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Temperature and microstructural condition dependence for thermal diffusivity and thermal condutivity of a casting Al-Si-Cu-Mg alloy

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Thermal and electrical properties as well as mechanical properties of age-hardenable Al alloys are affected, both at room and at high temperature, by their microstructural condition. This behaviour has to be considered not only for wrought but also for casting alloys, such as for the Al-7Si-0.5Cu-0.4Mg, characterized by multiple precipitation sequences investigated in the paper. In these conditions the temperature dependence of thermophysical properties, generally obtained performing tests during isochronal heating, is not only related to the initial microstructural condition, but also to heating rate, a test parameter whose range is often limited by testing methodologies and equipments. These effects have to be taken into account in cases where a multipurpose material characterization or a comparative analysis of result is intended to interpret microstructural changes. Ex-situ tests can help the separation of microstructural changes effect from temperature-related ones. Examples of the combined techniques and analyses are illustrated.

KEYWORDS: Al-7Si-0.5Cu-0.4Mg, TEMPERATURE-DEPENDENCE, THERMAL DIFFUSIVITY, ELECTRICAL CONDUCTIVITY, DILATOMETRY

INTRODUCTION

Among the widely applied Al-Si-Mg alloys, the simple addition of Cu demonstrated to beneficially improve the high temperature performance [1, 2], so that temperature and stress/strain cycles can be withstood by complex-geometry components without the addition of exotic elements. When these alloys, with excess Si and Cu-containing, are solution treated and artificially aged, secondary Si intragranular particles adds up to the metastable phases of β-Mg_2Si precipitation sequence [3] and to phases of the quaternary Q-phase one [4]. The relatively high dissolution temperatures and slow coarsening kinetics of these phases lead to increase both temperature and time at which particle strengthening occurs with respect to Al-Si-Mg alloys.

As for other age-hardening alloys intended to be artificially aged (AA) or serviced at relatively high temperature, the following points should be considered: i) local cooling rate following a solution heat treatment (SHT) affect precipitate evolution during aging/service, both in terms of precipitate, volume fraction, nucleation sites and kinetics; ii) secondary phases affect not only strength, but also on the change of volume of the alloy, iii) secondary phase-related effects

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can be observed also for thermal or electrical properties. In parts of complex geometry and service conditions, the interaction between all these features is not easy to foreseen and good understanding of separate effects should be considered.

Focusing on point (i), the effect of SHT and of its final cooling on further precipitation during aging treatments at 180-230°C of Al-7Si-0.5Cu-0.4Mg alloy with homogeneous solidification structures was shown to be negligible for SHT cooling rates exceeding 10-20 K/s by Ram et al [6] and will be not investigated in the present paper. Concerning points (ii) and (iii), the temperature-dependence of age-hardening alloys can significantly differ from that of commercially pure Al, with thermophysical properties both to initial microstructure and heating rate in the widely adopted isochronal-type tests, where adopted heating rates are related to test methodology and equipment used to obtain specific properties. Multiple characterization techniques and heating rates can be successfully used to improve the interpretation of microstructural changes, well exemplified in [7]. Whenever the multipurpose material characterization could include only a limited set of tests, or lab equipment has different operating ranges, the set-up of experiments should be taken into account. The possibility to split microstructural condition from test temperature effects, and of excluding this latter could also be helpful for these analyses. A comparative analysis of characterization methods is here proposed for Al-7Si-0.5Cu-0.4Mg where multiple precipitation sequences of low amount of secondary phases occur. This paper shows the effects induced by initial temper and testing conditions on in-situ dimensional stability and thermal diffusivity, and ex-situ electrical conductivity.

MATERIALS AND EXPERIMENTALS

Tab.1 - Chemical composition of the investigated alloy (mass %).

Si	Cu	Mg	Fe	Mn	Ti	Al
6.83	0.531	0.379	0.107	0.073	0.12	Bal.

The investigated material was an Al-7Si-Mg-Cu alloy (actual chemical composition given in Table 1). Cylinder heads parts were cast by the Rotacast®-method, where the crucible and attached mould slowly rotate around a defined horizontal axis, allowing the liquid metal to progressive and regularly fill the mould. 15X15 mm2 section bars were machined from as cast parts in regions where SDAS was close to 32 βm [6]. Cylindric samples for dilatometric tests (5 mm diameter, 20 mm length) and discoidal samples (12.7 mm, 2 mm thickness) for thermal diffusivity and eddy current tests were machined from these bars.

In order to test the alloy in different temper conditions, in addition to the samples in the as-cast (AC) condition (tested some months after casting), other sets of samples were solution heat treated (SHT) at 530°C for 4.5 h and quenched in water at about 15°C/s. Some specimens were tested immediately after SHT or stored at -18°C before testing. (SHT+AA4h) condition was obtained after SHT followed by, artificial aging at 230°C for 4h to obtain an overaged [6], but rather microstructurally, mechanically and dimensionally stable condition.

Ex-situ indirect electrical conductivity measurements at 20°C were performed by eddy current with frequency 60 kHz with an 8 mm diameter probe. Sets of 5 measurements were performed on water cooled samples extracted from a ventilated oven following set thermal cycles. Specifically, these ex-situ tests were performed at different times during the heat treatment of SHT+AA4h sample to check the sensitivity of the method to microstructural changes. Later, the tests were performed on AC, SHT, SHT+AA4h samples, during isochronally furnace heating from 20 to 530°C at 1°C/min and 10°C/min rates, corresponding to those adopted in thermal diffusivity and dilatometric tests.

Thermal diffusivity of samples in the three alloy conditions were performed by means of Laser Flash Analyzer during heat cycles 20-530-20°C in vacuum with an average heating rate of 1°C/min (0.6-2°C/min actual range).

Dilatometric tests on different initial conditions have been performed on a vertical dilatometer equipped with quartz rod, with 20-530-20°C heating/cooling cycles at 10 and 1°C/min.

RESULTS AND DISCUSSION

Electrical conductivity

The room temperature electrical conductivity of a single specimen at different times of the heat treatment cycle is correlated to the microstructural condition, as shown in Figure 1-left, where the temperature profile of the heat treatment is plotted in blue color. Figure 1 presents the average of the 5 measurements; standard deviation data are not shown, and they range between 0.01 and 0.025 MS/m depending on the material condition. During the first isothermal treatment, the initial high electrical conductivity of the AC sample decreased within the first few minutes spent at 530°C to an almost constant value. The following isothermal aging treatment at 230°C brought a progressive increase of the electrical conductivity that is still increasing after 4h holding. This behaviour can be correlated to the amount of elements remaining in solid solution in the α -phase at different time. This simplified explanation further neglects the effects different solute elements and of the presence of secondary phases. At the high SHT temperature, elements rapidly diffuse and with high solubility, such as Mg and Si, rapidly enter in solid solution causing a rapid decrease of electrical conductivity. During the artificial aging stage, the formation of second phases progressively depletes the matrix of solute elements, thus increasing its electrical conductivity. It can be worth mentioning that at this aging temperature the alloy reaches peak hardness in about 1 hour [2], after which electrical conductivity still increases.

The results of isochronal ex-situ electrical conductivity tests on AC, SHT, and SHT+4hAA samples are shown in Figure 1-rigth. The general trend can still be explained in terms of solid solution content (mainly of Mg and Si). First, above 200°C precipitates form in SHT sample, while they increase in AC sample and, in a less extent, in overaged sample. Then, the conductivity starts to decrease due to solid solution above about 350°C,

converging to the same value for all the samples, since the final microstructural condition is the same. The

increase of electrical conductivity occurs more rapidly and at lower temperatures for low temperature rates.

Only above about 450°C, the differences between different heating rates and initial material conditions reduce.

In the SHT sample, the increment of the conductivity is higher than in AC and SHT conditions due to the highest change in element solubility.

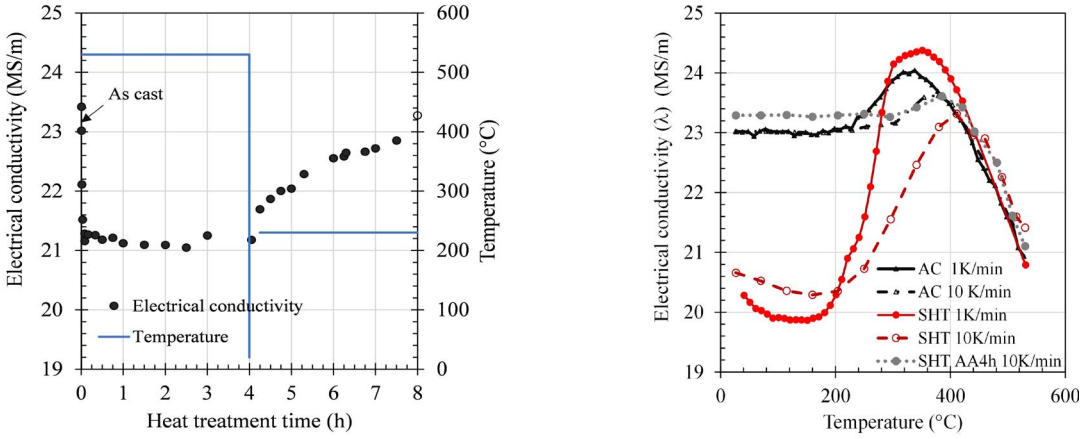

Fig.1 - Results of ex-situ electrical conductivity tests performed at room temperature during two-step isothermal heat cycle on AC sample simulating SHT and artificial aging (left) and isochronal heating tests at 1 and 10°C/min performed on specimens in different initial conditions (right).

THERMAL DIFFUSIVITY

The results of temperature-dependent thermal diffusivity for the investigated alloy in three different initial conditions are shown in Figure 2. The thermal diffusivity (D) is directly correlated to the thermal conductivity (λ), and inversely to the density ρ and the specific heat cp: ($D = \lambda/(\rho * c_p)$). The diffusivity in the alloy have roughly the same temperature trend as the thermal conductivity, at least in conditions where and both density and c_p have smooth and minor changes (for example related to secondary phases).

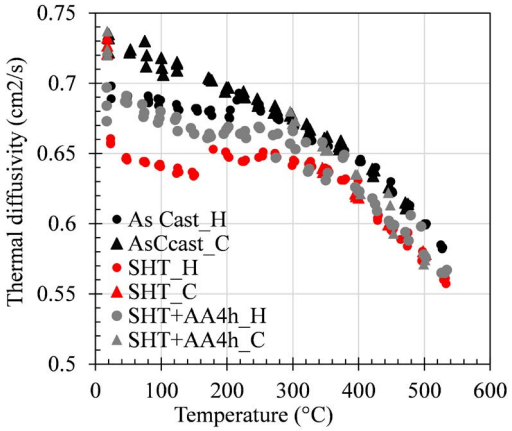

Fig.2 -Temperature-dependency of thermal diffusivity (D) for the investigated alloy in three different initial conditions. For each experimental condition, data taken during the heating and cooling parts of the cycle are plotted with different symbols (H and C, respectively) to highlight their differences.

Experimental data taken during the slow isochronous heating and cooling are plotted with different symbols to highlight the correlation of thermal diffusivity to the actual microstructural composition at the moment at which the measurement was taken. During heating up to about 350-400°C, the three curves became closer. The trend of the curve is also the same during the slow cooling from 530°C. The complete separation of temperature-only effects from those related to microstructural changes is not possible in these in-situ tests.

Nevertheless, the abovementioned correlation of diffusivity to thermal conductivity and the Wiedemann–Franz law, correlating which states that the ratio between thermal conductivity and electrical conductivity increases with temperature [9], allow a simplified approach for thermal diffusivity evolution. This can be considered as the overlapping of the decreasing trend for pure aluminium overlapped to changes related to alloying atoms in solid solution, as discussed for electrical conductivity. The approach allows comparison between these later trends and those for ex-situ electrical conductivity. In SHT condition, their solute atoms decrease more significantly with respect to initial content, provoking a large drop in the diffusivity values. Above 150-200°C, the data for initial conditions converge, with an increased effect of solute atoms that reduces diffusivity more rapidly than for pure aluminium [8].

DILATOMETRIC TESTS

The results of dilatometric tests show that the thermal strain originated by a unit change in temperature (coefficient of thermal expansion) is not constant, but it shows peak/valleys (Figures 3a and 3b) whose position depends on the initial microstructural condition and heating rate. These changes can be correlated to the formation/dissolution of different phases, whose specific volume differs from that of the matrix. Thus, the amount of the phases present at each temperature change the actual specimen length with respect to the general trend of a constant coefficient of thermal expansion. Specifically, in the case of casting Al-Si-Mg [9] and wrought Al-Mg-Si alloys [10], where the amount of Si exceeds that for the only formation of precipitates of the β-Mg_2Si sequence, the precipitation of secondary silicon particles with diamond structure causes an increase of specimen length [9], while the formation of precipitates of β-Mg_2Si and their dissolution in Al-Mg- Si alloys do not correspond to any peak/valley in dilatometric curves [9].

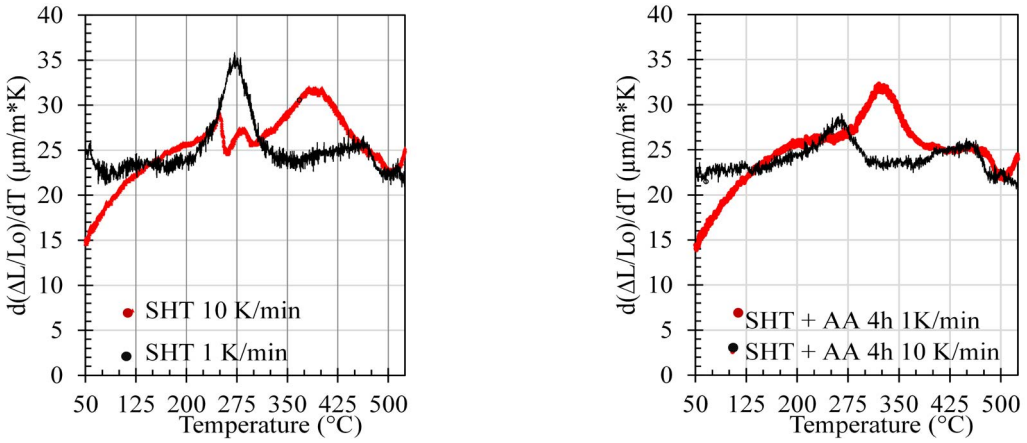

Fig.3 - Results of dilatometric tests performed at 1 and 10 °C/min heating rate on samples of the Al- Al-7Si-0.5Cu-0,4Mg after Solution Heat Treatment (left) and after further aging at 230°C for 4 h (rigth).

The identification of peaks on the basis of dilatometric tests only is not straightforward, as in DSC analyses.

The peak of elongation corresponding to Si formation can help the identification of peaks in materials characterizations involving both techniques. In the present cases, DSC tests and TEM analyses show that the nucleation of secondary Si starts in a temperature range between 230°C and 280°C, and concurrently β″ Mg_5Si_6 transforms into β′-$Mg_{1.8}Si$ [10]. This is compatible with the upward peak obtained in the present work on the SHT sample at 10°C/min and also to the absence of the same peak in the specimen artificially aged for 4 hours tested at the same heating rates. . The kinetics for the formation and dissolution of secondary Si and their related phases is a function of the heating rate: the higher the heating rate, the higher temperature needed for precipitation of secondary Si.

CONCLUSIONS AND FINAL REMARKS

The simple testing program carried out on the Al-7Si-Mg-Cu alloy demonstrate that thermo-physical properties of age-hardenable alloys are both temperature- and microstructure- dependent, with this latter effect being more significant for the metastable SHT condition. The temperature dependence of thermal diffusivity of the three samples gives an example of this. From the point of view of material characterization in view of making data available for the design of high-temperature, long-term service components, the more stable aged/serviced material could be more suitable than initial unstable material. Alternatively, the progressive change of properties during aging/service should be taken into account, adding complexity to the modelling of thermal diffusivity. Similar consideration could be done for dilatometric tests and for temperature-dependent electrical conductivity tests (not considered here). Under less unstable conditions the material properties are also less affected by the heat cycle selected to investigate the temperature-dependence of properties (heating/cooling rates in isochronal tests). In age hardening alloys isochronal tests for one or a set of thermophysical properties could be also used as a tool to investigate by relatively simple tests, the microstructural changes taking place within the material,aiming for example at modelling their kinetics. The heating rates available for different property and equipment are often not overlapping. Considering the thermal diffusivity, dilatometry and calorimetric tests here mentioned, the latter are more often performed at low heating rates (0.2-6°C/min are for example reported in [7]), while the set heating rate can increase up to 40°C/min in several DSc equipment, with the smallest sample and furnace sizes. Without mentioning the advantages/disadvantages of adopting high or low heating rate for different techniques, the adoption of a wider range for them and the possibility of clear identification of microstructural changes can help to study complex kinetics of phase transformations. Lastly, The possibility to carry out ex-situ tests (in this case electrical conductivity) on a quenched microstructure was observed to eliminate the temperature effect from that of the microstructural changes induced by isothermal or isochronous. This tool, allowing to operate with different heating rates, represents an additional tool for the identification of thermal events-microstructural change

and for modelling of these latter.

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