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Optimization of the Machining Process of AlSi12Cu1(Fe) Alloy Castings

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Abstract

This paper presents a dimensional analysis of die castings made from AlSi12Cu1(Fe) alloy. The machining process was optimized to minimize downtime and equipment usage while maintaining product quality and production efficiency. The castings, shaped as hydraulic valves, were produced using a four-cavity die-casting mold. Due to difficulties in achieving the required geometric dimensions, each casting from a specific cavity was machined on separate Computerized Numerical Control (CNC) machines. This work focuses on the dimensional analysis of castings from each mold cavity and the optimization of the production process. Based on the analysis, it was observed that the castings could be divided into two distinct groups: the first group contained castings that, after machining, exhibited similar measurement values and remained within the specified dimensional tolerances, while the second group failed to meet the required tolerances. As a result of the conducted analysis, a new machining strategy can be proposed—assigning castings from each group to different CNC machines. This would eliminate the need for frequent machine retooling and significantly reduce production downtime. The findings point to a potential solution for optimizing the machining process and improving overall manufacturing efficiency.

Keywords: Production optimization, Hydraulic valve, AlSi12Cu1(Fe) alloy

1. Introduction

The production of aluminum casting alloys has been steadily increasing both in Poland and globally. In 2000, the global output of aluminum casting alloys was approximately 8.05 million tonnes, rising to about 14.22 million tonnes by 2022. In Poland, this trend is also evident. In 2000, domestic production stood at around 50 thousand tonnes, while by 2022 it had grown to approximately 252 thousand tonnes, representing a fivefold increase over 22 years [1, 2]. It is noteworthy that over 60% of global aluminum alloy production utilizes High Pressure Die Casting (HPDC), which significantly contributes to the manufacture of castings with tight dimensional tolerances [3].

Pressure die casting is considered more economical compared to other casting methods, enabling the production of thin-walled components with complex shapes and minimal machining [4]. To achieve optimal results at the lowest cost per part, it is crucial to determine during die design how the component will interface with the rest of the assembly. This aspect is particularly important in terms of final surface finish quality and dimensional tolerance compliance [5]. In [6], researchers analyzed the effect of varying part geometry and mold constraints on dimensional deviations. They concluded that the use of different allowances and the thermomechanical behavior of metal during cooling within the mold cavity result in cast components being heavier than their original designs. This mismatch leads to increased costs, as the actual geometry often significantly deviates from the intended design.

Manufacturers of aluminum alloy components must consider several factors when aiming to achieve dimensional conformity. These include the impact of the mold parting line, non-uniform casting shrinkage, machine rigidity, machining strategy and parameters, the size and support of the component, the condition of the cutting tools, and material properties [7–9]. Due to increasingly stringent dimensional and surface finish requirements—both of which affect product quality and performance—monitoring deviations has become essential. Among many factors influencing the quality of finished products, as well as the surface, tribological wear of the mold and the effects associated with cyclic thermal load should also be taken into account [10-13]. In the production of pressure castings, among other things, the surface quality is a parameter that tempers or rejects the product for further processing. Preliminary quality assessment can be conducted manually by skilled personnel; however, the use of coordinate measuring machines (CMMs) ensures high precision and repeatability in measurements [14], significantly reducing human error in the evaluation of cast components.

This study presents a dimensional analysis of pressure die castings made from the AlSi12Cu1(Fe) alloy to support the optimization of machining processes. The analyzed components—valve-shaped castings—were produced in a mold featuring four cavities. Due to challenges in achieving the specified dimensional tolerances, each casting from a given cavity was machined on a separate CNC machine (a total of four machines). Dimensional measurements of the castings were performed using a Mitutoyo Euro 9106 coordinate measuring machine. The analysis focused on three dimensions influenced by the raw material and two dimensions related to the machining tools. The aim of the study was to evaluate dimensional variations of castings from individual mold cavities and to optimize the production process by reducing the number of CNC machines required for machining.

2. Research Objective and Materials

The research was conducted using an AlSi12Cu1 alloy, with elemental composition specified in Table 1, in accordance with standard [15]. The castings were produced in the form of hydraulic valves using an automated die casting center equipped with a Frech DAM 500 F pressure die casting machine.

Table 1.
Chemical compositions of $AlSi_{12}Cu_1$ [15]

Chemical element	Chemical composition [%]
Si	10.50-13.50
Fe	1.30 max
Cu	0.7-1.2
Mn	0.55 max
Mg	0.35 max
Ni	0.30 max
Zn	0.55 max
Sn	0.10 max
Ti	0.20 max
Pb	0.20 max
Cr	0.10 max

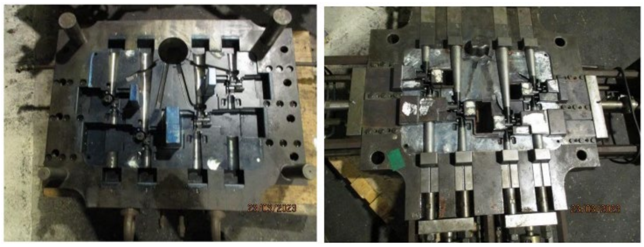

Fig. 1. Left and right halves of the multi-cavity die mold

Figure 1 presents the four-cavity die mold used in the production process, while Figure 2 shows the resulting aluminum casting, including the gating system and cavity identification.

Following casting, the valves underwent surface cleaning in a Walther Trowal THM 500 shot blasting machine to remove rust, oxides, and residues, as well as to deburr sharp edges and eliminate surface defects such as thin injection flash.

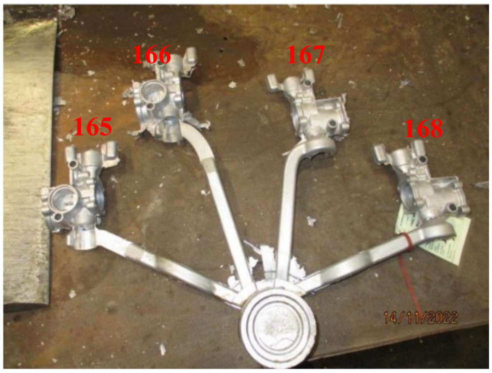

Fig. 2. Aluminum casting produced in a four-cavity mold, with numbered cavity identification

Machining was performed on a Chiron FZ 12 W CNC machine. The machining references included a sheared pinhole and a mating plane (see Fig. 3). These references were selected for their direct and inseparable geometric relation to the machined surfaces—either dimensionally or through positional conditions (shape and position deviations).

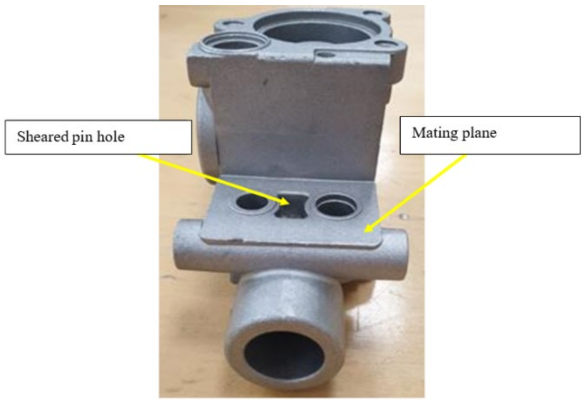

Fig. 3. Machining reference bases for the hydraulic valve

This study focused on analyzing the dimensional stability of machined parts under a single CNC machine setup. The goal was to produce parts meeting customer specifications, namely:

- Distance from Datum A: 36 mm with +0.15 mm tolerance (Fig. 6, mark 1).
- Parallelism of one surface to Datum A: 0.25 mm (Fig. 6, mark 2).
- Hole diameter: Ø39.1 mm with 0.1 mm tolerance (Fig. 6, mark 3).
- Perpendicularity of the hole to Datum A: 0.02 mm (Fig. 9, mark 4).
- Hole dimension Ø8 × 8 mm: tolerance of 0.022 mm (Fig. 9, mark 5.

3. Results

Figure 4 presents the valves before and after treatment, clearly illustrating the visual differences between the raw and finished surfaces. Surface characteristics were evaluated through visual inspection and surface roughness measurements. The surface topography was analyzed using LEXT software (DSX1000 Software Ver. 1.2.5), dedicated to the Olympus DSX1000 digital microscope. The surface roughness parameter Sa (surface arithmetic mean height) was determined. The changes in the Sa parameter after casting, after shot blasting and after machining are show in Figure 5.

In the as-cast condition (see Fig. 5a), the surface is characterized by a clearly visible, irregular structure with numerous depressions and roughness features typical of an unprocessed casting surface. After shot blasting (see Fig. 5b), the structure becomes noticeably more uniform – loose particles and major surface irregularities are removed, and the surface acquires a more homogeneous character with fine traces of shot impacts. In the final stage, after machining (see Fig. 5c), the surface becomes significantly smoother and more regular, with visible tool marks and a substantial reduction in overall surface roughness.

Fig. 4. Comparison of parts before (right) and after (left) machining

Dimensional measurements were carried out on a Mitutoyo Euro 9106 Coordinate Measuring Machine (CMM). The ambient temperature at the beginning of measurements was 20°C, in accordance with standard [16]. Each part was measured over a period of approximately 7 minutes. The parts were mounted on a dedicated fixture and measured using a TP200 probe with a 1 mm stylus ball [17].

a)
b)
c)

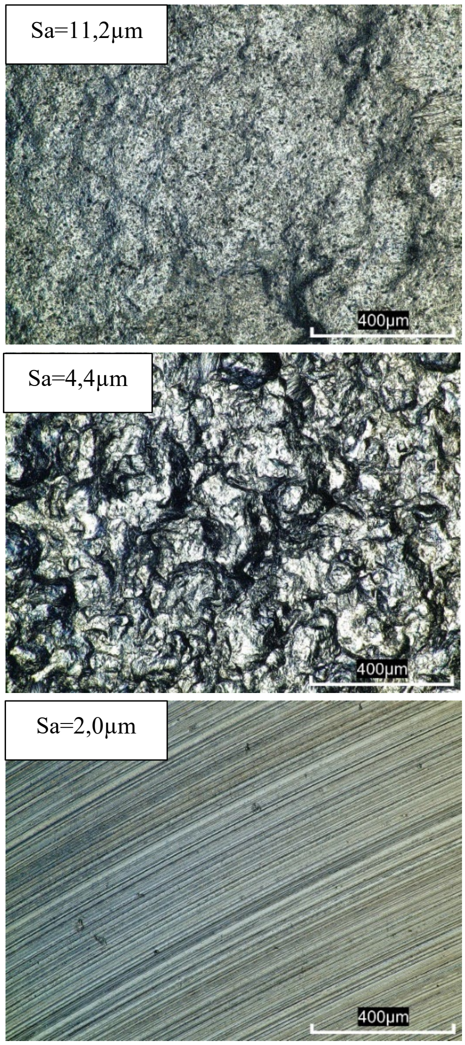

Fig. 5. Surface macrostructures and surface roughness parameter Sa: (a) after casting, Sa= 11.2 µm; (b) after shot blasting, Sa= 4.4 µm; (c) after machining, Sa= 2.0 µm, 240× magnification

To analyze the dimensional variation, 10 parts were measured from each of the four die cavities—numbered 165, 166, 167, and 168. The mating plane, designated as Datum A on the technical drawing, was adopted as the primary reference base for both machining and measurement operations. Three dimensions dependent on the raw casting (based on Datum A), and two tool-dependent dimensions were selected for detailed analysis.

The first casting-dependent dimension analyzed was 36 +0.15 mm (see Fig. 6). This dimension was established from the raw surface (not subjected to machining) identified as Datum A. The 36 mm value was achieved by a facing operation using a milling head, representing the distance from Datum A to the bottom surface of the component.

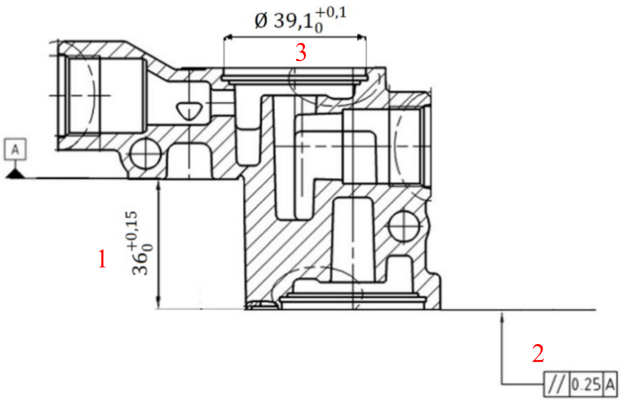

Fig. 6. Key analyzed dimensions: distance 36 +0.15 mm (mark 1), parallelism 0.25 mm (mark 2), diameter Ø39.1 +0.1 mm (mark 3)

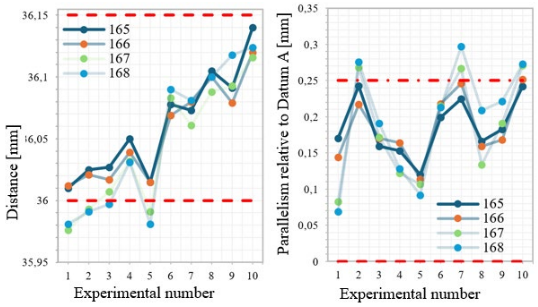

Fig. 7. Comparison of the 36 +0.15 mm dimension (see Fig. 6) and parallelism 0.25 mm to Datum A for ten castings from each mold cavity. Cavities numbered 165, 166, 167, and 168 were used for identification purposes (see Figure 2)

The second analyzed feature was the parallelism // 0.25 mm relative to Datum A—evaluating the parallelism of the machined face (resulting from the facing operation to 36 mm) against the raw base surface.

The third dimension analyzed was a diameter of 39.1 +0.1 mm, where the casting's accuracy impacts primarily the positional correctness of the feature, not its actual diameter.

All three analyzed dimensions are marked in Figure 6. Figures 7 and 8 compare the measurement results, where red dashed lines indicate the allowed dimensional tolerances.

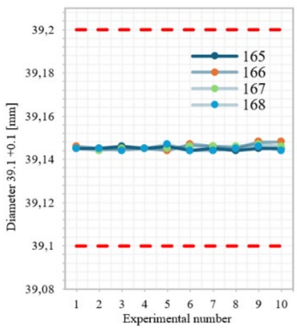

Fig. 8. Comparison of diameter Ø39.1 +0.1 mm for ten castings from each mold cavity. Cavities numbered 165, 166, 167, and 168 were used for identification purposes (see Figure 2)

The fourth analyzed feature was perpendicularity 0.02 mm to Datum A, while the fifth was the perpendicularity of a Ø8 × 8 mm hole relative to the raw mating surface (Datum A). The measurement locations are marked in Figure 9. Measurement results for these features across ten castings from each cavity are presented in Figure 10, with red dashed lines indicating permissible dimensional tolerances.

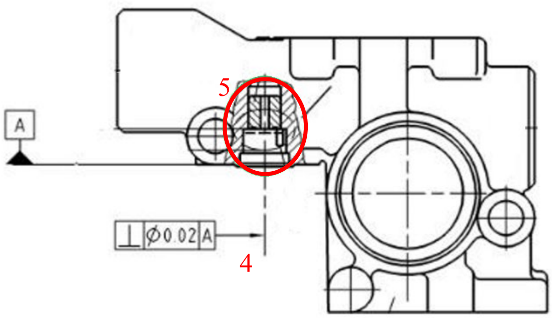

Fig. 9. Perpendicularity ⊥0.02 mm to Datum A (mark 4) and Ø8 × 8 hole (highlighted with a red ellipse, mark 5)

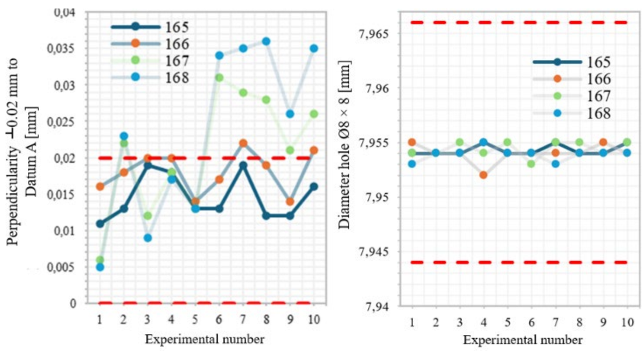

Fig. 10. Comparison of perpendicularity 0.02 mm to Datum A and Ø8 × 8 hole dimension. Cavities numbered 165, 166, 167, and 168 were used for identification purposes (see Figure 2)

4. Summary

Due to dimensional convergence observed in specific surface areas of the components, the machining company decided to process castings separately based on the mold cavity from which they originated. Each casting, depending on its mold cavity, is assigned to a different CNC machine, each configured with individualized settings. This approach facilitates the elimination of dimensional inconsistencies and ensures greater process stability and repeatability.

However, the main drawback of this solution lies in the necessity of frequently reconfiguring the CNC machines when the raw castings from a particular cavity are depleted. Transitioning to a new set of castings from a different cavity requires machine setup adjustments and verification measurements in the metrology lab, resulting in prolonged production downtime. This stands in direct opposition to one of the core principles of lean manufacturing—SMED (Single-Minute Exchange of Die)—which aims to minimize changeover time. Extended downtimes of this nature generate significant financial losses for the facility.

The dimensional inconsistencies observed in the machined castings were directly related to the specific mold cavity from which each casting originated. Upon analysis, it was found that castings from cavity 165 remained within the acceptable tolerance range for all examined features. Similarly, castings from cavity 166 met the required tolerances in nearly all cases. The only deviation was observed in the perpendicularity to Datum A for samples 7 and 10 (see Fig. 10), where the measured values were 0.022 mm and 0.021 mm, respectively—slightly exceeding the specified maximum of 0.02 mm.

In contrast, castings from cavities 167 and 168 exhibited dimensional deviations in consistent patterns across the same measurement points. Specifically:

- For the 36 mm +0.15 mm distance from Datum A, deviations were noted in samples 1, 2, 3, and 5;
- For parallelism relative to Datum A, out-of-tolerance values appeared in samples 2, 7, and 10 (see Fig. 7);
- For perpendicularity of the hole to Datum A, deviations were present in samples 6 through 10 (see Fig. 10).

However, in all analyzed cases—regardless of the mold cavity—dimensions associated with the hole diameter Ø39.1 mm with a 0.1 mm tolerance (see Fig. 8) and the Ø8 × 8 mm hole dimension with a 0.022 mm tolerance (see Fig. 10) remained within the specified limits.

The conducted analysis revealed that castings could be divided into two distinct groups based on their mold cavity origin: Group 1—castings from cavities 165 and 166, and Group 2—castings from cavities 167 and 168. Components within each group exhibited similar dimensional characteristics after machining and remained within the specified tolerance range.

Based on these findings, a new machining strategy can be proposed: castings from Group 1 (cavities 165 and 166) should be machined on one CNC workstation, while castings from Group 2 (cavities 167 and 168) should be machined on a separate workstation. This approach eliminates the need for frequent machine retooling, thereby reducing downtime and improving overall production efficiency.

The analysis thus demonstrates a viable method for optimizing the machining process, ensuring dimensional repeatability while aligning with lean manufacturing principles.

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