

## Evaluation of the thixoformability of the A332 Alloy (Al–9.5 wt%Si–2.5 wt%Cu)

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**Abstract** The main purpose of this article is to develop and/or use a commercial conventional low-cost raw material as thixoforming material in order to diminish the costs of the thixoforming process. Semi-solid technology usually uses aluminium low-silicon alloys such A356 (Al–7.0 wt%Si) as raw materials. High silicon content alloys with a quasi-eutectic composition diminish the semi-solid range, making it difficult to control the thixoforming temperature, although present excellent mechanical properties. This article reports on the semi-solid behaviour of Al–9.5 wt%Si–2.5 wt%Cu (A332). Thermo-Calc simulations and experimental DSC techniques were used to map the temperature transition from solid to liquid in order to achieve the best semi-solid behaviour and hence the best thixoforming temperature. Samples were reheated at three temperatures to 30, 45 and 60% of the solid fraction applying holding times of 0, 30, 90 and 210 s. The morphological evolution and semi-solid behaviour of the samples at these temperatures were determined via the fixed platen compression test. The structure showed the best semi-solid behaviour at 572 °C, with an apparent viscosity of up to  $1.5 \times 10^5$  Pa s. The results indicated that the semi-solid behaviour of the commercial Al–9.5 wt%Si–2.5 wt%Cu alloy is similar to that of the alloy A356. Despite its large dendritic structure it is possible, with the correct combination of temperature and time, to use this alloy as raw material for the thixoforming process. Furthermore, semi-solid parts can be produced by thixoforging

using this low-cost material without any special preparation.

### Introduction

Thixoforming technology has made considerable advances since its initial discovery in 1973 [1]. Although, after almost 40 years, few raw materials are still used as thixoforming materials. In fact, only A356 and A357 are used extensively in industry [2]. Semi-solid raw material (SSM), which is more expensive than the raw material normally used in the conventional process, typically costs 150% more than die casting materials and 125% more than squeeze casting or permanent moulding material.

A comparison of the overall costs of tooling, capital, labour, heat treatment, machining, finishing, etc. indicates that bottom-line casting costs are about 100% higher than those of die casting, but 10% lower than squeeze casting and 50% lower than permanent moulding. The development of new low-cost alloys and a new low-cost process could be the key factor for the dissemination of this technology [3].

Previous papers described attempts to produce such raw materials using ultra-grain refining [4–6] cooling slope [7] and electromagnetic stirring techniques [8–10]. They showed that the viscosity of the Al–Si alloy system varies very little as a function of the solid fraction, and that a low-silicon alloy can have almost the same viscosity as the A356 alloy [4, 9, 10].

The structure of this article follows that of a previous paper [10], discussing the rheological behaviour of the conventional Al–9.5 wt%Si–2.5 wt%Cu (close to A332 composition), produced by Direct Casting (DC), as a function of heat treatment at solid fractions of 30, 45 and

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**Table 1** Chemical composition of the Al–9.5 wt%Si–2.5 wt%Cu (in wt%)

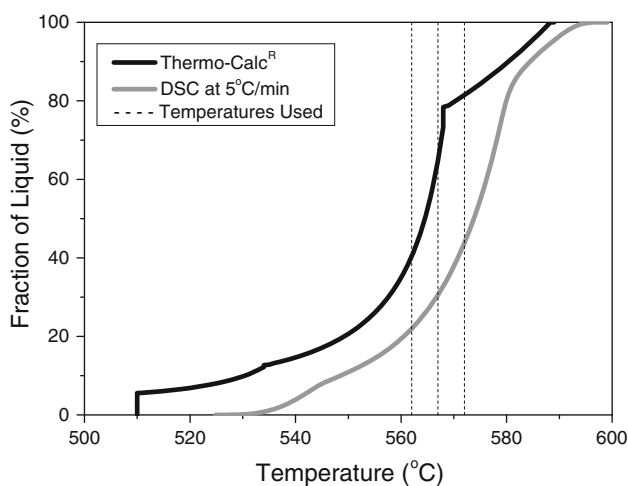
Alloy	Si	Cu	Mg	Fe	Mn	Zn	Ti
Alloy specification	9.50 ± 0.50	2.50 ± 0.30	≤1.00	≤0.50	≤0.30	≤0.30	≤0.10
Alloy	9.92	2.78	0.72	0.30	0.05	0.03	0.019

60%, and describing the thixoforming of this alloy in an industrial eccentric press using an open die. The heating at semi-solid state allows the study of the morphological evolution [4] and the compression test, via the fixed platen (developed by Laxmanan and Flemings [11]), is used to determine the apparent viscosity of such materials. The main purpose is to develop and/or use a commercial conventional low-cost raw material as thixoforming material.

## Methodology

First, is important to notice that the methodology adopt here follows the same methodology as shown in previous papers [4, 9, 10] for the characterization of the as-cast structure, as well as, the morphological modifications at the semi-solid state, and its rheological behaviour.

Table 1 lists the chemical composition of the commercial Al–9.5 wt%Si–2.5 wt%Cu alloy (close to A332) produced by DC (300 mm diameter ingot). As can be seen, the materials were produced within the range of the chemical composition adopted. The material was characterized using an Anacon BILL OES spectrophotometer.



**Fig. 1** Transition of the Al–9.5 wt%Si–2.5 wt%Cu alloy from solid to liquid according to Thermo-Calc<sup>®</sup> simulation and the experimental DSC technique. Temperatures used: 562 ± 2 °C for 60%  $f_s$ , 567 ± 2 °C for 45%  $f_s$ , and 572 ± 2 °C for 30%  $f_s$

## Characterization of the semi-solid transition

The solidus and liquidus temperatures were determined by the DSC technique using a Netzsch STA 409C thermogravimeter (only at 5 °C/min due to limitation of the equipment) and Thermo-Calc<sup>®</sup> simulation software. Figure 1 shows the transition expected using the two techniques. The morphological evolution of the alloys was studied using the Scheil model to determine the temperature corresponding to 30, 45 and 60% solid fractions. To study its morphological evolution, samples 15 mm tall and 20 mm diameter were reheated from room temperature up to the semi-solid state in 5 min (approximately 110 °C/min) and hold at those temperatures for 0, 30, 90 and 210 s in the same solid fractions.

The 0, 30, 90 and 210 s holding times were chosen due to the industrial processing, which is time dependent rather than temperature dependent. Usually the raw material is processed by heating during 7/8 min, so depending upon the size and mass, the material could be at the desired temperature at 5 or 7 min. Study of the morphology at this range of time is the study of the best and worst scenario for thixoforming.

As can be seen in Fig. 1, the Thermo-Calc<sup>®</sup> prediction differs by approximately 10 °C from the DSC technique. Due to this difference, the average temperatures were chosen (with an interval of only 5 °C) due to the fact that both techniques are inconclusive, i.e. 572 ± 2 °C for 30%  $f_s$  (solid fraction), 567 ± 2 °C for 45%  $f_s$  and 562 ± 2 °C for 60%  $f_s$ . The aim was to determine the evolution of the structure and its corresponding viscosity within a very narrow window for the thixoforming process, i.e. the worst and best scenarios.

## Characterization of the morphological evolution

The original structures and the samples reheated to 30, 45 and 60%  $f_s$  were characterized to determine their primary particle/globule size and shape (a) and their grain size (b).

All the samples were ground with 220, 320, 400, 600 and 1200 grit sandpaper, polished with 6 μm diamond paste, and finished with 1 μm diamond paste. After polishing, the samples were etched using Keller's reagent (2.5 mL HNO<sub>3</sub>, 1.5 mL HCl, 1 mL HF and 95 mL H<sub>2</sub>O), submerging the samples in the reagent for 10 s. After etching, the samples were rinsed under running water for about 30 s

and dried. The metallographic analysis was performed in a Leica DM IL optical microscope. The primary particle size was measured using the Heyn intercept method, following the ASTM E112 (1996) standard. The primary particle/globule was counted in five different fields on each micrograph, and five images were recorded from different sections of each sample, making a total of 25 counts of primary particles in each sample. The value of the shape factor (roundness) of each alloy was estimated using the ImageJ 1.40 g software.

The grain size was characterized by colour metallography. The same samples used for the previous characterization were etched again, this time using a 6% HBF<sub>4</sub> electrolytic solution and applying a voltage of 20 V for about 90 s under constant moderate agitation. The samples were then rinsed under running water and blow-dried. They were then analysed under the same microscope, using polarizing filters to obtain the colour images of their grains, so that grains with the same crystal orientation presented a similar colour, facilitating their identification and characterization. Heyn's intercept method was also used to determine the grain size, with 25 grain counts made in each tested condition.

#### Characterization of semi-solid behaviour

Compression tests were performed using the aforementioned solid fractions and holding times and employing a Materials Testing System (MTS 810) device (5 min to heat at the desired temperature and holding time of 0, 30, 90 and 210 s). To keep the temperature constant during the test, the parallel platen was heated in a small furnace, prior to testing. The samples were 15 mm tall ( $H_0$ ) and their diameter was 20 mm. Compression testing was carried out with the classical Laxmanan and Flemings compression platens test [11], which used a 12.5 mm diameter and 6.25 mm high Sn–15 wt%Pb samples and assumes a Newtonian behaviour, but in the present case a constant deformation is applied (10 mm/s compression rate ( $\delta H/\delta t$ )), leading to a 1 s test without any lateral constraint. The results were plotted as strain ( $F$ ) versus deformation ( $H$ ) and transformed into apparent viscosity ( $\mu$ ) versus shear rate  $\dot{\gamma}$  using the following equations [4, 11, 12]:

$$\mu = \left( \frac{8\pi F}{3V^2} \right) \left( \frac{1}{H^4} - \frac{1}{H_0^4} \right)^{-1} t \quad (1)$$

$$\dot{\gamma} = - \left( \sqrt{\frac{V}{\pi}} \right) \left( \frac{\delta H/\delta t}{2H^{2.5}} \right) \quad (2)$$

where  $\mu$  is the apparent viscosity (Pa s),  $F$  is the load (N) in time  $t$  (s),  $V$  is the sample's volume (m<sup>3</sup>), which is considered constant,  $H$  is the instantaneous height (m) and

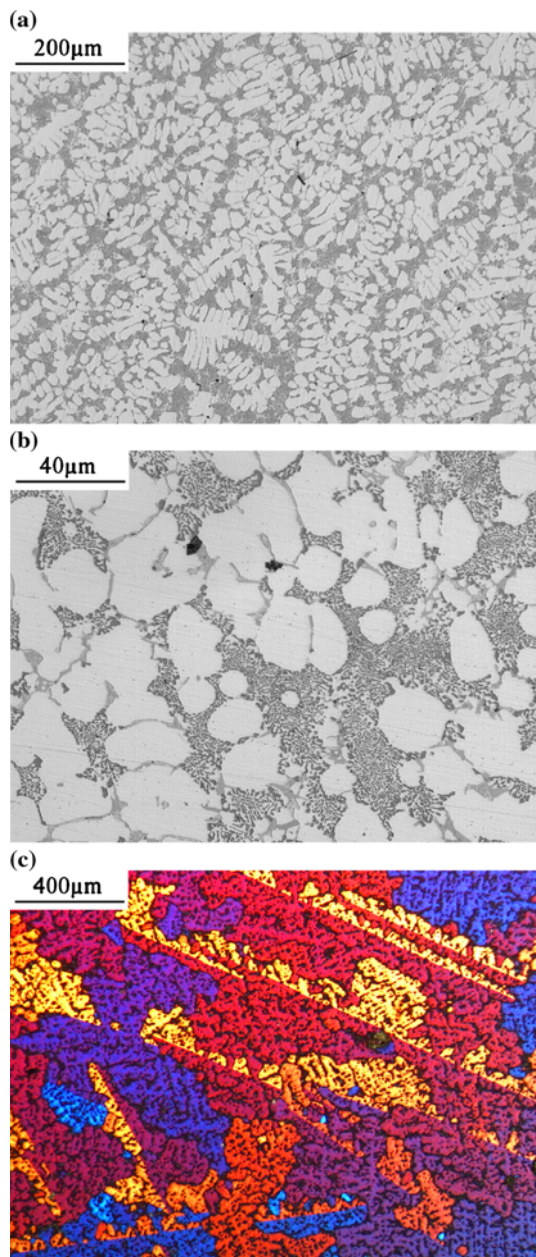
$H_0$  is the initial height (m). Three sets of tests were performed for each temperature and holding time.

#### Results

Figure 2 shows the original microstructure of the as-cast Al–9.5 wt%Si–2.5 wt%Cu alloy. The image captured by conventional metallography shows the classical as-cast coarse heterogeneous primary particle phase (secondary dendritic arm spacing of  $35 \pm 15 \mu\text{m}$ ) with poor particle distribution and the eutectic Al–Si surrounding the alpha phase dendritic structure. At higher magnification it is possible to observe the morphology of the eutectic. It is possible to see a very fine silicon-faceted particles of about 1  $\mu\text{m}$  in the aluminium FCC alpha phase ( $\alpha$ ). This eutectic will liquefy after the heating, previous to thixoforming, and will help to lubricate the forming process. At the semi-solid state it is expected that solid grains surrounded by liquid will be obtained. In the black and white micrograph, it is possible to observe the primary phase but it is not possible to see the grain structure and its morphology.

The image obtained by colour metallography shows a large expanded grain structure with heterogeneous columnar grains comprising a very large dendritic skeleton. The grain structure also shows grains with low angle grain contour, i.e. the dendritic structure contains two different colours resulting from a small change in the crystal direction, mostly due to the abnormal grain size. The large grain size and distribution could preclude the use of this material as a thixoforming raw material. In fact, this is considered a poor structure for the thixoforming process, which usually needs a very fine globular structure with small rather than dendritic grains.

For this alloy, Thermo-Calc<sup>®</sup> predicts that the transition from solid to liquid begins at approximately 510 °C (Fig. 1.) with liquefaction of the Al<sub>2</sub>Cu precipitates. Liquefaction of Al<sub>5</sub>Cu<sub>2</sub>Mg<sub>8</sub>Si<sub>6</sub> occurs from 510 to 533 °C, while that of eutectic Al–Si occurs from this temperature up to 568 °C. Liquefaction of primary alpha phase aluminium begins from this point on. The expected liquidus temperature is 584 °C, leading to a 74 °C solid to liquid interval. However, the DSC technique predicts the liquefaction of Al<sub>2</sub>Cu precipitates at temperatures ranging from 525 to 543 °C, followed by Al<sub>5</sub>Cu<sub>2</sub>Mg<sub>8</sub>Si<sub>6</sub>, as well as the eutectic, ranging from 543 to 578 °C, and liquefaction of alpha phase aluminium from 578 °C up to its liquidus temperature at 594 °C, leading to a 69 °C interval. This difference of about 10 °C was determinant in set the temperatures for morphological and rheological behaviour tests at 562, 567 and 572 °C. These temperatures represent the average temperature of both techniques. Normally the industrial application implies the temperature as the control



**Fig. 2** Original as-cast structures of the A332 (Al-9.5 wt%Si-2.5 wt%Cu) alloy. Conventional metallographic image at lower (a) and higher (b) magnification and c colour metallographic image showing the expanded grain structure

set for this process, and the solid/liquid fraction as a result of the temperature used. To determine the ideal thixoforming temperature is the key to the success of this process.

In the groundbreaking paper of Liu et al. [13], the authors established the thixoformability criteria commonly adopted for SSM raw materials: a) ‘the highest knee on the fraction liquid versus temperature curve should occur between 30 and 50% liquid’; b) ‘fraction liquid sensitivity at 0.4 fraction liquid ( $(df_L/dT)_{f_L=0.4}$ ) should be as small as

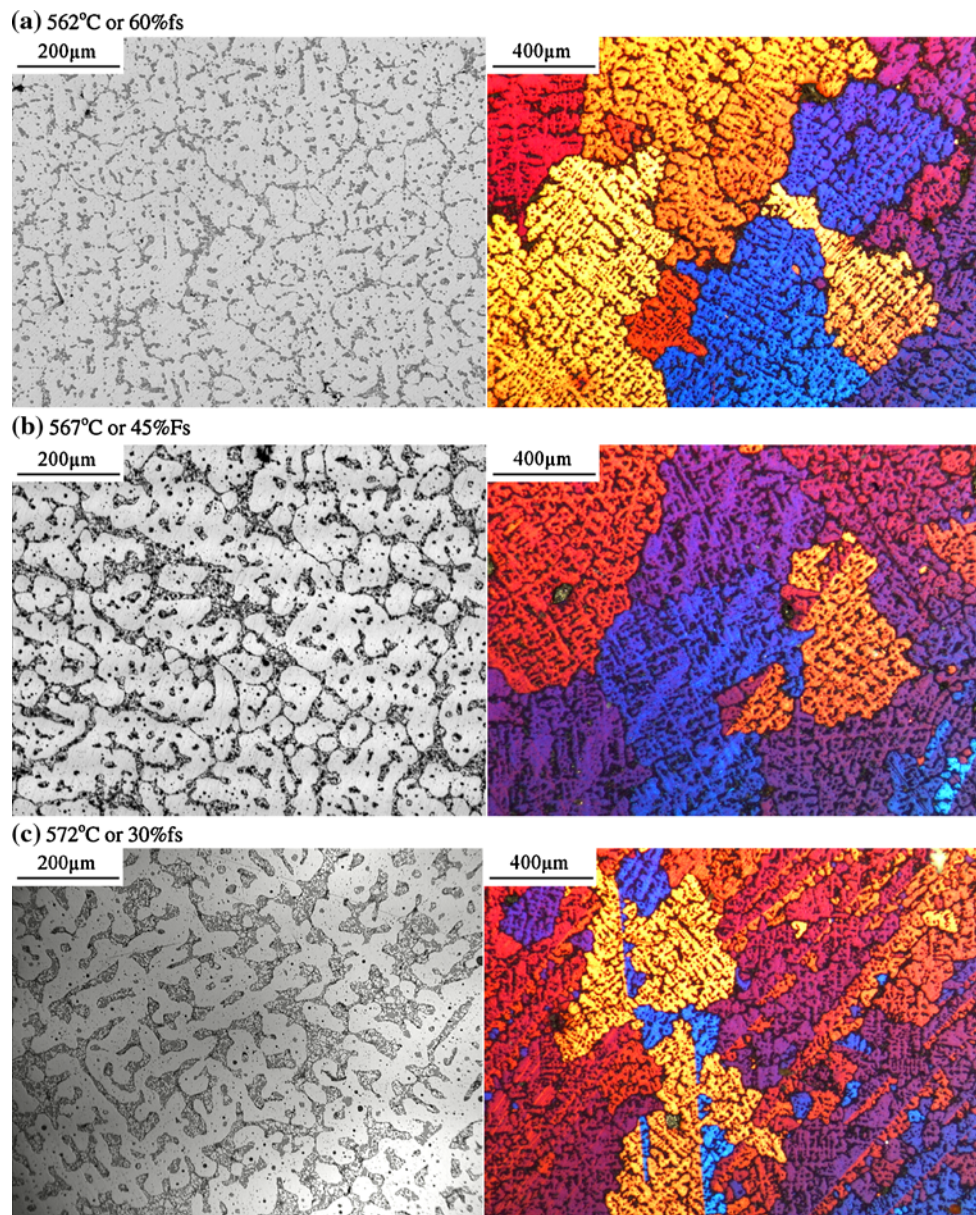
possible (the authors suggest less than  $0.03 \text{ K}^{-1}$ )” or  $3\%/K$ , i.e. less than 3% of variation by K (or  $3\%/^{\circ}\text{C}$ ) and c) ‘the solidification interval, the temperature interval between the liquidus and solidus temperature should be not be too wide (the authors suggest less than  $130 \text{ K}$ ’.

This way it is expected a not to good thixoformability of the Al-9.5 wt%Si-2.5 wt%Cu alloy due to: a) the knee for this alloy, i.e. the temperature corresponding to the final liquefaction of the eutectic and the start of liquefaction of the primary phase occurs at 80% of liquid fraction for both measurement techniques; b) at 0.4 fraction liquid the  $(df_L/dT)_{f_L=0.4}$  is 3.15 or  $2.91\%/^{\circ}\text{C}$  measured by Thermo-Calc<sup>®</sup> and DSC techniques, respectively, i.e. this means a high sensitivity at this fraction liquid, but if is considered the knee at 80% fraction liquid, for thixo-injection process for example, the sensitivity decrease to  $0.9\%/^{\circ}\text{C}$  according to Thermo-Calc<sup>®</sup> but  $4.87\%/^{\circ}\text{C}$  according to DSC. If Thermo-Calc<sup>®</sup> is correct one have a more controllable process, but if DSC is correct the process will become instable. Is important to notice that Liu et al. [13] were concerned about the difference of temperature from the skin to centre of the billet, but the sensitivity criteria could also be applied to the stability of the industrial process: it is necessary materials that present lower variation of fraction solid as a function of the temperature.

Finally the solidification interval predicted by Thermo-Calc<sup>®</sup> and DSC are  $74^{\circ}\text{C}$  ( $74 \text{ K}$ ) and  $69^{\circ}\text{C}$  ( $69 \text{ K}$ ), respectively, within the recommended. Concluding, thermodynamically, according to Atkinson’s criteria, the Al-9.5 wt%Si-2.5 wt%Cu alloy could be considered a non thixoformable material due its temperature sensitivity, but are these criteria definitive? Is it possible to thixoform this material, despite the negative prediction? The low cost of this raw material leads to the thixoforming tests, explained hereafter.

The experimental procedure was conducted to verify the effect of these temperatures on the microstructure and to analyse the morphological evolution. Figure 3 illustrates this transformation, showing the Al-9.5 wt%Si-2.5 wt%Cu heated up to 562, 567 and  $572^{\circ}\text{C}$  and immediately quenched (0 s), which is supposed to be sufficient to produce 40, 55 and 70% of liquid (60, 45 and 30%  $f_S$ ). Due to Ostwald ripening and coarsening mechanisms, a considerable amount of entrapped liquid was formed in the samples reheated at 562 and  $567^{\circ}\text{C}$ . In fact, for those lower temperatures, a large primary skeleton was formed. This leads to an expectation of poor rheological behaviour, i.e. a higher stress is expected in the thixoforming process.

Again [4, 8] is important to notice that, in order to better observe the semi-solid structure, the colour metallograph is indispensable, because allowed us to better observe the grain boundary. In fact the eutectic that is supposed to be liquid at the eutectic temperature starts the liquefaction



**Fig. 3** Al–9.5 wt%Si–2.5 wt%Cu reheated to: **a** 562 °C or 60%  $f_S$ , **b** 567 °C or 45%  $f_S$ , and **c** 572 °C or 30%  $f_S$  and immediately quenched (holding time of 0 s). *Left* conventional metallographic

image showing the primary particle phase size and distribution and the eutectic Al–Si. *Right* colour metallographic image showing the grain structure

process at this boundary. After the melt of the grain boundary initiates the melting of the eutectic inside the grain. The conventional metallography does not show this clearly.

The alloy reheated to 572 °C and quenched displayed a very distinct behaviour, with extensive formation of liquid and a considerable change in structure. Note the coarse alpha phase surrounded by the eutectic phase (in black and white metallography), as well as the large grain size (in the colour metallographic image), but of smaller size than the samples treated at the low temperature. This can be attributed to the fact that most of this structure was formed

during quenching of the liquid. The morphology of the abnormal grains that remained solid at this temperature did not change significantly, and the small grains are originated from the solidification of the liquid. The final microstructure shows abnormal grains surrounded by small grains.

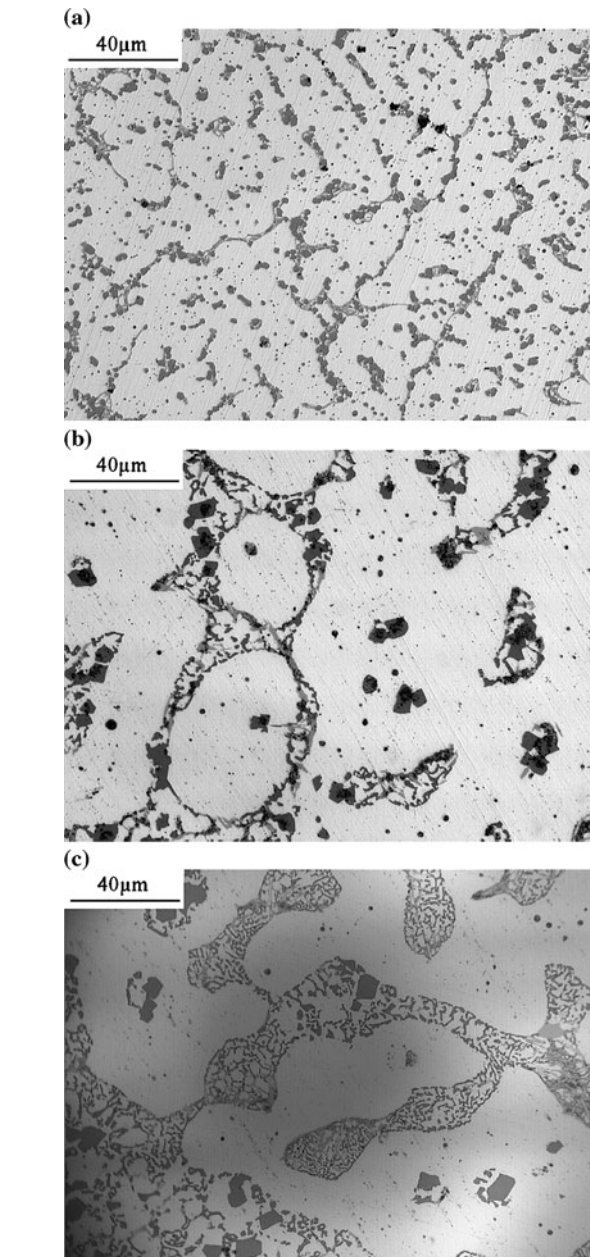
The ImageJ software also revealed that the area of the modified molten eutectic phase in this sample was approximately 40%. According to Thermo-Calc<sup>®</sup>, all the eutectic phase should be liquid at 572 °C; in fact, 80% liquid was expected using the simulation software. However, at this temperature, the DSC technique indicated only 40–45%. This metallographic evidence could lead to a

misinterpretation suggesting the DSC as definitive technique. But, it is necessary lead into account the effect of the secondary solidification, i.e. the alpha phase formed during the quench on the surface of the alpha phase that remained solid at this temperature, this way it can be concluded that the Thermo-Calc<sup>®</sup> software is more accurate in determining the solid/liquid fraction than the DSC technique, which indicated 40–45%. Therefore, further experiments should be performed to identify the best thixoforming temperature. Further empirical evidence is the fact that in one test, performed at 580 °C, the sample collapsed completely. This evaluation could be corroborated by the viscosity tests and will be shown next.

It is also important to notice that the heating at the semi-solid state changes the morphology of the eutectic phase. Figure 4 shows, at higher magnification, the silicon-faceted particles. At lower temperature only the agglomeration of the silicon occurs. This could be damaging for the final piece because the mechanical properties depend upon the distribution of the silicon in the aluminium alpha phase. At 567 °C, a higher amount of liquid was formed in the semi-solid state, therefore, is possible to observe silicon particles in the agglomerated form as well as the eutectic silicon/aluminium. At 572 °C, it is possible to observe that a large amount of liquid was formed at the semi-solid stage and the solidification of this liquid originates the traditional eutectic similar to the as-cast condition but instead, a very fine eutectic structure, a coarse one. The rapid solidification of the thixoformed piece could solve this problem in order to improve mechanical properties.

It is also important to notice that the silicon particles were present at primary particle boundary. The dendritic structure changed into a more globular one, and the eutectic occupies the former dendritic arm space. When compared to the original as-cast structure (Fig. 2b), the coarsening of the particles can be seen. Despite this, the acicular form, usually found in this alloy when as-cast is not present, indicating that the mechanism used to change the morphology of the silicon, from acicular to near globular particle, is still present, i.e. it is not necessary the silicon modification stage process, such as the use of strontium or sodium [14]. Despite the coarse structure, the form of these silicon particles should present final mechanical properties higher than for the same alloy as-cast without the modification, but inferior to die-cast injected parts.

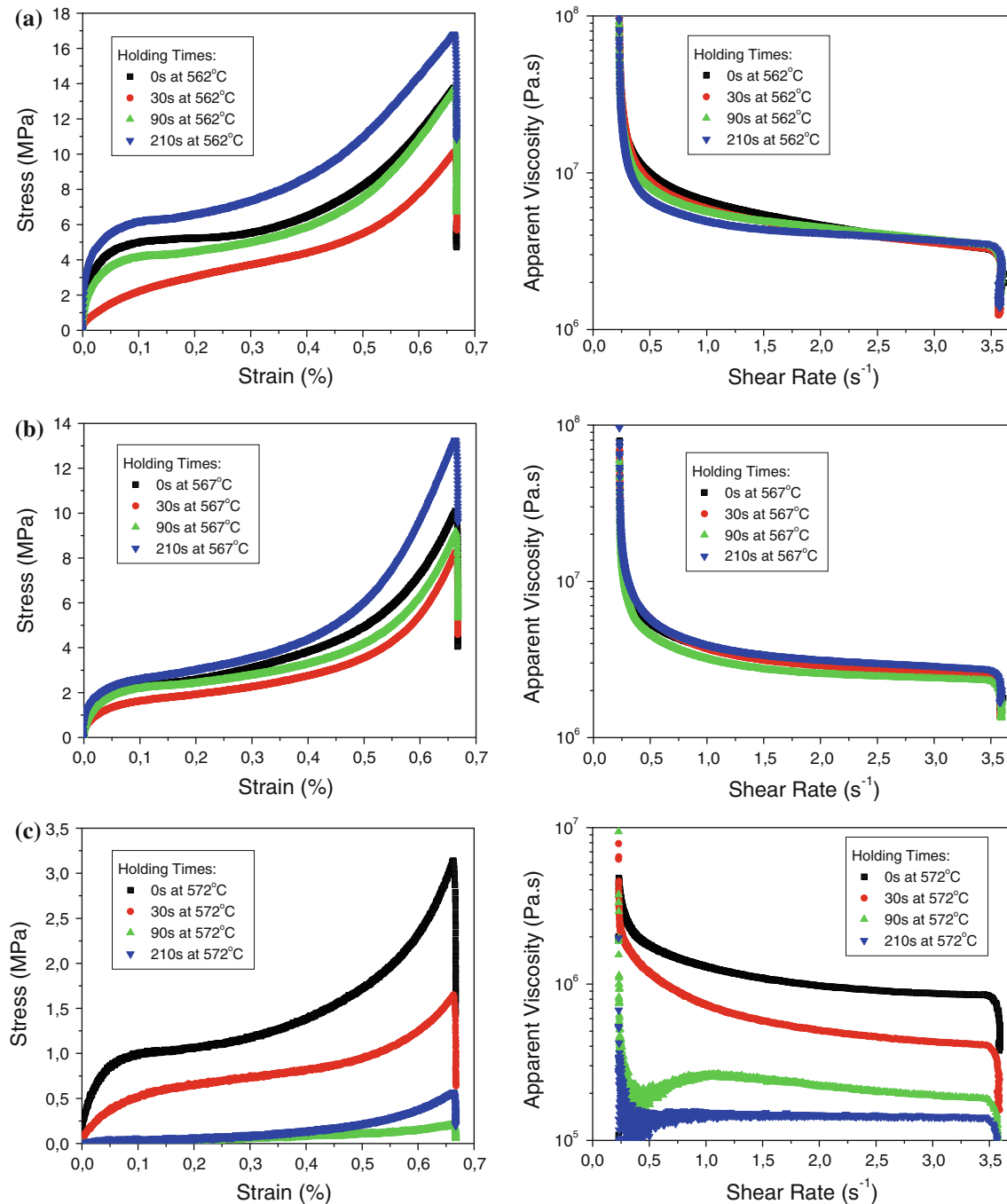
Figure 5 shows the stress versus strain curves obtained from compression tests of the Al–9.5 wt%Si–2.5 wt%Cu heated up to 562 °C or 60%  $f_s$ , 567 °C or 45%  $f_s$  and 572 °C or 30%  $f_s$ . As expected, it can be observed that at higher temperatures lower stresses are necessary to deform the structure. The interaction of the liquid (rich in eutectic Al–Si) is responsible for this phenomenon. The liquid



**Fig. 4** Al–9.5 wt%Si–2.5 wt%Cu reheated to: **a** 562 °C or 60%  $f_s$ , **b** 567 °C or 45%  $f_s$ , and **c** 572 °C or 30%  $f_s$ —morphology of silicon-faceted particles

phase reduces its viscosity, decreasing the stress necessary to deform the material.

The compression tests also show that the temperatures of 562 and 567 °C produce a very small amount of liquid, leading to a very high stress for deformation, although this stress is still lower than the necessary for the hot forging of this alloy. This could be explain due to the fact that the higher amount of solid at this lower temperature keeps the dendritic skeleton intact and could lead to form more connexions. Another phenomenon is observed: the stress



**Fig. 5** Stress  $\times$  Strain curves and the corresponding apparent viscosity versus shear rate obtained from the two platen compression test in order to evaluate the semi-solid behaviour of the Al-9.5 wt%Si-

2.5 wt%Cu heated up to **a** 562 °C or 60%  $f_s$ , **b** 567 °C or 45%  $f_s$  and **c** 572 °C or 30%  $f_s$ . It is important to notice the difference among the scale used

for deformation is higher for the 90 and 210 s holding times. Usually when the material reach the semi-solid temperature the melting of the eutectic phase will destroy the interconnection of the skeleton, but a small period of time is necessary for that. First, at 0 s holding time there is not enough time to completely break the skeleton, after 30 s the separation of skeleton parts took place, but the

coarsening, as well as, Ostwald ripening phenomena lead to globularization and agglomeration of particles, and at this lower temperature the coarsening is facilitate, due to the approximation among particles.

Still, the stress versus strain curves shows the typical semi-solid behaviour. At the beginning a high stress is necessary to start the deformation process that continues

with the separation of the solid part from the liquid, and at the end of the compression test, most of the liquid had segregated and the contact solid/solid began to restrain the deformation increasing the stress. For all temperatures this phenomena was observed, especially at 572 °C.

At 572 °C, the thixotropic behaviour can be easily observed: the semi-solid material needs a low stress to start deformation; after a very short period of time, or at a very low stress the material starts its homogeneous deformation. It is important to notice that the semi-solid behaviour calculated from Laxmanan and Flemings equations [11] does not lead into account the segregation phenomena and assumes a Newtonian behaviour. The same assumption was adopted in this article. The homogeneous deformation occurred after 0.1 (10%) deformation. After this point, the semi-solid material began to expel the liquid existing inside and between the particles, and reached steady state. After 0.4 (40%) deformation, most of the liquid was expelled and the material became a quasi-solid material. At this point, the stress increased again to the maximum.

The extreme difference of behaviour between the 562/567 °C and the 572 °C tests indicates that Thermo-Calc<sup>®</sup>, which indicates a presence of 70 up to 80% of fraction liquid, is more accurate than DSC technique as shown before. In fact DSC indicates only 40% of fraction liquid at this temperature.

The Al–9.5 wt%Si–2.5 wt%Cu alloy, however, presented a different behaviour, compared to the A356 [4]. A higher stress was required to start the homogeneous deformation at 0 and 30 s. In this case, interconnections between the primary  $\alpha$  particles occur. The  $\alpha$  particles are “welded” together forming a 3D structure. It is necessary a period of time to elapse for the liquid eutectic to melt those contacts as informed before. For the 90 and 210 s, the stress necessary for the deformation is very low and the Stress  $\times$  Strain curves are insufficient to explain the semi-solid behaviour [4, 10].

Figure 5 also shows the apparent viscosity as a function of the shear rate, which could be a more consistent method to shown this semi-solid behaviour. Note that the behaviour of the semi-solid was almost the same at 562 and 567 °C, showing almost no variation in the amount of solid, and that the Thermo-Calc<sup>®</sup> technique predicted a value closer to the experimental one. In this case, the maximum tension in the compression test was 13.7 MPa, which is still lower than conventional forming process. However, the material showed a normal semi-solid behaviour at 572 °C with 40% liquid (DSC) or 80% liquid (Thermo-Calc) when compared to conventional semi-solid materials. In previous paper using the same compression test technique for the A356 alloy, the rheological behaviour was similar [4].

First, at 0 and 30 s of holding time, the behaviour was comparable to that occurring at the temperatures of 562 and

567 °C. A certain period of time was required for the liquid to completely dissolve the solid/solid contacts of the dendritic skeleton. In the A356 alloy after 30 s the skeleton was dismantle. Most of the solid/solid contacts melted between 90 and 210 s at 572 °C and the material behaved like molten glass ( $1.5 \times 10^5$  Pa s or 0.6 MPa), i.e. this material needs more time at the semi-solid temperature in order to achieve the best thixoforming behaviour.

In general, the higher the solid fraction the greater the material’s viscosity. This phenomenon is explained by the lower liquid content lubricating the contact among primary particles and, in this particular case, the dendritic skeleton as well.

Thus, the viscosity is more strongly affected by the holding time at higher temperatures due to the dismantling of the skeleton. The holding time in the semi-solid range affects materials in different ways. Usually, the longer the holding time the lower the viscosity, because of the globularization phenomenon. However, in some cases, a longer holding time causes agglomeration of the primary particles. This phenomenon was not observed here.

It is also important to note that the semi-solid behaviour of the Al–9.5 wt%Si–2.5 wt%Cu at 572 °C was similar to that of the Al–7.0 wt%Si–0.5 wt%Mg (A356) at 580 °C or 45%  $f_s$ , i.e. viscosity ranging from  $1.5 \times 10^5$  to  $10^6$  Pa s versus  $10^5$  to  $4 \times 10^5$  Pa s at the same shear rate [4]. A shear rate varying from 0 up to  $3.5 \text{ s}^{-1}$  was used in the present case because the main purpose was to develop the thixoforging process rather than thixo-injection moulding, which uses a shear rate of more than  $200 \text{ s}^{-1}$ .

Therefore, the compression test showed that this alloy can be used as a thixoforming raw material even for a near eutectic composition, due to the fact that at higher temperatures it presents similar behaviour compared to the A356 [4, 9, 12]. The key is to maintain control of the process: a very narrow window implies a good control of temperature with minimum variation and a good control of time. Dismantling the dendritic skeleton requires a holding time of more than 90 s. Therefore, is important to notice that in this paper the liquid segregation, as well as, the final mechanical properties of the thixoformed piece was not studied. Further studies will be conducted.

## Conclusions

The results indicated that the semi-solid behaviour of the Al–9.5 wt%Si–2.5 wt%Cu alloy (close to the A332 composition) is similar to that of the alloy with Al–7.0 wt%Si–0.5 wt%Mg (A356), which is normally used in the thixoforming process, leading to a viscosity of close to  $1.5 \times 10^5$  Pa s. Despite its large dendritic structure it is possible, with the correct combination of temperature and



time, to use this alloy as raw material for the thixoforming process. Furthermore, semi-solid parts can be produced by thixoforging using this low-cost material without any special preparation.

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