Materials and Design 119 (2017) 54–64

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Thermal stability of the lightweight 2099 Al-Cu-Li alloy: Tensile tests and microstructural investigations after overaging

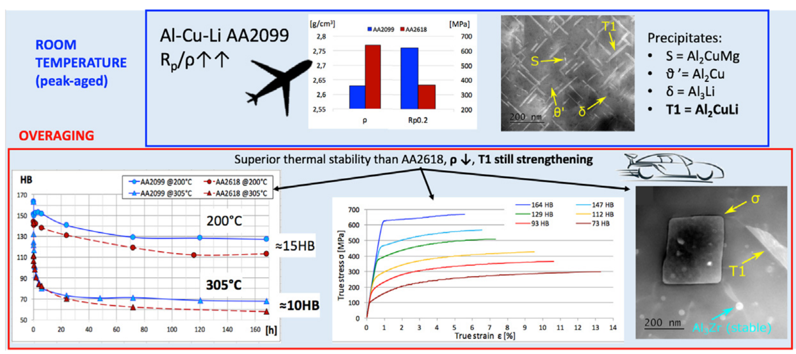
E. Balducci [a,*], L. Ceschini [a], S. Messieri [b], S. Wenner [c], R. Holmestad [c]

[a] Dept. of Industrial Engineering, Alma Mater Studiorum University of Bologna, viale del Risorgimento 4, Bologna, Italy
[b] Ducati Motor Holding, Bologna, Italy
[c] Dept. of Physics, Norwegian University of Science and Technology, Høgskoleringen 5, Realfagbygget D4-153, Trondheim, Norway

HIGHLIGHTS

- Lightweight AA2099 exhibits thermal stability comparable or even higher than Al-Cu alloys specifically developed for high T
- Overaged AA2099 showed high residual tensile strength, suggesting potential use in high T yet lighter automotive components
- STEM investigations revealed the superior thermal stability of T_1 phase (typical of Al-Cu-Li alloys) compared to ϑ and S

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 October 2016
Received in revised form 16 January 2017
Accepted 19 January 2017
Available online 21 January 2017

Keywords:
Al-Cu-Li alloy
Thermal effect
Hardness test
Tensile test
Microstructure
STEM

ABSTRACT

The thermal stability of the lightweight, T83 heat treated 2099 Al-Cu-Li alloy was assessed in the temperature range 200–305 °C, through both hardness and tensile tests after overaging. After prolonged thermal exposure, the alloy exhibited a better performance compared to aluminium alloys specifically developed for high temperature applications, with the advantage of a considerable lower density. The tensile behaviour was modelled through Hollomon's equation as a function of residual hardness. The changes in the alloy performance were explained through both SEM and STEM investigations. Microstructural analyses gave evidence of Ostwald ripening, while fractographic analyses revealed a transition from an intergranular to a ductile fracture mechanism in the overaged alloy. STEM investigations highlighted the superior thermal stability of the T_1 phase compared to ϑ and S strengthening phases, which dissolved during overaging at 245 °C. The study underlines the need to enhance the formation of T_1 precipitates when high temperature strength is required. The results of the present study suggest that the 2099 alloy is a very promising candidate for automotive engine components, which are extremely demanding in terms of both thermal resistance and lightweight.

1. Introduction

The 2099 Al alloy belongs to the third generation of Al-Li alloys, which are high performance and lightweight materials. Lithium exhibits the lowest density among metals, equal to 0.534 g/cm^3, hence it

* Corresponding author.
E-mail address: eleonora.balducci6@unibo.it (E. Balducci).

http://dx.doi.org/10.1016/j.matdes.2017.01.058
0264-1275/

significantly contributes to a density reduction of the alloy. The substantial influence of Li addition in density reduction was at first underlined by Peel et al. [1] in the empirical formula to calculate Al alloy densitie (Eq. (1)).

$$\rho\ (g/cm^3) = 2.71 + 0.024Cu + 0.018Zn + 0.022Mn–0.01Mg–0.004Si–0.079Li \quad (1)$$

Eq. (1): Empirical formula to evaluate the density of Al alloys; atomic symbols represents the concentration of the element in wt%. The benefit of Li addition is clearly visible [1].

Another relevant aspect is that Li increases the Young's elastic modulus of the alloy (around 6% increase due to 1 wt% Li addition [2]). Combined with the possibility to use conventional production processes, the enhancements in specific strength and stiffness have made Al-Li alloys a competitive alternative to more conventional aluminium alloys (such as those of the 6XXX and 7XXX series) for structural applications in the aerospace field [3–7], due to the consistent improvements in payload and fuel efficiency.

Rioja et al. [2,8] offered a comprehensive review on the microstructural and technical issues which finally lead to the development of the complex third generation of Al-Li alloys. Starting from the first generation, a significant enhancement in fracture toughness has been achieved thanks to both a specific balance in chemical composition and a simultaneous optimization of the thermo-mechanical processing. To obtain the maximum benefits in terms of mechanical properties, Al-Li alloys need to be processed to the T8 condition (solution, quench, cold stretch, artificial aging), the key point being the generation of the desired texture and sub-structure to make the precipitation more effective and uniform [9,10]. Cold deformation, in fact, induces a dislocation network which acts as nucleation site for co-precipitation of strengthening intermetallics (mainly Cu and Li based); the result is, therefore, both a refinement of precipitates microstructure and a reduction in precipitation at grain boundaries, which is deleterious in terms of toughness [2,11]. Together with an increased Cu/Li ratio, T8 heat treatment promotes the formation of the T_1 (Al_2CuLi) phase at the expenses of δ′ (Al_3Li) precipitates [2,12–16], which offers the maximum strengthening effect and is more thermally stable. In addition to these strengthening phases, the relevant presence of Cu and Mg in Al(-Cu)-Li alloys leads to the formation of θ′ (Al_2Cu), S′ (Al_2CuMg) and σ ($Al_5Cu_6Mg_2$) phases. Mg is also known to promote the nucleation of T_1 precipitates at the expenses of θ′ [17].

Usually, Zr and Mn are also added in low quantities; these elements are known to form Al_3Zr (spherical) and $Al_{20}CuMn_3$ (rod-like shaped) dispersoids, essential to control texture, to pin grain and sub-grain migration and to inhibit recrystallization, enhancing fracture toughness [2,11,18–20]. Given the opposite microsegregation patterns of Mn and Zr in Al, the joint addition of these elements is thought to produce a more uniform dispersion coverage, even if recent studies highlighted a reduction in recrystallization resistance [19].

An overview of the microstructural features of the 2099 Al-Cu-Li alloy is offered by Rioja et al. in [2], whose schematic is reported in Fig. 1. Further in-depth microstructural investigations are present in literature, which confirm the abovementioned features and characteristics of both strengthening precipitates and dispersoids [11,21,22].

Since the '80s, several studies have been carried out on T8 heat treated AA2099, due to its interesting properties for aerospace applications, however there is a substantial lack of studies focusing on the thermal stability of this alloy. Very few studies, whose aim is mainly linked to the design of the aging treatment, deal with thermal exposure of AA2099 at medium-high temperature (that is below 200 °C), but little attention has been given to microstructural features [15,21,23,24].

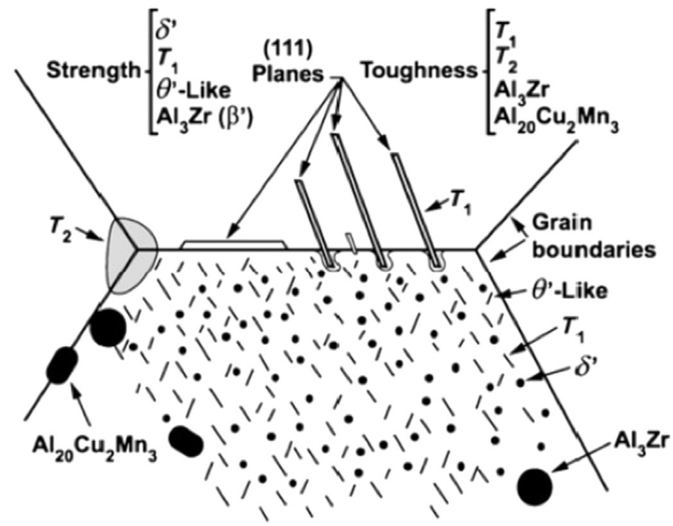


Fig. 1. Schematic of Al-Cu-Li 2099 alloy microstructural features, focusing on precipitates and dispersoids [2].
Reprinted under Springer permission.

Jabra et al. [25] firstly evaluated the response of AA2099 to prolonged thermal exposure at elevated temperatures (180 °C, 230 °C, 290 °C), in order to replicate a range of possible thermal environments. For all the investigated temperatures, a decrease of tensile properties was found, coupled with an increase of the elongation to failure. Even if the decay of tensile properties showed a good correlation with residual hardness data, no systematic relationship was determined. Moreover, up to date, there is a total lack of microstructural investigations on the high temperature overaging of the AA2099 alloy, which still raises open questions about the thermal stability of its precipitates, or about which type of precipitates are needed during the aging treatment in case of high temperature applications.

Further studies are therefore required in order to completely characterise the alloy strengthening mechanisms and, above all, to evaluate the maximum service temperature the alloy is able to withstand without a significant strength loss. The study falls within a wider context: the huge benefits of AA2099 in terms of mass savings make it a potential candidate not only for structural components in the aerospace field, but also for automotive applications, even for engine components. The increasingly topical race to boost fuel economy, which today involves car manufacturers, has not to be neglected. Since automotive applications are extremely challenging in terms of both specific strength and service temperature, the aim of this study is to evaluate the possibility to expand the 2099 temperature range of applications. Time-Temperature-Hardness curves, tensile tests at room and high temperature on peak-aged and overaged samples, and microstructural investigations through both Scanning and Transmission Electron Microscopy have been carried out, in order to outline the microstructural modifications which mainly affect the mechanical behaviour of the alloy.

2. Experimental

The material used in the present study was a 2099 Al-Cu-Li alloy, provided by Alcoa in the form of extruded bars with 85 mm diameter. The alloy was industrially heat treated according to the T83 condition (which consists of solution treatment, quench, 3% stretching at room temperature followed by artificial aging). The chemical composition limits of AA2099, provided by the supplier, are reported in Table 1.

In order to assess the thermal stability of the alloy, several specimens $(10 \times 15 \times 6)\ mm^3$ in size, were cut from the T83 extruded bar. The samples were then subjected to different overaging heat treatments in the temperature range 200–305 °C, the soaking time ranging from 2 min up to 168 h. Additional overaging curves at lower temperatures