THIXOCASTING OF AN A356 ALLOY: TENSILE STRENGTH, POROSITY AND FATIGUE BEHAVIOUR

[*]M. Ferrante, [*]E. A. Vieira, [**]E. de Freitas, [**]C. T. Ruckert, [**]W. W. Bose F
[*]Federal University of São Carlos - Department of Engineering Materials - São Carlos, BRASIL
[**]University of São Paulo - Department of Materials, Automotive and Aeronautics, São Carlos, BRASIL

Abstract

Near-equiaxed microstructure was obtained in an A356 by the following raw material conditioning processes: (i) deformation-recrystallization thermomechanical treatment (TTM), (ii) magnetic stirring (MHD) and (iii) low pouring temperature (LPT). Specimens for porosity assessment and microstructural studies, for tensile and fatigue tests were obtained from a specially designed thixocast part. Microstructure was described by quantitative features such as particle average radius, interparticle spacing, shape factor and entrapped liquid volume fraction. Results showed a relative uniformity both of microstructure and tensile behaviour, with the MHD and TTM specimens exhibiting a slight advantage. Porosity was found to be minimal, with the LPT material exhibiting the highest level among the three semi-solid specimens. Finally, low cycle isothermal and thermomechanical fatigue tests were performed on the TTM-conditioned material; fatigue life was much longer than that of the permanent mould cast material, a behaviour attributed to its globular microstructure and lower porosity level.

Riassunto

La struttura semi-equiassica è stata ottenuta in una lega A356 mediante i seguenti processi: (i) trattamenti termomeccanici (TTM) deformazione-ricristallizzazione, (ii) agitazione magnetica e (iii) bassa temperatura di colata (LPT). I provini per l'accertamento della porosità e per lo studio della microstruttura, per le prove di fatica e di trazione sono stati ottenuti da un componente tixocolato. La microstruttura è stata descritta in modo quantitativi considerando il raggio medio delle particelle e la distanza tra loro, il fattore di forma e la frazione della fase liquida intrappolata nei grani. I risultati mostrano una relativa uniformità sia della microstruttura che del comportamento a trazione, i provini ottenuti da fuso trattato con MHD e successivamente con TTM il comportamento è leggermente superiore. La porosità è risultata minima mentre il materiale LPT mostra il più alto livello di porosità tra i tre provini prodotti in semisolido. Le prove di fatica sia isotermica che in condizioni a carico e T variabile hanno mostrato che la vita è stata molto più lunga rispetto ai provini colati in stampo permanente, comportamento attribuito alla sua struttura microglobulare e alla bassa porosità.

1. INTRODUCTION

One of the goals of the transport industry is weight reduction; indeed, it has been shown that replacement of steel by Al alloys can lead to a 20 – 30% weight saving which translates into fuel economy and lower tail pipe emissions [1]. Presently, Al alloys can be found in numerous applications such as crankshafts, head cylinders, gearbox cases and heat exchangers. Thus, for further weight reduction the use of Al alloys should be extended to suspension parts, structural frames or space-frames (body-in-white), and both to internal and external body panels. The requirements regarding strength and fatigue properties for suspension components cannot be met by the conventional casting processes whilst forging is a too expensive technology for the car industry.

Semi-solid casting is a relatively new technology which combines the forming capabilities of pressure die casting with the mechanical properties of forged products. Presently thixocasting can be applied to some steels, to Mg alloys, but above all to Al-Si alloys, particularly the A356 and A357.

The main requirement for semi-solid casting is a non-dendritic microstructure [2], and to date a number of microstructural conditioning techniques were devised for this purpose. The resulting structure of the spheroidal α-phase into the liquid eutectic phase has adequate viscosity and good flow properties so as to assure smooth mould filling and absence of porosity and shrinkage voids. The last two features result from the fact that much less liquid is involved in semisolid than in conventional casting methods; typically, a solid/liquid ratio of 1:1 is the standard procedure. The influence of porosity on mechanical properties is well known; for instance, in the A356 a volume fraction of pores close to 1% reduces both fatigue life and endurance limit by 50% and 20%, respectively, provided that other microstructural features are equal [3]. Finally, freedom from pores and voids means that components produced by means of semi-solid techniques, can be precipitation heat treated and welded.

Although the potential benefits of semi-solid processing have been recognized, economic considerations are still unfavourable due to the high plant investment. Therefore a great deal of research and development efforts is currently directed to new microstructural conditioning techniques. Among these the "UBE New Rheocasting" and its variations [4, 5], and the "Low Temperature Pouring" technique, combined with multiple nucleation and dendrite spheroidization [6] are quite promising, but the resulting microstructural characteristics need to be compared with those obtained by conventional cast process.

In the present paper three differently prepared raw materials are compared under four different points of view, viz: microstructure, porosity level, static strength and fatigue behaviour. Correlations between porosity, microstructure conditioning techniques and tensile properties were established and both isothermal and thermomechanical fatigue tests were carried out, by comparing the specimens microstructurally conditioned, under deformation/recrystallization process, with those conventionally cast. Thermomechanical fatigue tests took place under simultaneous thermal and mechanical loads, a condition that reproduces quite accurately the working environment of engine components such as cylinder heads.

2. EXPERIMENTAL METHODS

1. Microstructural conditioning.

Three different raw material groups were produced by employing the following conditioning processes:

(i) **deformation/recrystallization (TMM):** an A356 commercial, Sr modified ingot was remelted, inoculated with Ti-0.5%B and poured into a 250 x 135 x 55 mm^3 steel mould. The resulting plate was homogenized 24h at 540°C, warm rolled (≈ 300°C) up to 30% reduction and recrystallization annealed.

(ii) **magnetic stirring (MHD)**: a 110 mm length of a 150 mm diameter A356 billet supplied by FORMCAST INC. was partially re-melted at 580°C and stirred.

(iii) **low pouring temperature (LPT)**: an A356 commercial ingot was re-melted, modified, inoculated, poured at 635°C into a Cu mould and homogenized as in (i).

Finally, reference material for the conventional permanent mould casting process (PMC) was obtained by pouring at ≈700°C the A356 alloy into a steel mould. The MS material was chemically different from the ingot which originated the other specimens, but differences were not significant, as shown in the Table 1.

Table 1: Chemical composition of the original A356 (wt %)

Raw material	Si	Mg	Cu	Fe	Mn	Zn	Ti
NC / TMT / LPT	7.13	0.40	0.01	0.12	0.007	0.007	0.006
MS	6.60	0.34	–	0.15	–	–	–

2. CHARACTERIZATION

(i) **Microstructure**. Microstructural parameters such as particle size (R), and contiguity (Q), shape factor (F), plus entrapped liquid volume fraction (f_{Le}) were determined by optical microscopy supported by quantitative image analysis (IMAGE PRO-PLUS®). The shape factor was calculated using the formula $F = 4 \pi A / P^2$ (A = area; P = perimeter; F = 1 _ perfect sphere; F = 0 _ needle).

(ii) **Tensile and fatigue properties**. Tensile tests on MHD, LPT and TTM specimens were carried out in an INSTRON MD500 universal machine. Thermomechanical fatigue (TMF) tests were performed in a MTS 810 servo hydraulic machine under deformation control with R = - 1. Tests took place at 120 and 280°C and a drop of 50% of the maximum stress during the experiment was taken as the fatigue criterion. In order to avoid the building up of excessive temperature gradient during thermal cycling, a relatively large test period of 300 s was chosen, thus resulting in a very low frequency. The temperature cycle was of the triangular type. The isothermal fatigue tests were performed at the above temperatures and at 0.5 Hz. All fatigue tests were performed only on the PMC and TMT-conditioned specimens, with the latter taken from the thixoformed part (fork) shown in Figure 1; solid fraction and soaking time were kept equal to 0.4 and 30', respectively.

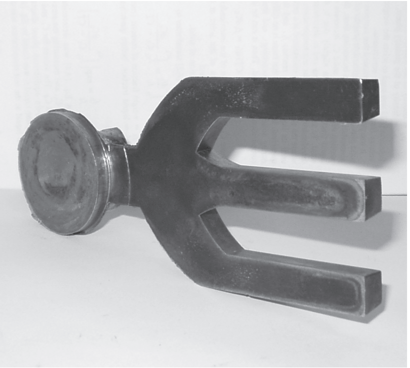

Fig. 1: Fork employed for tensile, fatigue tests and pores volume fraction measurements. Thixocasting was carried out after 30' at 600°C, corresponding to fs = 0.4.

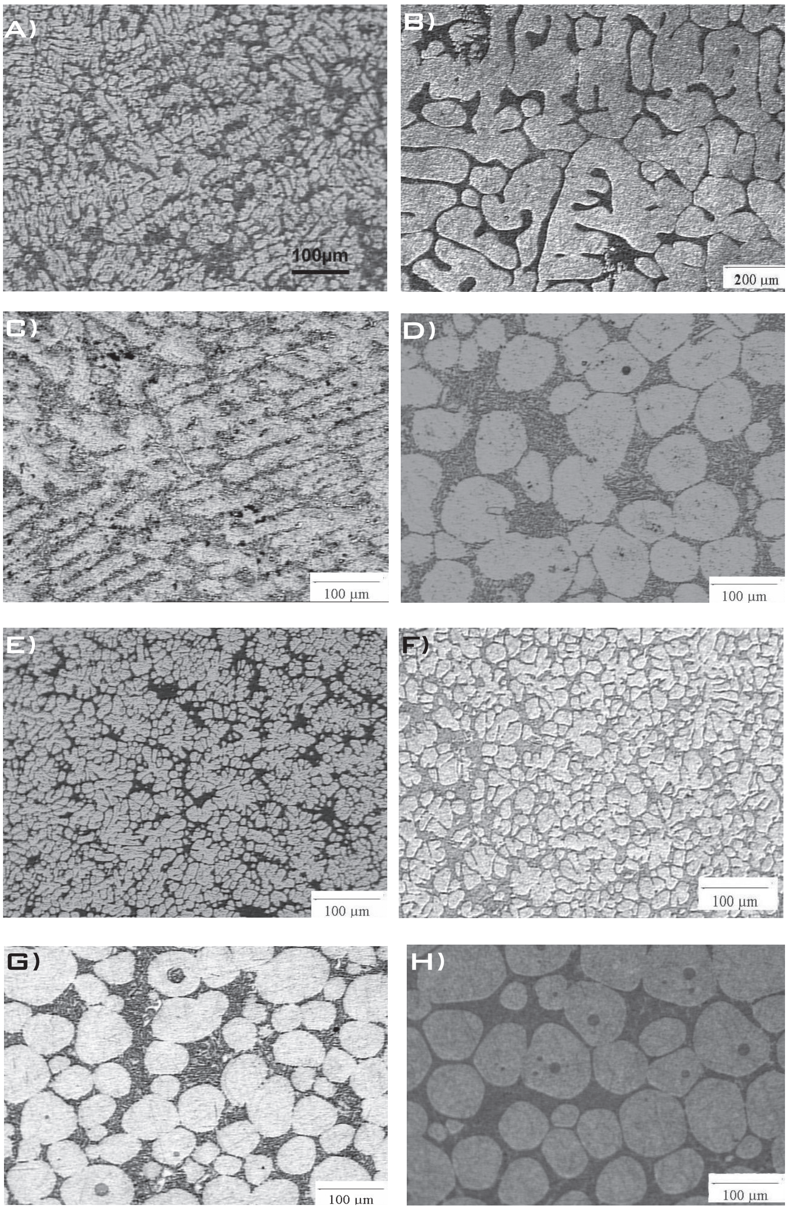

Fig. 2: Optical micrographs of the samples: (a, b) PMC; (c,d) TTM; (e,f) MHD; (g,h) LPT. Micrograph depict initial states and after partial remelting (580°C maintained during 30').

4. HEAT TREATMENTS

The fork was solution heat treated (540°C/2 h) and aged at 155°C/1 h. In order to test the effects of a different ageing schedule the solution heat treatment time was changed to 30', 1 and 4 h and the standard ageing treatment was modified to 170°C/4h.

3. RESULTS AND DISCUSSION

1. MICROSTRUCTURE

The Fig. 2 shows the microstructures of four A356 samples produced by: (a, b) permanent mould casting – PMC, and by the three different conditioning techniques: TTM (c, d); MS (e, f), and LPT (g, h). Micrographs on the left column depict the material in the initial state; that is, as-cast (a, g), as deformed (c) and as supplied by the manufacturer (e). The right column shows the corresponding partially remelted semi-solid microstructures, maintained at 580°C (f_s = 0.5) for 30'. It is apparent that all the conditioning processes here employed produced a spheroidal microstructure. Regarding the particle size and shape, all processes gave similar results. Of course, despite Ti-B inoculation the permanent mould ingot cast at normal pouring temperature (≈700°C) showed to be completely unsuitable for semi-solid forming, but it was included only to underline the strong effect of a 65°C pouring temperature difference and controlled cooling, compare micrographs b (PMC) with h (LPT) sample. The Figure 3 summarizes the quantitative metallographic parameters: particle radius (R), contiguity (Q), shape factor (F) and entrapped liquid (f_{Le}). The data supports quantitatively the above comments on the micrographs. The linearity of the R^3 against soaking time plot suggests that the Al-α particles grow by a diffusion-controlled mechanism. Another feature of the semi-solid state is how fast the liquid forms: indeed, by the moment the soaking temperature is attained, the contiguity decreases from 1 to 0.25, and the equilibrium value (0.20–0.25) is reached in the next 60 s. Taking 1200 s as a reasonable soaking time, the TTM sample contiguity value is the most favorable, followed by the LPT and MHD samples. Same comment is valid for the shape factor. As for the entrapped liquid, although its proportion is higher in the MHD samples, it is still too low to have any harmful effect. It may be useful to recall that entrapped liquid decreases the effective liquid fraction thus impairing flow properties.

The porosity level measured in the fork-shaped sample is shown in Figure 4. One can be seen that the LPT material exhibits the highest pore volume fraction; however, in absolute terms, it is quite low since the typical defect level of conventionally cast products is in the range 1.5 – 2.0 % [7].

2. TENSILE PROPERTIES OF HEAT TREATED PARTS

The Figure 5 shows results of tensile tests carried out on specimens heat treated according to different schedules (see figure caption for details). In order to interpret the data the following background must be taken into account: (i) the standard T6 heat treatment for the A356 alloy is 540°C 6-

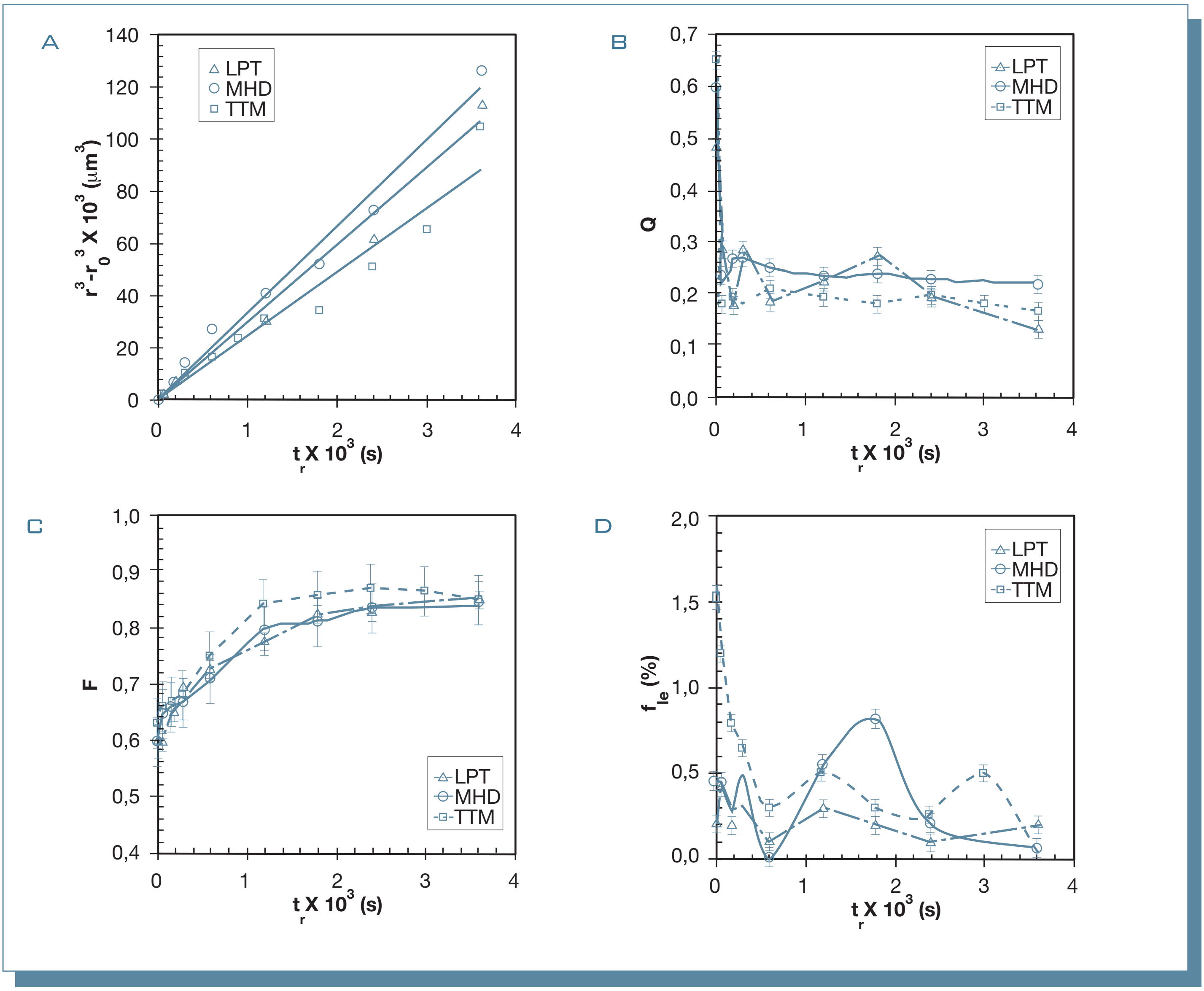

Fig. 3: Graphs of the quantitative microstructural parameters as a function of the conditioning process (TTM, MHD, LPT) and of soaking time at 580°C (f_s = 0.5): (a) Al-α particle size - R; (b) particles contiguity - Q; (c) shape factor - F, and (d) entrapped liquid volume fraction - f_{le}.

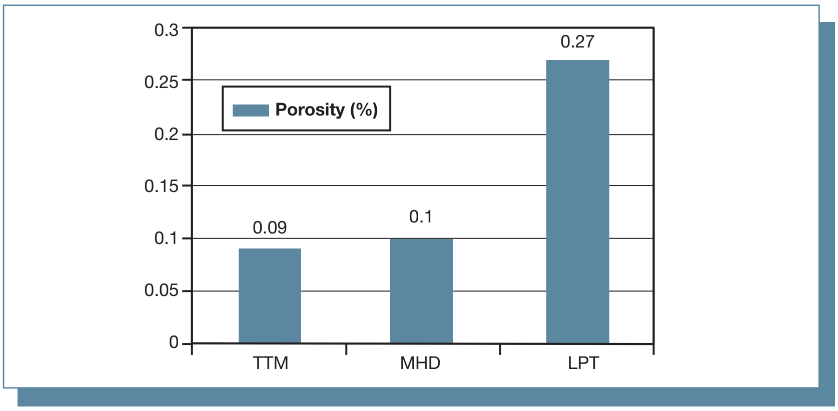

Fig. 4: Porosity distribution measured in the fork specimen; the alloy was conditioned by TTM and the solid fraction was equal to 0.4.

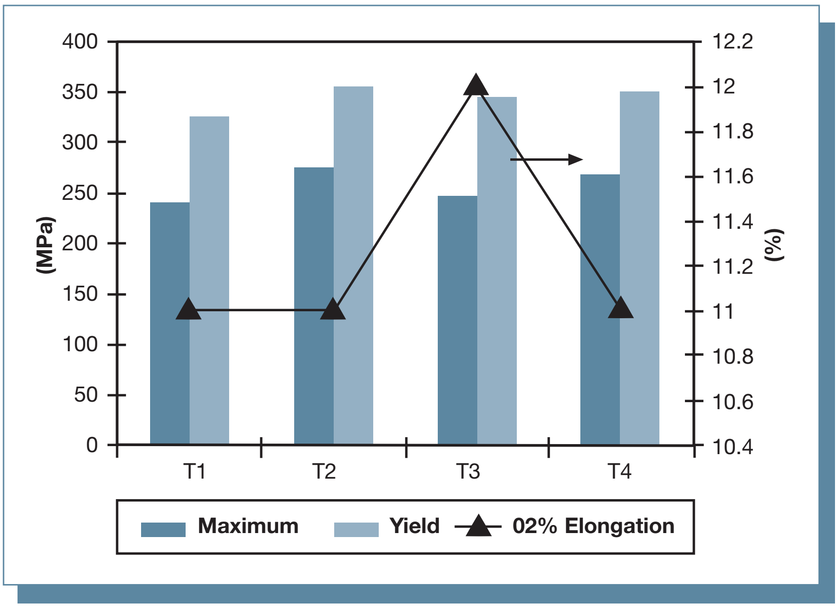

Fig. 5: Tensile properties of the demonstration part subjected to the following heat treatments schedules, (T6 is underlined):
T1: 540°C / 0 h 30' + 155°C / 12 h; T3: 540°C / 12 h + 155°C / 12 h
T2: 540°C / 1 h + 155°C / 12 h; T4: 540°C / 12 h + 170°C / 4 h

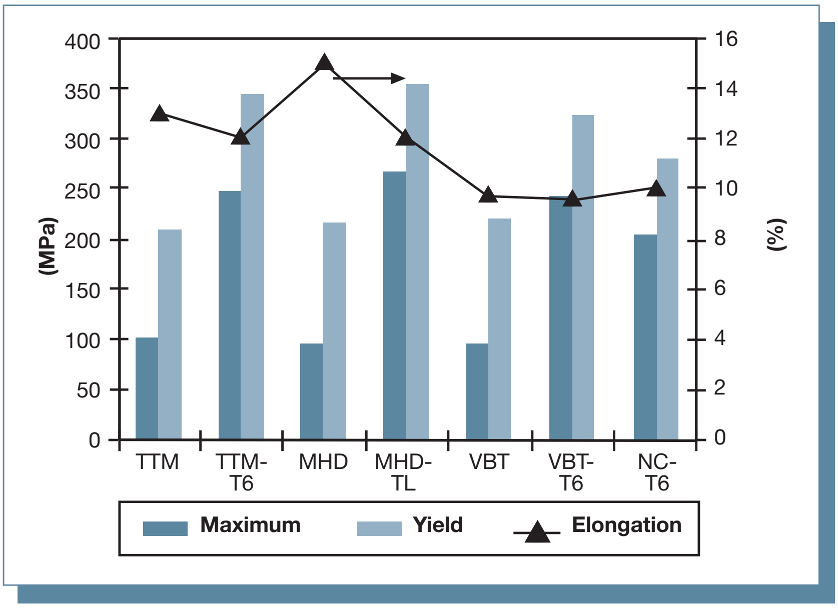

Fig. 6: Tensile properties of thixocast samples compared with those of the permanent mould cast specimens (PMC).

12 h/ quenching/ 155°C / 6-12 h with peak strength achieved after 8h ageing time; (ii) the tensile properties of semi-solid A356 T6 specimens were reported by Atkinson and Liu [8] in the range: $\sigma u = 280–320$ MPa and $\sigma y = 220–270$ MPa, whilst elongation was in the range: 8-13%. Similar values were reported by Young and Eisen [9]. Therefore the present set of results is more than acceptable; moreover, it shows that a short solute heat treatment, that is, 1h instead of 4h, or a shorter ageing treatment (170°C / 4 h) are equally effective when compared with the standard procedure. It must be pointed out that the 1% loss of ductility associated to the modified ageing treatments (TA, TB and TD) is quite small. The present data support findings by Rometsch and Schaeffer [10] who in A356 showed that high tensile strength can be achieved by a short heat treatment and that ageing between 150 and 190°C produces almost identical yield strength.

Tensile behaviour and response to the conventional T6 heat treatment for differently conditioned materials are summarized in Figure 6 and compared with the PMC material. Results show that yield stress is at least 16% higher than that of the permanent mould cast specimen; ductility is also higher, except for the LPT sample which has the same elongation. The best combination of properties was achieved by MHD and TTM – conditioned specimens, which are almost indistinguishable on this respect.

As for the correlation between strength and porosity, tensile specimens machined out from forks which were thixocast with differently conditioned slurries, gave different porosity levels and a range of yield and elongation values. The data, collected in Figure 7, show that average pore size is close to 20 μm. The largest pore had an equivalent diameter equal to 100 μm.

Studies on porosity and fatigue behaviour emphasize the importance of pore maximum size and seek to determine the critical size for fatigue crack initiation. In the present investigation, however, any comparison with literature data on critical pore size would be meaningless, since results are affected by pore shape, other microstructural variables and by test parameters. At any rate, the present results show a strong correlation between porosity and elongation but none with respect to yield strength. Similar behaviour was obtained in a 356 alloy by McDowell et al. [11], who found that relatively small pores, that is, below 50 μm, only affect the stress-strain curve beyond the yield stress.

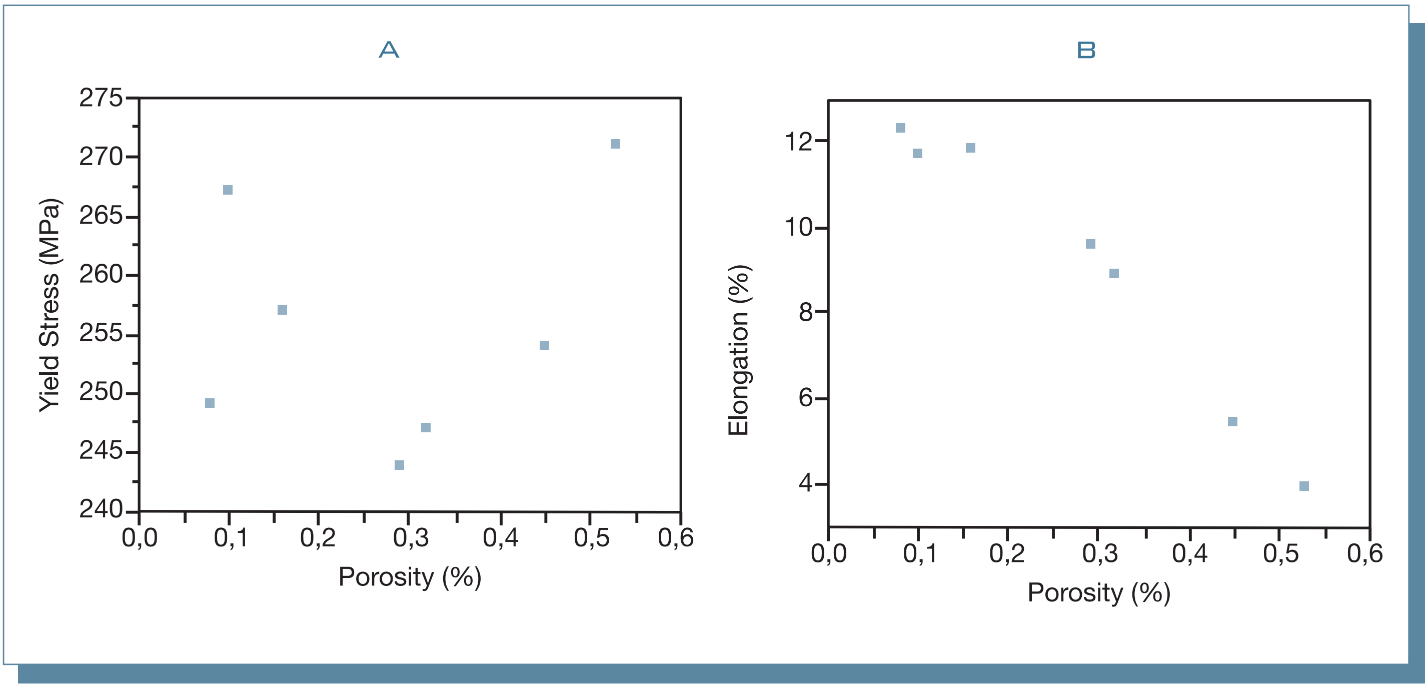

Fig. 7: Yield strength (a) and elongation (b) as a function of the porosity level of fork specimens.

3. THERMOMECHANICAL FATIGUE BEHAVIOUR

Results of the isothermal fatigue test are shown in Figure 8; it is apparent that, regardless testing temperature, the thixocast material fatigue behaviour is clearly superior to that cast in a permanent mould. Data also shows that fatigue life decreases with temperature due to the intervention of creep mechanisms; however, for high strain the lower temperature performance deteriorates, as seen for the thixocast sample. A possible explanation for this trend is that high stresses, by amplifying the effect of internal defects, lead to crack nucleation and growth, thus causing a chain of events that offset temperature as a cause of fatigue damage.

As for the thermomechanical fatigue study, Figure 9 shows that the fatigue behaviour of thixocast specimens (TTM) is definitely superior to that of its permanent mould cast counterpart (PMC). This result can be ascribed to the low porosity level and globular microstructure of the former material. It is well known that pores are detrimental defects since they act as nucleation sites for fatigue cracks, and the present measurements show that in the permanent mould cast specimens the porosity level is much higher than in the thixocast set of samples. Moreover, those pores are very large, in the range 300 – 500 μm compared with ≈ 100 μm for the thixocast material, besides being irregularly shaped. High cycle fatigue tests of Al casting alloys showed that interaction of dislocations with grain boundaries and/or eutectic particles are important crack initiators [12].

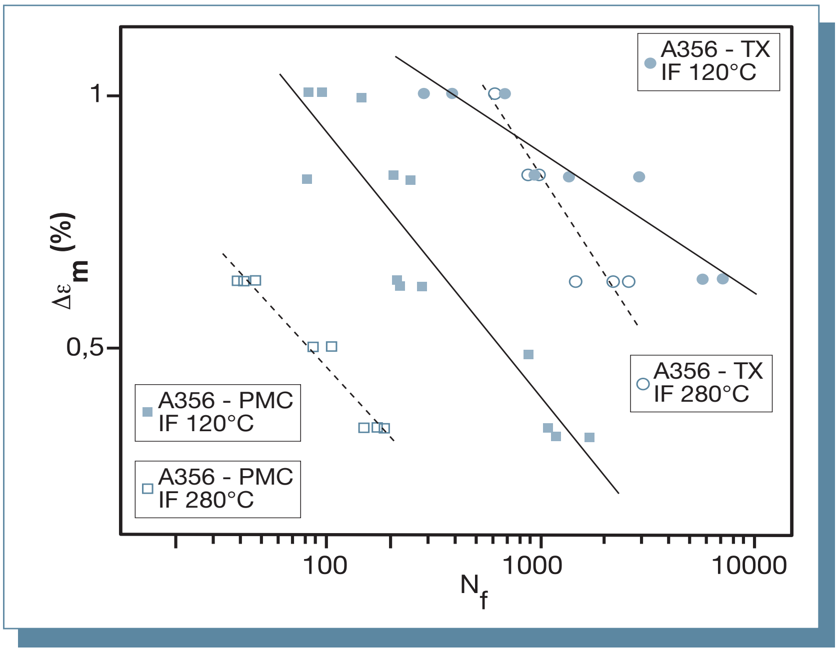

Fig. 8: Isothermal fatigue test for thixocast (TX) and for permanent mould cast specimen (PMC), performed at 120 and 280°C.

Thus, the higher the continuity of the Al-α phase - that is, free from boundaries and eutectic particles - the more the dislocations will be able to move inside the grains without exerting a hardening effect. In this sense the microstructure of the thixocast alloy is quite favourable and as a consequence it shows better performance under thermomechanical fatigue conditions.

Another comment regarding crack propagation stems from the fact that

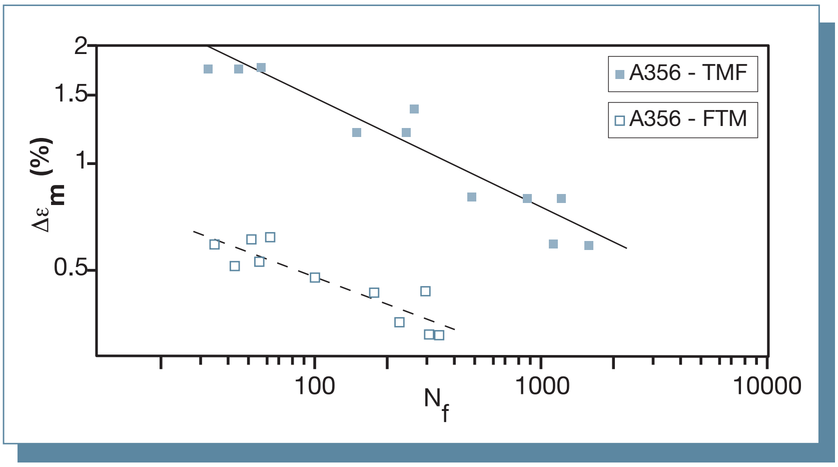

Fig. 9: Deformation-life curves for thixocast (TX) and for permanent mould (PMC) cast specimens. Thermomechanical fatigue test.

fracture tends to move within the eutectic phase [13], thus the Si particles shape, size and spacing are very important factors. In the thixocast material the eutectic phase is more refined than in the PMC sample due to the faster solidification rate caused by the lower heat content of a 0.5 volume fraction liquid phase, therefore the propensity to particle fracture / debonding is reduced. As for the Si particle spacing, a comparison of the partially remelted PMC microstructure, see Figure 4-b, with the microstructures of any of the semi-solid material, Figures 4-d, e, or g) shows that the interdendritic spacing in the PMC material is smaller than the one of the TTM, MHD or LPT samples. Consequently, the Si - particles mean free path is larger in the semi-solid material and fatigue life is extended.

4. CONCLUSIONS

1. The LPT conditioning technique produces microstructures very similar to those obtained by more conventional methods, such as TTM and MHD;
2. Porosity is related to the conditioning mode; thus, TTM and MHD samples exhibited the lowest (0.09 – 0.10%) and LPT the highest (0.27%) pore content. Maximum pore size was 100 μm and overall, porosity in the semi-solid samples is much lower than in the conventionally cast alloy, including the LPT-conditioned material.
3. Tensile properties are comparable to the literature average values for thixoformed A356 and higher than those of conventionally cast A356. Shorter precipitation heat treatment schedules were assessed and showed to be as effective as the standard solution / ageing heat treatment times.
4. Regardless the conditioning technique employed, there is a strong correlation between porosity and ductility but none linking the former with yield strength.
5. Deformation – life curves obtained in both isothermal and thermomechanical fatigue tests showed that the TTM – conditioned A356 has a much better performance than the permanent mould cast material. This was attributed to its lower porosity level, globular microstructure, higher continuity of the Al-α particles and refined eutectic Si particles.
6. Similarity of both microstructure and tensile properties of all thixocast material suggests that the TTM fatigue performance will be deployed also by the MHD and LPT specimens.

ABBREVIATIONS

TTM:	thermomechanical (conditioned);
PMC:	permanent mould cast;
MHD:	magnetohydrodynamical (conditioned);
TMF:	Thermomechanical fatigue (test);
LPT:	low pouring temperature (conditioned);
TX:	thixocast.

REFERENCES

[1] Haszler, A. and Vieregge, A. *Recent Developments in Aluminium Alloys for the Automotive Industry.* Mat. Sci. Eng. A280 (2000) 37 – 49

[2] Flemings, M.C. *Behavior of Metal Alloys in the Semisolid State.* Metall. Trans. A22 (1991) 957 – 981.

[3] Buffière, J-S., Savelli, S. Jouneau, J.H., Mairie, E. and Fougères, R. *Experimental Study of Porosity and its Relation to Fatigue Mechanisms of Model Al-Si7-Mg0.3 Cast Al Alloy.* Mat. Sci. Eng. A316 (2001) 115 – 126.

[4] UBE INDUSTRIES Ltd. *Method and Apparatus for Shaping Semisolid Materials.* European Patent # EPO 745 649 A1, December, 4, 1966.

[5] Jorstad, J.L. *Semi-solid Materials Processing: The High Integrity Die Casting Process.* Die Cast Engineer, 48, N° 9 (2004) 42 – 48.

[6] Browne, D.J., Hussey, M.J., Carr, A.J. and Brabazon, D. *Direct Thermal Method: New Process for the Development of Globular Alloy Microstructure.* Int. J. Cast Metals Research, 16 N° 4 (2003) 418 – 426.

[7] Li, C. Ellyin, F. Koh, S. and Oh, S.J. *Influence of Porosity on Fatigue Resistance of Cast SiC Particulate-Reinforced Al-Si Alloy Composite.* Mat. Sci. Eng. A276 (2000) 218 – 225.

[8] Atkinson, H.V. and Liu, D. *Development of High Performance Aluminum Alloys for Thixoforming.* 7th Int. Conf. on Semi-Solid Processing of Alloys and Composites, Tsukuba., Japan, 2002, pp. 51–56.

[9] Young, K. and Eisen, P. *SSM (Semi-Solid Metal) Technological Alternatives for Different Applications.* Metall. Sci. Technol. 18 (2000) 11 - 15.

[10] Rometsch, P.A. and Schaffer, G.B. *An Age Hardening Model for Al-7Si-Mg Casting Alloys.* Mat. Sci. Eng. A325 (2002) 424 – 434.

[11] McDowell, D.L., Gall, K., Horstemeyer, M.F. and Fan, J. *Microstructure-Based Fatigue Modeling of Cast A356-T6 Alloy.* Eng. Fract. Mech. 70 (2003) 49 – 80.

[12] Lados, D.A. and Apelian, D. *Fatigue Crack Growth Characteristics in Cast Al-Si-Mg Alloys: Part I. Effect of Processing Conditions and Microstructure.* Mat. Sci. Eng. A385 (2004) 200 – 211.

[13] Maier, H.J., Smith, T.J. and Sehitoglu, H. *Modeling High Temperature Fatigue Behavior of Cast 319 Type Aluminium Alloy. VDI Berichte, 1472 (1999) 409 – 422.*