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Analysis of Selected Production Parameters for the Quality of Pressure Castings as a Tool to Increase Competitiveness

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Abstract: The research conducted in the paper highlights the importance of pressure or holding pressure in the mold cavity as a critical production parameter in the high-pressure die casting process for Al-Si alloys. The experiments revealed a direct correlation between the pressure or holding pressure in the mold cavity and the mechanical properties of the castings, including ultimate tensile strength, percentage share of porosity, and the structure of the alloys. The results of the experiments showed that increasing the pressure or holding pressure in the mold cavity led to an increase in ultimate tensile strength and a reduction in the porosity of the castings. The higher pressure or holding pressure also resulted in the elimination of pores in the casting, which further improved its mechanical properties. The increase in ultimate tensile strength and reduction in porosity can be attributed to the better filling of the mold cavity, leading to reduced air entrapment and porosity in the castings. Overall, this paper emphasizes the need for optimizing the technological parameters of the die casting process to ensure the high-quality and efficient production of castings with reduced defects. The results of this study suggest that controlling the pressure or holding pressure in the mold cavity can significantly improve the mechanical properties of the castings, which is essential for achieving the desired quality standards.

Keywords: die casting; production parameters; molding pressure; porosity; quality

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1. Introduction

High-pressure die casting (HPDC) technology is indeed a popular method used in the production of castings, particularly for smaller, lighter, and more intricate products with precise dimensional requirements. This process is commonly employed for manufacturing components with complex shapes and thin walls. HPDC emphasizes achieving a high-quality surface finish, typically smooth in appearance. Most castings produced using this technique are made from non-ferrous metal alloys, such as aluminum, zinc, and magnesium [1,2].

The electrotechnical, gas, aviation, and automotive industries have stimulated an abrupt development of progressive foundry technologies. Vehicles consist of a few parts produced from steel, cast iron, and non-ferrous metals. Approximately 15–20% of automotive parts are castings produced by diverse casting methods. The castings represent mainly key components of the energetic system and important construction elements. Die casting technology of non-ferrous metals and their alloys under high pressure ranks among the newest technologies in the foundry industry. Over a relatively short period, the technology has won recognition in the case of mass and bulk production of castings. The increase of casting share in modern structures requires knowledge of the foundry processes [3–5].

Indeed, high-pressure die casting technology is known for its ability to produce precise castings with minimal material waste. It is a highly efficient method that allows for the transformation of raw materials into a final product with excellent dimensional accuracy and surface finish. It is a means of casting production in the case that the molten metal

is injected into a permanent mold at a high speed of 10–100 m·s^{-1} such that the metal reaches the gating system under the influence of high pressure (the melt is being cast by the pressure of up to 500 MPa). Throughout solidification, the metal remains under pressure, i.e., the process is referred to as multiplication. High filling speed and high pressure allow the casting of thin-walled and rather fragmented castings which in many cases do not require further machining other than the removal of sprues and fins [6,7].

The properties and quality of castings produced using die casting technology are influenced by various factors throughout the entire process. These factors play a crucial role in achieving the desired final shapes, dimensions, and surface quality. By carefully considering and optimizing these factors, manufacturers can achieve high-quality castings with complex shapes, accurate dimensions, and excellent surface finish. Close attention to mold design, gating and venting systems, cooling, alloy selection, mold quality, machine parameters, and metallurgical factors is crucial in ensuring successful die casting production [8–10]. A complex of all the aforementioned factors and parameters determines a precondition to produce high-quality castings. Technological parameters significantly influencing mechanical properties involve casting pressure (holding pressure) and thermal conditions of the die casting process [11,12].

1.1. High-Pressure Die Casting Pressure

The pressure exerted on the liquid metal during mold filling is essential to ensure proper filling speed and overcome resistance within the mold cavity. To achieve high casting quality, it is important to carefully control the pressure and timing during the die casting process. Controlling the pressure during the die casting process is essential for producing high-quality castings with intricate shapes, dimensional accuracy, and a smooth surface finish. Optimizing the hydrostatic pressure, holding pressure, and flow kinetic energy ensures effective mold filling and helps minimize defects, resulting in superior casting properties. Proper pressure management is a key element in achieving the desired characteristics and quality in high-pressure die casting technology [13].

The pressure acting upon the metal in the filling chamber during the die casting process has a significant impact on the mold cavity filling time and, consequently, the properties of the final casting. The timing and magnitude of the pressure influence the casting's homogeneity and mechanical properties, especially when the pressure affects the casting at the beginning and during solidification [13,14]. The development of this pressure influence varies based on the filling mode used in the die casting process [15].

1.2. Thermal Conditions in Die Casting of Metals

In the die casting process, temperature plays a critical role, particularly due to the impact of thermal stresses on the die casting mold. Maintaining optimal temperatures for various thermal factors is essential to ensure high-quality castings. The temperature difference between the liquid metal and the die casting mold leads to thermal stresses. Rapid heating and cooling cycles during the casting process can cause thermal shocks, which can result in mold stress and potentially lead to mold damage or premature failure. To minimize mold stress and ensure its longevity, the die casting mold must be preheated to an optimal temperature before the casting process begins. The temperature of the casting alloy is closely related to the mold temperature. Generally, the mold temperature should be higher than the metal temperature by approximately 50–60 °C. This temperature difference allows for effective heat transfer from the molten metal to the mold, ensuring proper solidification and minimizing thermal stresses. By maintaining optimal temperatures for the casting alloy, die casting chamber, and mold, manufacturers can ensure consistent and high-quality castings. Effective temperature control helps minimize mold stress, reduce the risk of defects, and achieve the desired dimensional accuracy, surface finish, and mechanical properties in the die casting process [15].

In the die casting process, when molten metal with a high temperature is injected into a relatively cold mold, certain challenges can arise, particularly related to the greasing agents

and insufficient surface insulation of the mold. If the molten metal at an extremely high temperature meets the greasing agents, it can cause thermal stress to the superficial layers of the mold. This stress can potentially lead to surface defects and damage to the mold. If the mold cavity surface temperature is insufficient, meaning it is too cold, it can cause premature cooling of the molten metal upon contact. This premature cooling can result in the formation of weld lines and cold shuts on the surface of the castings. When the molten metal experiences rapid cooling in the mold, it can result in super-cooling, which can lead to extreme internal stress within the castings. The presence of such internal stresses can negatively affect the mechanical properties of the castings and may result in subtle cracks or even casting failure. By addressing these factors and ensuring proper temperature control, mold surface insulation, and selection of greasing agents, manufacturers can minimize the formation of defects, internal stresses, and cracks, resulting in higher-quality castings with improved structural integrity [16,17].

Temperature balance in the die casting process can be expressed by the following relations [18]:

$$Q_1 + Q_2 - Q_3 - Q_4 = Q_1 \tag{1}$$

with:

Q_1—the heat for the mold preheating [J];
Q_2—the heat delivered by the casting [J];
Q_3—the heat released by the casting to the mold [J];
Q_4—the heat reduced by the casting heat released from the mold [J].

The amount of heat delivered by the casting Q_2 can be calculated as follows:

$$Q_2 = m_k[c_L(t_l - t_s) + l + c_S(t_s - 20)] \tag{2}$$

with:

m_k—casting weight + 0.6 sprue weight [kg];
c_L—specific heat of molten alloy [J·kg^{-1}·K^{-1}];
c_S—specific heat of solid metal [J·kg^{-1}·K^{-1}];
t_l—metal temperature in casting [°C];
t_s—solid temperature [°C];
l—latent heat of metal [J·kg^{-1}].

The amount of heat released by the casting to the mold Q_3 can be calculated as follows:

$$Q_3 = \alpha F_{odl}\left(t_l - t_f\right)\tau_l \tag{3}$$

with:

α—heat transfer coefficient [W·m^{-2}·K^{-1}];
F_{odl}—the surface of the casting [m^2];
t_f—mold temperature [°C];
τ_1—time of mold cooling [s].

The amount of heat released with the casting from the mold Q_4 can be calculated as follows:

$$Q_4 = m_k c_s(t_2 - 20) \tag{4}$$

with:

t_2—temperature of the casting removed from the mold [°C].

Consequent modification of Equation (2) to the form of $Q_2 - Q_3 - Q_4 = 0$ and substitution of Equations (3)–(5) will result in the following equation of temperature balance:

$$m_k[c_L(t_l - t_s) + l + c_S(t_s - 20)] - m_k c_s(t_2 - 20) = \alpha F_{odl}\left(t_l - t_f\right)\tau_l \tag{5}$$

1.3. Foundry Alloys Al-Si

Aluminum alloys are widely used in the foundry industry due to their favorable properties, such as low weight, good machinability, and castability. The die casting process is especially popular for producing complex-shaped and high-precision aluminum castings. This process involves injecting molten metal into a mold at high pressure, which results in a high-quality surface finish and dimensional accuracy of the final product. As demand for lightweight and high-performance components increases in various industries, including automotive, aerospace, and consumer electronics, die-cast aluminum alloys are expected to continue to grow [19,20].

Al-Si alloys, also known as silumin, are widely used due to their favorable properties, including low specific weight, high corrosion resistance, and good castability. These alloys have a low tendency to shrink and crack, which makes them suitable for producing thin-walled castings with complex shapes. However, their machinability is slightly worse than other aluminum alloys due to the presence of hard and abrasive silicon particles [21–23].

The selection of the appropriate aluminum alloy for casting depends on both design and foundry properties. Design properties refer to the mechanical properties at standard, low, or high temperatures and the density–strength ratio, corrosion resistance, weldability, and machinability. These properties can be adjusted by selecting the appropriate alloy composition and heat treatment. On the other hand, foundry properties mainly relate to the casting process, including the running-in capacity, low tendency to shrink, low inclination to crack, and clink formation. The foundry properties can be optimized by adjusting the process parameters such as casting temperature, mold design, gating system, and cooling rate [24,25].

The phase structure of Al-Si binary alloys is determined by the Al-Si equilibrium diagram (Figure 1). This diagram shows the phase relationships between aluminum and silicon as a function of temperature and composition. The Al-Si binary diagram is important in determining the processing conditions required to produce castings with the desired properties [3].

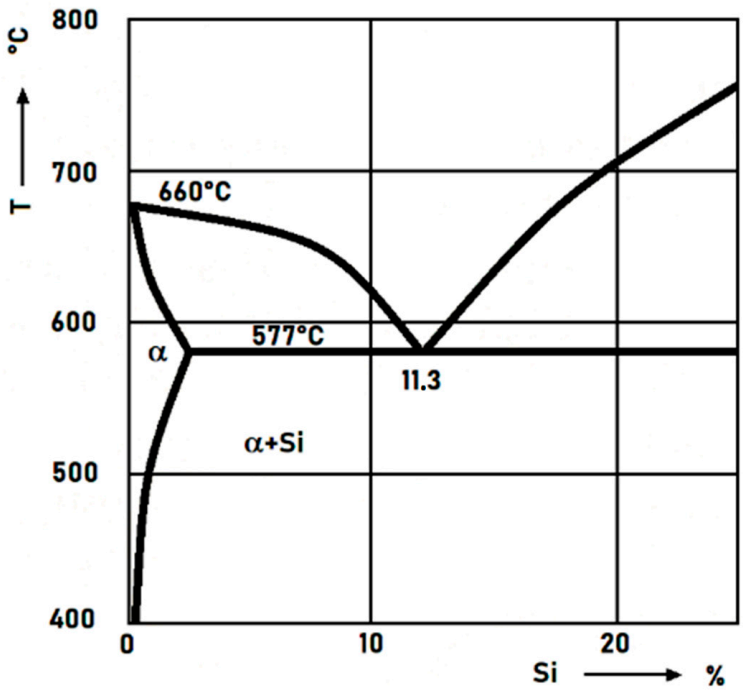

Figure 1. Al-Si binary diagram.

Aluminum has a relatively low melting temperature of around 660 °C, which makes it easily melted and cast into various shapes. Is lightweight with a specific gravity of

about 2.7 g/cm^3, making it ideal for applications where weight reduction is important. Aluminum exhibits excellent electrical conductivity, making it widely used in electrical wiring and components. It also has high thermal conductivity, making it useful in heat transfer applications, and is highly ductile, meaning it can be easily formed and shaped without breaking. This property makes it suitable for various forming processes like rolling, extrusion, and forging. While aluminum possesses good ductility, it generally has lower strength compared to other metals. However, the strength of aluminum can be enhanced through alloying and heat treatment processes. Silicon has a high melting temperature of approximately 1430 °C, making it suitable for applications that require materials with high temperature stability. Like aluminum, silicon has a low specific gravity, which contributes to its lightweight nature. Silicon is a brittle material, meaning it tends to fracture or break when subjected to stress or impact. Its brittleness makes it less suitable for applications requiring high toughness or impact resistance. Both aluminum and silicon have their unique properties and are widely used in various industries and applications [26,27].

Aluminum and silicon form a binary eutectic alloy known as α + Si. The eutectic point represents the composition and temperature at which the alloy has its lowest melting point and exhibits a specific microstructure. The eutectic temperature for the α + Si alloy is typically stated as 577 °C. The eutectic composition of the α + Si alloy is approximately 11.3% silicon by weight. However, it is important to note that different scientific literature may mention slightly different silicon concentration values for the eutectic composition. Understanding the eutectic behavior of the α + Si alloy is crucial for optimizing casting processes, alloy design, and the performance of aluminum–silicon-based materials [3].

The α-phase in Al-Si alloys indeed refers to the solid solution of silicon in aluminum. Its maximum solubility of silicon occurs at the eutectic temperature, which is the temperature at which the alloy composition has the lowest melting point. At the eutectic composition (approximately 11.3% silicon) and temperature (around 577 °C), the α-phase can have a maximum solubility of about 1.65% silicon. However, at lower temperatures, such as around 200 °C, the solubility of silicon in aluminum decreases significantly to about 0.05–0.1%. In binary Al-Si systems, the eutectic is a mixture of the α-phase (aluminum-rich solid solution) and almost pure silicon. The eutectic structure consists of dark grey silicon particles distributed within a light matrix of the α-phase. The amount, shape, size, and distribution of these free silicon particles in the eutectic microstructure can significantly impact the mechanical properties of the Al-Si alloy. For example, the presence of more free silicon can improve the alloy's wear resistance but may reduce its ductility. The distribution of silicon particles also affects the alloy's overall strength and toughness [28,29].

The eutectic structure in Al-Si alloys provides several advantages such as good running capacity and reduced shrinkage, cracking, and microporosity formation. The amount, shape, size, and distribution of free silicon particles within the eutectic microstructure have a significant influence on the mechanical properties of Al-Si alloys. Additionally, the α-phase, which is a solid solution of silicon in aluminum, plays an important role in the alloy's structure and mechanical behavior.

Al-Si-based alloys are commonly classified based on their silicon content. The eutectic composition of the Al-Si binary system is about 11.3% Si, and alloys with Si content below or above this value are referred to as sub-eutectic or supra-eutectic, respectively. The silicon content affects the properties of the alloy, such as its mechanical strength, ductility, and machinability [30,31].

The Al-Si-based alloys (silumin) can be classified based on their hardenability by heat treatment as follows [32,33]:

(a) Non-hardenable alloys, as the name suggests, cannot be hardened by heat treatment. They typically contain 5 to 20% silicon as well as other admixtures, with manganese being the most important one. The addition of manganese to silumin alloys helps eliminate the negative effects of iron impurities. Manganese acts as a scavenger, binding with iron and forming stable compounds, thereby improving the overall quality and performance of the alloy. Adding copper to silumin alloys can increase their endurance strength. Copper

acts as a strengthening element, contributing to the alloy's mechanical properties. However, it is important to note that the addition of copper may slightly decrease the corrosion resistance of the alloy. Eutectic silumin alloys typically have silicon content ranging from 10% to 13%. This silicon content offers a favorable combination of foundry properties and mechanical performance. The eutectic composition ensures good casting characteristics and solidification behavior, resulting in sound and defect-free castings. The strength of silumin alloys can vary depending on the alloy composition and any additional admixtures. Typically, the strength of these alloys ranges from 200 MPa to 300 MPa or higher, with the exact strength influenced by factors such as the silicon, copper, and manganese content. Silumin alloys, especially those with higher silicon content, exhibit good corrosion resistance, particularly in water environments. While the addition of copper may slightly reduce corrosion resistance, the overall corrosion resistance of silumin alloys remains relatively high compared to many other metals and alloys.

(b) Al-Si-based alloys that are hardenable with the addition of Mg or Cu are known as heat-treatable alloys. The addition of Mg or Cu to Al-Si alloys allows the formation of additional strengthening phases, such as Mg_2Si or Al_2Cu, which can increase the strength and hardness of the material. Alloys with these additional elements can be heat-treated to further increase their strength. The ultimate tensile strength of these alloys can exceed 300 MPa, and they can withstand mechanical stress at elevated temperatures ranging from 250 to 275 °C.

1.4. Aluminum Alloys and Their Range of Physical and Mechanical Properties

It is common for the physical properties of materials to be influenced by the presence of impurities or by the specific conditions of the material. Table 1 provides an overview of the key physical properties of Al-Si alloys. However, it is important to note that some of these values can vary significantly depending on the specific composition and processing of the alloy. Additionally, some of the values provided in the table may only be informative and not necessarily directly applicable to a particular use case. It is always important to carefully consider the specific material properties and characteristics when selecting or using Al-Si alloys for a given application.

Table 1. Key properties of aluminum alloys.

Heat conductivity	80–160 $W \cdot m^{-1} \cdot K^{-1}$
Specific heat	900–995 $J \cdot kg^{-1} \cdot K^{-1}$
Heat expansion coefficient	16.5–24 $\times 10^{-6}$ K^{-1}
Melting temperature	475–677 °C
Max. operating temperature	130–220 °C
Electric resistance	2.5–8 $\mu\Omega \cdot cm$
Density	2500–2900 $kg \cdot m^{-3}$

Al-Si-based alloys can be heat-treated to increase their strength and hardness. The choice of heat treatment parameters (time, temperature, quenching medium, etc.) can significantly affect the resulting microstructure and mechanical properties of the alloy. Therefore, the heat treatment process must be carefully controlled to achieve the desired properties [31].

The values presented in Table 2 are informative only, and the actual values of mechanical properties of Al-Si-based alloys can vary depending on various factors such as the composition of the alloy, the manufacturing process, and the testing conditions [34,35].

Table 2. Informative ranges of mechanical properties of Al-Si alloys.

The Young's modulus or Elastic modulus	72–89 GPa
Ultimate tensile strength	228–330 MPa
Yield strength	97–250 MPa
Elongation	2.5–9%
Hardness	65–150 BHN

2. Materials and Methods

For our experiments, we used an $AlSi_9Cu_3$ alloy, and the chemical composition must comply with DIN EN 1706 to ensure the consistency and reliability of the results, as the properties and behavior of the alloy can vary depending on its composition.

The chemical composition of the $AlSi_9Cu_3$ alloy we used consisted of approximately 9% silicon (Si) and 3% copper (Cu), and the rest was aluminum (Al) along with trace amounts of other elements such as iron (Fe), manganese (Mn), and magnesium (Mg). The specific composition may vary slightly depending on the manufacturer or specific application requirements. Figure 2 shows the raw casting component that was used for experimentation.

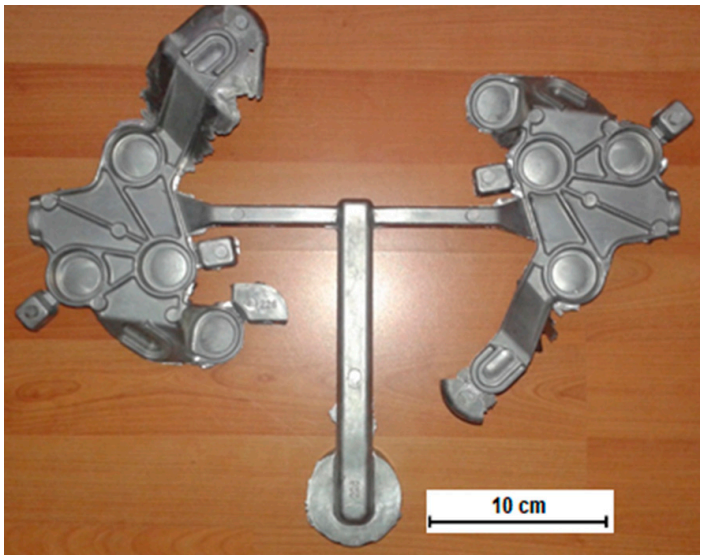

Figure 2. A non-machined component was used for experimentation.

The Al-Si-Cu alloy is commonly used in the automotive industry due to its excellent casting properties and machinability. The addition of Cu improves machinability and allows for automatic hardening after fast cooling in water. The presence of Mg in the alloy helps improve casting properties. Fast cooling leads to the formation of a supersaturated solid solution α (Al), which then precipitates with subsequent structure hardening. This alloy is used in the production of various automotive castings such as engine blocks and gear cases [36,37].

The process of aging (natural hardening) can significantly impact the material's properties, such as its hardness, strength, and ductility. As a result, it is important to consider the time lag between casting and processing procedures to achieve optimal machining conditions. By allowing sufficient time for the material to age, the machining conditions can be improved, and the service life of the tool can be extended. Table 3 provides information on the physical properties of the casting material, including its density, solidus temperature, and liquidus temperature. Table 4 provides information on the mechanical properties of the casting material, including its ultimate tensile strength, yield point, elongation, and Brinell hardness.

Table 3. Physical properties of casting.

Density [g·cm^{-3}]	2700
Solidus temperature [°C]	525
Liquidus temperature [°C]	610

Table 4. Mechanical properties of the casting.

Ultimate tensile strength	min. 240 MPa
Yield point Rp 0.2	min. 140 MPa
Elongation A5	min. < 1
Brinell hardness test HB	min. 80

The experiments were conducted using the die casting machine CLV 250, which is commonly used in the production of castings for the automotive industry. The use of a die casting machine can have an impact on the properties of the casting, as the high pressure can lead to changes in the microstructure and properties of the material. Therefore, it is important to carefully control the parameters of the die casting process to ensure that the resulting casting meets the desired specifications. The basic parameters of production equipment designed to produce castings are shown in Table 5.

Table 5. Operation parameters of die casting machine designed to produce castings CLV 250.

Dimensions	2 × 3.2 × 8.7 m
Weight	27 t
Engine performance	37 kW
Locking force	600 t
Injection force	65 t
Ejection force	35 t
Min./max. mold height	400–900 mm

2.1. Setting of Technological Parameters of Die Casting

To ensure successful casting production, it is important to maintain consistent parameters during the die casting process. The given values provide some of the key parameters used in the experiments, including the plunger speed during chamber and gating system filling, the plunger speed when filling the mold cavity, the melt and mold temperatures, the casting solidification time, and the standard set pressure or holding pressure in the filling chamber. The constant speed of 0.15 m·s^{-1} during chamber and gating system filling ensures that the liquid metal is gradually introduced into the mold without causing any turbulence or defects. Once the chamber is filled, the plunger speed increases to 4.5 m·s^{-1} to quickly fill the mold cavity before solidification occurs. The constant melt temperature of 660 °C and mold temperature ensure that the metal remains in a liquid state and can flow easily into the mold. The casting solidification time of 30 s provides enough time for the metal to cool and solidify before the mold is opened.

The pressure in the filling chamber plays a crucial role in ensuring proper mold filling and achieving the desired casting quality. In the high pressure die casting process, it is essential for the pressure to be sufficiently high to overcome the resistance posed by the solidifying metal in the mold's thin sections and any trapped gases within the casting. To explore the effects of different pressure or holding pressure values on casting quality, the experiments were conducted at various pressure levels, including 22 MPa, 28 MPa (the standard set pressure or holding pressure), and 32 MPa.

2.2. Tensile Test—Strength Limit

A tensile test is a common method used to determine the mechanical properties of materials. Testing specimens are subjected to tension until they reach their breaking point, allowing the ultimate tensile strength to be determined. In this research, the ultimate tensile strength was measured according to ISO standards. The relationship between ultimate tensile strength and the change in pressure-holding parameters with constantly set speed-injected values was examined. To perform the tensile test, a universal TIRA test machine was used as the testing equipment. This machine applies a tensile load to the specimen until it breaks, allowing for the measurement of mechanical properties such as strength and ductility. The results of the tensile test can provide valuable information about the suitability of the material.

2.3. Preparation of Metallographic Specimens for Porosity Detection

Porosity is a common defect that can occur in aluminum castings, and it is often caused by the presence of hydrogen gas. When the aluminum alloy is melted, it can absorb hydrogen gas from the surrounding environment, such as water vapor in the air or moisture in the mold. During solidification, the hydrogen can be released from the melt and form bubbles or pores in the casting, leading to reduced mechanical properties and potential failure under stress. The amount of porosity in casting is influenced by various factors, including the melt temperature, the casting process parameters, and the design of the mold. To ensure high-quality castings, it is important to control these factors and minimize the presence of harmful gasses in the melt [8,37]. The parts of the casting that were identified as potential areas for increased porosity were chosen based on knowledge and experience with similar castings, as well as any visual inspection and non-destructive testing results. These areas may be thinner sections of the casting or areas where the flow of the molten metal is more complex, leading to more potential for gas entrapment. By examining the areas of the casting that are more susceptible to porosity formation and comparing the results for different pressure or holding pressure, we can determine how the variation in pressure affects the formation of porosity in those areas. This information can then be used to optimize the casting process and reduce porosity in the final product.

The use of a circular saw with water cooling (MIKRON manufacturer, Bratislava, Slovakia) and carefully selected technological parameters for cutting the casting were important for obtaining high-quality specimens for further testing. The low compressive force of the cutting wheel and high rotations per minute (3000) ensured a clean and precise cut without causing any damage to the specimens. Additionally, the use of dent acryl resin for casting the specimens ensured their stability and consistency during testing (Figure 3).

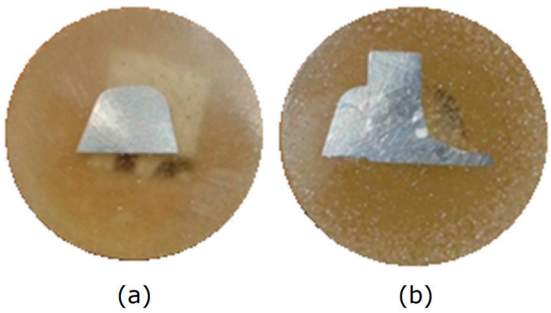

Figure 3. Specimens for (**a**) polishing and (**b**) grinding for optic microscopy.

The process of preparing specimens for examining porosity under a microscope involves carefully controlling the parameters of mechanical grinding with water and polishing with a diamond paste to achieve a smooth and even surface suitable for microscopic examination. The process was carried out using a semi-automatic polishing machine called Struers LaboPol-5. The technological parameters of grinding include the use of sandpaper with a grading of 1200, which is a fine abrasive material suitable for producing a smooth

surface. The revolutions of the grinding wheel were 300 rev·min^{-1}, which is a relatively low speed that is suitable for controlling the amount of material removed during grinding. In the grinding processes, the compressive force exerted by the grinding wheel onto the specimens was selected based on the surface irregularities of the specimens. This adjustment was done to ensure effective material removal and achieve the desired surface finish. One cycle of grinding the surface lasted for 3 min. The specimen had a rough surface, and it required more than one grinding cycle to achieve the desired surface quality. Therefore, the specimens underwent two cycles of grinding, each lasting for 3 min.

After the grinding process, the ground specimens underwent further preparation, which involved polishing using the same machine but with a polishing wheel. Polishing is an essential step to refine the surface finish and achieve the desired level of smoothness and shine. During the polishing process, diamond pastes with diverse grading were used. The first step in polishing was to use diamond paste with a lubricating component DiaDuo with a grading of 3 μm. This paste was applied manually by estimation, and the amount of polishing paste added dropwise onto the polishing wheel is indicated by the machine while polishing. The second step in polishing was to use diamond paste with a grading of 1 micrometer. This step was carried out for one cycle, lasting for 3 min. The technological parameters of polishing include revolutions of the wheel set at 150 rev.min-1, which is a relatively low speed suitable for controlling the amount of material removed during polishing. The polishing process involves using two different diamond pastes with specific grading sizes. The period of a single polishing cycle for both diamond pastes was 3 min. For the diamond paste with a grading of 3 μm, the specimen was subjected to one polishing cycle. Each polishing cycle lasted for 3 min. For the diamond paste with a grading of 1 micrometer, the specimens undergo one polishing cycle lasting for 3 min. By performing multiple polishing cycles with the appropriate diamond pastes, the goal was to gradually refine the surface and achieve the desired level of smoothness and surface quality. The use of different grading sizes allowed for progressive polishing, starting with a coarser grade and progressing to a finer grade, resulting in a high-quality polished surface on the specimens.

The final quality of the polished specimens was checked using the microscope 2303 Intraco Micro with a trinocular head. The examination of all three specimens determined which of them met the required quality standards and which of them needed to be re-polished. The specimens that met the required quality standards were used for porosity evaluation. The evaluation of porosity in the casting involved using the optical microscope 2303 Intraco Micro. The scratch pattern of each specimen was imported into a camera interface to produce a final image for evaluation to ensure accurate porosity assessment and specific areas of the specimens were selected for analysis. These areas needed to be perfectly polished to prevent any scratches, dents, or cracks from being mistaken as pores by the software. The final images of the specimens, obtained through the microscope, were then processed using image analysis software called Stream Motion, developed by the Olympus Company. Graphic filters in the program were used to evaluate porosity. These filters were set to find a specific color in the evaluated image. Each filter had a defined sensitivity that prevented interference in the detection zone of another filter. Before the measurement, the filters were set to an adequate sensitivity to detect only the pores. The analysis of the objects in the images was then performed by the program to find all the required conditions, such as color and size, for the evaluation of pores. The program saved the results of all specimen values in tables.

3. Results

The experiments focused on investigating the impact of specific technological parameters of die casting machines on the mechanical properties of the castings produced through the die casting process. The primary parameters studied were the pressure and holding pressure in the filling chamber. The ultimate tensile strength, porosity, and structure of the castings were the key properties analyzed about these parameters.

3.1. Evaluation of Ultimate Tensile Strength

Figure 4 shows the measured values of ultimate tensile strength at constant plunger speed (4.5 m·s^{-1}) in the filling chamber for the different levels of pressure or holding pressure in the mold cavity (22, 28, and 32 MPa). As ultimate tensile strength is a key parameter for evaluating the mechanical properties of castings, the results provide important information on the effect of different process parameters on the mechanical strength of the castings.

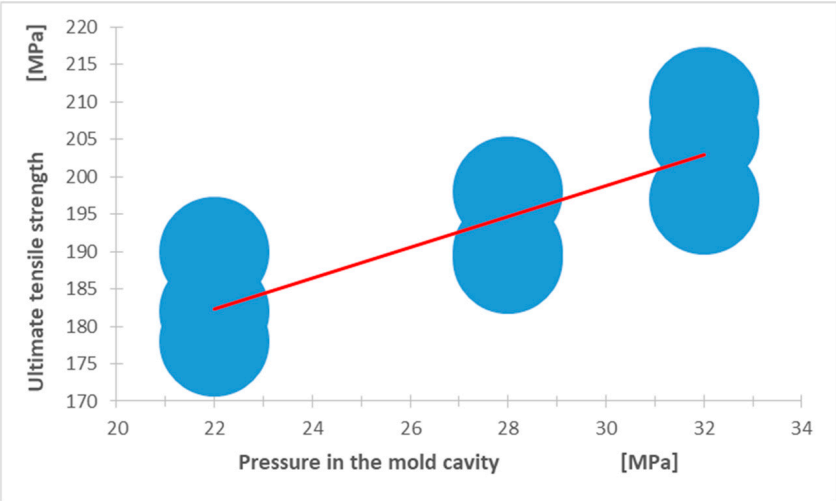

Figure 4. Dependence of ultimate tensile strength on the change of pressure in the mold cavity.

The experimental data (Figure 4) demonstrate the relationship between the change in pressure or holding pressure in the mold cavity and the measured ultimate tensile strength of the castings. The graph indicates that as the pressure or holding pressure in the mold cavity increases, there is a corresponding increase in the values of ultimate tensile strength. The upward trend observed in Figure 4 suggests that higher pressure or holding pressure in the mold cavity during the die casting process leads to the improved ultimate tensile strength of the castings. This indicates that increasing the pressure helps to enhance the mechanical properties and strength of the castings. In the case of higher-pressure values, the undesired phenomenon of slight mold opening occurred with consequent injection in the dividing plane during the forcing-in process. The measured values can be used to determine the optimal pressure or holding pressure levels in the mold cavity for achieving the desired ultimate tensile strength of the castings. For instance, if the desired ultimate tensile strength is 200 MPa, the results in Figure 4 can be used to select the appropriate pressure or holding pressure level that can produce castings with the desired strength. Overall, the evaluation of ultimate tensile strength is crucial in assessing the mechanical properties of castings and optimizing the die casting process for producing high-quality castings.

3.2. Macro and Microscopic Analysis

We carried out a macroscopic and metallographic analysis to investigate the causes of the inhomogeneity of mechanical properties. After carrying out the tests intended for the evaluation of the tensile strength limit depending on the change in the pressing speed of the piston and the pressure or pressure in the mold cavity, the test rods (Figure 5) were subjected to macro- and microscopic analyses. Metallographic analysis showed that in all analyzed samples the structure is the same and is so by the chemical composition and the action of pressure during crystallization.

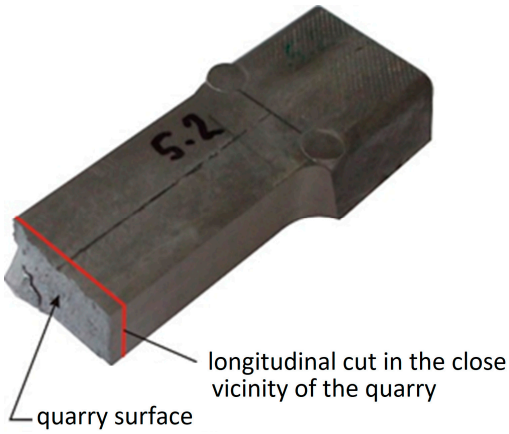

Figure 5. Sampling scheme for the evaluation of the porosity of the test rod.

3.3. Evaluation of Casting Porosity

The porosity of casting was evaluated using an optical microscope, and the resulting images were analyzed using Stream Motion software (Figure 6). The software uses graphic filters with defined sensitivity to detect and evaluate pores in the images. Before measurement, the filters are set to an appropriate sensitivity level to ensure that only pores are detected. The objects in the images that meet all required conditions and differ in color from their environment are analyzed, and the program saves the results of all specimen values in tables, which are then used to generate graphical representations of the data.

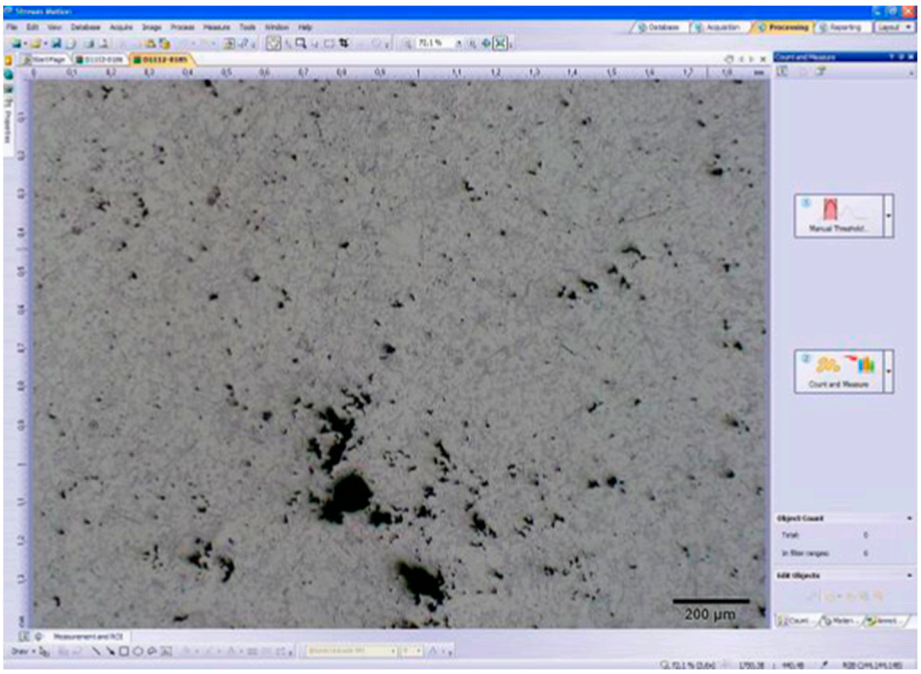

Figure 6. Evaluation of casting porosity in the Stream Motion.

Figure 7 displays photographs that were used for the casting porosity analysis, and, for each specimen, three independent spots were selected to measure and evaluate porosity. It was necessary to select spots that were perfectly polished to avoid any scratches, dents, or cracks in the specimens that could be mistakenly evaluated as pores by the software. If such imperfections were included in the analysis, the porosity measurement results would be misrepresented, and the software could potentially overestimate the occurrence of porosity. Therefore, it was important to ensure that the selected spots were free of any such imperfections to obtain accurate measurements of the porosity of the casting.

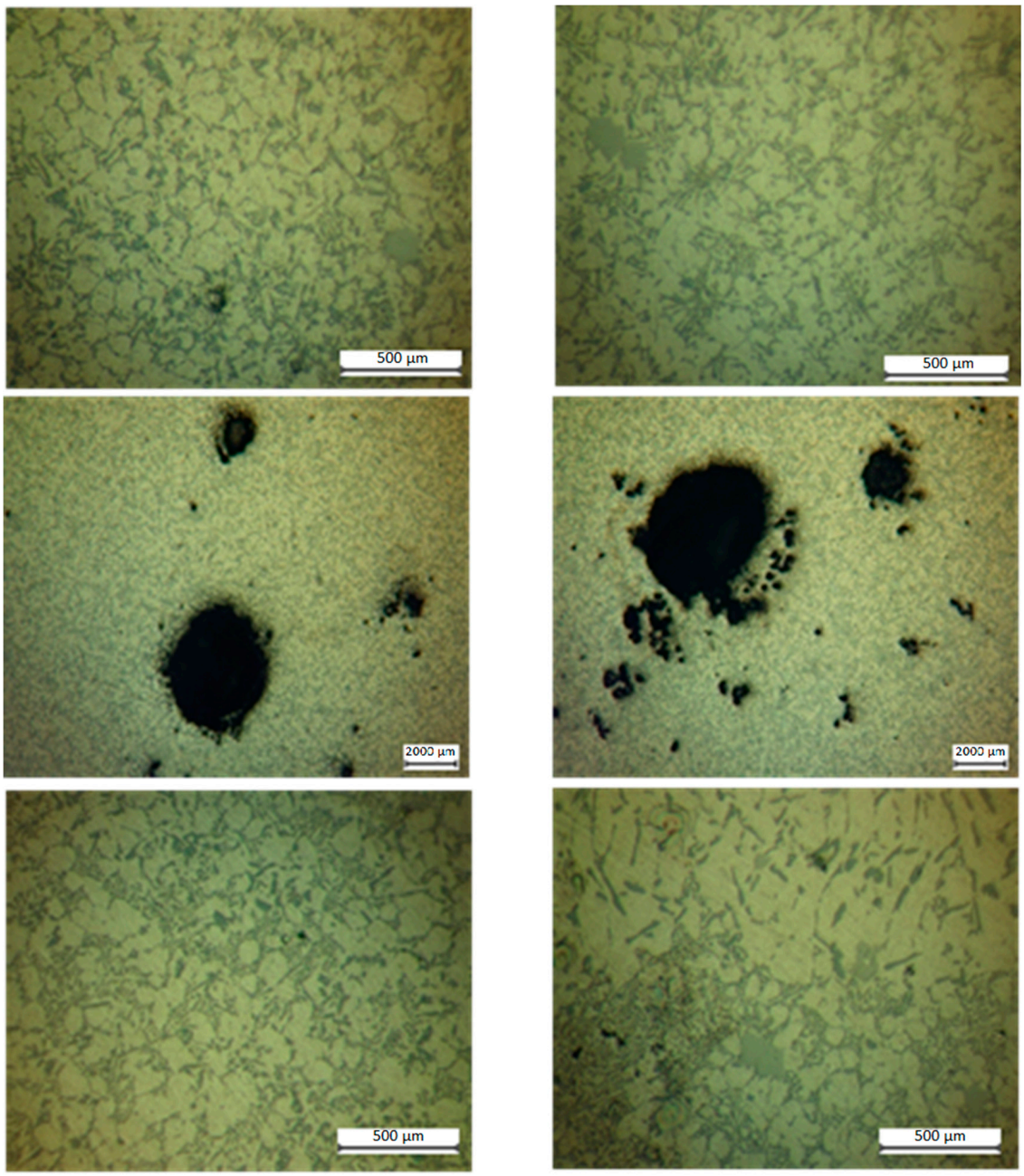

Figure 7. Metallographic photographs of specimens obtained by optical microscopy.

According to the graphical representation shown in Figure 8, there is a decrease in porosity when the pressure or holding pressure in the mold cavity increases. The decrease in porosity with increasing pressure or holding pressure indicates that higher pressures exerted during the die casting process led to a denser and more compact internal structure of the castings. The measured values of the porosity in the examined samples support this conclusion. It is important to note that the decrease in porosity may not continue indefinitely with increasing pressure or holding pressure. At some point, the porosity may reach a minimum value, and further pressure increases may not result in a significant decrease in porosity. It is also possible that excessive pressure or holding pressure could lead to other defects in the casting, such as cracking or distortion, and, therefore, the optimal pressure or holding pressure must be determined based on a careful evaluation of the casting quality.

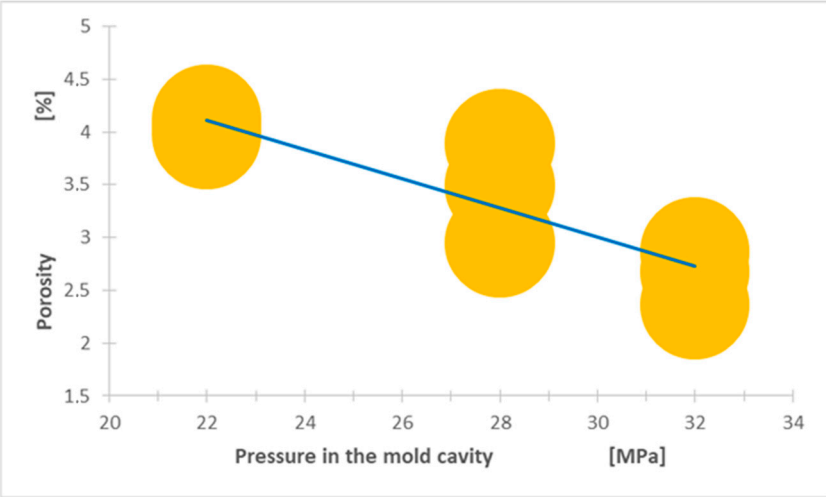

Figure 8. Porosity dependence on the change of pressure in the mold cavity.

As shown in Figure 8, there is a clear correlation between the change in pressure or holding pressure in the mold cavity and the porosity values of the casting. As the pressure or holding pressure increases, the porosity values decrease, which is generally considered desirable for castings. This is because a lower porosity typically results in higher mechanical properties and better overall quality of the casting. However, it is important to note that the relationship between pressure and porosity is not linear, and, at some point, further pressure increases may not result in significant improvements in porosity or other mechanical properties. Therefore, it is important to determine the optimal pressure or holding pressure based on careful evaluation of the casting quality and other relevant factors.

3.4. Analysis of Structures

The structure of the analyzed test rods is consistent with the composition of the alloy. It is formed from alpha solid solution excluded primarily and eutectic consisting of an alpha solid solution and silicon. The presence of very fine crystals in the band of the solidified casting near the face of the mold (Figure 9) is typical for all analyzed samples, and the thickness of this band varies from a few µm to 1 mm. This band is known as the "fine crystal band," and it is a result of the cooling process during the casting of the test rods. The transition from the fine crystal band to the area of the coarser structure is smooth, indicating that the cooling process was consistent throughout the test rods. Overall, these findings provide valuable information on the microstructure and properties of the test rods, which can be used to optimize the manufacturing process and improve the quality of the final product.

The formation of a band of fine structure is related to the degree of undercooling at the face of the mold, which in turn depends on the temperature of the mold, the location of the notch, and the method of filling the mold. Assuming the same temperature of the mold, when the melt flow hits the cold wall of the mold, which has a lower temperature than the melt, crystallization occurs with a very high degree of undercooling and a precisely defined direction of heat removal. This creates a band of fine crystals with preferential orientation in the direction opposite to the direction of heat removal. However, further crystallization takes place when thermal and pressure conditions are changed, which leads to a violation of the directionality of solidification. In this case, the filling mode of the mold may prevail over the heat removal rate, leading to a variation in the structure of the test rods.

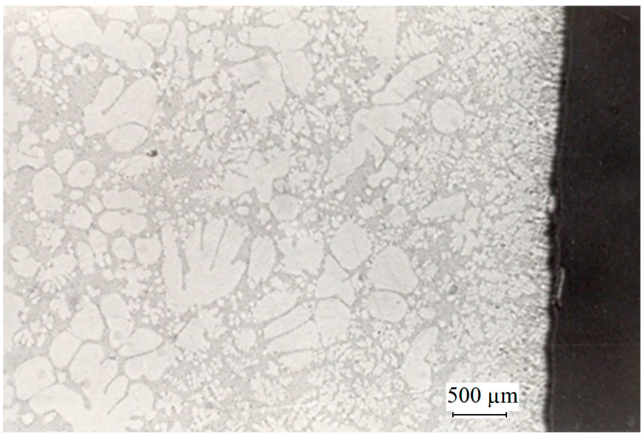

Figure 9. Microstructure of the edge part of the sample.

According to the standards, it can be difficult to assess the beta phase in die castings, and even at a 2000-fold magnification, the readability of the structure may be indistinct. To overcome this challenge, the morphology of the eutectic silicon was analyzed using a growth electron microscope (REM). This technique allows a more detailed analysis of the structure at a higher magnification, providing greater clarity and accuracy in the determination of the morphology of silicon. The results of these observations are documented in Figures 10 and 11, which provide valuable information on the morphology of the eutectic silicon in the test rods. This information can be used to optimize the manufacturing process and improve the quality of the final product, as the morphology of the eutectic silicon can significantly impact the properties of the alloy.

In Figures 10 and 11, the dark areas represent the alpha solid solution, while the white particles represent the eutectic silicon. Upon enlarging the area on which the eutectic occurs (Figure 11), it is possible to see the joining together of individual eutectic cells, which is manifested in the image by light, curvilinear strips of different lengths. This may be related to the application of pressure during crystallization and the position of the boards in the plane of the cut. The observation that due to pressure in the structure, only quantitative changes take place to reduce the structural parameters is significant. This conclusion encourages further investigation into the possibilities of modifying eutectic silicon with surface-active elements during pressure casting to achieve its branching with very favorable dimensional parameters.

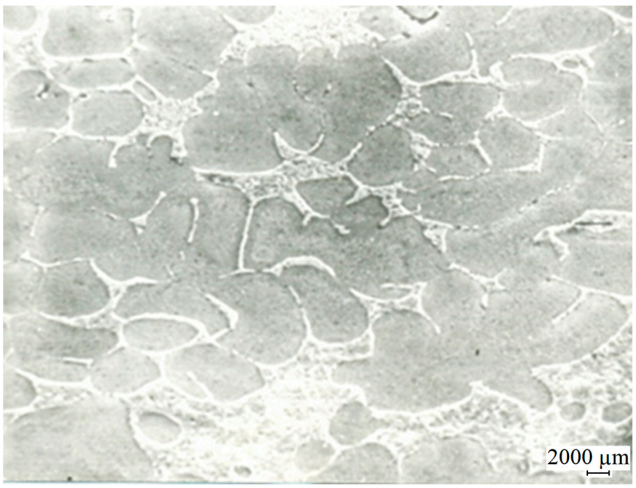

Figure 10. Basic structure.

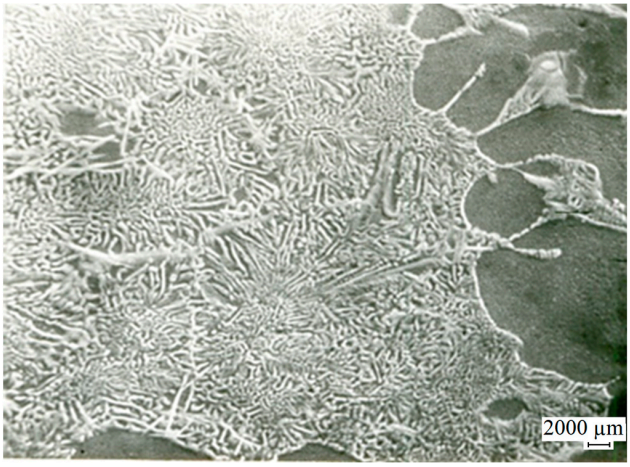

Figure 11. The cohesion of eutectic cells.

3.5. Analysis of Foundry Errors

Based on a macroscopic point of view, the fracture of super eutectic silumin is brittle and planar, and it is arranged perpendicular to the tensile force. This type of fracture occurs when the alloy contains many fine particles that do not allow for internal plastic deformation of small volumes of metal between the particles with a small proportion of macroscopic deformation. The brittle phase in super eutectic silumin is the eutectic silicon. During loading, brittle failure occurs due to the splitting of unmodified silicon. This can be attributed to the fact that the eutectic silicon in the alloy is not modified with surface-active elements, which would allow for its branching and improve the dimensional parameters. As a result, the unmodified eutectic silicon acts as a stress concentrator, leading to the brittle fracture of the material.

The macroscopic analysis of the fracture surfaces of the analyzed samples revealed that the fracture was caused by low-energy ductile tearing and had a brittle appearance (Figure 12). The initiation of the fracture was mainly due to foundry errors, which may have led to the presence of defects in the material such as pores, inclusions, or other discontinuities. These defects act as stress concentrators, leading to the initiation and propagation of cracks which result in the fracture of the material.

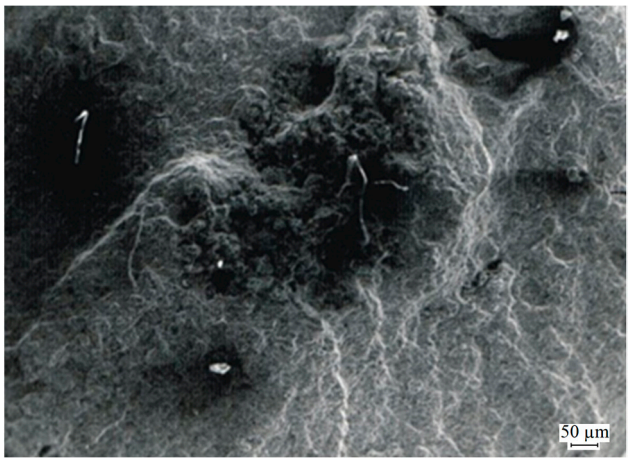

Figure 12. Macroscopic view of the quarry.

The microscopic analysis of the fracture surfaces of the analyzed samples revealed that the nature of the failure was the same for all samples. As shown in Figure 13, a typical violation of the alpha phase dendrites and eutectic was observed. In addition, several foundry defects were observed on the fracture surfaces:

1. Cavities with a surface formed by dendrites: These are voids or cavities that form during the solidification process due to the shrinkage of the material. The surface of the cavity is lined with dendrites, which are the result of the growth of the primary solid phase during solidification. The presence of these cavities can act as stress concentrators and promote crack initiation and propagation. In addition, between the dendrites, a membrane of Al_2O_3 oxide was observed, which can further weaken the material.
2. Al_2O_3 particles: These are small particles of Al_2O_3 oxide that are present in the material. These particles can act as stress concentrators and promote crack initiation and propagation.

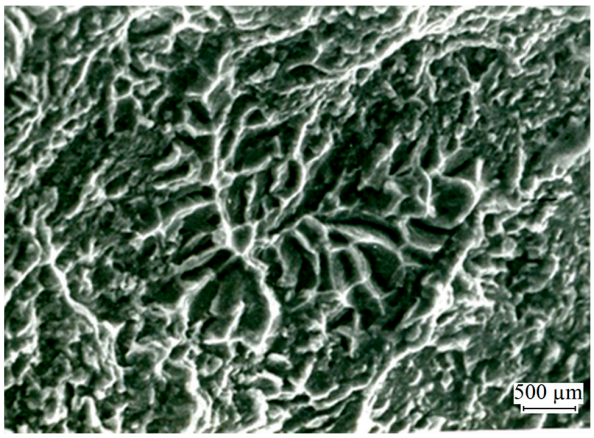

Figure 13. The nature of breaking α solid solution dendrites and eutectics.

It is important to note that the presence of these foundry defects can affect the mechanical properties of the material and reduce its strength and ductility. Therefore, it is crucial to minimize and control the occurrence of these defects during the casting process to ensure the quality and reliability of the final product.

It is not uncommon for gas to be trapped in the mold during the casting process, leading to the formation of bubbles or voids in the final product. These voids can weaken the structural integrity of the casting and lead to failure under stress. The voids or bubbles observed in the analyzed samples were caused by the trapping of gases and air in the mold during the casting process. These voids are classified as type 1 errors and are likely due to the turbulent flow of the melt during casting (Figure 14). Given the wall thickness of the castings, their fine-grained structure near the mold face, and the applied pressure, it is unlikely that hydrogen exclusion was the cause of these voids.

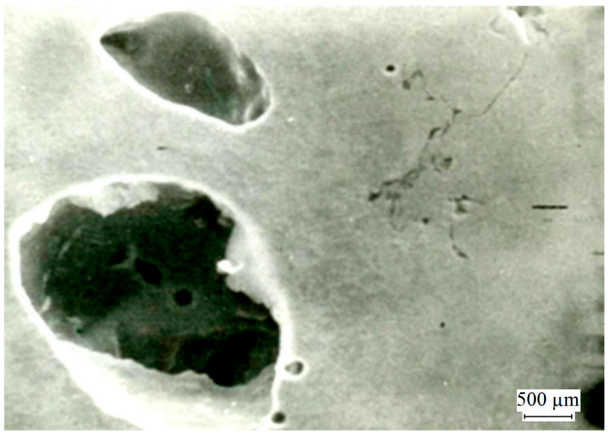

Figure 14. Exogenous bubble on metallographic cut.

The presence of Al_2O_3 (Figure 15) and detail (Figure 16) particles can indicate the presence of non-metallic inclusions in the alloy, which can originate from a variety of sources, including the alloying elements, refractory materials used in the melting furnace or casting equipment, or the atmosphere in which the casting process takes place.

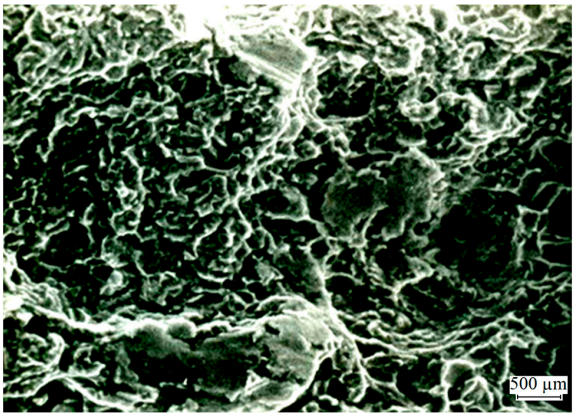

Figure 15. Al_2O_3 particles on the fracture surface.

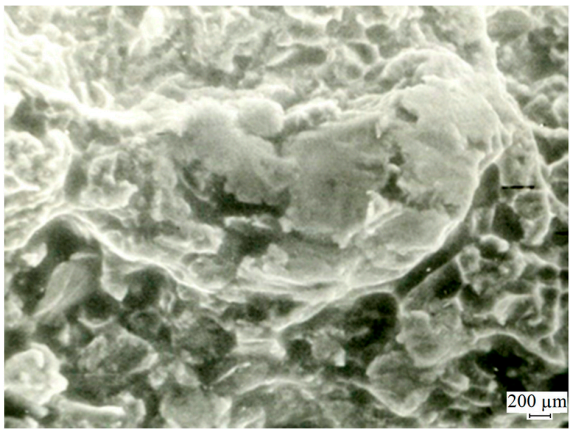

Figure 16. Detail from Figure 15.

The presence of groups of Al_2O_3 (Figure 17) particles suggests that they may have been introduced into the melt in clusters, possibly due to contamination of the raw materials or poor mixing of the melt. It is important to minimize the presence of non-metallic inclusions in the alloy to improve its mechanical properties and reduce the risk of quarry and failures.

Figure 17. Grouping of Al_2O_3 particles.

Al_2O_3 particles have a greater effect on reducing mechanical properties than bubbles, whereas they act as stress concentration points and can cause local weakening of the material, leading to decohesive failure. This can reduce the overall strength and toughness of the material, especially if the concentration of Al_2O_3 particles is high. Therefore, it is important to minimize the occurrence of such particles in the casting process.

4. Conclusions

Based on the results of the performed experiments, several conclusions can be drawn regarding the effect of pressure or holding pressure on the tensile strength limit and porosity of castings produced in the pressure casting process:

- The experiments showed that higher values of holding pressure can have both positive and negative effects. On the positive side, higher holding pressure can improve the filling of castings by reducing the amount of air trapped in the casting, leading to a decrease in porosity. This results in an overall increase in the quality of the internal structure of the castings. However, it was observed that higher holding pressure values can also lead to a shorter life of the mold and increased downtime during the pressure casting process.
- The experiments revealed that higher pressure values can lead to an undesirable condition where the mold is slightly opened with subsequent injection in the parting plane during the pressing process. This indicates that excessively high-pressure values can cause mold-related issues and affect the integrity of the castings.
- The research findings establish a clear connection between the chosen technological parameters, i.e., pressure or holding pressure, and the resulting mechanical properties and quality of the castings produced in the pressure casting process. Measured tensile strength values and porosity values are largely related.
- The monitored technological parameters—pressure or pressure in the mold cavity together with the closely related temperature conditions in the pressure casting—are among the basic factors that affect the quality of the final casting.
- In addition to pressure or holding pressure, other parameters such as injection speed, melt temperature, and cooling can also influence the resulting properties of the castings. In the conducted experiments, these parameters were kept constant to isolate the specific effect of pressure or holding pressure on the castings. However, it is important to note that in real production scenarios, these parameters would typically vary, and their interaction with pressure or holding pressure may affect the final quality of the castings.
- The effect of ideal input conditions on the final quality of castings cannot be definitively determined in a general sense. The impact may vary depending on the specific casting design, material, and production environment. Therefore, it is essential to conduct comprehensive studies and experiments, considering various process parameters, to understand their individual and combined effects on the resulting properties and quality of the castings.

The influence of technological parameters, such as pressure or holding pressure, on the final mechanical properties of castings and the inner structure is consistent with the findings of other researchers in the field of die casting [13,14,32]. This indicates a common understanding and agreement on the impact of these parameters on the quality of castings. Increasing the holding pressure consistently leads to a decrease in the percentage share of porosity in castings. This correlation highlights the importance of pressure control in minimizing porosity and improving the overall quality of the castings.

From the comparison of the conducted research, conclusions can be drawn that:

- Measured values are specific and valid for the selected combination of technological parameters and selected material, and, when evaluating the results, it is necessary to consider the testing conditions and the possible occurrence of errors.
- The achieved results can serve as a foundation for the technical preparation of casting production. They provide valuable insights for optimizing the properties and quality of

castings. These results can be used as a starting point for determining the appropriate values of the examined technological parameters based on the quality requirements of specific types of castings.

- The research findings highlight the need to take appropriate measures when optimizing the input technological parameters in the pressure casting process. For example, increasing the pressure or pressure in the mold cavity should be done in a way that does not compromise operator safety, the service life of the mold cavity, or the idle time of the pressure casting machines.
- Knowledge describing the interrelationship and relationship between the technological parameters of pressure casting and the final properties of castings represents an important aspect of technological practice that affects the required final quality of castings and increases the efficiency of the entire production process.
- From the perspective of achieving increasing production efficiency, reducing the occurrence of defective pieces, and quality of castings, it is important to optimally set the technological parameters of pressure casting. The research confirms that appropriate parameter settings are vital for achieving the desired outcomes.

Conducting research and implementing inspections in various casting establishments can greatly contribute to maintaining and improving the final quality of castings. It is crucial to monitor the production process and periodically inspect the properties of the castings, especially in cases where a higher amount of returnable material is used.

Scheduling regular inspections helps identify any undesirable changes in the composition of the melt, which can have a significant impact on the resulting casting quality. By detecting such changes early on, companies can take corrective measures to ensure consistent and desired casting properties.

For companies experiencing a growing trend of customer complaints or encountering defects and errors in manufactured components, it is highly recommended to introduce inspections specifically focused on testing the mechanical properties and internal structure of the castings. This helps identify any issues related to the input technological parameters that affect the final quality of the castings.

While inspections and additional testing activities do incur costs, they are considered a worthwhile investment for companies seeking to improve quality and meet customer requirements. By proactively addressing quality concerns, companies can minimize the occurrence of defects, reduce customer complaints, and enhance overall customer satisfaction. Moreover, the long-term benefits, such as improved reputation and customer loyalty, outweigh the initial investment in inspections and testing.

Therefore, companies in the casting industry need to prioritize quality improvement measures and consistently invest in inspections and research to ensure high-quality castings and meet the expectations of their customers.

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