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Heat Treatment of Aluminum Castings Combined with Hot Isostatic Pressing

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Sand castings often contain pores, especially shrinking pores. These have a detrimental effect on the mechanical properties. Using hot isostatic pressing (HIP), it is possible to close pores. For precipitation hardening aluminum alloys it is common practice to improve mechanical properties by heat treatment. Involving different mechanisms both processes result in an improvement of the mechanical properties. Hence it is worth to find out, if a combination of the two processes can lead to synergetic effects. Previous experiments on a solid solution strengthened aluminum alloy have shown that pressure at annealing temperature exerts an influence on the microstructure and on the precipitation behavior and is affecting the mechanical properties. Therefore, it is sensible to design an overall process integrating the heat treatment into HIP. With the objective of defining optimal parameters for a combined process, the influence of pressure and process-related quenching rates on the mechanical properties under constant annealing conditions (time and temperature) is investigated. To quantify their effects Brinell hardness, elongation, tensile and yield strengths are measured in the as-cast condition and after different heat treatment steps performed at elevated as well as at ambient pressure. Microstructure analysis and determination of the density are employed to monitor changes in porosity for a set of process parameters. For the experiments sand cast samples of the aluminum alloy AlSi7Mg0.3 with an initial porosity of about 0.6 % are used.

Keywords: *Hot Isostatic Pressing (HIP), heat treatment, castings, mechanical properties, density;*

1. Introduction

Depending on the casting method cast parts exhibit porosity, which has a negative influence on the mechanical properties. Hot isostatic pressing (HIP) is a method to reduce porosity and to improve mechanical properties, especially the fatigue strength. This is achieved by heating the castings to temperatures below the solidus temperature and simultaneously applying a high isostatic gas pressure [1-3]. Besides HIP, the heat treatment of precipitation hardening aluminum alloys is widely used to improve mechanical properties, whereby mainly the static strength can be increased. To exploit this mechanism, it is necessary to cool down the parts rapidly from the annealing temperature after a defined holding time. The quench rate exerts a significant influence on the precipitation behavior and consequently on the mechanical properties. To achieve an optimum in strength and ductility a quench rate of about 4 K/s, which is equivalent to sand quenching, is recommended [4].

Although both processes (i.e. HIP and precipitation) result in an improvement of the mechanical properties, the mechanisms involved are different. It is worth to find out whether or not a combination of both processes can lead to synergetic effects. Concerning the similarity of the holding temperature and time during HIP and solution annealing, it is sensible to design an overall process integrating the heat treatment into HIP. Previous experiments on a solid solution strengthened aluminum-silicon alloy have shown that the effects on the microstructure and on the precipitation behavior of Si caused by annealing under elevated pressure differ from those at ambient pressure [5]. Starting from these results, the influence of pressure and quenching rates on the mechanical properties under constant annealing conditions (time and temperature) is investigated to define optimal parameters for a combined process.

2. Experimental procedure

2.1 Design of experiments

To study the mechanism of heat treatment under pressure, the following design of experiments has been carried out as shown in Table 1 and Fig. 1. As references the initial state and the state after a conventional heat treatment and standard HIP was investigated (tests 0-3). During heat treatment the specimens were solution annealed at 540 °C for 2 hours in a standard furnace with a subsequent quenching in water, followed by artificial ageing at a temperature of 165 °C for 150 minutes. For comparison, also the heat treatment without ageing was conducted. Standard HIP was carried out in a laboratory hot isostatic press (manufacturer: Epsi, Belgium) with the same solution annealing parameters at a gas pressure of 75 MPa under standard cooling conditions by simply switching off the oven. Argon was used as inert process gas.

In addition, the combination of standard HIP with a subsequent heat treatment in two different steps as mentioned above was investigated (tests 4 and 5). Further to these tests, first experiments for an integrated process were performed. There, the samples were cooled down in the hot isostatic press using the so-called Jet-cooling system after solution annealing at a pressure of 75 MPa with and without subsequent ageing (tests 7 and 8) outside the isostatic press. Jet-cooling means that the process gas is cooled at the furnace wall by circulation and additional fresh gas supply while maintaining the pressure. To analyze the effect caused by different cooling rates under pressure, the standard HIP procedure with a subsequent ageing (test 6) was added.

Table 1: Schedule of experiments and their denomination

Treatment condition	No.								
	0	1	2	3	4	5	6	7	8
Initial state	x								
HIP with standard cooling (HIP/SC)				x	x	x	x		
HIP with Jet-Cooling (HIP/JC)								x	x
Solution annealing with water quenching (SA)		x	x		x	x			
Ageing (A)			x			x	x		x

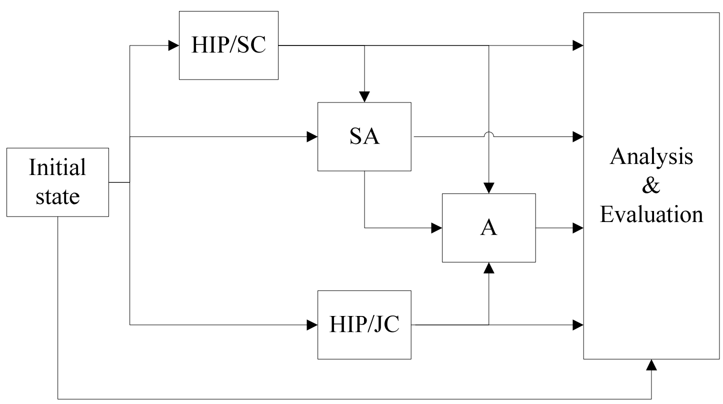


Fig. 1: Illustration of the experimental design.

2.2 Overview of testing

For the investigations cylindrical raw samples of the strontium-modified alloy AlSi7Mg0.3 (similar to EN AC-42100 according to DIN EN 1706) were produced by sand casting. The chemical composition of this alloy is shown in Table 2. From the raw material stock sample rods of diameter 16 mm and length 72 mm were machined. They were taken from the center of the stock, where the material shows a constant secondary dendrite arm spacing of 44 µm along the length of the sample rods.

Table 2: Chemical composition of the raw material (wt.%)

Al	Si	Fe	Cu	Mn	Mg	Zn	Ni	Ti	Sr
balance	7.07	0.13	0.009	0.019	0.36	0.007	0.003	0.133	0.0236

The density in the initial state of all samples is measured by the principle of Archimedes. From this it is traceable, if a possible variance of the test results is caused by different densities in the initial states and hence by different initial porosities.

In order to calculate changes in density depending on the treatment condition mass and volume were measured before and after the treatment by employing seven specimens. For two of the seven specimens also CT-scans in both states are performed to monitor changes in porosity at high resolution. Furthermore, five cylindrical specimens were machined for strength testing. The same specimens were used for analyzing Brinell hardness and microstructure.

3. Results and discussion

3.1 Density and porosity

In the initial state the specimens exhibit a nearly constant average density at about 2.652 g/cm³ with a deviation of +/- 0.001g/cm³. After the treatment all samples from tests involving HIP (tests 3-8) exhibit a significant increase in density of about 0.025 g/cm³ (see Fig. 2a). Relating this value to the theoretical density of 2.70 g/cm³ calculated from the density of the specific alloy, the change in density is 0.93 %. This means that HIP effects an increase of the density of 0.93 % for the investigated alloy as compared to the ideal density of a pore-free material. The increase in density is associated with a decrease in volume (see Fig. 2a). In contrast, the influence of an increase in mass at most 0,002g caused by oxidation is negligible.

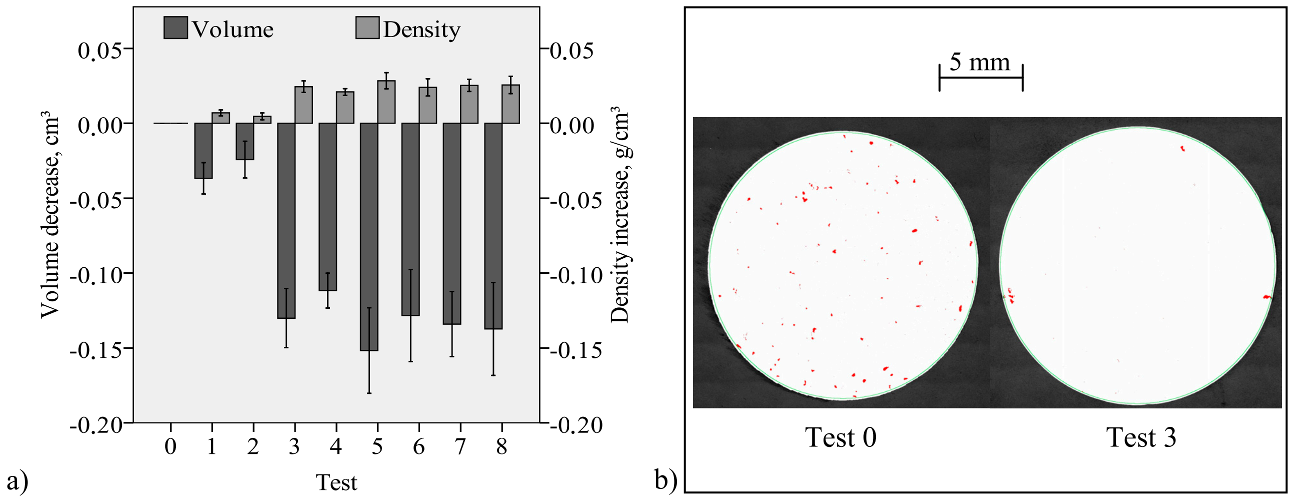


Fig. 2: a) Volume decrease and density increase depending on the treatment conditions; b) Porosity (marked red) after the treatment for test 0 and 3.

As described in literature the main reason for the volume decrease in HIPped materials is the reduction of porosity as shown in the micrographs of Fig. 2b: in the initial state (test 0) the pores are evenly spread to give an average porosity of 0.61 %, after HIP (test 3) nearly all pores are closed with the exception of surface near pores resulting in an average residual porosity of 0.07 %. Thus, a high isostatic pressure of 75 MPa during solution annealing leads to a decrease in porosity by about 0.54 %. If the main effect of HIP is reduction of porosity, this determined porosity should be equal to the calculated value of 0.93 %, which is the difference in density compared to a pore-free material. Because the two values differ (0.39 %), changes in porosity are not the only reason for changes in density and volume. As shown in Fig. 2a, the heat treatment itself seems to cause an increase in density of about 0.006 g/cm³ on average associated with a change in volume of about 0.03 cm³ (see the values of test 1 and 2 in Fig. 2a). This volume decrease is probably related to changes in crystal structure and lattice parameter due to precipitation and solution processes [5].

Calculating the change in density solely from the effect of pressure, the increase in density caused by heat treatment has to be subtracted from the increase in density measured in HIP-samples. Relating the corrected value of 0.019 g/cm³ to the theoretical density of 2.70 g/cm³ the change in density is 0.70 %, which is close to the change in porosity of 0.54 % as analyzed from micrographs. Hence, the main influencing factor for a change in volume and density of the precipitation hardening aluminum alloy AlSi7Mg0.3 resulting from HIP is the reduction of porosity, but the influence of the microstructural changes caused by heat treatment must be taken into consideration as well. However, until now it remains unclear, whether high pressures of HIP pronounce the decrease in volume caused by metallurgical effects mentioned in [5]. This would explain the remaining difference between the calculated and the measured porosity reduction of 0.16 %.

3.2 Mechanical properties

The results of the tensile tests are shown in Fig. 3. The initial state (test 0) exhibits a yield strength of 85 MPa, a tensile strength of 118 MPa and an elongation to fracture A_5 of 1.7 %. All treatments result in an increase of yield strength $R_{p0,2}$ and tensile strength R_m in comparison to the initial state (test 0). A significant increase in elongation can be recognized for all samples subjected to a HIP-treatment (tests 3-8). HIP with Jet-cooling (test 7) results in a degradation of the elongation as compared to HIP with standard cooling (tests 3). Ageing after HIP (tests 6 and 8) results in a decrease in elongation, too. Hence, the worst elongation for a HIP-treated sample is shown by test 8, but compared to the initial state it is still more than 50 % higher. On the contrary, a complete heat treatment with solution annealing, quenching and ageing causes a reduction in elongation (test 2) of about 30 %, whereas the water-quenched samples show a marginal increase after solution annealing (test 1). The highest elongation of 6.6 % is exhibited by test 4 after a second solution annealing following the first one during HIP.

Similar to elongation a subsequent heat treatment after HIP produces the best results for the tensile strength with a value of 249 MPa (test 5). This high level is achieved because both the individual processes, heat treatment (test 2) as well as HIP (test 3), cause a significant increase in tensile strength. Consequently HIP with Jet-cooling yields values superior to HIP with standard cooling conditions (test 7 vs. 3, test 8 vs. 6) caused by the higher quenching rate of about 0.5 K/s versus 0.4 K/s within the temperature range of 540 °C to 200 °C. Although the quenching rate of the Jet-cooling-system is still much lower than that of standard water-quenching (400 to 500 K/s [4]), the tensile strength after solution annealing and quenching shows exactly the same value for tests 1 and 7. Hence, the expected lower increase in strength caused by the lower quenching rate seems to be balanced by an increase caused by pressure during HIP. In contrast the results are different after a subsequent ageing: a standard heat treatment (test 2) shows results better by 9 % than those with ageing after HIP and Jet-Cooling (test 8). This is due to the much higher fraction of silicon and magnesium dissolved in the aluminum lattice after the rapid water quenching, which leads to a more efficient precipitation hardening in the ageing process. Increasing the cooling-rate in the hot isostatic press could lead to a markedly higher tensile strength to a similar extent as a subsequent heat treatment after HIP.

The quenching rate is at least as important for the yield strength as for the tensile strength. Hence, Jet-cooling leads to better results compared to standard cooling of HIP-samples (test 7 vs. 3, test 8 vs. 6). However, the highest yield strength of 191 MPa is exhibited by the samples subjected to the usual heat treatment with water quenching (test 2). Contrary to tensile strength and elongation, HIP with normal cooling (test 3) increases yield strength only slightly in comparison to the initial state (test 0). Based on this results it is expected, that a subsequent heat treatment after HIP (test 5) leads to an equal or even higher yield strength than a usual heat treatment (test 2). In contrast the measured values show that a subsequent heat treatment after HIP causes a significantly lower increase in yield strength. Therefore, a subsequent heat treatment after HIP does not lead to satisfying results for a combination of HIP and heat treatment concerning yield strength.

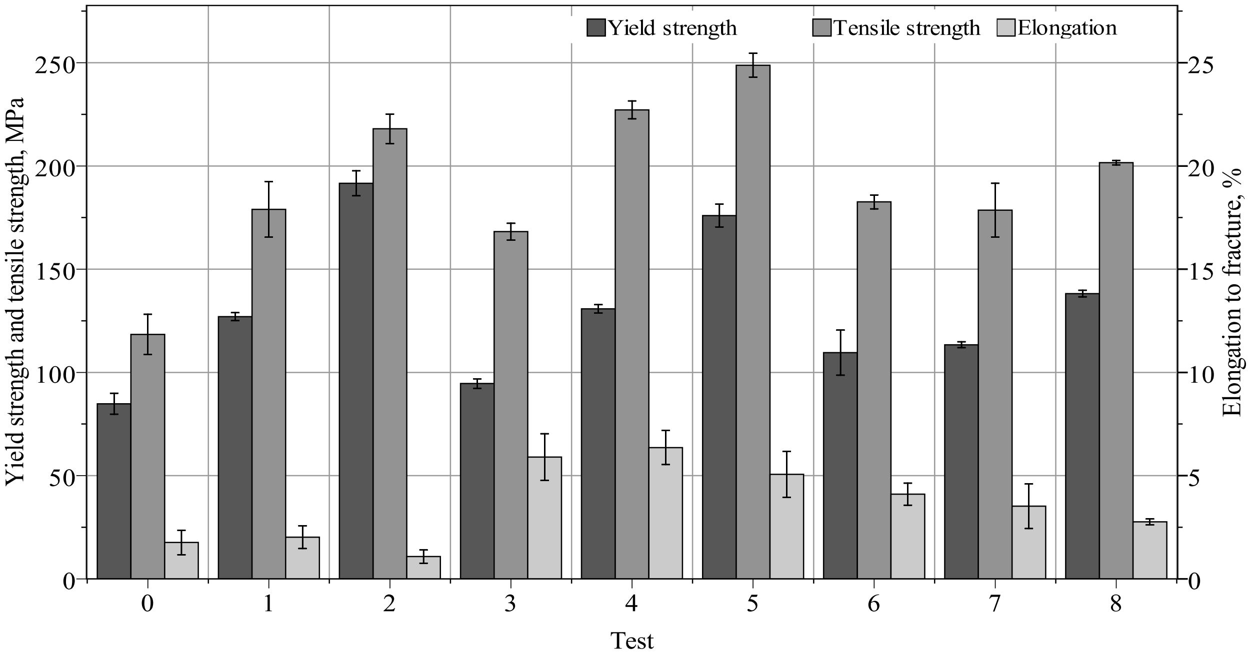


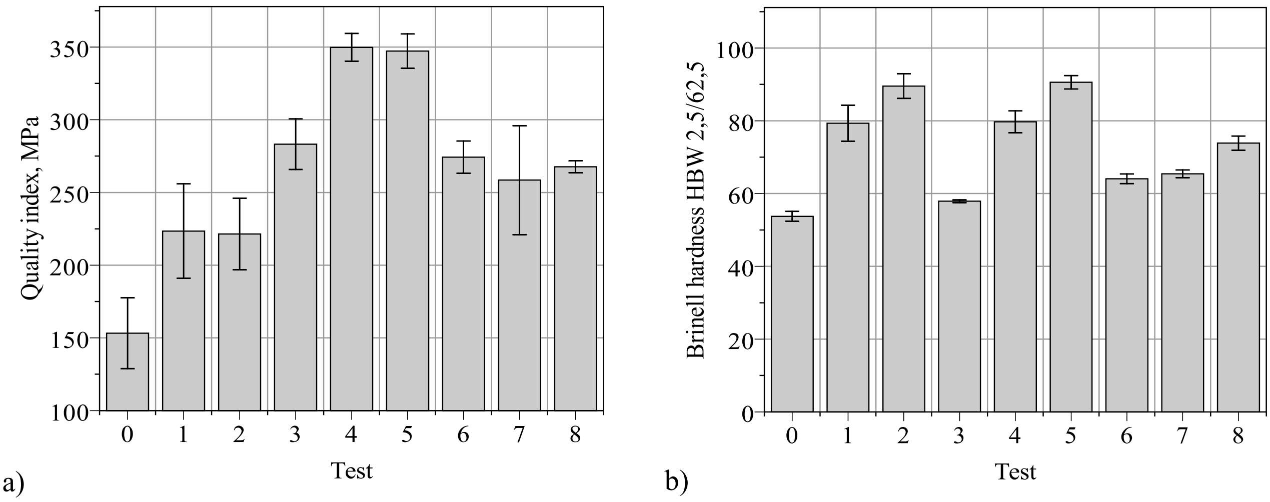
Fig. 3: Yield strength, tensile strength and elongation from the individual tests.

For a quantified comparison of different casting qualities the quality index Q was proposed by Drouzy et.al. [6]. The Q-index is obtained by inserting R_m (in MPa) and A_5 (in %) into the relation

$$Q = R_m + a \cdot \log(A_5)\,. \qquad (1)$$

For the alloy EN AC-42100 the constant a is 150 MPa [6, 7]. Because of the positive influence of HIP on elongation and tensile strength it is clear, that the Q-index plotted in Fig. 4a for all tests involving a HIP-treatment (tests 3-8) is higher than for the initial state (test 0) and for only heat treated samples (tests 1 and 2). The best results are shown by samples subjected to the subsequent heat treatment after HIP (tests 4 and 5), probably as a result of the double solution annealing. Ageing does not influence the value of the Q-index, no matter in which state the samples were before (test 2, 5, 6 and 8) However, the Q-index is an appropriate indicator for showing changes in quality caused by HIP or heat treatment. However, for the interpretation of the effects of HIP combined with a subsequent heat treatment the low yield strength (test 4 and 5) has to be taken into consideration in addition to the Q-index.

Besides tensile tests the Brinell hardness *HBW* was measured. As shown in Fig. 4b standard HIP slightly increases hardness (test 3) compared to the initial state (test 0), but a standard heat treatment has a substantially higher impact (test 2). After a standard solution annealing all water-quenched samples are on the same hardness level, no matter whether they were HIP-treated before (test 4) or not (test 1). This implies that the effect of HIP is lost by a subsequent heat treatment. Therefore, it is sensible for an increase in hardness as well as in yield strength to integrate quenching into HIP. Quenching by Jet-Cooling (test 7 and 8) causes a significant increase in hardness compared to quenching with standard cooling (test 3 and 6), although the two quenching-rates do not differ significantly in comparison to an ideal quench rate of about 4 K/s at ambient pressure [4]. This unexpected high effect on hardness by this low difference in the cooling rates can also be seen in the measured values of the tensile tests. Hence, further research is required to elucidate the influence of quenching rates in a hot isotatic press on the mechanical properties of aluminum castings.



a) b)

Fig. 4: a) Q-Index and b) Brinell hardness from the individual tests.

4. Conclusion

The investigation of the mechanical properties shows that a subsequent heat treatment after HIP exhibits a significant increase in tensile strength and elongation compared to a standard heat treatment. In contrast the results in yield strength are insignificantly lower while hardness is on the same level. An integrated process consisting of solution annealing and cooling under pressure in a hot isostatic press followed by subsequent ageing results in higher strength than using standard HIP and a better ductility than from a standard heat treatment. However, due to the low quenching rate in the laboratory hot isostatic press, the mechanical properties of the uneconomic combination of HIP with a subsequent heat treatment cannot be achieved yet. Hence, further investigations are needed to find the right pressure and cooling parameters for the optimization of both strength and ductility of aluminum castings. Based on these results, a concept for a cooling-system will be developed, which offers optimal quenching rates under isostatic gas pressure.

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