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Application of Liquid Hot Isostatic Pressure Technique for Processing of Aluminum Cast Articles

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A new technique of liquid hot isostatic pressure (LHIP) was developed to process aluminum cast articles. It was shown that the LHIP processing of sand cast parts from an AA356.02 led to increase in yield stress from ~200 MPa to ~230 MPa, ultimate stress from ~275 MPa to 310 MPa and total elongation from ~4% to 7.5%. The fatigue limit for aluminum sand cast articles subjected to LHIP increases by a factor of 1.7 and attains 140 MPa. It was shown that the positive effect of LHIP on mechanical properties is attributed to the elimination of shrinkage porosity in sand cast articles. As a result, under fatigue the crack initiation mostly takes place at lateral surfaces of the samples subjected to LHIP, whereas shrinkage pores in sand cast articles play a major role in crack initiation.

Keywords: *aluminum alloys, casting defects, strength and plasticity, fatigue behavior; liquid hot isostatic Pressing (HIP); shrinkage porosity.*

1. Introduction

To meet the demand for low-cost and high-strength automotive components the new technique of aluminum casting are extensively developed [1, 2]. However, there exists the other approach to enhance mechanical properties of aluminum casting. A two-step technique consisting of conventional casting process followed by hot isostatic pressing (hipping) is considered as advanced one to produce high-quality castings [3]. Initially, the isostatic pressure in hipping arose from gas pressurizing with the surface of the object. The application of a high inert gas pressure at high temperature provides the elimination of such casting defects as shrinkage porosity and hydrogen pin-holes. It was shown that the use of HIP is suitable for upgrading casting by its densification. Mechanical properties of cast aluminum components are improved significantly [4] by the elimination of shrinkage and hydrogen porosities. However, the utilization of this technique for processing of aluminum casting is currently limited due to the fact that HIP requires complicated and high-cost facilities. In addition, the hipping cycle times are generally ~8-16 hours. This technique is not suitable for mass production of high-volume components associated with the automotive industry. If reliability of aluminum casting components is extremely important, the HIP process characterized by high-added cost could be useful. The high cost of hipping restricts its commercial application to a limited range of low-volume high-performance components, primarily for use in the aerospace industry [5].

To overcome economic limitations of the hipping a process patented as Liquid Hot Isostatic Pressing (LHIP) [6] was developed 15 years ago for application in automotive industry. The isostatic pressure in LHIP process arises from a molten media. A specific vessel for LHIP was developed to provide the pressurization of aluminum components [4, 6-8]. The use of conventional hot working equipment and a high decrease in hipping cycle time to 3-5 minutes provided a substantial reduction in LHIP added cost to ~0.25-0.4 USD per 1 kg of hipped aluminum casting. As a result, this processing is capable for application in mass production. Recently, a new technique of LHIP was developed in Russia [7]. The main advantage of this technique is a feasibility to use conventional hydraulic presses for isothermal forging that provides lower investments for implementation of this technique into industry.

There is a distinct difference between HIP and LHIP consisting in duration of a pressurization cycle. This difference is highly important for the densification process. The process of pore elimination occurs in two stages under hipping [1, 4]. At first stage, the closure of an isolated pore takes place under isostatic pressure being larger than the yield stress of a material at a hipping temperature [3, 8]. It should be noted that the pores shrink rapidly. Therefore, this stage is completed both under HIP and LHIP cycles. At the second stage, the bonding of the mutual opposite surfaces of the collapsed pores, which are pushed together like in a planar crack, occurs, because atoms diffuse in both directions across the interface [3, 8]. In other words a kind of diffusion-controlled local bonding takes place providing complete elimination of pore trails. The sustain time of 1 hour or longer is necessary to complete this process [3] controlled by drift diffusion [8]. It is well-known [3] that the healing of the pores takes place under hipping. However, under LHIP, the pore elimination could not be completed, and the collapsed pores could still hamper the mechanical properties of an alloy. Their surface facing portions remain disconnected. Therefore, a detailed study of the effect of LHIP on mechanical properties is necessary; the mechanical properties of aluminum castings processed by LHIP and HIP have to be compared.

The aim of present study is to report the effect of LHIP on mechanical properties of an AA356.02 aluminum alloy which is a high strength cast alloy exhibiting good castability. This alloy is widely used for automotive components. Sand cast of the AA356.02 alloy by the method patented by Disamatic provides lower cost of different automotive components as brake calipers, pistons, suspension arms etc in comparison with traditional sand cast technique. However, this cast alloy contains a certain amount of pores, which significantly affect the mechanical properties of the component produced from this alloy. The elimination of porosity is an important task to improve the performance of this material. The development of a technique, which will provide both the low-cost of aluminum castings due to the use of Disamatic process and high reliability and enhanced fatigue strength due to the application of LHIP, is extremely important. This allows satisfying the demand for low-cast and high-performance automotive components.

In the present study the sand cast of AA356.02 is used as an object. The results obtained are compared with mechanical properties of the non-hipped similar alloy and investment castings from an AA356.02 subjected to HIP [5]. Specific attention will be paid to the evaluation of the endurance limit of the AA356.02 subjected to LHIP due to the importance of enhanced fatigue resistance for high-performance automotive parts which have to be highly reliable.

2. Experimental methods and material

The AA356.02 examined in this study was in form of bars with a 19 mm diameter and a 120 mm height. These bars were produced by sand cast technique through Disamatic method by Robinson Foundry, Inc. Their chemical composition was (in wt.%) Al-7%Si-0.37%Mg-0.16%Ti-0.02%Sr-0.17%Fe- 0.1%Cu. All samples were subjected to solution treatment at a temperature of 520°C for 12 hours. After completion of the solution treatment these specimens were subjected to LHIP at the similar temperature under a pressure of 120 MPa followed by water quenching without any intermediate heating. Dwelt time under isostatic pressure was ~30 sec. Next, the specimens were aged at 175°C for 8 hours. These specimens are denoted as hipped AA356.02-T6, herein. For comparison, the samples after solution treatment were water quenched followed by artificial aging at 175°C for 8 hours. These specimens are denoted as sand cast AA356.02-T6, herein.

Full details of the principles of LHIP technique and design of the LHIP vessel were given in [7]. In the present study, the LHIP was conducted using an isothermal vessel (Fig. 1) fabricated from high strength heat-resistant steel. This vessel having inside dimensions of a 100 mm diameter and a 350 mm depth was set up on a computer controlled hydraulic press with a 400 ton force and a 500 mm ram to apply pressure. This vessel was heated to 520°C and contains molten salt with the following composition (in wt.%) 35%$BaCl_2$-45%$CaCl_2$-20%NaCl. Total duration of a LHIP cycle including installation of the hot specimens inside the vessel, sealing, pressurization, specimen extraction and water quenching was less than 3 minutes. Notably, the salt retained at the sample surface was eliminated during water quenching.

Tensile specimens with a 6 mm gauge length and a 2 mm gauge width were machined from the sand cast and hipped samples with a gauge length parallel to its height. Tension test was carried out using an Instron model 5882 testing machine at room temperature. Fatigue tests were carried out at ambient conditions using an Instron model 8801 servohydraulic system on tension at the asymmetry coefficient R=0.1 and 30 Hz frequency in order to obtain S-N curves. The specimens for fatigue tests with a 25 mm gauge length and a 5 mm diameter were cut from the sand cast and hipped samples and then were mechanically and electrolytically polished to remove a damaged layer from the surface. At least, three samples were tested per a point in the both type of mechanical testing.

Fig. 1. LHIP vessel with 400 tons press capacity

Structural characterization of the hipped and sand cast AA356.02-T6 alloys was carried out using the samples cut parallel to their axis. As a result, different areas from the center to the edge of the sample cross-sections were examined using an Olympus GX70 optical microscope. Details of metallographic technique were reported in previous work [9]. After the fatigue tests the fracture surfaces were examined using a FEI Quanta 200-3D scanning electron microscope to reveal the fracture mode and fatigue crack initiations sites. In addition to the metallographic technique, the volume fraction of porosity was concurrently determined by the buoyancy method which was described in details in previous work [9].

3. Results and Discussion

3.1 Microstructure

Fig. 2(a) and (b) shows the microstructures of the sand cast AA356.02-T6. It is seen that coarse shrinkage pores with irregular shape were found in this material; a typical solidification structure of hypoeutectic Al-Si alloys is observed. Needle-shaped particles of $FeAl_3$ phase were rarely found; particles of Si having a plate-like or equiaxed shape are strongly dominated (Fig. 2(b)). These eutectic Si particles are relatively homogeneously distributed on macroscale level. On mezoscale level, these particles are located within eutectic areas which delimitate areas of aluminum matrix. It is worth noting that fine cavities with an essentially equiaxed shape can be also observed (Fig. 2(b)). This kind of pores is usually interpreted in terms of nitrogen entrapped cavitation [4].

LHIP leads to the elimination of shrinkage porosity (Fig. 2(c)); retained coarse pores can be observed very seldom. However, cavities having an equiaxed shape can be found in the hipped AA356.02-T6 (Fig. 2(d)). It was shown that their volume fraction in the sand cast AA356.02-T6 and in the hipped AA356.02-T6 is essentially the same. It seems that the gas-filled pores acquire more equiaxed shape after LHIP.

Data of densities are summarized in Table 1. It is seen that LHIP leads to 4-times decrease in porosity of the sand cast AA356.02-T6. There is a great difference in data of metallographic analysis and buoyancy method. The first technique shows that higher densification occurs in the sample centre in comparison with the sample edge. However, this conclusion is not supported by the data of buoyancy method.

3.2 Mechanical properties

Table 2 summarizes the tensile properties of the AA356.02-T6 in sand cast and hipped conditions. It is seen that LHIP leads to an increase of 15 pct. of the yield stress; total elongation increases significantly from ~4.5 to ~8%. In addition, the LHIPping significantly reduces the scattering of tensile properties, especially ductility data. It is worth noting that mechanical properties of the hipped AA356.02-T6 are higher than those of the components of this alloy fabricated by the rheocasting technique [1] and the AA356 without Sr modification subjected to HIP [10]. The yield stress of a component from the AA356.02 produced by investment casting followed by HIP [5] is slightly higher than that of the hipped AA356.02-T6 and components from an AA356 produced by lower pressing casting [1]. It is worth noting the ductilities reported in works [1, 5] for different kinds of AA356 material do not exceed 4.5pct.

Table 1. Porosity volume fraction (in pct.) for the sand cast and hipped AAA356.02-T6

Technique/material state	Sand cast	Hipped – edge of sample	Hipped – center of sample
Metallographic technique	3.66	1.18	0.88
Buoyancy technique	0.93	0.226	0.24

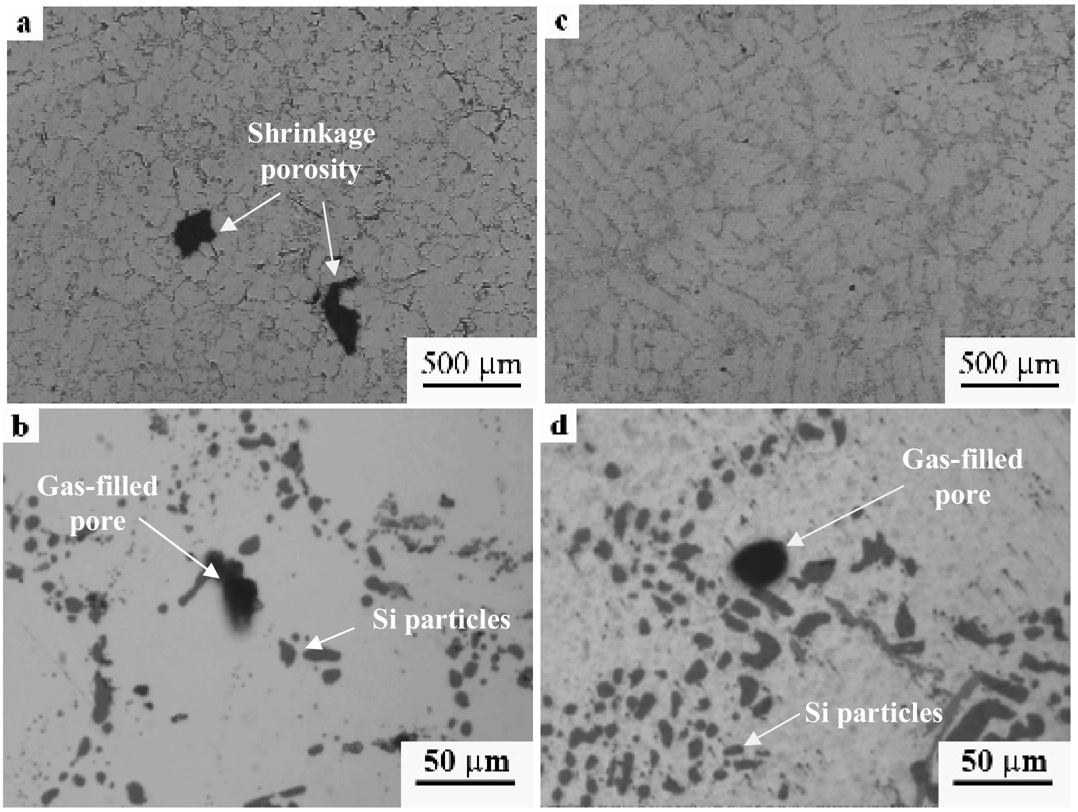

Fig. 2. Typical optical microstructures of the sand cast AA356.02-T6 (a, b) and the hipped AA356.02-T6 (c, d)

Table 2. Effect of LHIP on the tensile mechanical properties

Mechanical properties	Sand cast AA356.02-T6	Hipped AA356.02-T6
Yield stress, σ_{02} (MPa)	203	230
Ultimate strength, σ_B (MPa)	289	317
Elongation-to-failure, δ (%)	4.5	7.7

Fig. 3 shows the S-N data obtained from the sand and hipped AA356.02-T6 materials. It is seen that LHIP leads to a significant increase in fatigue resistance. The fatigue strength of the sand cast AA356.02-T6 at 10^7 cycles is about 80 MPa. This value matches with high accuracy with fatigue strength reported for components produced by investment casting from the AA356.02 [5]. The fatigue strength of the hipped AA356.02-T6 was evaluated as 140 MPa that is higher than that reported for this alloy subjected to conventional HIP [5] or processed through rheocasting or low-pressing die casting [1].

SEM fractographs of the sand cast and hipped AA356.02-T6 materials are shown in Fig. 4. In the sand cast AA356.02-T6 the fatigue cracks are initiated from coarse shrinkage pores (Fig. 4(a)). At high stress level, multiple cracks are generated and grew from several shrinkage voids. Subsequent linkage of these cracks leads to fatigue damage. While at low stress level, one shrinkage pore usually acts as a site for crack initiation. Stable crack growth takes place in a brittle manner (Fig. 4(b)) that is a specific feature of fatigue damage of the sand cast AA356.02-T6. Ductile tire tracks are rarely observed within this area (Fig. 4(b)). This failure mode can be termed as cyclic cleavage. In contrast, at overload stage, the fatigue fracture occurs in essentially ductile manner; well-defined grain boundary extrusions and many dimples with silicon particles inside were found (Fig. 4a). It is worth noting that dimensions of areas of crack initiations and stable crack growth do not exceed 200 and 400 μm, respectively.

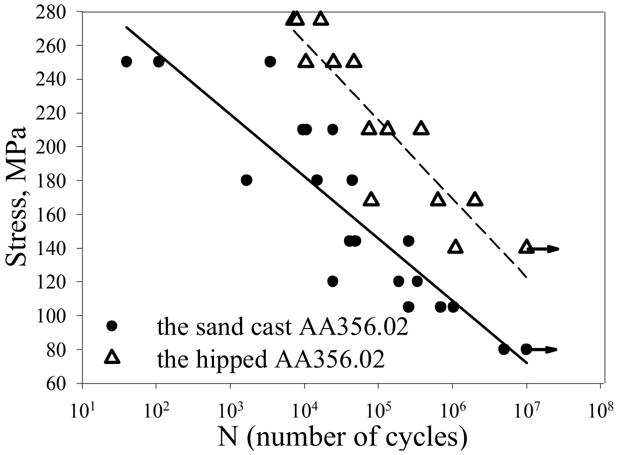

Fig. 3. S-N curves for the sand cast AA356.02-T6 and the hipped AA356.02-T6

There is a strong difference between the sand cast and hipped AA356.02-T6 (Fig. 4(c-e)) in mechanisms of crack initiations and stable crack growth. As a rule, in the hipped AA356.02-T6 the crack initiation occurs at lateral surface. At high stress level, cracks could be initiated at silicon particles within specimens. However, these microcracks play a minor role in fatigue damage. Crack initiations at surfaces leads to fatigue damage. Notably, near lateral surface the zones of crack initiation and stable crack growth are relatively large, their dimensions exceed 1 mm (Fig. 4(c)). Under stable crack growth the fracture surface displays many micro-cliffs exhibiting zigzag configuration (Fig. 4(e)); the extensive formation of secondary cracks takes place. There exists a weak evidence for striations (Fig. 4(e)). This fracture fashion is typical for wrought aluminum alloys. Therefore, stable crack growth in the hipped AA356.02-T6 accompanies by extensive microplastic deformation and occurs in ductile manner. The visible microscopic ductile fracture is observed within the region of overload (Fig. 4(d) and (e)).

Thus, LHIP eliminates the shrinkage porosity in the sand cast AA356.02-T6 strongly hindering crack initiations under fatigue. As a result, a significant increase in endurance limit takes place. It seems that crack initiations at shrinkage cavities is a main factor restricting yield stress and fatigue limit of the sand cast AA356.02-T6. Elimination of shrinkage porosity allows attaining the same mechanical properties of the sand cast material as in the same material processed by modern casting techniques. It seems that complete elimination of collapsed pores by diffusion bonding of their facing surface portions is not important for mechanical behavior of the hipped material due to the fact that fatigue cracks could not be initiated at these pores. This is why the fatigue endurance obtained in the present study and one of an AA356.02 subjected to HIP [5] are essentially the same.

The internal porosity arisen from the precipitation of air could not be eliminated by HIP [3]. These pores can be shrunk under pressure. However, it leads to significant increase of the gas internal pressure, and the pore may recover its shape under subsequent heat treatment. However, these cavities are relatively fine and exhibit an equiaxed shape. As a result, their presence is not important for fatigue strength at low stress applied; no crack initiation at these pores was found. At the same time, this type of cavitation affects fatigue resistance at high stress level.

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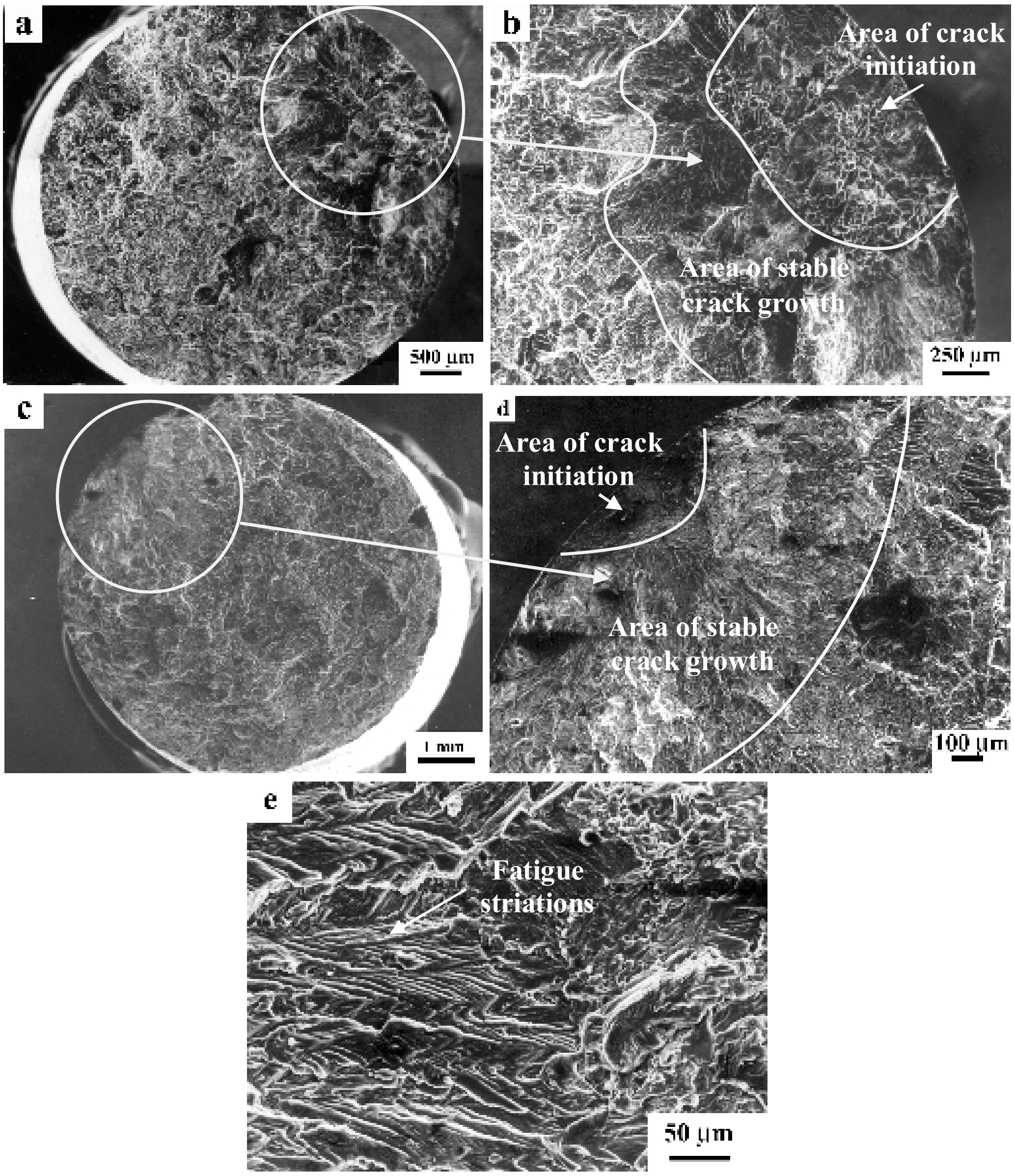

Fig. 4. SEM of fractured surfaces of the sand cast AA356.02-T6 (a, b) and the hipped AA356.02-T6 (c, d, e)

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