The Effect of High-Pressure Die Casting Parameters on the Microstructure and Mechanical Properties of A356 Aluminum Alloy

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Introduction

The casting method is widely used in various industries today for producing parts with complex geometries and high repeatability. Through sand casting, large and intricately shaped components that are unattainable by other processes can be manufactured economically. Among the diverse casting techniques, high-pressure die casting (HPDC) is frequently employed for parts requiring high production rates, tight tolerances, and good surface quality. The HPDC process enables the production of complex parts with minimal need for subsequent machining operations like material removal, making it suitable for mass production and ensuring reproducibility of parts.

High-pressure die casting is a process where molten metal is injected into a die cavity under high pressure. A wide range of critical components requiring precision, such as bicycle parts, cutlery, watches, air conditioners, ashtrays, hand tools, motors, locks, pulleys, valves, tractor and train components, electrical appliances, binoculars, air brake systems, military equipment, and rocket parts, can be produced via HPDC (Aslan, 2007). This method offers advantages like tight tolerances and excellent surface finish, allowing for dimensional tolerances of ±0.12 mm and surface roughness values as low as 0.5-3 µm. Eliminating the need for additional machining provides significant cost and time savings. Furthermore, the ability to produce thin-walled sections and achieve production rates of up to 500 parts per hour enhances the method's appeal. Despite its numerous advantages, drawbacks include high mold and machine costs and its primary suitability for metals with lower melting points, such as aluminum, magnesium, zinc, and tin.

High-pressure die casting is implemented in two main variants: hot-chamber and cold-chamber die casting. This system, first patented and applied in the early 1900s, generally consists of the die, piston, molten metal chamber, gas accumulator, and die locks. It is the most preferred method for metals with low melting points like zinc, magnesium, tin, and lead (Kaplan, 2012). This method can produce very small parts and achieve high surface precision, around ±0.05 mm. As the process operates between 70-350 bar, part surface accuracy is very high (Duran, 2014). Cold-chamber die casting is preferred for metals with melting points above 600°C, such as aluminum, magnesium, and copper. This method is also referred to as metal injection. Its primary advantage is that the high-temperature metal does not affect the piston-cylinder mechanism directly. The metal is melted in a separate furnace from the injection machine, ladled, and then poured into the machine's chamber. The pressure within the die cavity in this process typically ranges from approximately 50 to 1000 bar.

Successful high-pressure die casting requires the selection of appropriate process parameters, primarily casting temperature, pressure, and solidification time. Additionally, die and material parameters are crucial. Factors influencing the method can be categorized into three groups:

- A properly functioning casting mechanism with factors like applying and releasing suitable pressure.
- A correctly designed and manufactured die.
- A suitable alloy.

These characteristics must be evaluated not in isolation but as an integrated whole, ensuring coordinated control over the entire casting process (Aslan, 2007).

The literature contains studies investigating the effect of process parameters on the mechanical properties and quality of parts produced by high-pressure die casting. Among them, Wang et al. (2022) examined the effect of process parameters on mold filling and feeding for a part produced via HPDC from ADC12 aluminum alloy. Trials conducted with different metal temperatures and piston speeds were compared with simulations, leading to part production based on these comparisons. In the produced samples, the piston fast shot speed (2nd and 3rd phases) was found to have the most significant effect on melt filling and part feeding. It was noted that low melt temperature could easily lead to gas porosity. The effect of the the piston slow-shot speed (1st phase) on gas porosity was attributed to the entrapment of air from the injection chamber into the metal.

Jarfos et al. (2022) investigated the relationship between machine settings and in-cavity conditions to understand the transitions between different filling stages and the final intensification pressure settings. A pressure sensor was placed inside the die cavity to indirectly measure pressure development over time, monitor in-cavity conditions, and track the filling process. By analyzing the pressure-time profile, they studied the maximum pressure and pressure acceleration. The study concluded that using higher intensification pressures positively affected casting integrity. High intensification pressure was reported to have a more significant impact than the second-stage filling speed.

In their study, Zhang et al. (2021) investigated the effect of modifying piston motion curve profiles on mechanical properties. Tensile specimens produced via HPDC from A356 aluminum alloy were examined based on experimental and modeling results. Porosity prediction was performed through HPDC process simulation and validated with microstructural analysis. Results indicated that increased piston speed led to a more homogeneous distribution of oxides, resulting from fragmentation and transport of free-surface oxides. This reduced oxide distribution contributed to improved tensile properties in the cast specimens. Accordingly, increased piston speed was observed to lead to a tendency for reduced porosity distribution.

In a study conducted by Toptaş (2014), the feasibility of producing a pistol frame, originally manufactured by forging, using the high-pressure die casting method with a suitable raw material was investigated. Experiments were performed for appropriate raw material selection. It was found that when 6082 Al alloy was subjected to T5 and T6 heat treatments, the properties achieved reached strength levels comparable to those of HPDC products after die casting followed by quenching. Productions with and without vacuum application were carried out, confirming that vacuum application eliminated internal voids formed within the parts.

In the study by Yalçın et al. (2012), eight different parameters were tested by varying casting pressure, casting speed, and product cooling method. It was determined that part quality increased when the injection parameters for the high-pressure die casting of Etial 150 aluminum alloy were set to an injection speed ratio of 100% and an injection pressure of 150 bar, coupled with water cooling of the ejected parts. Water cooling of the produced specimen resulted in a 3% increase in strength.

The examined studies demonstrate different yet complementary approaches to HPDC process optimization. These studies confirm the strong connection between process parameters, microstructure, and mechanical performance, forming the scientific foundation upon which this research is based.

This study is derived from a MSc thesis (Tekin, 2022) that investigated the feasibility of producing a passenger car stabilizer bar, traditionally manufactured by forging, using the aluminum high-pressure die casting (HPDC) process. The primary goal was to analyze and resolve the fracture problem occurring during the component's essential 'cover closing' forming operation. The overall research was conducted in two distinct phases: the first focused on the effect of HPDC parameters on the mechanical properties of the A356 alloy, and the second involved product-driven process optimization through die design simulation, production, and functional testing. This paper presents the results of the first phase: a systematic investigation into how HPDC process parameters influence the mechanical properties of the A356 aluminum alloy.

Materials and Experimental Procedure

Material and Melt Preparation

The A356 (AlSi7Mg) aluminum alloy was used in this study. The chemical composition of the A356 series Al-Si7Mg alloy is given in Table 1. This alloy is frequently preferred in aluminum casting methods. This material is known for its high fluidity and sufficient strength. Additionally, the material offers suitability for plastic forming thanks to its adequate ductility.

Table 1

Chemical composition of A356-0 aluminum alloy

Si	Fe	Cu	Zn	Mn	Mg	Ti	Other	Al
6.5-7.5	0.20	0.2	0.1	0.1	0.25-0.45	0.20	0.15	the rest

The alloy was melted in a 600 kg capacity natural gas-fired tilting furnace (Figure 1) at 720°C. The chemical composition of the melt was verified using spectrometry to ensure material conformity. To eliminate dissolved gases, particularly hydrogen, the molten metal was degassed in a 250 kg ladle (Figure 2) using a rotary degasser with nitrogen gas for 180-220 seconds at 600 RPM. The melt quality was assessed by comparing the densities of two samples solidified under vacuum and atmospheric pressure, respectively, using a vacuum density test instrument (Figure 3). A lower density difference indicates a cleaner, degassed melt.

Figure 1

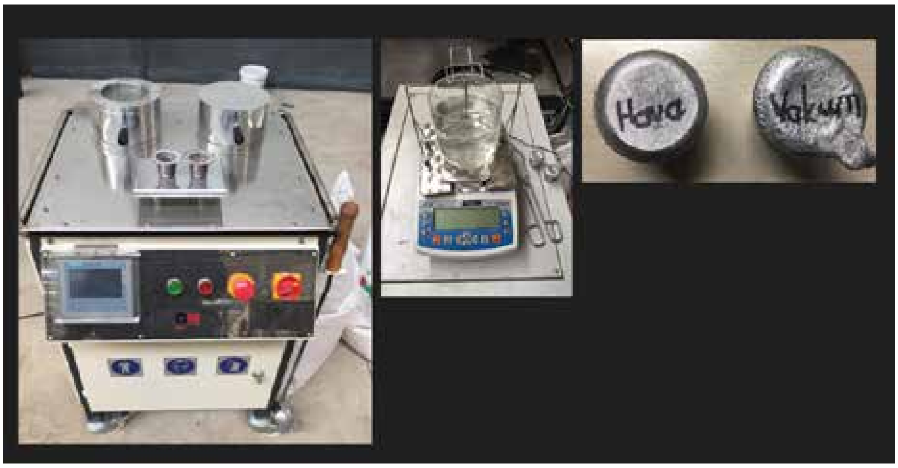
Tilting type melting furnace

Figure 2

Degassing process using nitrogen gas

Figure 3

Vacuum density tester



High Pressure Die Casting (HPDC) Process

The HPDC experiments were conducted on an Era press cold-chamber die casting machine (Figure 4) with a 7720 kN clamping force and a 60 mm diameter piston. The injection process, controlled by a PLC, occurs in three phases (Duran, 2014):

- First Phase (Slow Shot): The molten metal advances slowly to the gate.
- Second Phase (Fast Shot): The metal is injected into the die cavity at high velocity.
- Third Phase (Intensification): High pressure is applied to feed the solidified casting.

To avoid confusion in the literature regarding pressure definitions, this study uses the specific injection pressure (the pressure exerted by the piston on the molten metal in the chamber) as the relevant parameter.

Figure 4

Cold chamber horizontal injection press

Experimental Design and Tensile Sample Extraction

A Taguchi L9 orthogonal array was employed to efficiently study the effects of three parameters at three levels each (Table 2): melt temperature, injection velocity (second phase), and intensification pressure. The experimental design is shown in Table 3. For each of the nine parameter sets, five repetitions were produced, totaling 45 castings. To ensure process stability, three initial shots were discarded after each parameter change before collecting samples for testing. Tensile test specimens were machined from the cylindrical central section of the cast stabilizer bars, as illustrated in Figure 5. The overall HPDC process flow is summarized in Figure 6 and a photograph of the final cast parts is provided in Figure 7.

Table 2

Parameter levels used in the experiments

	1	**2**	**3**
Temperature (°C)	700	720	740
Velocity (m/s)	2	2.5	3
Pressure (bar)	850	1010	1290

Table 3

Experimental design (L9 Array)

Exp. Number	Temperature (°C)	Velocity (m/s)	Pressure (bar)
1	700	2	850
2	700	2.5	1010
3	700	3	1290
4	720	2	1010
5	720	2.5	1290
6	720	3	850
7	740	2	1290
8	740	2.5	850
9	740	3	1010

Figure 5

Stabilizer Bar Manufactured by HPDC Process

Figure 6

Flow Chart of the HPDC Process

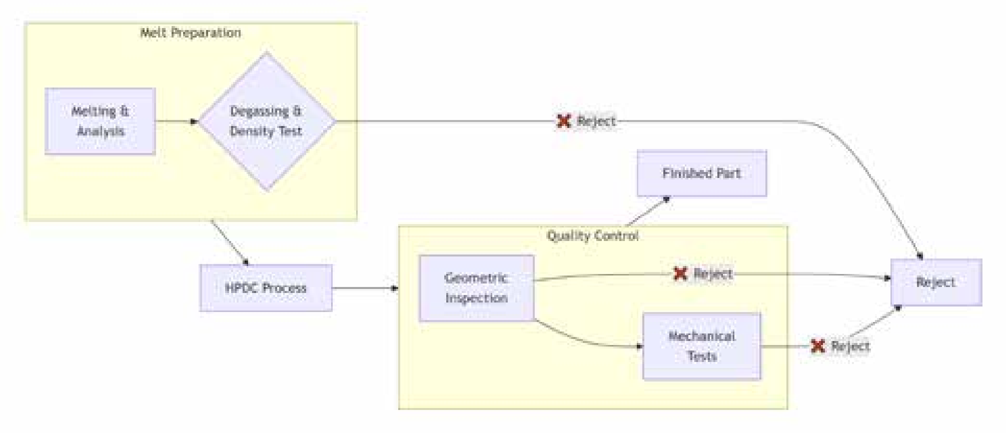
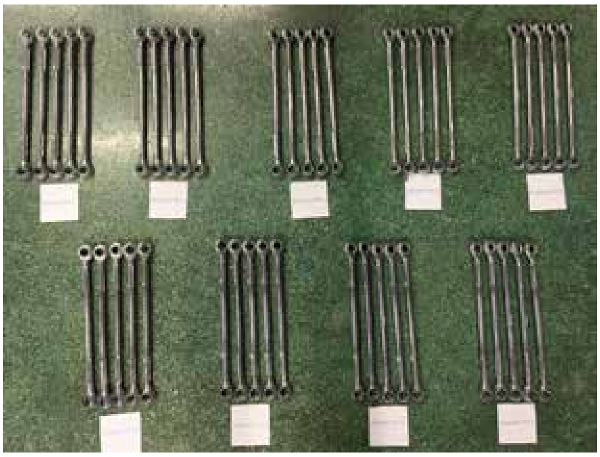


Figure 7

Test strips produced for 9 different test parameters



Tensile test specimens were machined from the cylindrical central section of the cast stabilizer bars. The tensile bars were processed on a CNC lathe to the dimensions specified in the ASTM E8 standard (Figure 8). Subsequently, the threads at both ends were formed on a thread rolling machine to prepare the specimens for tensile testing (Figure 9).

Figure 8

Dimensions of the manufactured tensile test specimen

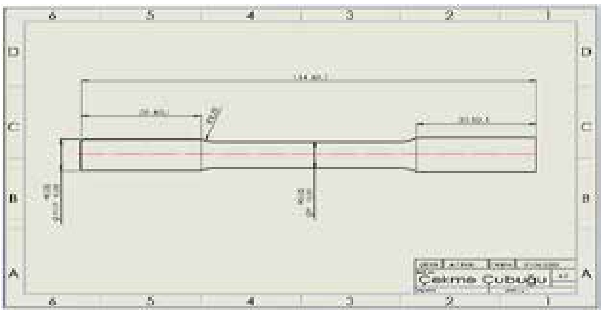


Figure 9

Ready-made tensile bar and grouped samples

Tensile tests were conducted at room temperature at a speed of 5 mm/min using a Devotrans DVTNU model 100 kN capacity testing machine.

Microstructural Characterization

Sections for microstructural analysis were carefully extracted from the HPDC specimens using an abrasive cutting machine with water cooling to prevent microstructural alterations from heat buildup.

The sectioned samples were then mounted in bakelite and prepared using a Buhler brand grinding and polishing machine. The preparation procedure was performed as follows:

1. **Grinding:** A sequential grinding process was conducted using 180, 320, 500, 800, 1200, and 2400 grit abrasive papers.
2. **Polishing:** The ground samples were subsequently polished using a 3 µm diamond suspension for rough polishing, followed by a final polishing step with a 0.87 µm silica suspension.
3. **Etching:** To reveal the microstructure, the polished surfaces were etched using an aluminum micro-etchant with a composition of 0.5% HF and 99.5% distilled water.

The prepared samples were examined using a Nikon ECLIPSE MA200 optical microscope. Microstructural images were captured at 100x magnification (200 µm scale).

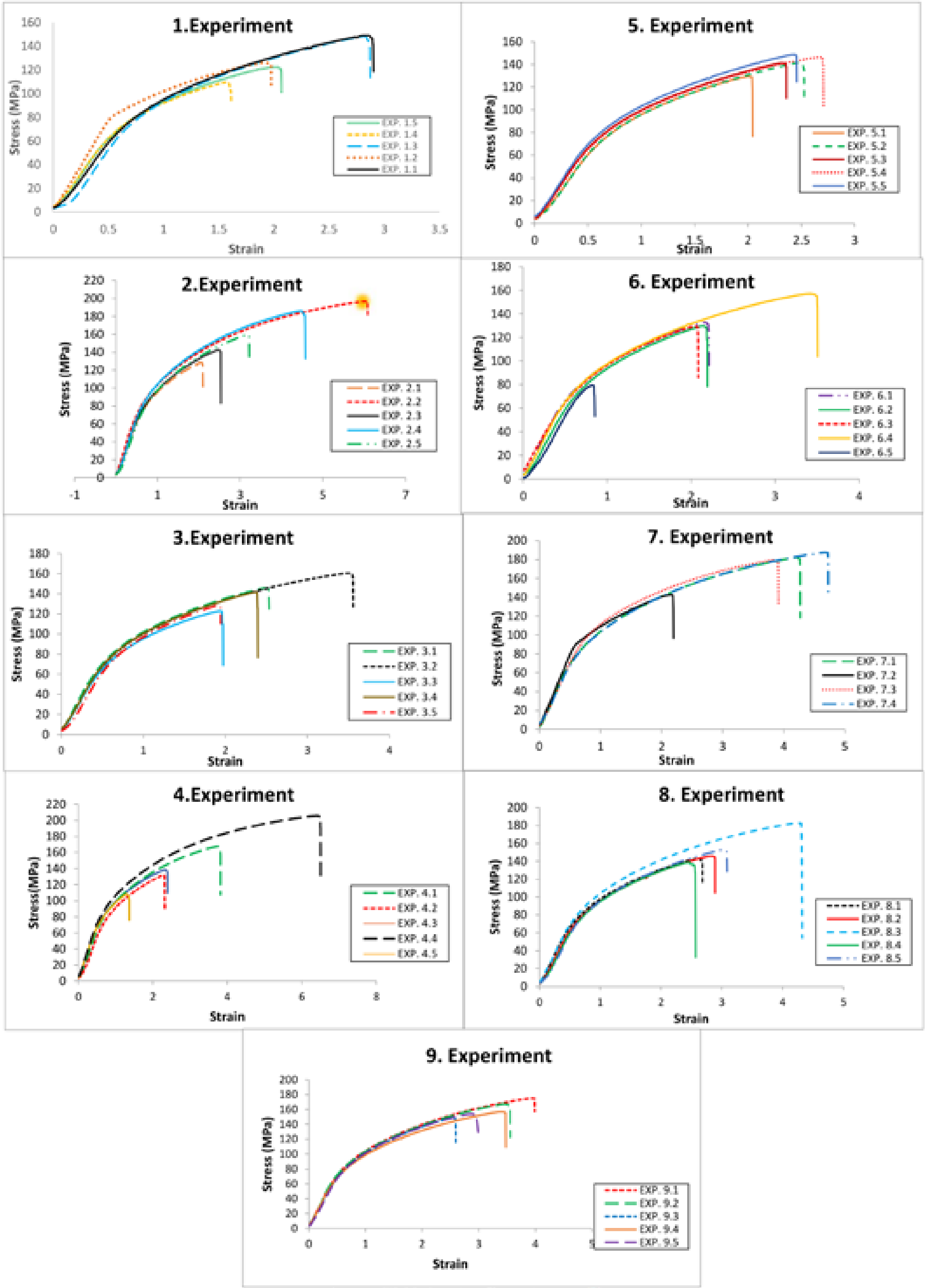
Results and Discussion

Tensile tests were conducted on specimens prepared from stabilizer bars produced under nine different conditions according to the Taguchi L9 experimental design. The results are presented in Figure 10. Each experiment was repeated five times, and the graphs show the

stress-strain curves for all repetitions. The graphs indicate no significant differences in yield strength among the replicates. Furthermore, the yield curves for almost all repetitions overlapped. However, some replicates showed considerable deviation from the average in terms of ultimate tensile strength and percent elongation. Although produced under the same conditions, differences were observed in the mechanical properties of the samples. It is thought that uncontrolled factors caused some test results to be very close to each other, while others differed.

Figure 10

Results of all repeated tensile tests



After the tensile tests, it was determined that brittle fractures occurred in the tensile specimens, as seen in Figure 11. In the HPDC process, the likelihood of porosity formation is very high due to aluminum's affinity for hydrogen. It is thought that this situation causes different porosity levels in the samples produced in each cycle, consequently leading to variations in ductility values. Therefore, differences exist between the replicates of the same experiment. A representative tensile test curve, taken as the average for each experiment, was used to compare the tensile curves of parts produced under different manufacturing conditions, as shown in Figure 12.

Figure 11

Fracture Surface Images After the Tensile Test

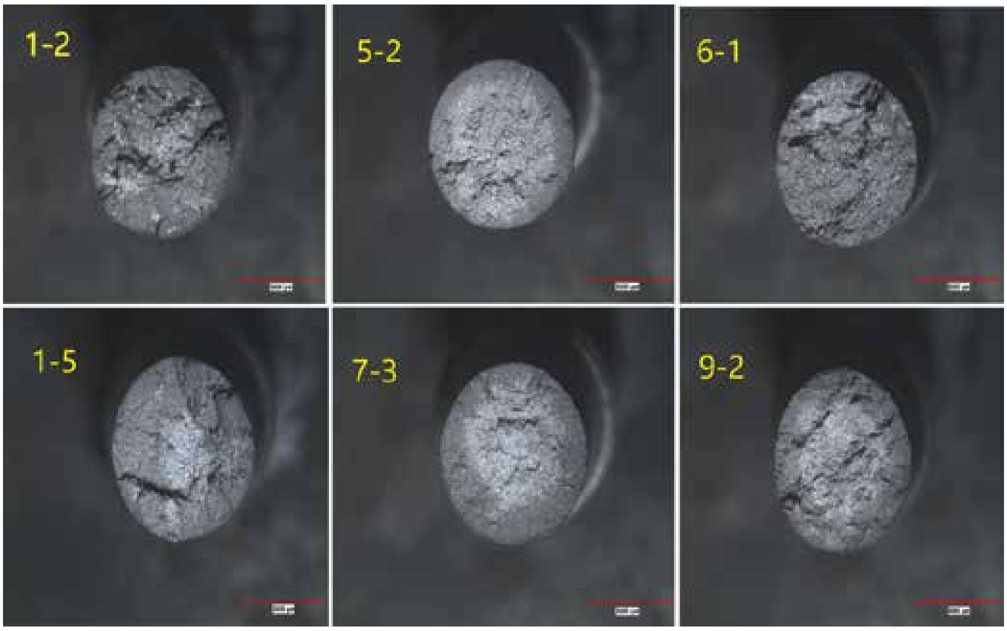
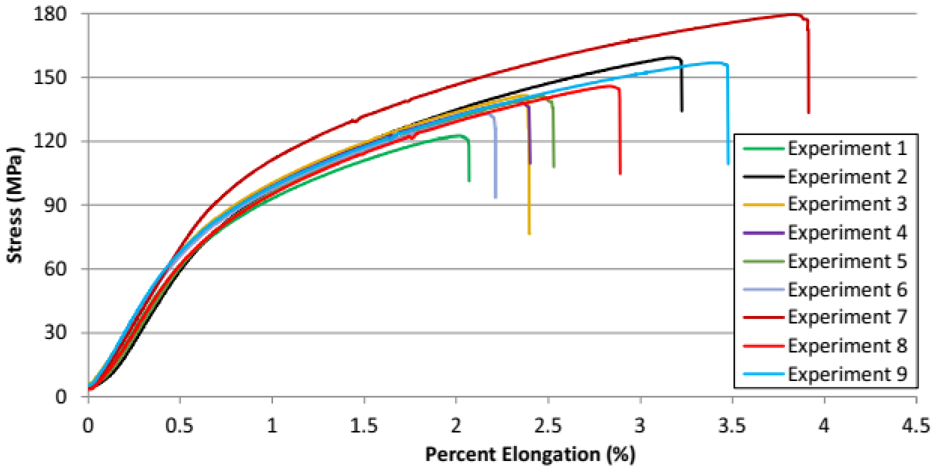


Figure 12

Comparison of the Average Tensile Curves for the Nine Different Experiments Conducted According to the Experimental Design Matrix



According to the results, the highest yield strength was observed for parts produced in Experiment 7, which used the highest temperature (740°C), the lowest speed (2 m/s), and the highest pressure (1290 bar). These specimens also exhibited higher yield and tensile strength, as well as higher percentage elongation values compared to those produced under other conditions. In contrast, the worst mechanical properties were obtained for parts produced in Experiment 1, which used the lowest temperature (700°C), the lowest speed (2 m/s), and the lowest pressure (850 bar). While there was no significant difference in stress levels among the yield curves from other experiments, differences occurred in the percentage elongation.

To investigate the effect of process parameters on mechanical properties in more detail, the yield strength, percentage elongation, and plastic strain values obtained from each experiment were calculated, compared and analyzed using ANOVA. The yield strengths calculated from the tensile tests are compared in Figure 13. The bar charts in the figure show the average values for the experiments, and the scatter of the data is shown as error bars on each column. When creating the graph, the values that deviated the most from the average were discarded, and the results of at least three values closest to the average were used. The numerical values of the results are given in Table 4

Figure 13

Comparison of the Average Yield Strengths of the Experiments

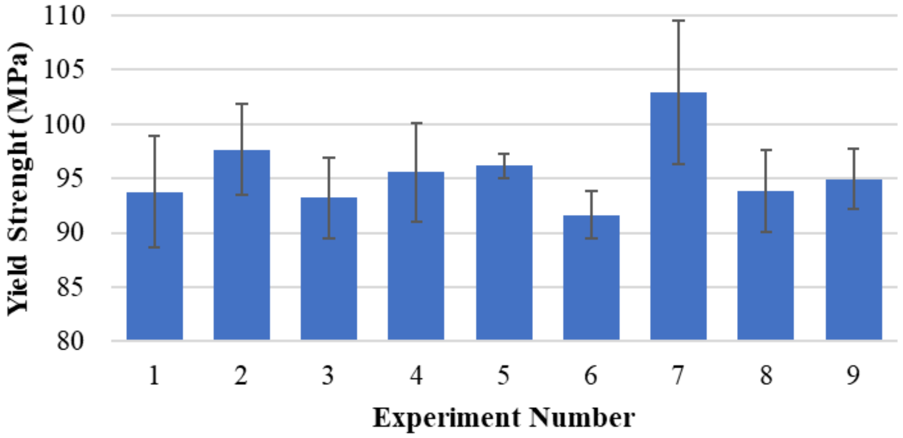


Table 4

Yield strength values

Yield Strength (MPa)	1	2	3	4	5	6	7	8	9
1. Repetition	97.57	93.17	91.81	99.41	96	90.2	96.2	89.63	96.2
2. Repetition	94.3	95.45	95.25	95.5	96.26	89.78	103.02	92.06	94.43
3. Repetition	87.98	95.63	97.1	100.5	95.04	92.06	100.68	95.39	96.97
4. Repetition	89.24	101.15		92.84	95.56				96.8
Average	**92.27**	**96.35**	**94.72**	**97.06**	**95.72**	**90.68**	**99.97**	**92.36**	**96.10**
Std Dev	**4.46**	**3.39**	**2.68**	**3.54**	**0.53**	**1.21**	**3.47**	**2.89**	**1.16**

The average yield strength ranged from a minimum of 90.7 MPa to a maximum of 100 MPa. Analysis of variance (ANOVA) was performed to determine the effect of the parameters on yield strength, and the results are given in Table 5. According to the ANOVA results, only the pressure parameter had a P-value less than 0.05. Therefore, it was concluded that only the pressure parameter had a statistically significant effect on yield strength. Since the P-values of the other parameters were greater than 0.05, it was determined that the temperature and speed parameters did not have a significant effect on yield strength. The contribution percentage of the pressure parameter to the yield strength was approximately 73%. The R^2(adj) value, representing the reliability of the system from the regression analysis, was 88.74%. While values of 70% and above are considered acceptable in engineering problems, 88.74% clearly indicates that the experiments and analyses are highly reliable. The main effects plots for the parameters on yield strength are shown in Figure 14. Accordingly, it is observed that as the pressure, which is the most influential parameter, increases, the yield strength also increases. Therefore, it was concluded that the most suitable pressure value for the production of the stabilizer bar, among the selected levels, is 1290 bar. Although no significant effect of temperature and speed parameters on yield strength was found, it can be said that high temperature and low speeds tend to increase the yield strength. This situation can be explained by the reduction in porosity formation at high temperatures, low speeds, and high pressures.

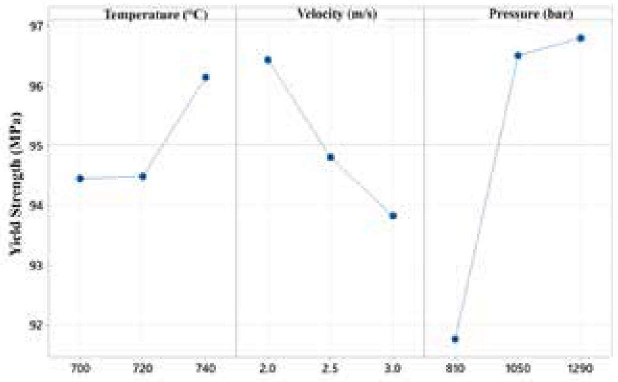
Table 5

Results of the Analysis of Variance (ANOVA) Performed on the Yield Strength

Parameter	Degrees of Freedom	Sum of Squares	Contribution %	Mean Square	F-value	P-value
Temperature	2	5.616	8.56%	2.8078	3.04	0.247
Velocity (m/s)	2	10.356	15.78%	5.1781	5.61	0.151
Pressure (bar)	2	47.795	72.84%	23.8974	25.89	**0.037**
Error	2	1.846	2.81%	0.9231		
Total	**8**	**65.613**	**100.00%**			

Figure 14

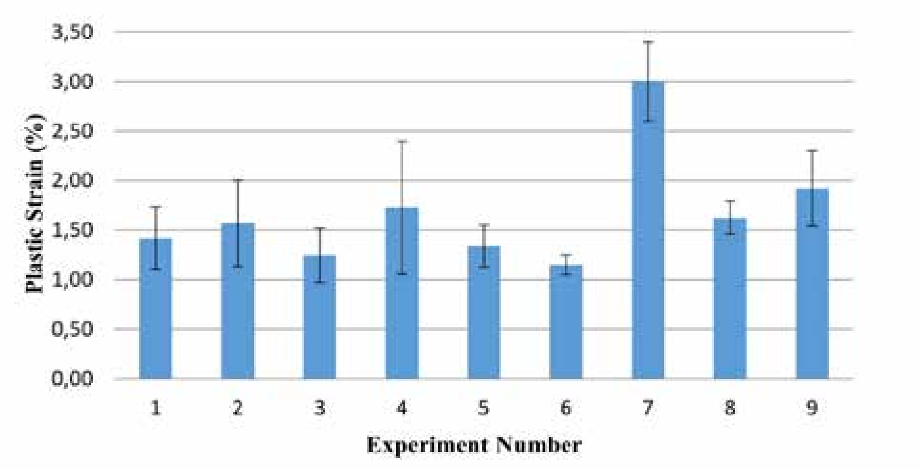
Main Effects Plot for Yield Strength



In a tensile test, the elongation that occurs from the point the material begins to yield until its fracture is termed plastic strain. Since the study aimed to investigate the effect of die-casting parameters on the plastic deformation behavior of the material, the plastic strain values, rather than the total percentage elongation, were taken as the performance criterion. The plastic strain values obtained from the experiments, conducted with five repetitions for each of the nine different experimental conditions, are presented in Figure 15.

Figure 15

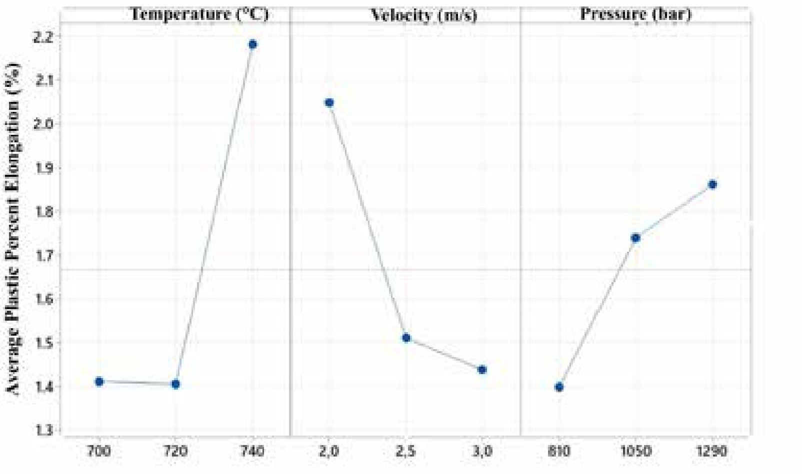
Plastic Strain Values (%) for the Nine Experiments



The plastic strain varied between 1.15% and 3%. The highest elongation was obtained at the highest temperature, highest pressure, and lowest speed parameters, while the lowest elongation occurred at the highest speed, lowest pressure, and medium temperature level. From this, it can be said that the most suitable parameters for the plastic deformation capability of the stabilizer bar produced from A356 aluminum alloy are the highest pressure, lowest speed, and highest temperature levels.

Figure 16

Main Effects Plot of Parameters on Plastic Strain



When ANOVA was performed on the experimental results to investigate the effects of the parameters in more detail, it was seen that statistically significant results were not obtained because the P-values of the parameters at the selected levels were above 0.05. The R^2(adj) value from the regression analysis, representing the reliability of the experimental results, was 57.7%. Therefore, it was evaluated that the main effects plots given in Figure 16 can be used to approximate the effect of the parameters on plastic strain.

An increase in temperature from 700°C to 720°C did not cause a change in plastic strain; however, an increase from 720°C to 740°C caused a 57% increase in plastic strain. Increasing the speed from 2 m/s to 2.5 m/s resulted in a 25% decrease in plastic strain. When the speed was increased from 2.5 m/s to 3 m/s, the decrease in plastic strain continued. Increasing the pressure from 850 bar to 1290 bar contributed to a 32% increase in plastic strain. Thus, it was concluded that temperature has a greater effect on plastic strain than the other two parameters, and that high temperatures, high pressure, and low speed are more suitable for the plastic deformation capability of the A356 alloy.

Microstructural Analysis Results

To investigate the effect of process parameters on mechanical properties more comprehensively, microstructural images and fracture surfaces were obtained for selected experiments. Figure 17 presents etched micrographs at 100x magnification for Experiments 1, 5, 6, 7, and 9, revealing grain boundaries and secondary phases.

In the microstructure, the light-toned areas correspond to the α-aluminum phase, while the needle-like structures are the eutectic silicon phases. Although the secondary phases are generally distributed evenly along the grain boundaries, some localized clustering is observed. Furthermore, as seen in Figure 18, grey regions in the microstructure were identified as the β-Al_5FeSi phase. This intermetallic phase forms due to the low solubility of iron in aluminum and is highly brittle, consequently reducing the ductility of the material. Some black areas, indicating porosity, were also observed within the structure, albeit in small amounts. Porosity primarily occurs due to the easy dissolution and subsequent release of hydrogen in aluminum. Although the amount was limited, it is believed that these microporosities contributed to the significant variation in ductility observed between experimental replicates. Dendritic growth arms were visible in some samples. In conclusion, the microstructural examination revealed that, in general, the grain size, secondary phase morphology, and distribution were similar across the different experiments. This observation is consistent with the absence of major differences in mechanical properties between the experimental conditions.

Figure 17

Microstructural Images of the Tested Specimens

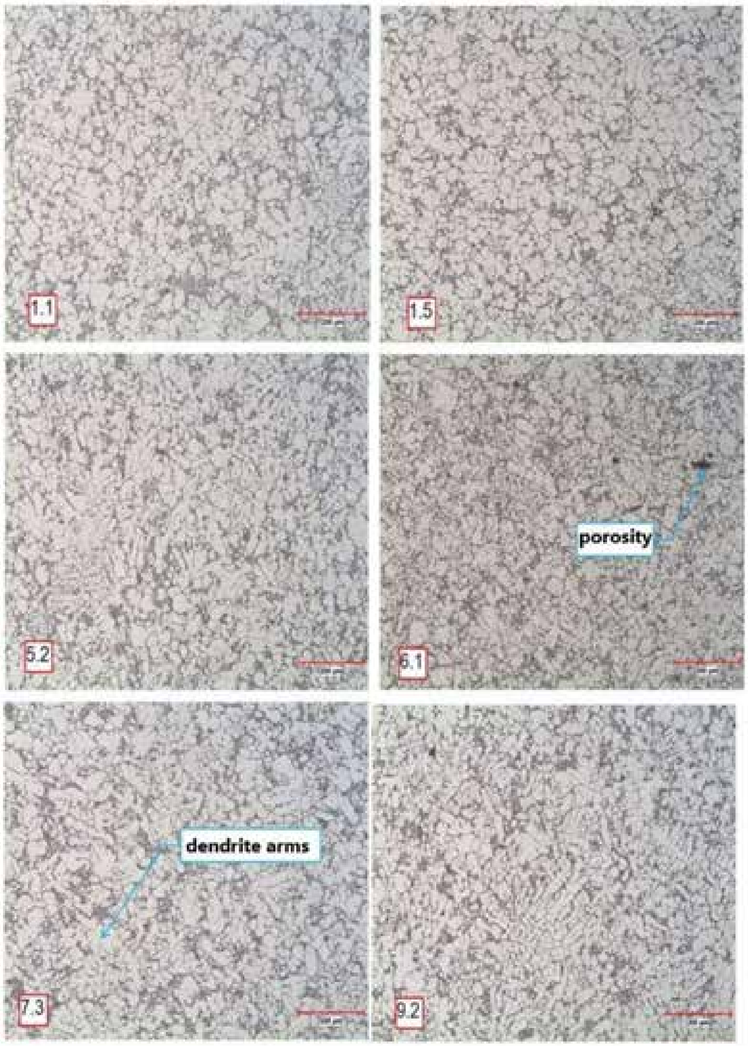
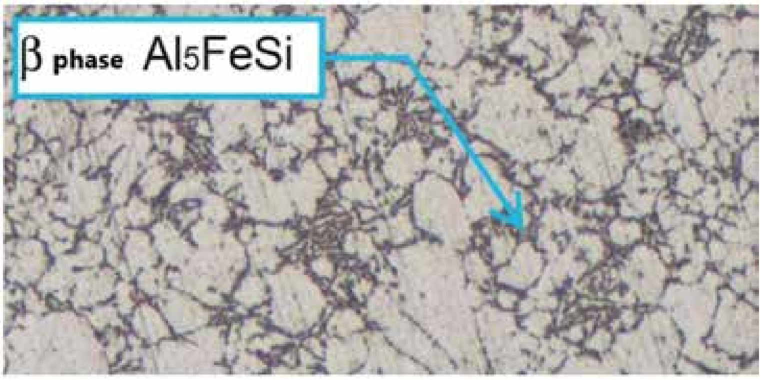


Figure 18

β-Al$_5$FeSi phase in the Microstructure



Conclusions and Recommendations

Conclusions

This study investigated the effect of process parameters of the high-pressure die casting (HPDC) method on the mechanical properties of A356 (AlSi7Mg) alloy. The die casting process was carried out according to a Taguchi L9 experimental design array, varying three levels of temperature, pressure, and velocity.After the tensile test specimens prepared from the cast parts, and tensile tests were conducted with five repetitions for each condition to investigate the effect of process parameters on yield strength, ultimate tensile strength, and plastic strain. Analysis of the tensile test results via ANOVA revealed that, statistically, only the pressure parameter had a significant effect on yield strength. The yield strength ranged from a minimum of 90.7 MPa to a maximum of 100 MPa. Pressure was responsible for 73% of the variation in yield strength, with a 5% increase observed as pressure rose. The ultimate tensile strength varied between 130 MPa and 185 MPa, generally achieving higher values at combinations of low temperature, low speed, and high pressure, which can be attributed to reduced porosity formation under these conditions. The plastic strain varied between 1.15% and 3%. It was concluded that the highest pressure, lowest speed, and highest temperature levels are the most suitable parameters for enhancing the plastic deformation capability of the A356 stabilizer bar.

Apart from the effect of pressure on yield strength, no clear and significant influence of the parameters was observed on the ultimate tensile strength and plastic strain. The microstructural investigation revealed that the grain size, secondary phase morphology, and distribution were generally similar across all experiments. This microstructural homogeneity is the primary reason for the lack of significant variation in mechanical properties. This similarity is likely because the differences between the selected parameter levels were insufficient to alter the microstructure significantly. Furthermore, it was concluded that the inherent uncertainty introduced by sporadic porosity formation also masked the potential effects of the process parameters.

Recommendations

To guide future research on high-pressure die casting, the following recommendations are proposed:

- The temperature parameter range could be widened to potentially induce more noticeable differences in the performance criteria.
- The chemical composition of the casting alloy could be modified to achieve higher ductility. Research into chemical compositions that enhance ductility is recommended.
- The effectiveness of the degassing process for removing dissolved gases, such as hydrogen, from the molten metal should be investigated. The optimal values for nitrogen gas volume, impeller rotation speed, and degassing duration could be studied to determine their specific impact on porosity formation.
- The effect of heat treatments on the mechanical properties of the produced castings should be investigated.

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