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*M. Rosso, *E. Romano - **S. Barone
*Material Science Department – Politecnico di Torino – Italy
**Teksid S.p.A. – Borgaretto (Torino) - Italy

PROPERTIES IMPROVEMENT OF THIXOFORMED PARTS BY LIQUID HOT ISOSTATIC PRESSING PROCESS

***M. Rosso, *E. Romano - **S. Barone**
***Material Science Department – Politecnico di Torino – Italy**
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Abstract

Introduced almost a century ago as a concept the hot isostatic pressing process has been widely and successfully used to treat aluminum casting for niche markets.
The reason why this post-processing idea is not applied to mass production is costs. In fact the media used to apply pressure on components to be treated in a vessel at high temperature,where the material softens and compacts uniformely, is a gas. Long treatment times added to highly risky plants are adding costs to the processing route.
Recently the partnership between Teksid and Idra is on the way to industrialize a new hot isostatic process, called Liquid Hot Isostatic Pressing – LHIP where the media used to apply pressure on the components to be treated is a liquid salt.
With this technology it is reasonable to think that mass production post-treatment of automotive aluminum castings will be achieved, with the goal of having stronger parts with higher fatigue properties and reduced scrap level in the foundry process production chain.
This paper describes the effect of LHIP on aluminum thixoformed castings, outlining the beneficial process effects on the mechanical properties.

Riassunto

Il concetto di pressatura isostatica a caldo fu introdotto circa un secolo fa ed è applicato con successo per trattare getti in lega di alluminio per mercati di nicchia.
Tra le ragioni principali che non permettono all'industria di utilizzare la tecnologia per alti volumi produttivi vi è principalmente il costo. Infatti il processo prevede di caricare i getti da trattare in autoclave dove un gas viene portato a pressione e temperatura elevata, tanto elevata da rendere il materiale facilmente deformabile e in grado di compattarsi in modo uniforme. La produttività e capienza dei forni di trattamento è limitata e la loro gestione molto delicata visti i possibili rischi di esplosione. Recentemente Teksid e Idra Presse hanno avviato uno sviluppo congiunto mirato ad industrializzare un processo innovativo di pressatura isostatica a caldo, chiamato Liquid Hot Isostatic Pressing, LHIP, in cui l'elemento adottato per applicare la pressione sui getti in alluminio da trattare è un liquido, una miscela di sali, anziché un gas. E' ragionevole pensare che con questa tecnologia sia possibile affrontare produzioni di elevati volumi quali quelle dei componenti di sicurezza dell'auto, cui sono richieste elevate caratteristiche meccaniche.
L'articolo illustra i risultati ottenuti su componenti formati con tecnologia thixo e successivamente sottoposti a LHIP, evidenziando, in particolare, l'effetto positivo sulla resistenza a fatica.

INTRODUCTION

The demand of light weight and near net shape components from the automotive industry to satisfy the emission legislation is stronger and stronger. In this contest the aluminum alloys castings met success and the shaping processes were continuously improved. Sand, as well as gravity and low pressure permanent molds are widely used to cast aluminum automotive components, especially structural parts. When a mass production of light alloys products is required conventional high pressure die casting is unquestionably the most often selected process, being it relatively inexpensive and suitable for a broad variety of components, however it is not capable of the same high product integrity and reliability achievable through concurrent processes. Among the traditiona l shaping technologies forging generally provides the highest properties available in formed aluminum products and is therefore used for many aerospace and automotive structural parts. The demand of light, reliable and safe components together with the continuous increase of competitiveness worked also as an intense driving force to the development of new technologies: squeeze casting, thixoforming, thixomolding and rheocasting processes came in age [1] and for different reasons thixoforming or Semi-solid forming is probably the most promising process. It is an effective near net shape forming process in which the metal is formed in the semi-solid state [2], Prof. Merton Flemings was the inventor of the process in the late 60's, early 70's.

THIXOFORMING PROCESS

The thixoforming process is capable of the dimensions, details and thin wall of conventional high pressure die castings while accomplishing the high integrity generally ascribable only to the highest quality gravity and low pressure permanent mold castings. With respect to squeeze casting process, a new competing technology able to assure high integrity parts having relatively thick sections, it is able to assure the same level of integrity but also in thinner cast sections. Squeeze casting works at higher temperatures, the molten metal slowly fills the die cavity and solidifies under high pressure (about 100 bars) which avoids many defects usually noted for die casting, while the Semi-solid forming works at lower injection temperatures with high solid &action, 0.6 to 0.8 of the material feedstock and the cycle time requirements are strongly reduced. The main need to realize a semi-solid process is to obtain a solid plus liquid slurry with consistent theological properties, followed by a simple transfer of the slurry to fill the die cavity. The ability consists in the suitable control of the rheological properties of the slurry, immense cost benefits are available by such a processing route.

The process requires a suitable raw material or feedstock, usually high purity alloy with a microstructure composed of clustered degenerate-dendritic particles in a matrix of second (eutectic) phase. To meet these features stirring methods are used during the cooling of the primary alloy to broken the dendritic structure and to obtain a globular α phase, as shown in figure 1 for the A356 alloy. These features causes thixotropic properties, meaning that if a slug of the material is heated into the two phase range, upon the application of shear, the slug became fluid.

The process flow steps are depicted in figure 2. The feedstock billet is heated between solidus and liquidus, injected into the die cavity and then the part is stripped. During the heating process the billet must retain its shape. Since the semi-solid is composed of solid particles with the remainder liquid, the particle size and shape and the fraction liquid are the controlling parameters [3]. The smaller and more rounded the particles and the larger the liquid fraction the lower the viscosity, the same parameters are also important in the control of the fluidity together with the benefits of a high latent heat of fusion of the liquid. A definite advantage of the process is that both the alloy solidification range and the shrinkage can be controlled by limiting the percent liquid in the semi-solid. The advantages of Semi-solid forming [4] are related to:

- low porosity (< 0.1%) with product of exceptional soundness,
- good combination of strength and ductility, • product complexity, close dimensional tolerances, near net shape, thin walls and excellent surface finish,
- low processing temperature and therefore short cycles times and low stress on tooling,
- ability to utilize unusua l alloys that normally prove difficult in liquid casting processes (wrought compositions, for instance)
- an ability to undergo a T-5 heat treatment without loosing ductility, thus often achieving required mechanical properties without the dangers of blistering, distortion or quench stress associated with the full T-6 heat treatment,
- the ability to form hypereutectic Al-Si alloys and MMCs while retaining the desirable size and distribution of primary or second phases developed during billet manufacturing under ideal continuous casting conditions (those phases don't re-melt or dissolve during Semi-solid forming),
- the product consistency that results from using the pre-cast billet that was manufactured under the same ideal continuous processing conditions that are employed to make forging or rolling stock.

A drawback is actually contrasting the lot of advantages, the cost of the pre-cast billet. In fact, it costs about as much as 35÷40 % over the cost of similar primary alloy purchased as foundry ingot for melting. A solution to this problem can came from the rheocasting process, in which the involved steps concern the melting of the alloy coupled with stirring effect during the solidification. From this point of view the process may be the same used to produce the feedstock billet for the thixoforming process. However at that

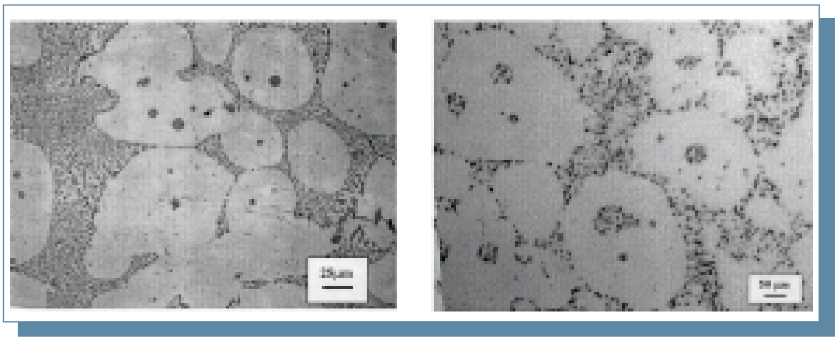

Fig. 1: Microstructure characteristics of a feedstock A356 aluminum alloy for thixoforming (left) and of the same alloy after thixoforming

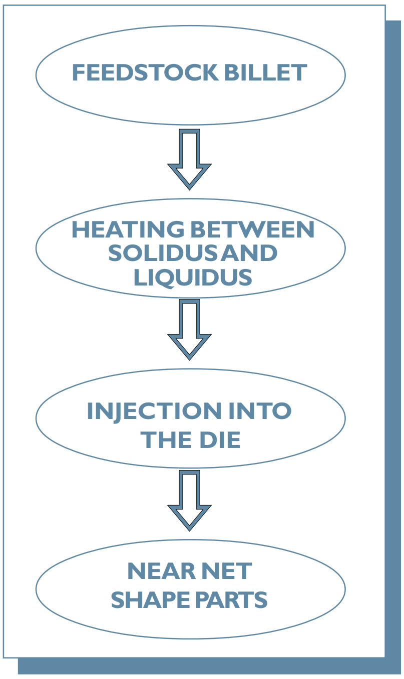

Fig. 2: Process flow steps in Thixoforming

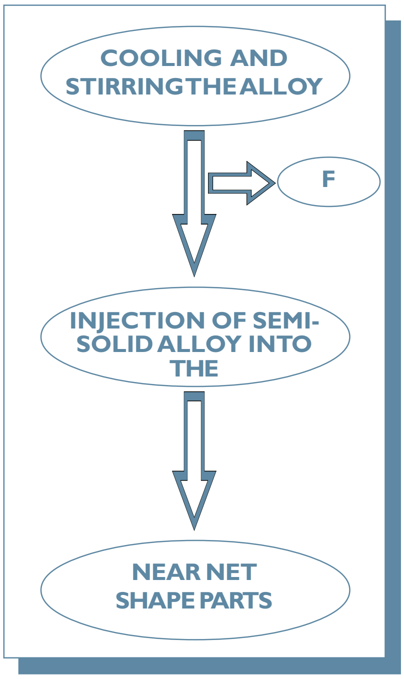

Fig. 3: Process flow steps in Rheocasting, F means feedstock billet for Thixoforming

point it is possible try to introduce the semi-solid alloy into the die cavity obtaining directly near net shape parts, as indicated by the flow diagram in figure 3.

Recently a new rheocasting process "NRC" [5] has been developed, in this process the slightly superheated melt alloy is taken from a holding furnace and poured into specially designed steel crucibles. In the crucible n-grains grow, fo l l owing forced homogeneous nucleation at the cup wall and in few minutes a stable skeleton of “-phase forms and the alloy reaches the semi-solid state producing a cylindrical shaped slug. At this point a high &equency induction heating is used to equalize the slug temperature before its casting into shape. This new process can work with conventional alloy melts, this means that foundries can use a wide range of alloys and apply their standard melting and recycling techniques, meeting a really low cost Semi-solid casting. Taking into account for the technical evolution, the Semi-solid forming process now appears to be very interesting both for the cost competitiveness and for the high integrity of the produced parts. It can compete with squeeze casting, as well as with the best permanent mold castings. It is well known that the properties of aluminum alloy cast parts, specially when produced by gravity casting, can be improved by applying HIP [6, 7], mainly for the reduction of defects and particularly of the porosity, moreover the recent development of the most economic LHP-Liquid hot isostatic process [8] increase the interest of this technique. This process is of course helpful also to eliminate some defects in the thixoformed parts [9]. As the HIP process LHIP is capable of eliminating some of the typical casting defects like micro and macro shrinkage porosity and hydrogen inclusion. Defects connected with the surface (i.e. cold shots, surface cracks), as well as nitrogen inclusions and oxides, cannot be eliminated. Process normal running parameters to obtain such results on A356 aluminum castings are:

- 1000-1200 ATM pressure
- 500-540°C salt temperature
- 20-35 seconds pressure applied
- 3 - 4 minutes total cycle time (including heating and cooling)

The mechanical properties attained by the heat treated thixoformed parts are very satisfying and it is difficult still improve them, however there is the impression that the LHIP process may be helpful to improve the fatigue properties, in this paper the first results attained on A356 alloy are presented and discussed.

EXPERIMENTAL PART

Sets of A356 alloy thixoformed suspension arm produced by Stampal Italy for TRW (Figure 4) were considered for the LHIP process. The parts have been treated in the TEKSID LHIP pilot plant. The castings were scrap parts out of normal production to have a result on the effect of LHIP on casting defects and an evaluation of achievable static mechanical properties. Successively parts under different heat treatment conditions have been LHIP treated to study the influence of the process on the mechanical, as well as on the fatigue properties, each batch was constituted at least by 15 parts. The different heat treatment conditions were:

A: T6 treated

B: solution treatment (2 h at 540 °C) followed by LHIP and then aged 3 hours at 160 °C

C: solution treatment (4 h at 540 °C) followed by LHIP and then aged 3 hours at 160 °C

D: T6 treated, LHIP and then T6 treated again, always with the same process parameters.

The condition A clearly refers to parts only heat treated but not subjected to LHIP in order to have a suitable comparison among the induced effects. The scrap parts were subjected to X ray radiography to detect the defect before and after the LHIP treatment. Tensile test specimens were obtained by dissections of LHIP treated castings, two samples each part were taken in two different directions, longitudinal and transversal, their average dimensions being: total length 87 mm and thickness 3.15 mm, the calibrated zone was 30 mm length and 8 mm wide. On these samples the tensile properties, yield strength, ultimate tensile strength and elongation have been measured. On the samples type D, axial fatigue tests have been performed using a Rumul resonant machine, type TESTROTONIC 100 kN, working in the Sequence range between 40 and 260 Hz. An alternate symmetric cycle, $R = \sigma_{min} / \sigma_{max}$, = -1, was adopted. The fatigue limit has

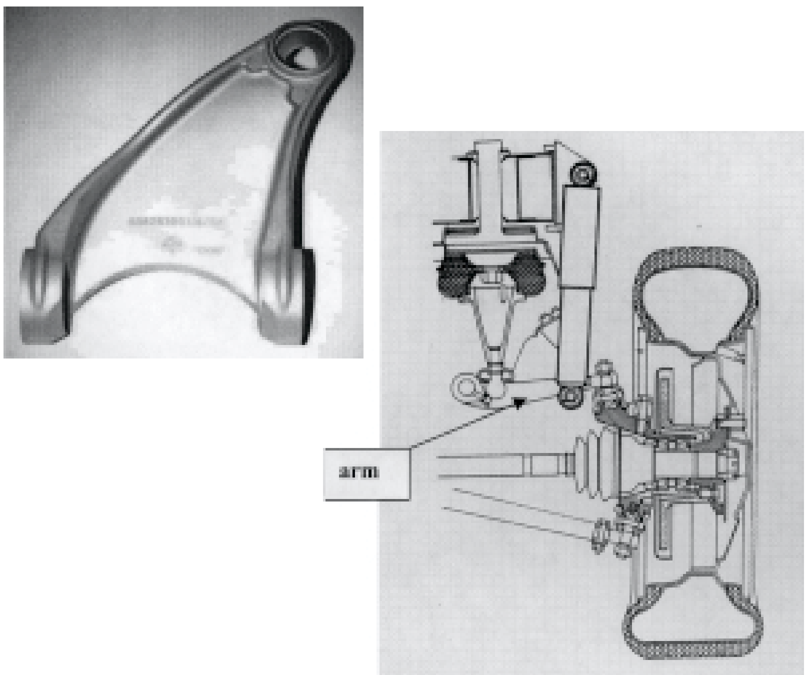

Fig. 4: Two different views of the suspension arm (not in scale)

been obtained using the Stair Case method and the Wohler curve for the 10%, 50% and 90% survival limits has been drawn and compared with literature data referred to the same alloy. Optical microscopy and SEM analysis were used to observe the microstructure features of the alloy and the morphology of the surface fracture of the samples.

EXPERIMENTAL RESULTS AND DISCUSSION

The main results of the radiography on different casting having cold shots as defects are summarized in Table 1. Other scraps were caused by gas porosity, after the LHIP process the pores disappeared as can see in figure 5. Also the shrinkage porosity was eliminated, confirming the capability of the process to eliminate most of the defects not connected with the surface without affecting the microstructure of the alloy as was observed on the polished sections of different samples by means of optical microscopy.

TABLE 1.
THE EFFECT OF LHIP ON THIXOFORMED CASTING QUALITY

Scrap part	As cast ZONE A	As cast ZONE B	As cast ZONE C	RX	After LHIP ZONE A	After LHIP ZONE B	After LHIP ZONE C	RX
N. 1	Cold shot	ASTM 1	ASTM 1	Scrap	Small cold shot	---	---	Good
N. 2	---	ASTM 2	ASTM 1	Scrap	---	---	---	Good
N. 3	---	ASTM 2	ASTM 1	Scrap	---	---	---	Good

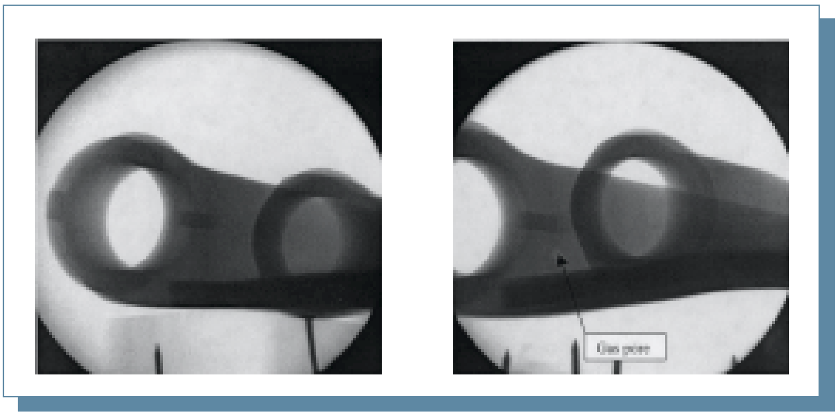

Fig. 5: Radiography of a scrap part, showing the presence of a gas porosity (left picture) before of LHIP treatment and the sound part after the execution of the process

TABLE 2.
YIELD STRENGHT, ULTIMATE TENSILE STRENGHT AND ELONGATION OF THIXOFORMED CASTINGS BEFORE AND AFTER THE LHIP TREATMENT

Scrap part	Zone	As cast Properties [MPa] Yield	As cast R_m	As cast A%	After LHIP Properties [MPa] Yield	After LHIP R_m	After LHIP A%
N. 1	B	267	304	6.7	220	306	11.4
	C	236	311	10	233	301	9.4
N. 2	B	235	288	4.7	236	296	5.7
	C	230	291	8	232	290	5.1
N. 3	B	254	310	6.7	220	290	6.0
	C	232	271	4.7	217	285	9.7
AVERAGE		242	296	6.8	226	294	7.8

The effect on mechanical properties evaluated on samples obtained by dissections of the scraped parts in the as cast state or aAer the LHIP process is shown in Table 2, where the only affected value on the static properties is elongation, with a gain of about 15% over the as cast material. Zones B and C in this case refers to the direction of dissection of castings, mainly longitudinal or transversal, they demonstrate no influence of the direction.
The properties measured on sound parts after different heat treatment conditions are summarized in Table 3, the reported values are the average of at least five tested specimens each considered direction, longitudinal and transversal. Also in this case no influence of the direction of the dissection sample was observed.
Table 2: average mechanical properties, yield strength (YS), ultimate tensile strength (UTS) with related Standard Deviation (o) and elongation of parts after different heat treatment conditions.
The influence of LHIP on the strength is not well defined, even if slightly lower values were measured for the samples not treated with usual T6 cycle, probably this is due to the low temperature value and the short time adopted for the solution treatment. However a great influence

on the elongation properties is evident, with an increase of this property close to about 40 % measured on the samples type C, that is solution treated 4 hours at 520 °C, LHIP processed and aged 3 hours at 160 °C. This sequence of treatments is also one of the cheapest because the expensive T6 treatment is practically included in the LHIP process. The large number of tests allowed also a statistical approach and in Table 3the standard deviation of the tensile strength properties are also shown, it is evident that the LHIP process reduced the standard deviation of yield strength and of ultimate tensile strength. Moreover, plotting the dispersion of these properties a Gauss curve was obtained (figure 6), showing that the LHIP met the goal to reduce the dispersion of mechanical characteristics. Being this a function of the defect level of the casting, the positive effect of the treatment is confirmed.
The observation of the fracture surface by SEM shows for the samples without defects mainly a dimple morphology, indicating the toughness characteristics caused by the performed processes, figure 7.
The fatigue tests were performed on the samples type D, that is T6 treated before and after the LHIP process, about 30 samples were used to obtain the Wohler curve drawn in figure 8, the fatigue limit was about 95 MPa. It is quite interesting to make the comparison (figure 9) between the obtained Wohler curve and the curves of A356 alloy components obtained in different ways, that is:

- Permanent mold and T6 treated
- Permanent mold + LHIP and T6 treated
- Thixoformed and T6 treated

As it was expected the lowest fatigue resistance is presented by the permanent mold castings T6 treated, while fatigue behavior of the thixoformed and T6 treated parts are higher. The execution of the LHIP on these castings causes a great improvement of fatigue resistance especially in the case of the first type of castings, this is a proof of the effect of the process and of its advantages. Concerning the thixoformed parts the fatigue improvement after LHIP is not so high as it was expected, probably this is due to two different concomitant effects. Test samples used for the fatigue tests in the case of the T6+LHIP+T6 thixoformed castings were different with respect to the other ones and not conforming the ASTM Standards, this can be influent on the obtained resuls. The second aspect is mainly theoretical and concerns the relation between the LHIP treat-

TABLE 3.
Average mechanical properties, yield strenght (YS), ultimate tensile strenght (UTS) with related Standard Deviation (σ) and elongation of parts after different heat treatment conditions

Condition	YS [MPa]	σ_{YS}	UTS [MPa]	σ_{UTS}	E [%]
A: T6	224.3	12.87	295.1	12	9.4
B: 520 °C, 2 h + LHIP + ageing.	196.1	8.97	273.3	8.25	12.5
C: 520 °C, 2 h + LHIP + ageing.	217.6	9.38	287.6	7.99	13.1.
D: T6 + LHIP + T6	230.0	8.91	295.5	8.46	10.4

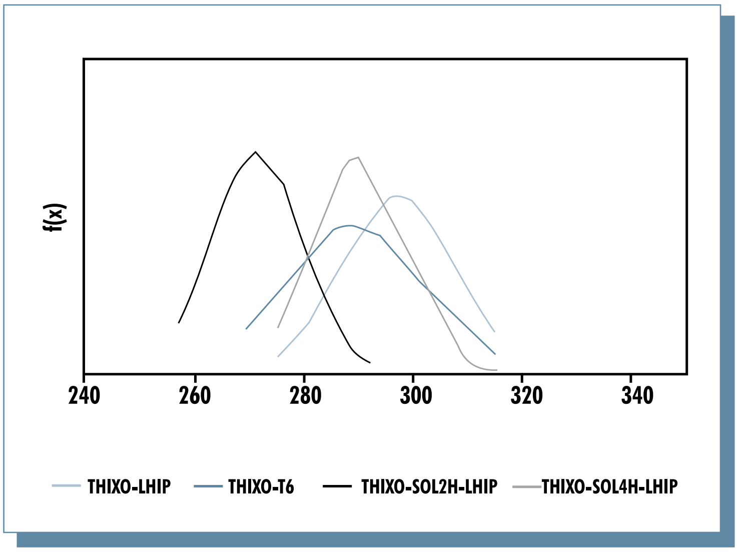

Fig. 6: Gauss distribution of the ultimate tensile strenght

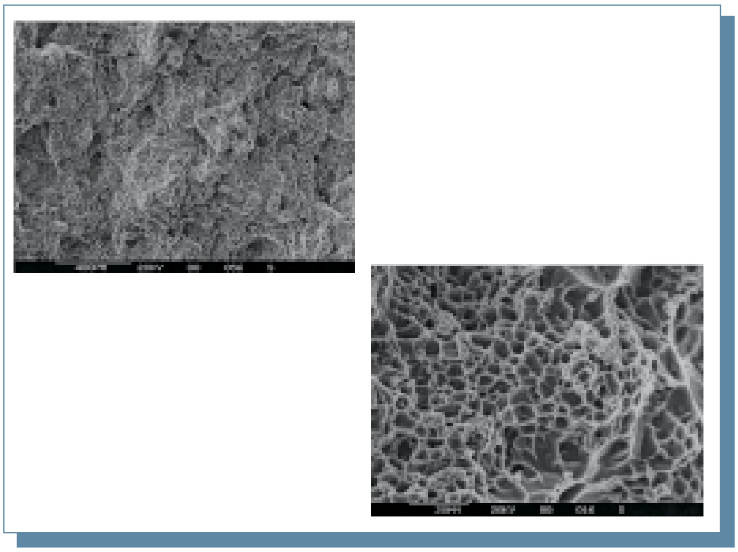
Fig. 7: Fracture morphology of specimens after treatments: 520 °C, 4h+LHIP+ageing 3h at 160 °C

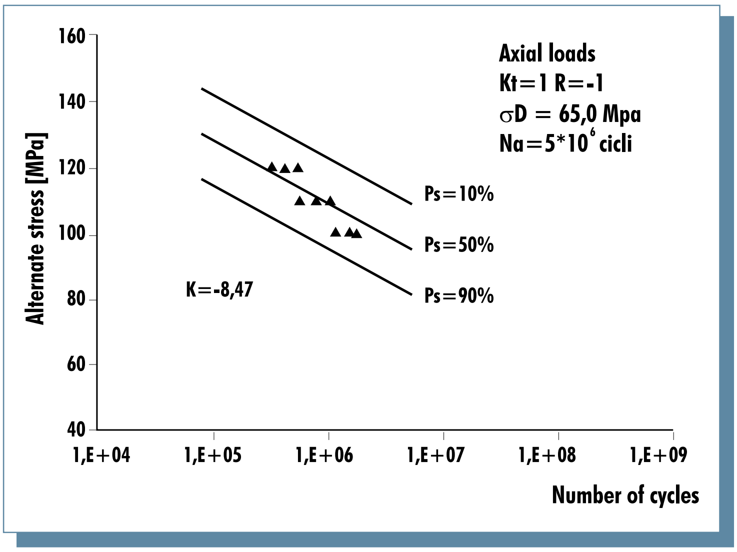

Fig. 8: Wohler curve for the T6+LHIP+T6 trated castings

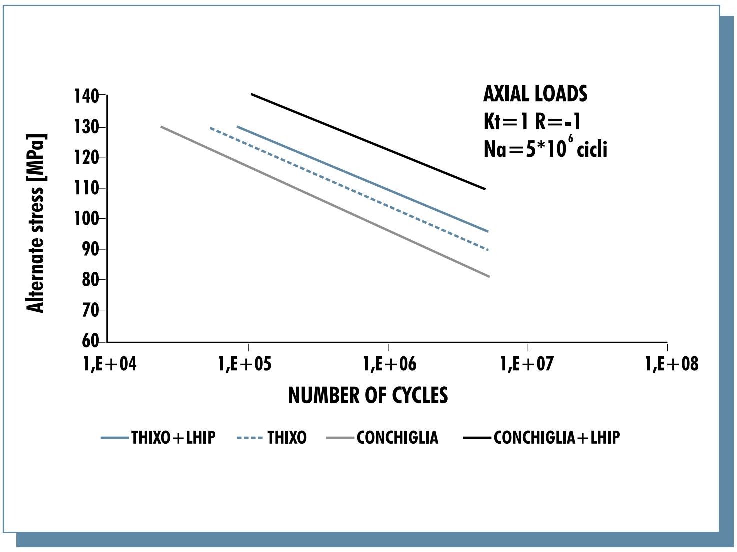

Fig. 9: Comparison between Wohler curves at 50% survival probality of different A356 castings

ment and the defect level of the casting. It seems that LHIP is more effective on parts with an higher defect level. In fact, the thixoformed parts are characterized by lower number of pores with smaller size, smaller the pore higher the surface specific energy, consequently the pressure required to close a small pore will be higher than in the case of a large pore, this can explain a more important effect of LHIP on permanent mold castings rather than on thixoformed parts.

CONCLUSIONS

Liquid hot isostatic pressing is a new post treatment process for aluminum casting that can improve the soundness of the parts and increase the material mechanical properties at competitive costs. It can be advantageously applied also to thixoformed parts, in particular the treatment is able to:

- allow to recuperate scraps affected by the presence of gas (not nitrogen) and shrinkage porosity
- improve the ductility properties, without modifying the microstructure characteristics
- improve the fatigue resistance

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