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The effect of liquid hot isostatic pressing on fatigue properties of Al based castings

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Abstract

Because of weight and cost savings automotive manufactures are making more extensive use of cast aluminium alloys to replace forged and cast iron or steel components. The presence of pores in certain locations may reduce the fatigue life and it is cause of a large scatter in the mechanical properties of cast parts. This is of special concern for safety critical components.
In this work A356 T6 heat-treated specimens were drawn from a suspension arm, that was manufactured with two different low pressure foundry processes, permanent mould and Disamatic process, and they were subjected or not to liquid hot isostatic pressing in a salt bath at 120 MPa and 540 °C for 30 s. Then high-cycle axial fatigue tests were performed on smooth plane samples at room temperature with a tension compression ratio of –1, in order to obtain fatigue S-N curves in the different conditions. After LHIP it was found that there is a large increase of fatigue resistance and a remarkable decrease of the scatter of fatigue data, which is due to the presence of internal discontinuities. Optical microscopy and scanning electron microscopy (SEM) were used to document the elimination of porosity after LHIP and to show the different nucleation sites of fatigue cracks on the fracture surfaces in no-LHIP and LHIP conditions.

Riassunto

Numerosi componenti di meccanica dell'auto vengono oggi realizzati in leghe di alluminio in alternativa all'acciaio e alla ghisa per ragioni di alleggerimento. Come noto la vita a fatica dei getti in lega leggera è fortemente influenzata dalla presenza di porosità. Questo fenomeno risulta particolarmente critico per i particolari di sicurezza. Con il presente lavoro sono stati analizzati campioni di lega A356-T6 ricavati da componenti della sospensione prodotti con due tecnologie di colata in bassa pressione : conchiglia e Disamatic. Sui campioni sono stati valutati gli effetti del processo LHIP in bagno di sali a 120 MPa e 530°C per 30 secondi. In particolare sono stati osservati gli effetti del processo sulla vita a fatica ad alto numero di cicli e temperatura ambiente. Il processo LHIP aumenta notevolmente la resistenza a fatica dei getti e riduce la dispersione dei dati relativi.
L'analisi micrografica ed al microscopio a scansione ha permesso di documentare la riduzione di porosità nei getti trattati LHIP e l'effetto sulla fase di innesco della frattura.

Introduction

LHIP (Liquid Hot Isostatic Pressing) is a process that subjects a component to both elevated temperature and liquid isostatic pressure in a suitable vessel. Under these conditions of heat and pressure, internal pores or defects within a solid body collapse and weld up.
This process represents the evolution of HIP (Hot Isostatic Pressing), in which a gas, argon, is used as the pressuring medium. The HIP process was invented in the mid-1950s at Battelle Columbus Laboratories. The process was specifically developed as a gas pressure diffusion bonding technique for cladding nuclear fuel elements. In 1965 the use of hot isostatic pressing for improving the fatigue life of cast aluminium diesel engine was investigated. Further investigations into the effect of HIP on titanium and superalloy castings were conducted in the 1970s and they demonstrated that significant improvement in mechanical properties could be obtained [1]. Initially most of the casting being hot isostatically pressed were aerospace components, such as turbine blades and structural hardware for aircraft gas turbine engines. These expensive components could accept the high-added cost of the HIP process. Also the casting industry originally perceived HIP as a means to reduce its scrap rates. Prior to the development of HIP no other non-destructive technique was available for the economic repair of castings containing internal porosity. Recently, however the cost of HIP has been reduced (increased number and size of vessels dedicated to HIP of castings and improvements in equipment) to the point at which it is affordable for less critical applications. [2]. Anyway the HIP is a discontinuous process and it is hard to expect its integration into a productive cycle, e.g. of an automotive casting, also because of the elevate cycle times (4-6 hours).
LHIP presents two significant advantages because

it is a continuous process and it enables a drastic reduction of the process time, thus to make possible a high grade of automation. In this process the pressurizing medium is a salt bath, with a much higher density than argon at process temperature, and so it is able to reach high pressures in a shorter time.
This process is currently under development with the aim to upgrade the quality of castings. In fact castings may have internal defects such as gas porosity (due to trapped gases, such as hydrogen or air), interdendritic microporosity (due to shrinkage) and microcracks that form during solidification and that have an adverse effect on performance. Such pores tend to concentrate stress and therefore act as yield and crack initiation points. The more sharply angled a pore, the more the stress will be concentrated. The LHIP process heals these defects first through creep and plastic deformation and then by diffusion bonding of the surfaces of the collapsed area, creating a casting with a fully dense omogeneous microstructure. During processing the treatment temperatures are maintained with the plastic range of the material concerned, or more precisely, high enough for the diffusion bonding to occur but at the same time low enough to avoid undesidered microstructural modification such as grain growth.
The higher integrity and homogeneity of the casting after LHIP improves its mechanical characteristics with the subsequent increase of fatigue resistance but also of tensile and yield strengths, ductility and, creep life [3,4]. It also reduces the scatter of these properties. As the volume normally occupied by defects is limited, LHIP does not significantly modify the dimensions or the shape of the casting. In addition if large voids exist in the casting, surface depressions may develop as a result of material displacement during void closure. If small, uniformly distributed voids are present in a casting, a dimpled surface may be evident after hot isostatic pressing. Such a condition is typical in many sand-cast aluminium parts. LHIP treatment does not heal surface related defects. For this type of healing the part requires a coating to act as barrier against the pressurized liquid [3]. Furthermore, diffusion bonding does not occur when metal/metal contact is obstructed, if for example the surfaces of the defect are oxidized or if there is a gas inside the pore that does not diffuse in the material, e.g. air. In the figures 1 and 2 the possible situations are shown.

At the same time the use of aluminium castings in the automotive industry has seen ever increasing growth due to the economic savings of a reduced number of production steps compared to other manufacturing methods such as forging. These production advantages have lead to strong interest in aluminium castings for applications where stringent mechanical requirements must be met.
The fatigue properties of Al-Si castings alloys have been related to micro-

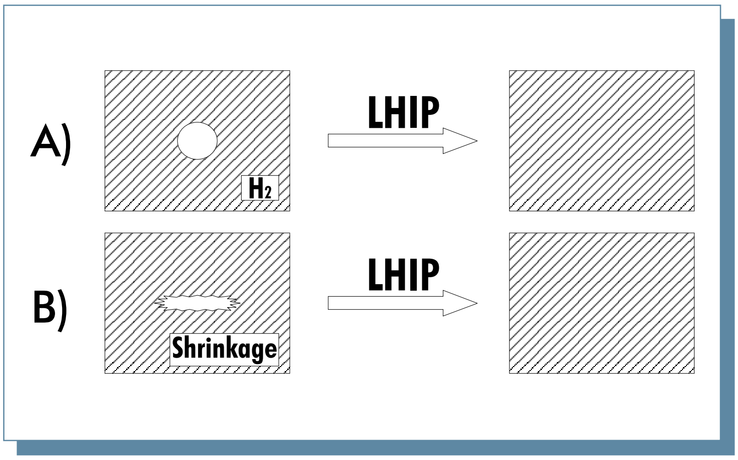


Fig. 1: Defects, which can be closed after LHIP:
a) H_2 pore, b) Solidification shrinkage

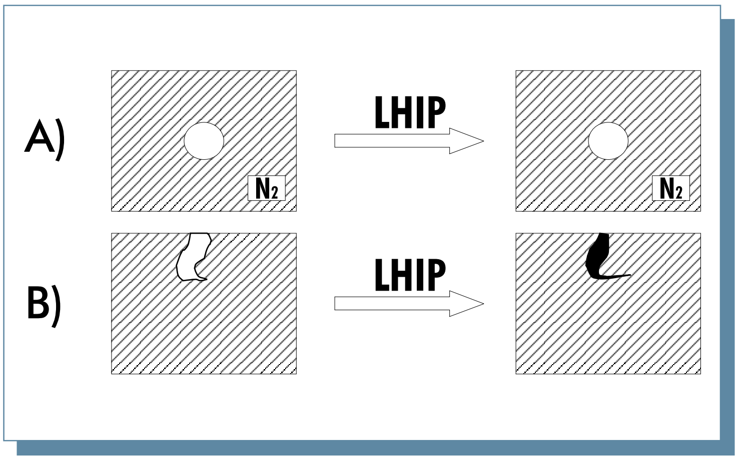


Fig. 2: Defects, which can not be removed after LHIP:
a) Air entrapped, b) Surface porosity

structural features such as secondary dendrite arm spacing (SDAS) [5] and porosity morphology and location [6], to variations in heat treatment [7] and to loading parameters such as the load sequence or the load ratio [8].
It is generally accepted that the fatigue process consists mainly of four important stages: microcrack initiation, microcrack coalescence and growth (small-crack propagation), macrocrack growth and final fracture. From the point view of fatigue life, the crack propagation dominates the low-cycle fatigue life and crack initiation controls the high-cycle fatigue life.

Fatigue cracks in aluminium alloys have been found to nucleate from slip bands, inclusion breakage and debonding, and grain-boundary separation, voids and notches [9]. Anyway in hypoeutectic Al-Si casting alloys, fatigue cracks usually nucleate from interdendritic shrinkage pores at or close to the specimen surface [5,7] and so cast pores constitute the main influence on fatigue properties. S-N fatigue curves are remarkably insensitive to the heat-treatment condition (either solution treatment or ageing treatment) in contrast to the behaviour of wrought alloys in which the fatigue resistance is usually closely related to the yield stress or the tensile strength [7]. The effect of hot isostatic pressing on the mechanical properties of aluminium alloys, especially fatigue behaviour, is not well understood.

In this work A356 T6 heat-treated specimens were drawn from a suspension arm, that was manufactured with two different low pressure foundry processes, permanent mould and Disamatic, and subjected or not to liquid hot isostatic pressing in a salt bath at 120 MPa and 540 °C for 30 s. Then high-cycle axial fatigue tests were performed on smooth plane samples at room temperature with a tension compression ratio of –1, in order to obtain fatigue S-N curves in the different conditions.

After LHIP it was found that there is a large increase of fatigue resistance and a remarkable decrease of the scatter of fatigue data, which is due to the presence of internal discontinuities. Optical microscopy and scanning electron microscopy (SEM) were used to document the elimination of porosity after LHIP and to show the different nucleation sites of fatigue cracks on the fracture surfaces in no-LHIP and LHIP conditions.

EXPERIMENTAL PROCEDURE

To understand the effect of LHIP on microstructure and fatigue behaviour of an Al based automotive part, A356 suspension arms were produced by through two different low pressure casting techniques, permanent mould and Disamatic process. In the figure 3 the automotive component is shown.

The main features required to a suspension arms are light weight and stiffness, fatigue resistance and elongation, yield and tensile strength. Such mechanical properties could be obtained by means of premium-quality Al alloys and tightly controlled process.

Aluminium-silicon alloys combine the casting advantages of high corrosion resistance, good weldability, and low specific gravity; aluminium-silicon alloys hardened by Mg_2Si have excellent casting characteristics, weldability, pressure tightness and corrosion resistance. These alloys are heat treatable to provide various combinations of tensile and physical properties that are attractive for many applications, including aircraft and automotive parts. Among the aluminium-silicon magnesium-silicide group, A356 (Al-6.5-7.5Si0.2Fe0.20-0.45Mg0.10Zn0.10Mn0.20Cu0.20Ti, [10]) is capable of much higher ductility than its lower purity counterpart, 356. A356 is among the premium-quality sand and permanent mould casting alloys specified for military and aircraft applications and for safety automotive components.

Fig. 3: Two different views of the suspension arm (not in scale)

As the casting processes concern the rapid solidification rates associated with low-pressure casting result in castings with finer grain size, smaller secondary dendrite arm spacings, and enhanced mechanical properties, such as strength and ductility. The main advantage related to Disamatic process is the high productivity rate. The cooling property of the sand mould materials doesn't enable to obtain very small dendrite arm spacings compared to other processes in chilled moulds.

The suspension arms were T6 heat-treated and were partially subjected to LHIP process, according to the following cycle:

- Solubilization: 8h at 540 °C
- LHIP
- Quenching: water at 60 °C
- Artificial ageing: 6h at 160 °C

The LHIP conditions are shown in the following figures.
Then the four categories of low pressure castings (permanent moulding T6, permanent moulding T6 and LHIPped, Disamatic T6, Disamatic T6 and LHIPped) were cut into pieces for the smooth plane fatigue specimens; the specimen geometry used in axial fatigue testing was from ASTM E466-72 [11]. Then high-cycle axial fatigue tests were performed on smooth plane samples at room temperature with a tension compression ratio of –1, in order to obtain fatigue S-N curves in the different conditions.
Optical microscopy and scanning electron microscopy (SEM) were used to document the elimination of porosity after LHIP and to show the different nucleation sites of fatigue cracks on the fracture surfaces in no-LHIP and LHIP conditions.

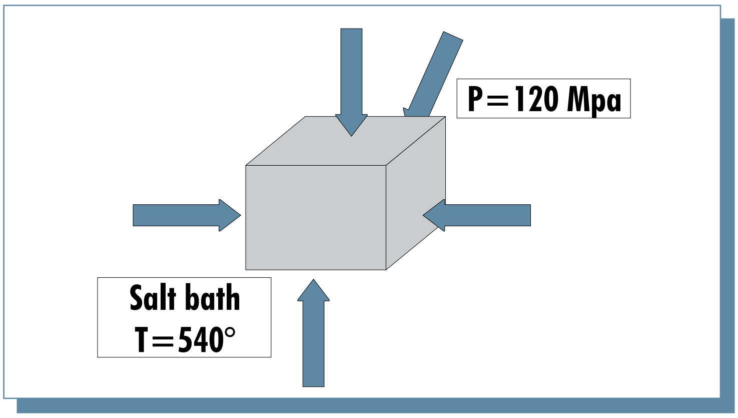


Fig. 4: Scheme of an element of material, which is subjected to LHIP in a melted salt bath

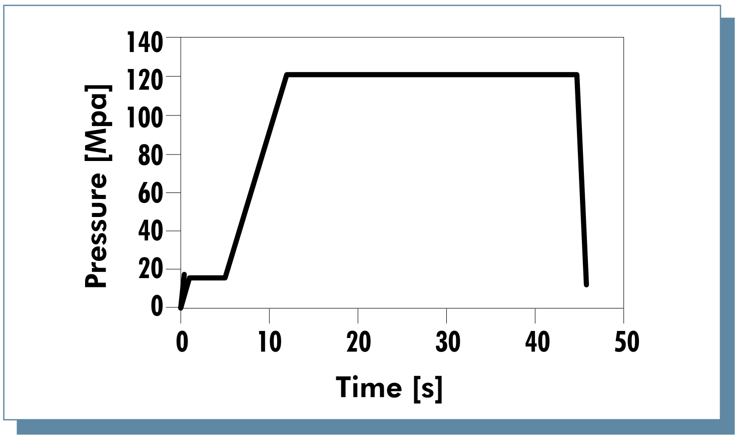


Fig. 5: Pressure in function of time during LHIP process

RESULTS AND DISCUSSION

The first result of LHIP process is the increase of the density of the treated parts, by means of the elimination of internal porosity. In fact radiographic inspections have shown that every automotive component subjected to LHIP is characterized by a 0-1 ASTM grade, defining the level of porosity. Instead not treated parts have a 1-2 ASTM grade.
Such result has been confirmed by a metallographic analysis of the sections extracted from the suspension arms in the different conditions, as it results clear in the following micrographs.
The not LHIP treated parts are characterized by two different kind of porosity: a more irregular one, that is interdendritic porosity, which is a consequence of the solidification from the liquid state and a rounded one, that is gas porosity. The samples from parts obtained by Disamatic process show a significantly bigger porosity in respect of the samples produced with permanent mould process, which also shows a finer microstructure. This is the typical microstructure of A356 T6 and micrographs show dendrites as the primary structure, with a eutectic mixture filling the interdendritic spaces. The silicon particles are distributed fairly uniformly in the microstructures observed before LHIP and they have a fine, spherical shape because of the modifying addition to the melt.

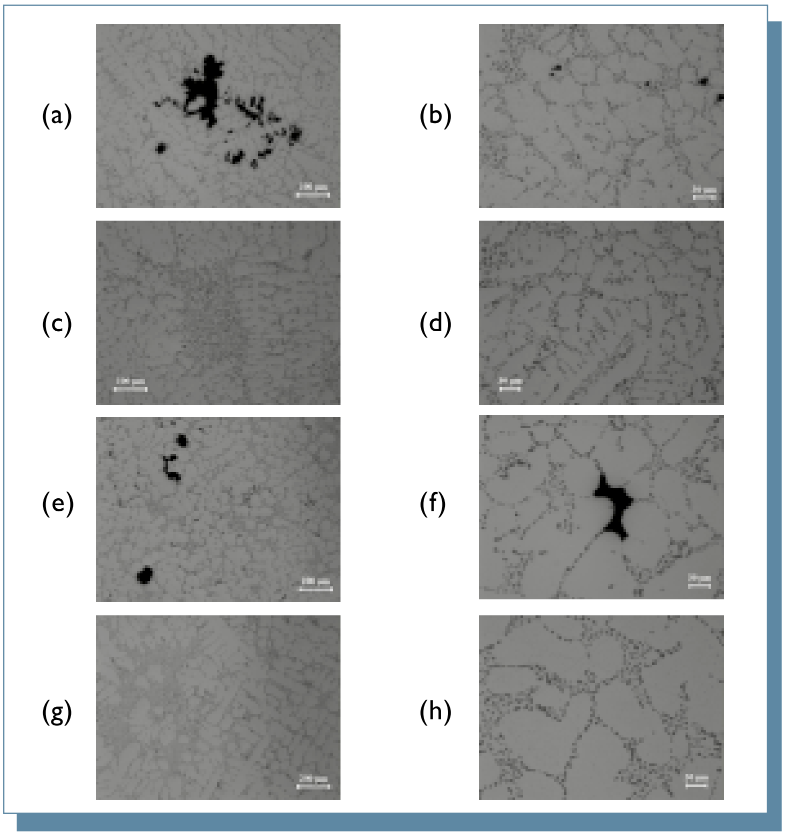


Fig. 6: The microstructure of A356 in the different casting conditions: permanent mould + T6 (a) and (b), permanent mould + T6 + LHIP (c) and (d), Disamatic + T6 (e) and (f), Disamatic +T6 + LHIP (g) and (h).

After the LHIP treatment there is a nearly complete closure of the internal pores, while the microstructure has not significantly changed, even if the micrographs show a little increase of the concentration of silicon particles in some zones. Anyway during LHIP the temperatures required for densification are low and the times at elevated temperature short. So the possible occurrence of secondary effect such as grain growth changes in precipitate distributions and changes in segregation pattern can be prevented. LHIPping pressures can also crack those brittle particles associated with porosity in ductile matrix, i.e. intermetallic compounds in Al alloys. Such effects underline the need for careful control of pressure and temperature ramp rates.

However the major effect of LHIP is the removal of porosity. The driving force for pore closure is the reduction in the surface area associated with pores. The driving force for the removal of small pores is greater than that for the removal of larger pores [3]. If the pores contain gas, the internal pressure of the gas will tend to oppose the driving force for shrinkage. In LHIP the external applied pressure adds to and completely swamps this driving force and almost inexorably causes any gases in a pore to dissolve into the matrix. The solubility of such gases increases with increasing pressure within the pore, which increases during the early stages of LHIP. Under pressure the gas diffuses to the surface, rather than to another pore as in sintering. The pore than collapse. It is only when a pore reduces to a diameter of perhaps 40 nm that the driving force due to surface energy becomes comparable with that due to the externally applied pressure. Yield stress decrease for most metals with increasing temperature. LHIP conditions are generally chosen so that the salt bath pressure is greater than the reduced yield point of the material at that temperature. Plastic flow can then occur on a microscopic scale; under LHIP conditions creep processes such as Nabarro-Herring creep (diffusion through grain interiors), Coble creep (diffusion around grain boundaries) and dislocation creep operate at relatively high rates. Finally the joining of the collapsed surface occurs through a diffusion bonding mechanism [3].

Data showing the effect of LHIP on static mechanical properties is given in table I for the different casting conditions. The averaged values of yield strength and ultimate tensile strength are better for permanent mould samples than Disamatic samples, because of a finer microstructure and a reduced porosity , as it is visible in the previous micrographs. LHIP does not improve the yield stress and ultimate tensile strength significantly, but the decrease of the internal porosity has an important effect on the tensile ductility with a nearly 50 % improvement.

In the following figures the results of axial fatigue tests, as Wohler curves, are shown for the different casting conditions. These curves were obtained first by estimating the fatigue limit (50 % level of probability of fracture) with Staircase method (15 tests with a 10 MPa step and 10^7 cycles as reference number of cycles). Then other fatigue proofs were performed at different levels of tension, so it was possible to estimate the characteristic straight line of the finite endurance zone by means of a linear interpolation.

In the figure 7 the effect of LHIP is evident on the fatigue curves for permanent mould and Disamatic specimens. LHIP improves the S-N fa-

TABLE 1.
RESULTS OF TENSILE TESTS (AVERAGED VALUES) IN THE LHIP AND NOT LHIP CONDITIONS

Casting condition	0,2% Yeld Stress (MPa)	Ultimate strenght (MPa)	Ultimate Strain (%)
Permanent Mould +T6	250	305	7,7
Permanent Mould +T6 +LHIP	263	310	11,1
Disamatic +T6	212	256	3,9
Disamatic +T6 +LHIP	218	270	6,9

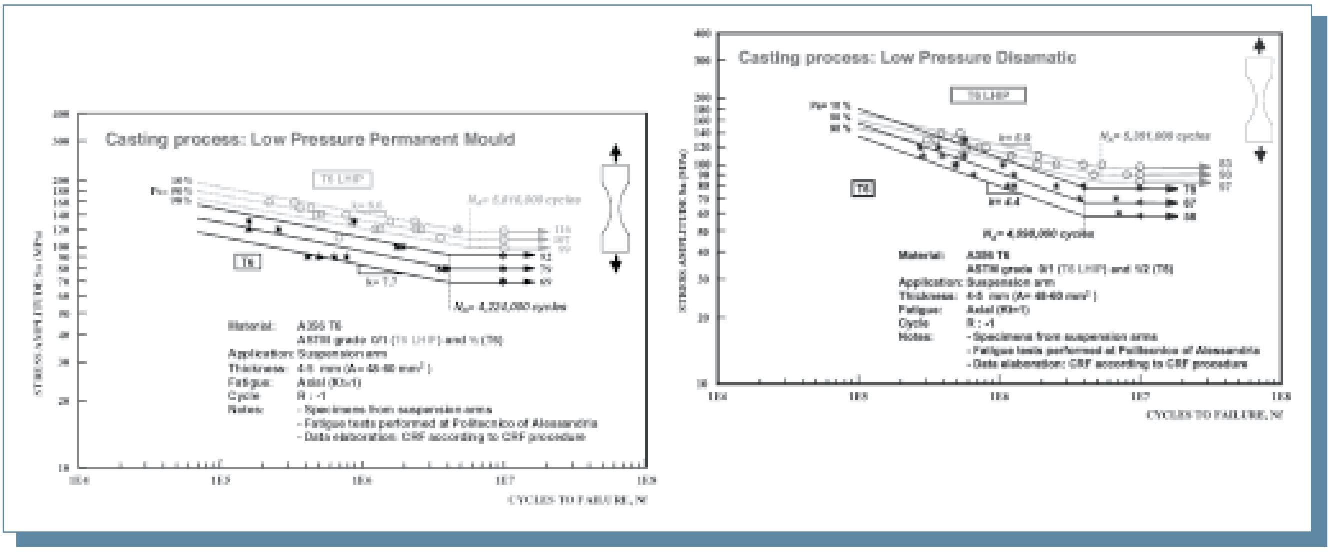


Fig. 7: S-N axial fatigue curves for A356 T6 in low pressure permanent mould (a) and Disamatic (b)condition subjected or not subjected to LHIP treatment

tigue life of cast A356 T6. The three LHIP curves (relative to the different probability of survival) are shifted up and the 50% fatigue limit for the specimens subjected to LHIP is 35% higher. Also the 90% (probability of survival) curve of the specimens subjected to LHIP is over the 10% (probability of survival) curve of not LHIP treated samples.

The standard deviation is much higher for not LHIPped material, so there is an important decrease of fatigue scatter after LHIP treatment. This scatter is explained by the repetition of relatively small loads, which enables weak properties of the materials to become dominant. Such properties include the local fluctuations of the composition; the different size and orientations of grain; the distribution and sizes of slag inclusions and of segregations; cavities, blisters, blow holes and microstructural defects in general. So the reduction in scatter is an experimental evidence of the removal of porosity by LHIP. Finally the slope of the straight line in finite endurance zone is higher for LHIPped specimens; this means that LHIP increases the reliability of the component because a little variation of the applied stress gives rise to a lower variation in the number of cycles to failure in respect of not LHIP treated material.

Fatigue crack initiation is very sensitive to the void content of a material. LHIP helps to close the voids present in the cast materials and, in this way, enhances their fatigue properties. This aspect has been confirmed by SEM analysis of fracture surfaces after fatigue tests.

Above all the fractographic observations have shown the possible nucleation sites of fatigue cracks for the specimens in the different casting conditions. Fatigue failure for not LHIPped test pieces generally tends to originate from interdendritic shrinkage below, or at, the surface. By contrast, when LHIPped test pieces eventually fail, they do so at large intermetallics, inclusions, surface-connected porosity or internal pores which could not be closed by LHIP, since these are the largest defects present within the structure. Thus to improve the properties of LHIPped materials further, attention should be focused on the refinement of cast microstructure and the removal of large inclusions.

Some scanning electron microscopy fractographies of failed test pieces are shown in the following figures. In figure typical fatigue-crack nucleation sites are related for A356 T6 failed specimens, that were not subjected to LHIP. The most significant observation is that in nearly all samples the preferential nucleation site of fatigue cracks is shrinkage interdendritic porosity close or at the surface. This is true for permanent mould failed specimens (figure 8a and 8b) and also for Disamatic failed specimens (figure 8c and 8d). This kind of discontinuity seems to be more deleterious than other defects, which are present in the material, e.g. gas porosities or oxides. Reducing the size of shrinkage defects will increase the fatigue life, but only up to the stage at which initiation from persistent slip bands on the surface becomes operative [7]. Other investigators [9,12] have observed that casting discontinuities of size similar to the silicon eutectic particles in Al-Si alloys will not have a detrimental effect on fatigue strength.

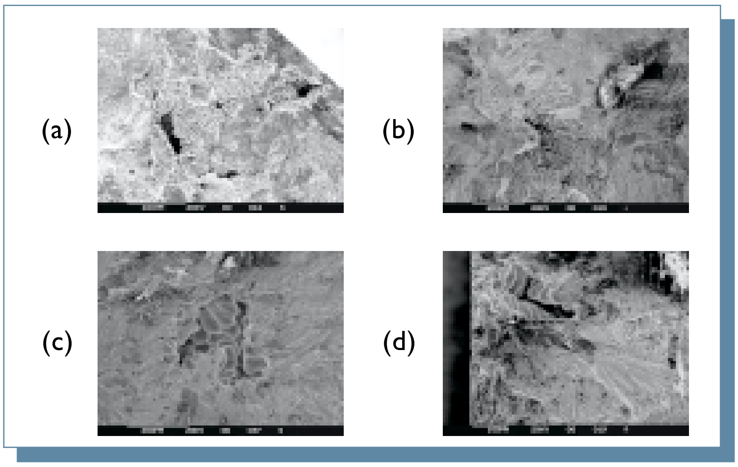


Fig. 8: Fatigue-crack nucleation sites for: (a) permanent mould specimen, tested at 80 MPa and failed at 3992807 cycles, (b) permanent mould specimen, tested at 130 MPa and failed at 161764 cycles, (c) Disamatic specimen, tested at 80 MPa and failed at 4013477 cycles, (d) Disamatic specimen, tested at 80 MPa and failed at 1151496 cycles

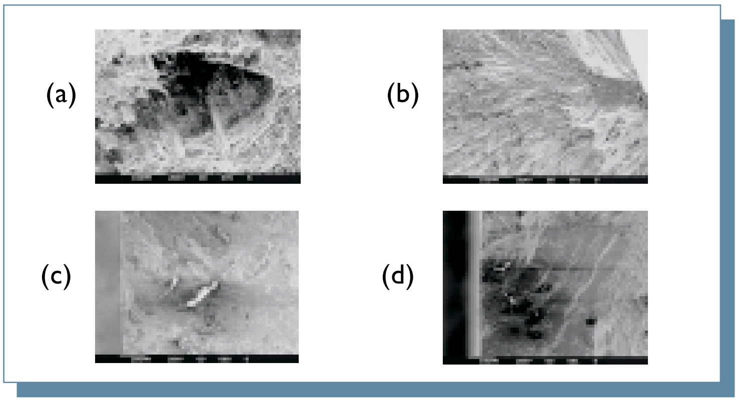
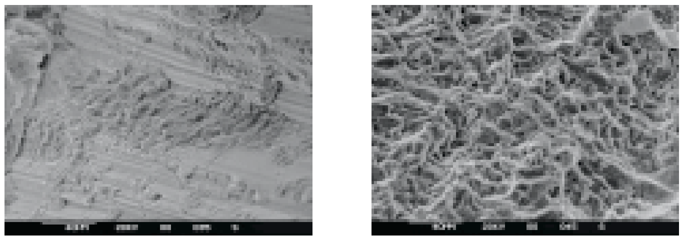


Fig. 9: Fatigue-crack nucleation sites for: (a) permanent mould LHIPped specimen, tested at 120 MPa and failed at 1249953 cycles, (b) permanent mould LHIPped specimen, tested at 140 MPa and failed at 780406 cycles, (c) Disamatic LHIPped specimen, tested at 90 MPa and failed at 4710397 cycles, (d) Disamatic LHIPped specimen, tested at 110 MPa and failed at 1205000 cycles

In the figure 9 initiation sites are shown for LHIPped samples, obtained by permanent mould process (figure 9a and 9b) and Disamatic process (figure 9c and 9d). The fatigue crack initiated mainly at the specimen surface since LHIP suppressed the voids in the material. Anyway also fatigue crack nucleation from oxides (figure 9c) and from pores, which were not closed by LHIP (figure 9a) are possible.

In the figure 10 the fatigue propagation and abruptly rupture zones are shown for two failed samples. This kind of surface morphology has been found for almost every sample, which was or was not subjected to LHIP



(a) (b)

Fig. 10: Typical propagation (a) and final fracture (b) zones of failed specimens

treatment. These zones are typical of the fracture surface of Al-Si alloys. The fatigue fracture surface near the initiation site has a flat aspect, with clear signs of the propagation of the crack under the action of an alternate load (see fatigue striations in figure 10a). Instead ductile dimples (figure 10b) cover the final fracture zone. Even if the final fracture occurred abruptly, the process is dominated by ductile rupture of the soft aluminium matrix involving the pull out of silicon particles. No evidence of particle cracking was found. This is in agreement with the work of Lee [12], which pointed that the propensity of particle cracking increases as the K increase, that is low-cycle fatigue, whereas particle decohesion and fatigue striation formation increase as the K levels decrease, that is high-cycle fatigue.

CONCLUSIONS

The effect of liquid hot isostatic pressing (LHIP) on the fatigue properties of Al based automotive parts (A356 suspension arms) was investigated. The following conclusions may be drawn from this work:

1. LHIP process increases the density of the treated parts, by means of the elimination of the internal porosity. The parts subjected to LHIP have a 0-1 ASTM grade against a 1-2 ASTM grade of parts, which were not LHIPped.
2. The removal of porosity has been confirmed by a metallographic analysis for both low pressure permanent mould and Disamatic samples. This occurs through plastic flow, creep and diffusion bonding mechanism.
3. The decrease of the internal discontinuities improves (50%) the tensile ductility.
4. The S-N axial fatigue curves of LHIPped samples are shifted up, with a 30-35 % improvement of 50% fatigue limit, which was determined by Staircase method.
5. The standard deviation is much higher for not LHIPped material, so there is an important decrease of fatigue scatter after LHIP treatment. The better reliability of LHIP treated component arises also from the higher slope of the straight line in finite endurance zone.
6. Scanning electron microscopy has shown that in nearly all samples, which were not subjected to LHIP, the preferential nucleation site of fatigue cracks is shrinkage interdendritic porosity close or at the surface. For LHIPped samples the fatigue crack initiated mainly at the specimen surface since LHIP suppressed the voids in the material; also fatigue crack nucleation from oxides and from pores, which were not closed by LHIP, are possible.

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