The Influence of Cooling Rate on Microstructure and Mechanical Properties of AlSi9Cu3

Matic Žbontar *, Mitja Petrič and Primož Mrvar

Department of Materials and Metallurgy, Faculty of Natural Sciences and Engineering, University of Ljubljana, 1000 Ljubljana, Slovenia; mitja.petric@omm.ntf.uni-lj.si (M.P.); primoz.mrvar@omm.ntf.uni-lj.si (P.M.)

* Correspondence: matic.zbontar@omm.ntf.uni-lj.si

Abstract: The aim of this study was to determine the correlation between the size and the distribution of microstructural constituents and their cooling rate, as well as the correlation between the mechanical properties and the cooling rate of AlSi9Cu3 aluminum alloy when cast in high-pressure die casting (HPDC) conditions. In other words, the ultimate goal of the research was to determine the mechanical properties for a casting at different cooling rates. Castings with different wall thicknesses were chosen, and different cooling rates were assumed for each one. Castings from industrial technological practice were systematically chosen, and probes were extracted from those castings for the characterization of their mechanical properties. Special non-standard cylinders were created on which compressive tests were carried out. The uniqueness of this research lies in the fact that the diameters of the designed cylinders were in direct correlation to the actual wall thickness of the castings. This is important because the solidification of metal in the die cavity is complex, in that the cooling rates are higher on the surface of the casting than in the center. Local in-casting cooling rates were determined using numerical simulations. It was discovered that with increasing cooling rates from 60 K/s to 125 K/s the values for strength at 5% deformation increased on average from 261 MPa to 335 MPa.

Keywords: HPDC; aluminum alloy AlSi9Cu3; cooling rate; solidification processes; mechanical properties

1. Introduction

Aluminum castings were the first important market soon after the commercialization of the electrolytic extraction of aluminum according to the Hall–Héroult method. Aluminum alloys were first used for decoration purposes due to their shine and low weight, and soon after they were competing with cast iron and bronze in the field of kitchen equipment. Aluminum castings became economically suitable for applications in industry after the gradual decrease in the price of aluminum at the end of the 19th century. The characterization of their physical and mechanical properties with performance testing were crucial factors for the constant development of new alloys. The invention of casting in permanent molds and pressurized filling as alternatives to sand casting have additionally promoted the development of new alloys which have had to be suitable for application and for the development process itself [1].

High-pressure die casting (HPDC) is the process of filling a cavity at a high speed and pressure in a preheated, usually steel (hot working tool steel) mold or tool, which enables the production of thin-walled castings and short production cycles. The cooling rates are very high, generally between 50 and 125 K/s, which has a direct effect on the size of the microstructural constituents, and that is why in most cases HPDC aluminum foundries do not use grain refinement and/or modification of the melt [2]. The arrival of aluminum alloy AlSi9Cu3 in the industry—also marked as 226 D according to German VAR and EN AC-46000 according to German DIN EN 1706 [3]—is the most commonly used...
alloy in the application of HPDC. A high percentage of silicon ensures good castability, while the addition of copper improves the machinability and mechanical properties of the casting. Solidification of aluminum alloy with silicon, copper, and iron was studied by Arnberg and Bäckerud [4]. The process starts with the nucleation of dendrite-shaped crystals of $\alpha_{\text{Al}}$ at 575.6 °C. With further cooling these particles grow, and at the coherency point the solid fraction solid is 11 vol. %. During dendrite thickening, and also later during $\alpha_{\text{Al}} + \beta_{\text{Si}}$ eutectic crystallization (which starts at 566 °C) intermetallic phases with iron form ($\text{Al}_{15}(\text{FeMn})_{3}\text{Si}_2$ or $\text{Al}_3\text{FeSi}$). At 503 °C when the solid fraction is 94 vol. %, $\text{Al}_2\text{Cu}$ starts forming, and in the last percent of the liquid phase, complex eutectic $\text{Al}_6\text{Mg}_2\text{Cu}_2\text{Si}_6$ is formed. Solidification is finished at 490 °C. The critical temperature at which the additional flow of melt through dendrites is limited is said to be 562 °C. At this temperature, eutectic crystallization is already taking place, and that is why mechanical properties are highly dependent on eutectic structure—that is, on the size and shape of the eutectic grains, which can be manipulated with the cooling rate [4]. The effect of cooling rate on the microstructure of $\text{AlSi9Cu3}$ cast in a permanent conically shaped mold has already been studied [5]. It was found that the grain size of primary aluminum dendrites decreased from 850 µm to 541 µm when the cooling rate was increased from 16 K/s to 100 K/s. The decrease in grain size of silicon particles was even more significant, from 52.2 µM to 12.8 µM for the same change in cooling rate. Casting failures on micro and macro levels such as macro porosity, micro shrinkage, hot tearing, gas and oxide film entrapment, non-metallic inclusions, and others [6–10] can also considerably or insignificantly affect the mechanical properties of the casting. The mechanical properties of high-pressure die-cast $\text{AlSi9Cu3}$ or similar were already extensively studied, but mostly with tensile testing of as-cast tensile probes. Szalva and Orbulov studied the effect of porosity on the mechanical properties (through tensile strength and strain) of $\text{AlSi9Cu3(Fe)}$ using as-cast tensile specimens [11]. Lumley, Deeva, and Gershenzon also used as-cast cylindrical and flat tensile specimens to study the correlation of casting defects on the mechanical properties of A380 alloy [12]. Adamane and co-authors summarized the effect of injection parameters on the porosity and tensile properties of die castings in their literature review [13]. Keru and Serçe in their work on the effects of injection parameters on the mechanical properties and porosity of as-cast A383 alloy specimens also used tensile tests to determine their mechanical properties [14]. It is also evident from recent studies in the field of aluminum matrix composites that researchers prefer to choose tensile strength measurements to evaluate the mechanical properties of alloy specimens. Kumar et al. [15] used flat test specimens to determine the strength and elongation of reinforced aluminum–silicon composites. The works mentioned above all used as-cast tensile specimens to describe the mechanical properties. In the present study, the mechanical properties are determined on specimens taken from the actual casting, which have relatively thin cross sections. The specimens are therefore very small and the mechanical properties are described using results from compression tests.

2. Materials and Methods

Figure 1 shows the timeline for the first part of the experimental procedure. The experimental work was carried out during the series production of castings with HPDC technology. Five whole shots were selected (hereafter referred to as castings Nos. 1 to 5) at random, carefully noting all parameters and conditions.
Figure 1. The first stages of the experimental procedure timeline.

As can be seen from Figure 1, the preliminary cycle was used to check the temperature field of the tool before and after spraying and air blowing. A FLIR i3 thermal imaging camera (FLIR Systems, Inc., Wilsonville, OR, USA) and the FLIR Tools computer application (FLIR Systems, Inc., Wilsonville, OR, USA) were used to record the temperatures. An average of all temperatures over the entire area of the mold excluding the casting system was considered. Thermal analysis using a CompactDAQ NI 2911 converter (National Instruments Corp., Austin, TX, USA) was performed in a sand measuring cell equipped with type K thermoelement (hereafter referred to as GSC—the gravity sand cast sample) and another sample cast in a steel mold (hereafter referred to as GDC—the gravity die cast sample), both at room temperature, at the beginning of the cycle.

Chemical analysis was performed using a SPECTROLAB spectrometer (SPECTRO Analytical Instruments, Kleve, Germany). The chemical composition of materials for casting Nos. 1 to 5 are presented in Table 1. All samples analyzed were inside the tolerance region according to standard DIN EN 1706.

Table 1. The chemical composition of samples for castings Nos. 1 to 5.

| Casting No. | 1     | 2     | 3     | 4     | 5     |
|------------|-------|-------|-------|-------|-------|
| Element    |       |       |       |       |       |
| Si         | 8.98  | 8.86  | 9.02  | 8.99  | 8.75  |
| Fe         | 0.541 | 0.533 | 0.548 | 0.561 | 0.524 |
| Cu         | 2.172 | 2.045 | 2.219 | 2.179 | 2.173 |
| Mn         | 0.3059| 0.3108| 0.3045| 0.3135| 0.3034|
| Mg         | 0.2595| 0.2429| 0.2530| 0.2407| 0.2441|
| Zn         | 0.593 | 0.589 | 0.584 | 0.587 | 0.593 |
| Ni         | 0.0493| 0.0454| 0.0510| 0.0499| 0.0471|
| Cr         | 0.0514| 0.0516| 0.0517| 0.0535| 0.0498|
| Pb         | 0.0694| 0.0650| 0.0674| 0.681 | 0.0665|
| Sn         | 0.0151| 0.0134| 0.0149| 0.0144| 0.0138|
| Ti         | 0.0496| 0.0500| 0.0508| 0.0503| 0.0496|
| Ca         | 0.0039| 0.0034| 0.0050| 0.0037| 0.0036|
| Sr         | 0.0007| 0.0007| 0.0007| 0.0007| 0.0007|
| Al         | 86.9  | 87.2  | 86.8  | 86.9  | 87.2  |

The cylindrical specimens for the compression test were dimensioned in the CAD program SolidWorks (Dassault Systemes, Velizy-Villacoublay, France) and are shown on a transparent model in Figure 2. These specimens were cut from the castings (Nos. 1 to 5) using the Haas VM3 CNC cutting machine (Haas Automation, Inc, Oxnard, CA, USA).
Samples for metallography were also taken from the same areas of the castings. The diameters of the specimens were directly proportional to the wall thickness of the area from which they were taken, and the height of the specimens was 1.2 times the diameter (H = 1.2 d). For each sample size, multiple areas were planned for collection to ensure reliability and repeatability, as shown in Figure 2 (3–4 samples per sample size).

![Figure 2. Cylindrical specimens of different diameters (3, 4, 6 mm) shown in a transparent 3D-model of the casting (HPDC- high-pressure die casting).](image)

2.1. Compression Tests

The specimens were taken from thin walls of the castings, and could therefore only be small and cylindrical, so compression tests were used to study their mechanical properties. It was also assumed that defects typical of the HPDC process would have less influence in the compression test than in the tensile test.

Cylindrical specimens cut from castings were compressed at room temperature at a deformation rate of 1 s⁻¹ on a Gleeble 3500 machine (Dynamic Systems Inc., Poestenkill, NY, USA). The machine measured the displacement of its jaws and the force applied to the specimen. From the data on deformation, stress, and rates of movement, stress–strain diagrams were drawn in Origin 9 (OriginLab Corporation, Northampton, MA, USA), from which the mechanical properties were determined. The mechanical properties were plotted in terms of R₅ (strength at first fracture—seen as a large change in strength on the graph), ε₅ (deformation as a percentage at R₅), and R₅. The measurement system used was not accurate enough to determine with certainty the elastic and plastic deformation area, so the strengths of the specimens were compared at 5% of the total elastic and plastic deformation. The specimens are shown in Figure 3. From left to right, two specimens with diameter 3 mm (small), two specimens with diameter 4 mm (medium), and two specimens with diameter 6 mm (large). The specimens are shown as examples to see the differences in dimensions. One sample of each size (S, M, L) from each of the five castings considered was prepared for the compression test.
Simulations were performed with the aim of finding local cooling rates in the castings using ProCast software (ESI Group, Paris, France) based on the finite element method. Volumes for casting with overflows, runner, chamber, and plunger were imported, and the tool volume was dimensioned simply to cover the whole shot. Triangular elements were chosen to generate the surface mesh; the element size was set to 1.3 mm for the casting volume and the smallest elements (0.8 mm) were defined at the edges of the gates. The surface mesh consisted of 142,278 triangles. A 3D mesh was then generated, which consisted of 2,699,476 tetrahedrons. The databases covering the thermodynamic properties of the materials were selected from the material databases included in ProCast. For the purposes of this study, the main input variables were the tool temperature and the heat transfer coefficient between the casting and the tool. The heat transfer coefficient was defined as temperature dependent with 2000 W/m²K when the alloy was in the liquid state, and 1700 W/m²K when the alloy was cooled in the solid state. The die temperatures varied from 160 °C to 220 °C with a step of 20 °C. The pouring temperature was set at 680 °C and the alloy was selected from the standard database. To calculate the filling, the filling level for the volume chamber was defined (melt in the chamber) and the time-dependent translation for the volume plunger was set, all according to the setting parameters in the foundry. Four simulations were carried out at different tool temperatures to obtain the cooling curves of the analyzed casting areas during cooling and solidification. These were necessary to determine the local cooling rates. The locations where the temperatures were simulated as a function of time are correlated with the locations where the specimens of different sizes were taken.

Simulations were also performed for a small steel die used to make GDC samples for metallography. The varying input parameter was pouring temperature, which was different for each sample (casting) according to the alloy temperature in the holding furnace.

2.3. Metallography

Microstructural analysis was performed on the samples from the same areas where the samples for the compression tests were taken, as well as on the GSC and GDC samples. The size, shape, and distribution of the microstructural constituents of the polished samples with the dependence on the cooling rate (or the wall thickness of the casting) were observed using the optical microscope Olympus BX 61 equipped with the camera DP70 (Olympus Europa SE & Co. KG, Hamburg, Germany). Measurements of microstructural constituents were performed using ImageJ software (NIH, Bethesda, MD, USA; LOCI, Madison, WI, USA).

Figure 3. Macro photograph of specimens with different sizes (small, medium, large) in direct correlation with the wall thickness of the castings used for compressive testing.
3. Results and Discussion

The simulation results show that almost 75% of the molten metal entered the casting cavity through the widest central inlet, and the average metal velocity during the second phase was 24 m/s when the metal entered the cavity. Approximately 2.25 s after the cavity was filled, the molten metal had already solidified in areas of the lateral inlets, where additional feeding was no longer possible. After approximately 3.45 s, the main inlet was also separated from the rest of the solidifying casting, and the solid fraction at this point was only 48.5%, which is why it was assumed that shrinkage porosity can occur in the areas that had not yet solidified. These were also the areas where specimens were planned for compression tests and microstructural analyses.

Figure 4 shows the cooling curves at each point where the samples were taken for each tool temperature. It can be seen very clearly how the time to solidus increased firstly with the tool temperatures and secondly with the wall thickness of the casting.

![Figure 4](image_url)

**Figure 4.** Cooling curves for tool temperatures 160, 180, 200, and 220 °C from the spot of planned: (a) large, (b) medium, and (c) small size samples in dependence with tool temperature acquired by simulation.
From the linear parts of the cooling curves prior to solidification the cooling rates ($v_{\text{cool}}$) were determined according to the following equation:

$$v_{\text{cool}} = \frac{T_1 - T_2}{t_2 - t_1}, \quad (1)$$

where $T_1$ is the temperature at time $t_1$ and $T_2$ is the temperature at time $t_2$, for each sample (large, medium, small), the results are shown in Table 2. Basically, $v_{\text{cool}}$ is the slope of a linear part of the cooling curve, and is mathematically a temperature difference divided by a time difference. As expected, the cooling rates decreased with increasing wall thickness and with increasing tool temperature.

**Table 2.** Cooling rates defined by simulations according to specimen size (in correlation with casting wall thickness) and set tool temperature.

| Tool Temperature | Large    | Medium   | Small    |
|------------------|----------|----------|----------|
| 160 °C           | 64.7 K/s | 100 K/s  | 127.9 K/s|
| 180 °C           | 62.1 K/s | 98.3 K/s | 123.6 K/s|
| 200 °C           | 59.9 K/s | 95.2 K/s | 119.7 K/s|
| 220 °C           | 52.3 K/s | 86.3 K/s | 113.4 K/s|

The microstructures of all inspected samples from casting one are shown in Figure 5, from which some differences in the size of the microstructural constituents (mainly dendrites) are evident, especially when comparing the samples from casting (HPDC—Figure 5a–c) with the gravity-cast samples (GDC—Figure 5d, GSC—Figure 5e).

**Figure 5.** Microstructures of samples: (a) 3 mm sample, (b) 4 mm sample, (c) 6 mm sample from high-pressure die cast (HPDC) casting No. 1, (d) the gravity die cast (GDC) sample, and (e) the gravity sand cast (GSC) sample cast simultaneously with the casting No.1 production cycle.
When examining the microstructures of the different samples, it was also found that the dendrites in the HPDC samples were not only smaller, but also “deformed”, globular and not continuous as in the samples from the GSC. Other microstructural constituents such as the eutectic $\beta_Si$ and iron phases were also found to be smaller at higher cooling rates, as shown in Figure 5. The sizes of these constituents were not determined, as thorough analysis could not be carried out due to their small size and the use of optical microscopy.

One of the microstructural properties that is a direct consequence of the cooling rate is the secondary dendrite arm spacing or SDAS, which is why it was measured in the microstructures. Measured SDAS values are shown in Table 3. Cooling rates for HPDC samples (taken from castings—large, medium, and small size) were obtained by interpolation according to measured tool temperatures and simulation results for each casting, Nos. 1 to 5. Additional numerical calculations were performed to obtain cooling rates for GDC samples and for GSC, cooling rates were obtained from cooling curves (not successful for casting sample 5, hence there is no result for this sample in the table). The columns in the table show the shortest and longest SDAS values measured, and the last column shows the average of all measurements. It can be seen that, as expected, the mean values of all measurements were inversely proportional to the cooling rate in almost all cases. In contrast, this study found that the inverse proportionality between the cooling rate and the minimum and maximum SDAS measurements was not always the case.

Table 3. Secondary dendrite arm spacing (SDAS) of all samples with dependence on cooling rate determined with numerical simulations.

| Casting No. | Sample | $v_{cool}$ (K/s) | SDAS$_{min}$ (µm) | SDAS$_{max}$ (µm) | SDAS$_{avg}$ (µm) |
|------------|--------|------------------|-------------------|-------------------|-------------------|
| 1          | HPDC-S | 125              | 4.05              | 11.69             | 7.7               |
|            | HPDC-M | 99               | 7.38              | 12.43             | 9.5               |
|            | HPDC-L | 63               | 7.28              | 11.32             | 9.45              |
|            | GDC    | 43.2             | 10.22             | 16.34             | 13.27             |
|            | GSC    | 4                | 36.48             | 53.08             | 42.82             |
| 2          | HPDC-S | 121              | 5.25              | 12.65             | 8.17              |
|            | HPDC-M | 96               | 6.62              | 10.92             | 9.1               |
|            | HPDC-L | 61               | 9.02              | 14.91             | 11.36             |
|            | GDC    | 47.1             | 8.99              | 14.95             | 11.89             |
|            | GSC    | 6.4              | 41.16             | 48.5              | 45.04             |
| 3          | HPDC-S | 120              | 6.19              | 10.59             | 7.94              |
|            | HPDC-M | 96               | 6.99              | 11.69             | 8.95              |
|            | HPDC-L | 60               | 7.48              | 12.06             | 9.76              |
|            | GDC    | 44.0             | 9.86              | 14.94             | 11.73             |
|            | GSC    | 4.8              | 35.03             | 49.56             | 39.08             |
| 4          | HPDC-S | 121              | 6.3               | 11.49             | 9.22              |
|            | HPDC-M | 96               | 8.37              | 14.51             | 10.22             |
|            | HPDC-L | 60               | 7.4               | 16.18             | 11.49             |
|            | GDC    | 44.0             | 10.18             | 17.67             | 12.51             |
|            | GSC    | 7.8              | 36.15             | 54.91             | 42.28             |
| 5          | HPDC-S | 120              | 5.49              | 12.01             | 8.92              |
|            | HPDC-M | 96               | 7.36              | 11.59             | 9.31              |
|            | HPDC-L | 60               | 5.43              | 14.17             | 9.18              |
|            | GDC    | 47.1             | 8.78              | 14.76             | 10.61             |
|            | GSC    | /                | 31.23             | 52.64             | 38.89             |

Figure 6 shows the scatter plot with the minimum, maximum, and average measurements for each sample. It can be seen how the results are overlaid for the results from the HPDC castings and from the GDC samples. The curve from the graph connects the average values of the measured SDAS from Table 3 and shows a trend of increasing SDAS with decreasing cooling rate.
Figure 6 shows the scatter plot with the minimum, maximum, and average measurements for each sample. It can be seen how the results are overlaid for the results from the HPDC castings and from the GDC samples.

The curve from the graph connects the average values of the measured SDAS from Table 3 and shows a trend of increasing SDAS with decreasing cooling rate.

Figure 6. Diagram of SDAS with dependence on cooling rate.

As described in the experimental section, compression tests were performed on the specimens at room temperature. The stress–strain curves for each specimen were obtained during the compression test. For illustration, the stress–strain curves are shown in Figure 7 for specimens of casting No. 5. Figure 7 shows how the mechanical properties of each specimen were determined from the graphs. The curves show the mechanical properties and their dependence on the cooling rates, that is, on the specimen diameters or wall thicknesses of the castings from which they were taken. Reproducibility was seen in castings 1 to 5, and the values for $R_5$ were always highest for the smallest specimens where the cooling rates were highest. Especially for the smaller specimens (medium and small size), there were often sudden stress drops during the test (i.e., when the first cracks started), which may be related to the porosities in the samples typical of HPDC castings. It is interesting to note that these sudden falls were more common in medium-size and small specimens. The reason could be that the material of smaller specimens had a higher strength ($\sigma$) and was therefore more brittle, and the material of large specimens was more ductile due to the different cooling rates. The values for strength at 5% of combined elastic and plastic deformation ($R_5$), strength at first fracture ($R_f$), and strain at first fracture ($\varepsilon_f$) were determined from these diagrams and are shown in Table 4. It can be seen that the mechanical properties at the level of the individual casting decreased with decreasing cooling rate, which had already been predicted on the basis of microstructural analyses, and on the basis of knowledge of the relationship between the sizes of the microstructural constituents and the mechanical properties (Hall–Petch relationship [16]).
Figure 7. Stress–strain diagrams from samples of casting No. 5.

Table 4. SDAS, mechanical properties, and cooling rates for samples from the castings.

| Casting No. | Sample Size | \( v_{\text{cool}} \) (K/s) | \( R_f \) (MPa) | \( \varepsilon_f \) (%) | \( R_S \) (MPa) |
|-------------|-------------|-----------------|-----------------|-----------------|-----------------|
| 1           | S           | 125             | 353.7           | 7.4             | 333.6           |
|             | M           | 99              | 351.4           | 14.3            | 298.7           |
|             | L           | 63              | 370.4           | 55.6            | 272.1           |
| 2           | S           | 121             | 370.2           | 7.9             | 343.5           |
|             | M           | 96              | 367.5           | 15.0            | 309.3           |
|             | L           | 61              | 381.9           | 47.9            | 264.9           |
| 3           | S           | 120             | 359.0           | 8.1             | 338.8           |
|             | M           | 96              | 364.5           | 15.1            | 315.7           |
|             | L           | 60              | 363.8           | 52.5            | 263.7           |
| 4           | S           | 121             | 363.4           | 8.1             | 339.8           |
|             | M           | 96              | 354.5           | 14.9            | 294.4           |
|             | L           | 60              | 349.5           | 48.4            | 241.9           |
| 5           | S           | 120             | 353.0           | 8.1             | 319.3           |
|             | M           | 96              | 354.6           | 15.5            | 287.7           |
|             | L           | 60              | 337.7           | 54.9            | 261.6           |

Figure 8 is a graphical representation of Table 4, showing the results of the compression tests as a function of cooling rate. In addition, average mechanical properties were calculated for groups of samples (S, M, L) with similar cooling rates (e.g., ca. 60, ca. 100, ca. 120 K/s) and presented in the form of curves showing the trends of the changes. It can be seen that \( R_S \) increased with increasing cooling rate, which cannot be said for \( R_f \). The \( R_f \) values were widely scattered for large samples, which can be associated with defects in the materials. The different percentages of discontinuities in the material of the large specimens could be the reason for the wide scatter of the results, since these specimens were taken at the sections where the last solidification occurred and therefore porosity could have formed according to numerical simulations. Higher strength in smaller specimens (S, M) caused a clear stress drop in the diagrams at first failure and \( R_f \) is therefore clear and easy to determine. It appears that more ductile large specimens (L) were not as affected by first initiated fractures and could be further deformed without a clear stress drop to ultimate failure. Nevertheless, the strain at failure/first fracture (\( \varepsilon_f \)) of the specimens shows how
groups of specimens with similar cooling rates had similar strains, even though the results for $R_f$ were more scattered and intertwined. Thus, specimens that solidified at higher cooling rates exhibited higher strengths and were therefore more brittle ($\varepsilon_f$ was lower).

Figure 8. Diagrams of: (a) strength achieved after a total of elastic and plastic deformation of 5%, results as a function of cooling rate; (b) strength at fracture (or first significant crack formation), results as a function of cooling rate; and (c) deformation at $R_f$, results as a function of cooling rate.

Comparing the results of the SDAS measurements with the mechanical properties from the compression tests, it can be seen how the distance between the secondary dendrite arms decreased with increasing cooling rate and the mechanical properties increased accordingly.
4. Conclusions

- According to the simulations performed, the tool temperature had a significant effect on the cooling rate, time to solidification, and thermal modulus of the casting. For further discussion, local cooling rates in the castings during solidification were calculated using numerical simulations.
- Specimens were successfully taken from the castings in direct correlation with wall thickness. Microstructural investigations and compression tests were carried out on these specimens.
- Secondary dendrite arm spacing (SDAS) was directly correlated with the cooling rate; when the cooling rate was increased from about 60 K/s to about 120 K/s, SDAS decreased by about 20% on average. The average values of all measurements for SDAS were generally inversely proportional to the cooling rate.
- The results show the expected trends, especially when comparing strength at certain deformation. Given the reduced SDAS and also other microstructural constituents, the strength at 5% elastic and plastic deformation ($R_S$) increased by 74.2 MPa or 28.7% on average.
- It has been suggested, and to some extent demonstrated, that compression tests can be used to determine mechanical properties on specimens taken from castings where it is not possible to make tensile specimens—especially when only a comparison from one specimen to another is required.
- The strength at failure/first fracture ($R_f$) results did not show a clear trend as a function of cooling rate, mainly due to the large specimens where first fracture could not be clearly determined, presumably due to increased ductility. The presented results are also widely scattered. $R_f$ is therefore not a reliable parameter to describe the mechanical properties, at least not in the way it was determined in the present study. Further tests with deeper analysis on specimens exhibiting higher ductility are required in order to be able to determine the time of first fracture.
- In this study it was shown that the mechanical properties were directly dependent on the size of the microstructural constituents or further on the cooling rates and solidification parameters.
- This subject is interesting from the perspective of industrial practice, where the mechanical properties could be determined on specimens taken from the castings, but additional tests are needed to clearly show the relevance of the proposed method.

Author Contributions: Conceptualization, M.Ž. and M.P.; methodology, M.Ž. and M.P.; software, M.P.; validation, M.Ž., M.P. and P.M.; formal analysis, M.Ž.; investigation, M.Ž.; resources, M.Ž.; data curation, M.Ž.; writing—original draft preparation, M.Ž.; writing—review and editing, M.Ž.; visualization, M.Ž.; supervision, M.P. and P.M.; project administration, M.Ž.; All authors have read and agreed to the published version of the manuscript.

Funding: We are grateful to the Slovenian Research Agency (ARRS) for funding under program grants P2-0344 and P2-0268. This work was also funded by the program MARTIN, supported by Slovenian Ministry of education, science and sport and European Regional Development Fund.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflict of interest.
Abbreviations

List of abbreviations and physical quantities.

HPDC  High-pressure die casting
GSC   Gravity sand casting
GDC   Gravity die casting
$R_f$ Strength at first fracture (MPa)
$\epsilon_f$ Deformation at $R_f$ (\%)
$R_5$ Strength at 5\% deformation (MPa)
$T$ Temperature (°C, K)
t Time (s)
$v_{cool}$ Cooling rate (K/s)
SDAS Secondary dendrite arm spacing
SDAS\text{min} Shortest SDAS measured
SDAS\text{max} Longest SDAS measured
SDAS\text{avg} Average of all SDAS measurements
HPDC-S; S Small specimen from HPDC casting
HPDC-M; M Medium specimen from HPDC casting
HPDC-L; L Large specimen from HPDC casting

References

1. Kaufman, J.G.; Rooy, E.L. Aluminium Alloy Castings: Properties, Processes, and Applications; ASM International: Cleveland, OH, USA, 2005; pp. 1–15.
2. Mallick, P.K. Materials, Design and Manufacturing for Lightweight Vehicles; Woodhead Publishing: Cambridge, UK, 2010; pp. 114–173.
3. Datta, J. Aluminium-Schlüssel, 6. Auflage; Aluminium-Verlag: Düsseldorf, Germany, 2003; pp. 68–69.
4. Arnberg, L.; Bäckerud, L. Solidification Characteristics of Aluminium Alloys; Dendrite Coherency; American Foundry Society (AFS): Des Plaines, IL, USA, 1996; Volume 3, pp. 113–131.
5. Petrič, M.; Medved, J.; Mrvar, P. Effect of grain refinement, modification and the cooling rate on microstructure of the 239 and 226 alloys. Giessereiforschung 2008, 60, 26–36.
6. Vander Voort, G.F. Metallography and Microstructures. In ASM Handbook; ASM International: Cleveland, OH, USA, 2004; Volume 9, pp. 112–115.
7. Li, S. Hot tearing in Cast Aluminium Alloys, Measures and Effects of Process Variables. Ph.D. Thesis, Worcester Polytechnic Institute, Worcester, UK, 2010.
8. Campbell, J. The consolidation of metals: The origin of bifilms. J. Mater. Sci. 2016, 51, 96–106. [CrossRef]
9. Dispinar, D.; Akhtar, S.; Nordmark, A.; Syvertsen, F.; Di Sabatino, M.; Arnberg, L. Correlation Between Mechanical Properties and Porosity Distribution of A356 in Gravity Die Casting and Low Pressure Die Casting. Adv. Mater. Res. 2012, 445, 283–288.
10. Eklund, J.E. On the Effect of Impurities on the Solidification and Mechanical Behaviour of Primary and Secondary Commercial Purity Aluminium and Aluminium Alloys. Ph.D. Thesis, University of Technology, Helsinki, Finland, 1991.
11. Szalva, P.; Orbulo, L.N. The effect of vacuum on the mechanical properties of die cast aluminum AlSi9Cu3 (Fe) alloy. Int. J. Met. 2019, 13, 853–864. [CrossRef]
12. Lumley, R.; Deeva, N.; Gershenzon, M. An Evaluation of Quality Parameters for High Pressure Die Castings. Int. J. Met. 2011, 5, 37–56. [CrossRef]
13. Adamane, A.R.; Arnberg, L.; Fiorese, E.; Timelli, G.; Bonollo, F. Influence of Injection Parameters on the Porosity and Tensile Properties of High-Pressure Die Cast Al-Si Alloys: A Review. Int. J. Met. 2015, 9, 43–53. [CrossRef]
14. Koru, M.; Serçe, O. The Effects of Thermal and Dynamical Parameters and Vacuum Application on Porosity in High-Pressure Die Casting of A383 Al-Alloy. Int. J. Met. 2018, 12, 797–813. [CrossRef]
15. Kumar, J.; Singh, D.; Kalsi, N.S.; Sharma, S.; Pruncu, C.I.; Pimenov, D.Y.; Venkateswara, K.R.; Kaplonek, W. Comparative study on the mechanical, tribological, morphological and structural properties of vortex casting processed, Al–SiC–Cr hybrid metal matrix composites for high strength wear-resistant applications: Fabrication and characterizations. J. Mater. Res. Technol. 2020, 9, 13607–13615. [CrossRef]
16. Zolotorevsky, V.S.; Belov, N.A.; Glazoff, M.V. Casting Aluminium Alloys; Elsevier: London, UK, 2007; pp. 281–284.