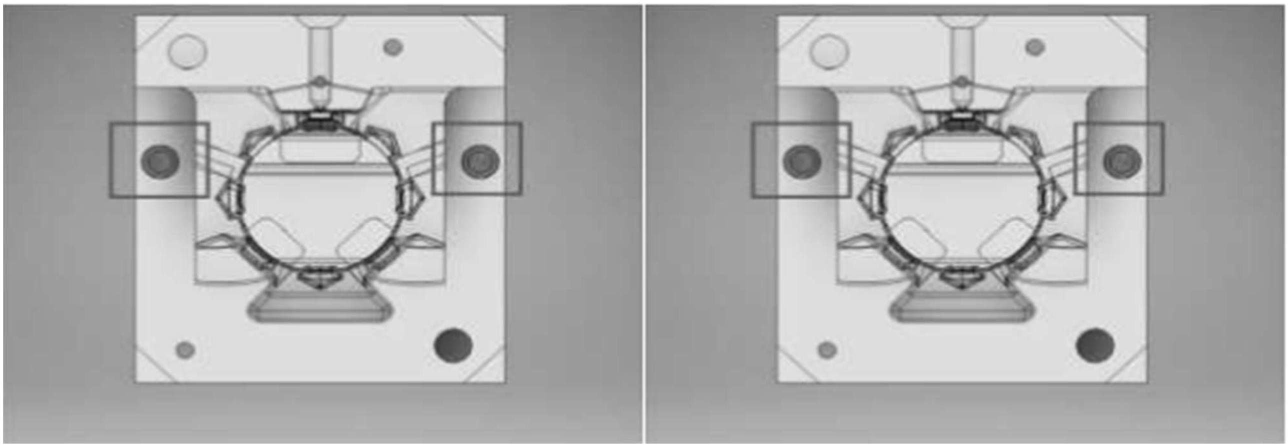

Fig. 8 *Guide bushings of the injection mould*

3 Results

The experimental phase of the research involves analyzing the measurement capabilities of the Kreon Aquilion optical 3D scanner. The scanning process takes into account the surface reflection to process the results effectively. The mould's wear was evaluated, and the most critical areas of stress were identified using the RGB map generated from the measured values. These findings were then utilized to optimize the design of the mould. The measured deviations were primarily concentrated around -0.05 mm, with the majority of deviations falling within the range of -0.05 mm to 0.05 mm.

The mould discussed in the paper has produced 20,000 moulded pieces, whereas conventional moulds made of the same material usually have a lifespan of 7,000 to 30,000 produced moulded pieces based on literature research. Due to the complex and intricate surfaces, which are significantly affected by multiple production cycles and other factors, achieving proper alignment has been a challenging task. Therefore, based on experimental measurements, the mould underwent modifications to facilitate, accelerate, and improve the alignment process, ultimately enhancing overall control over the mould's geometry. The mould was adjusted with the use of a shape insert, and the most exposed parts were replaced with steel components.

The required properties for mould production and operation can be summarized by the following key requirements:

- sufficient tensile and compressive strength, increased wear resistance, quenching/annealing, and reheat treatment
- minimal dimensional and shape deformations during quenching, excellent corrosion resistance, good machinability, and the possibility of cold forming.
- good abrasiveness/grindability and polishability in the refined/tempered state.

In the design of a new mould, reverse engineering was applied, where a new injection mould was developed based on the scanned moulded part, casting, and original mould. As observed in the experimental results, the parting plane area exhibited increased wear. Consequently, the geometry of the parting surface was modified. The modified parting plane features an increased draft angle, which positively contributes to reduced stress during mould closure.

The obtained results are applicable not only to moulds for metal casting but also to forging dies. The knowledge acquired through the experimental work has implications for both research and practical applications, particularly in the metrological analysis of scanning and reverse engineering processes. Furthermore, these findings can contribute to the enhancement of education in the areas of metrology, quality management, and computer-aided manufacturing technologies.

4 Conclusion

The present study focuses on the analysis of wear in injection moulds using reverse engineering. The manufacturing mould was made from Al-Cu4-Mg alloy (EN AW-2017A) and underwent measurements prior to and after producing 20,000 moulded pieces. This alloy contains a high copper content, making it suitable for machining. However, its corrosion resistance is relatively low, making it less favourable for welding applications. The moulds were equipped with shape inserts that were secured using ISO 8734 cylindrical pins 6-20 and EN ISO 4762 socket head cap screws with an internal hexagon.

The experimental methodology aims to compare the real geometry with the CAD model of the mould. Points were identified on the castings and transferred to the injection mould. The position of these points was linked to functional points on the casting and measured with a precision of hundredths of a millimetre using the Aquilion laser scanner. The scanning process was conducted at a temperature of 20°C, and the results were subsequently processed and evaluated, considering vector deviations.

Based on the results, we found that the parting surface experienced the most significant wear. These deviations can result in the production of moulded parts that do not meet specifications, emphasizing the importance of monitoring and adjusting them during the modification and sampling process. Using the experimental measurements, the mould was modified to enhance and expedite its alignment and overall control of the geometric component. Furthermore, adjustments were made to the geometry of the parting surface, including an increase in the draft angle, which positively impacts the stress during mould closure.

These findings and the methods of reverse engineering can be applied to other moulds used in metal casting and forging processes.

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