Anisotropy and size effect in tensile mechanical properties of Al-Cu-Li 2198 alloy

Examilioto, Theano; Klusemann, Benjamin; Kashaev, Nikolai; Riekehr, Stefan; Enz, Josephin; Alexopoulos, Nikolaos

Published in:
Procedia Structural Integrity

DOI:
10.1016/j.prostr.2017.07.052

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 5 (2017) 13–18

Structural Integrity Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Structural Integrity, ICSI 2017, 4-7 September 2017, Funchal, Madeira, Portugal

Anisotropy and size effect in tensile mechanical properties of Al-Cu-Li 2198 alloy

Theano N. Examilioti[a,b]*, Benjamin Klusemann[a,c], Nikolai Kashaev[c], Stefan Riekehr[c], Josephin Enz[c], Nikolaos D. Alexopoulos[b]

[a]*Insitute of Product and Process Innovation, Leuphana University of Lüneburg, D-21339 Lüneburg, Germany*
[b]*Department of Financial Engineering, University of the Aegean, Kountourioti 41, 82 132 Chios, Greece*
[c]*Institute of Materials Research, Materials Mechanics, Helmholtz-Zentrum Geesthacht, D-21502 Geesthacht, Germany*

Abstract

The anisotropy effect on tensile mechanical properties of an Al-Cu-Li (2198) alloy with regard to thickness of the specimens under different ageing conditions was investigated. Occurring size effects between macro and micro (0.5, 3.2 and 5.0 mm thickness and 10 and 50 mm gauge length) tensile specimens was discussed. The mechanical behavior of AA2198 was examined by taking into account the experimental results from micro-flat and standard tensile specimens. Higher thickness specimens showed higher elongation at fracture values and slightly lower yield stress properties. Anisotropy seems to be higher at T3 condition, while the lowest was noticed at the peak-ageing condition. The results showed that the micro-flat tensile specimens in T3 condition presented slightly lower yield stress (10 MPa difference) and essentially lower elongation at fracture values (more than 40 % decrease), when compared with the respective of higher thickness specimens. It was also shown that thicker (5.0 mm) specimens exhibit slightly higher tensile ductility properties (almost 17 %) and slightly lower tensile strength properties than the respective 3.2 mm thickness specimens. There is evidence of relative difference in mechanical properties due to the rolling process in the two sheet directions (L and T directions); such anisotropy difference seems to be marginal at the peak-ageing condition.

Peer-review under responsibility of the Scientific Committee of ICSI 2017

* Corresponding author. Tel.: +0030-2270-35464; fax: +0030-22710-35429.
E-mail address: t.examilioti@aegean.gr

2452-3216 © 2017 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the Scientific Committee of ICSI 2017
10.1016/j.prostr.2017.07.052

Keywords: aluminum alloy, anisotropy effect, tensile mechanical properties, size effect;

1. Introduction

Aluminum copper (Al-Cu) 2024-T3 alloy has been widely used for many decades in various aircraft sections due to its high damage tolerance capabilities. The aerospace industry is always demanding for innovative, lighter aluminum alloys with improved mechanical properties. Innovative, third generation aluminum-copper-lithium (Al-Cu-Li) alloys, have been recently developed as to replace the well-established 2024 alloy in critical aeronautical applications e.g. Rioja et al. (2012) and Alexopoulos et al. (2013).

Third generation Al-Cu-Li alloys provide improved mechanical properties and damage tolerance, e.g. Dursun and Soutis, (2014), that are quite often associated with the Li concentration which enables the formation of additional strengthening precipitates besides the *S* type particles, e.g. δ' (Al_3Li), θ' (Al_2Cu) T_1 (Al_2CuLi) particles reported in several articles, e.g. in Yoshimura et al. (2003), Li et al. (2008), and Steuwer et al. (2011). One major disadvantage in Li- bearing aluminum alloys are the anisotropic tensile mechanical properties. For the case of second-generation Al-Cu-Li alloys of the previous decade this disadvantage was often associated with the grain size differences. Several articles are referring to the damage tolerance of welded structures, e.g. Kashaev et al. (2014) and (2015). Mou et al. (1995), Cassada et al. (1991) and Alexopoulos et al. (2013) investigated the fatigue properties of AA2198 Al-Li alloy. In the last article it was shown that especially when considering the specific mechanical properties, AA2198 shows superiority over AA2024 in the regions of high-cycle fatigue and fatigue endurance limit.

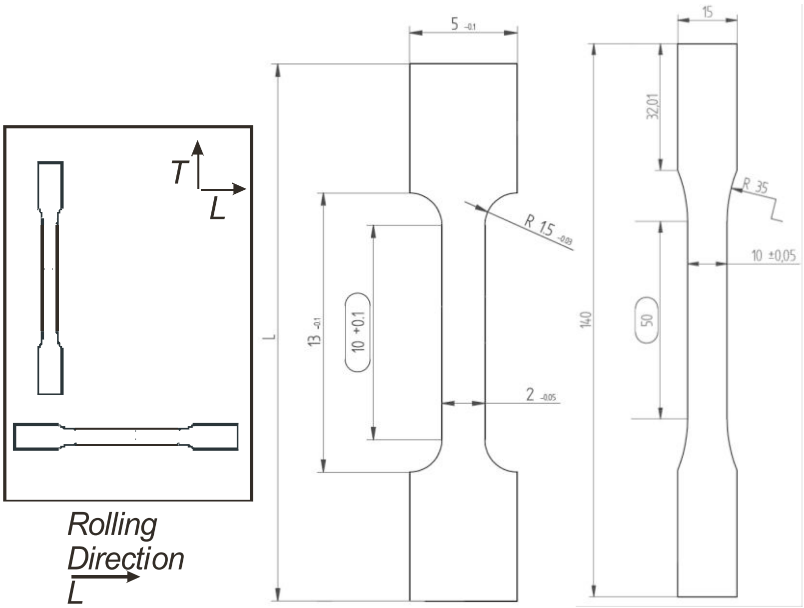
So far, literature reviews on the anisotropy effect for the third generation Al-Cu-Li alloys still remains rather limited. The anisotropy effect is more evident in thicker metals than sheets (e.g. plates) that show short transverse ductility. Third generation aluminum-lithium alloy 2198 presents a complex anisotropic behavior in the longitudinal and transverse directions. In general, AA2198 shows lower anisotropy degree in T8 condition compared with T3 condition, e.g. Prasad et al. (2013). Steglich et al. (2010) investigated experimentally and numerically the anisotropic deformation of AA2198-T8 occurring during mechanical loading with and without the presence of artificial notches. Chen et al. (2010) also investigated the plastic anisotropy and fracture mechanism of AA2198 and for two different heat treatments namely, T351 and T851. The results showed that the failure of the specimens depends on the anisotropic plasticity due to the differences for L and T loadings. Recently, microstructural analysis for AA2198 was carried out from Decreus et al. (2013) so as to investigate the influence of local microstructural changes with different ageing conditions.

2. Material and specimens

The material used in the present investigation was AA2198 with nominal thicknesses of 3.2 mm and 5.0 mm. Standard tensile specimens were machined from the rolling direction L (0^o) and vertical to rolling direction T (90^o) for both thicknesses, see **Figure 1**. Furthermore, micro-flat tensile specimens were extracted with electro discharge machining (EDM). The gauge length of the standard tensile specimens was equal to 50 mm, while 10 mm was the respective length of the micro-flat specimens. The thickness of the micro-flat tensile specimens was approximately 0.5 mm. The weight percentage chemical composition of AA2198 can be seen in **Table 1**.

Table 1. Chemical composition of aluminum alloy 2198.

Aluminum	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Li**	**Zn**	**Zr**	**Al**
alloy 2198	<0.08 %	<0.01 %	2.9-3.5 %	<0.5 %	0.25-0.8 %	0.8-1.1 %	0.35 %	0.04-0.18 %	remainder



(a) (b) (c)

Fig. 1. (a) Plate with sketch of the tensile specimens, indicating the rolling direction of the material; (b) typical geometrical dimensions of micro-flat specimens; (c) typical geometrical dimensions of standard tensile specimens. All dimensions in mm.

3. Experimental procedure

Tensile specimens were surface cleaned with alcohol according to ASTM G1 specification and then artificially aged (heat treated) in an electric oven with ± 0.1 °C temperature control for different ageing times. Artificial ageing heat treatment conditions were performed at 170 °C and for different ageing times, selected from Alexopoulos et al. (2016), that corresponds to all possible ageing tempers, namely Under-Ageing (UA), Peak-Ageing (PA) and Over-Ageing (OA). After removing the specimens from the heat treatment oven, the specimens were cooled down at room temperature and then they were immediately tested in order to assess the effect of artificial ageing on the respective tensile mechanical properties.

Tensile tests of the standard specimens were carried out in a servo-hydraulic Instron 100 kN testing machine according to ASTM E8 specification, while micro-flat tensile tests were performed on a Zwick 2.5 kN testing machine. All tensile tests were displacement controlled and the displacement rate of the crosshead was kept constant for all tests at 1 mm/min. Three specimens were tested per different batch in order to get reliable average data. An external extensometer for the standard specimens was attached at the reduced cross-section gauge length of the specimens, while a laser extensometer for micro-flat specimens was used. A data logger was used during all tensile tests and the values of load, displacement and axial strain were recorded.

4. Results and discussion

4.1. Effect of size of the specimens

A summary of micro-flat and macro-tensile mechanical properties results of the investigated AA2198 specimens is given in **Table 2**. Typical engineering stress-strain curves of specimens with different size and thickness are presented in **Figure 2** for comparison purposes. All specimens seem to present the same yield stress, regardless of specimen size and thickness. AA2198-T3 with 3.2 mm thickness exhibits high tensile ductility ($A_f \approx 17$ %), while elongation at fracture of the 5.0 mm thickness is marginally higher. On the contrary, micro-flat tensile specimens show limited capability for axial deformation as elongation at fracture hardly exceeds 10 %.

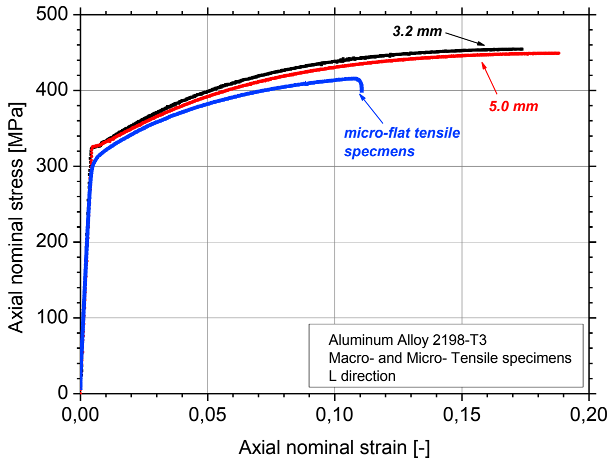


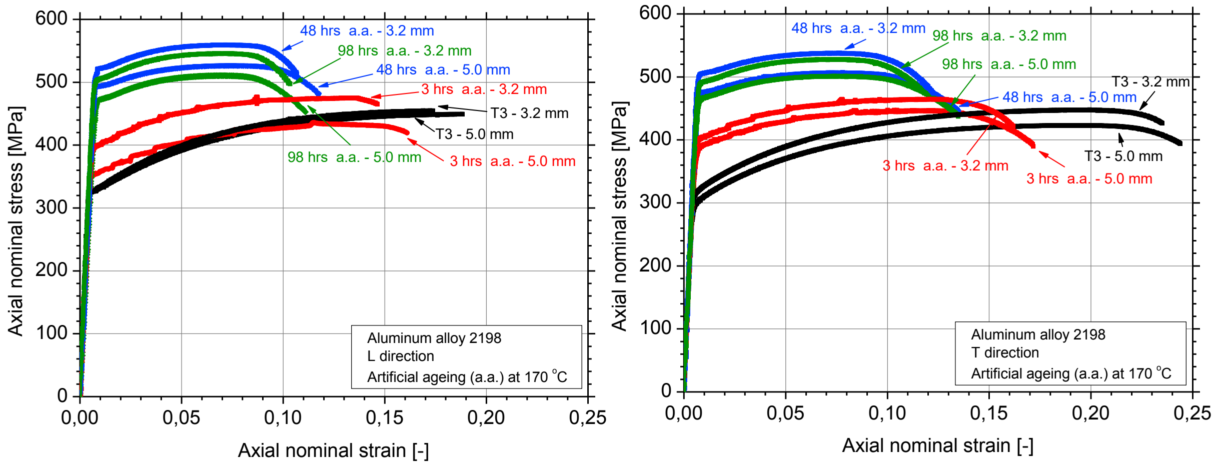
Fig. 2. Stress-strain curves of AA2198-T3 for different geometries and thicknesses.

Table 2. Average tensile mechanical properties of conventional yield stress $R_{p0.2\%}$, ultimate tensile strength R_m and elongation at fracture A_f along with standard deviation of aluminum alloy 2198-T3.

Alloy	Direction / thickness	$R_{p0.2\%}$ [MPa]	R_m [MPa]	A_f [%]
2198-T3	L direction, t = 0.5 mm	315 ± 4	418 ± 4	10.66 ± 0.74
	L direction, t = 3.2 mm	319 ± 8	448 ± 7	17.45 ± 0.75
	L direction, t = 5.0 mm	327 ± 1	448 ± 1	17.61 ± 0.51
	T direction, t = 3.2 mm	311 ± 5	443 ± 5	22.41 ± 0.65
	T direction, t = 5.0 mm	298 ± 4	422 ± 1	23.05 ± 0.61

4.2. Anisotropy

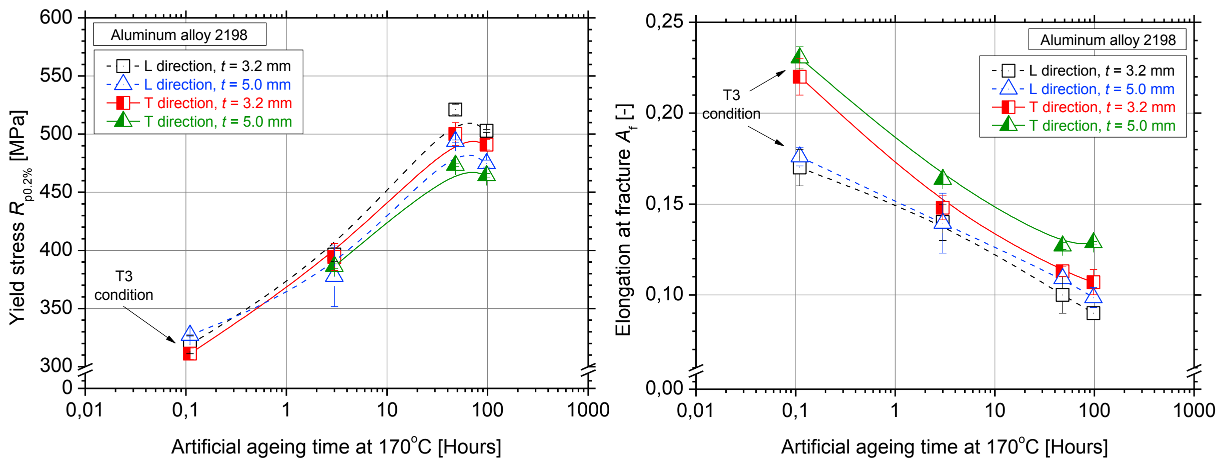
Representative engineering stress-strain tensile curves of specimens with different nominal thicknesses and for different artificial ageing times at 170 °C are presented in **Figure 3**. **Figure 3a** shows the respective results for the L sheet rolling direction, where it is evident that the 3.2 mm thickness specimens presented high elongation at fracture at the T3 condition (approximate 17 %) which decreased to approximate 10.5 % for the specimens with 98 h artificial ageing (OA). Ultimate tensile strength takes its highest value after 48 h artificial ageing. Hence, it can be clearly noticed that tensile ductility decreases and mechanical strength increases with increasing ageing time until the PA condition. Higher thickness specimens (t = 5.0 mm) exhibit slightly lower ultimate tensile strength. The respective results for the T rolling direction specimens that can be seen in **Figure 3b**. A general comment is that stress-strain tensile curves seem to have a similar behaviour with the respective specimens in L direction. In all specimens at T direction, ultimate tensile strength was increased to 520 MPa for the PA condition, as can be seen in **Figure 3b**. Comparing the available test results, it seems that with increasing artificial ageing time, the T direction presents higher elongation at fracture values when compared to the respective of L direction specimens.



(a) (b)

Fig. 3.Tensile flow curves of aluminum alloy 2198 with different thicknesses and artificial ageing conditions for (a) L and (b) T direction.

Figure 4a summarizes the conventional yield stress $R_{p0.2\%}$ results as average values together with the respective standard deviation. In the diagram, the investigated specimens correspond to all regions of heat treatment conditions, namely UA at 3 h, PA at 48 h and OA at 98 h ageing at 170 ºC. The experimental test results were interpolated with the aid of a B-Spline curve (eye-catch) in order to roughly assess the direction and size effect of each specimen. In T3 condition, $R_{p0.2\%}$ seems to take the same values for all investigated cases. Conventional yield stress seems to continuously increase up to 48 h (PA). The maximum $R_{p0.2\%}$ value was approximate 520 MPa for t = 3.2 mm in L direction (more than 60 % increase when compared to the respective value at T3 condition). In the T sheet rolling direction, specimens with 3.2 mm thickness exhibits $R_{p0.2\%}$ = 500 MPa for the same ageing time that is almost 5 % lower than the respective value in L direction. For the case of higher thickness (t = 5.0 mm) specimens, similar behavior with artificial ageing is noticed. For example, at PA condition an essential increase in $R_{p0.2\%}$ is noticed, that is approximate 50 % and 59 % higher than the T3 condition for the L and T directions, respectively. Likewise, an essential comparison can be made regarding $R_{p0.2\%}$ values between L and T directions for different artificial ageing conditions. For the case of 3.2 mm, this difference takes values in between 2 and 4 %, while approximate 10 % was noticed for the higher thickness specimens, especially at the T3 condition.



(a) (b)

Fig. 4. (a) Yield stress and (b) elongation at fracture A_f values for different directions, thicknesses and artificial ageing conditions.

Elongation at fracture values can be seen in **Figure 4b** as average values and standard deviation for the different thicknesses, directions and artificial ageing times at 170 ºC. For the case of T3 condition and 3.2 mm specimen thickness, elongation at fracture takes values of 22.4 % and 17.4 % for T and L direction, respectively. This corresponds to an approximate 28.6 % difference between the two values. Regarding artificial ageing, elongation at fracture continuously decreases up to OA condition, where an essential approximate 46 % decrease is noticed when compared with the respective elongation at T3 condition.

Conclusions

In the present work, the effect of anisotropy on AA2198 tensile specimens was investigated. Different thicknesses, directions and artificial ageing conditions were examined and the results can be summarized briefly as follows:

- Micro-flat tensile specimens present lower elongation at fracture when compared with thicker specimens.
- Thicker specimens exhibit slightly higher tensile ductility properties and slightly lower tensile strength properties.
- There is evidence of relative difference in mechanical properties due to the rolling process in the two sheet directions; such anisotropy differences seem to be marginal for PA condition.

References

Alexopoulos, N.D., Migklis, E., Stylianos, A., Myriounis, D.P., 2013. Fatigue behavior of the aeronautical Al-Li (2198) aluminum alloy under constant amplitude loading. International Journal of Fatigue, 56, 95-105.

Alexopoulos, N.D., Proiou, A., Examilioti, T.N., Kashaev. N., Riekehr. S., Kourkoulis, S.K., 2016, Mechanical performance of (Al-Cu) 2024 and (Al-Cu-Li) 2198 aluminum alloys under different artificial ageing conditions. Procedia Structural Integrity, 2, 3782-3783.

ASTM E8/E8M-13a, Standard test methods for tension testing of metallic materials, ASTM Int. 1-28. doi:10.1520/E0008_E0008M-11, 2013.

ASTM G1-03, 2011.Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens, ASTM International, West Conshohocken, PA, doi: 10.1520/G0001-03R11.

Cassada,W.A.,Shiflet,G.J.,Strake,E.A., 1991, The effect of plastic deformation on Al_2CuLi (T_1) precipitation, Metallurgical and Materials Transactions A, 22A, 299-306.

Chen, J., Madi, Y., Morgeneyer, T.F., Besson, J., 2011. Plastic flow and ductile rupture of a 2198 Al-Cu-Li aluminum alloy, Computation Materials Science, 50, 1365-1371.

Decreus, B., Deschamps, A., De Geuser, F., Donnadieu, P., Sigli, C., Weyland, M., 2013. The influence of Cu/Li ratio on precipitation in Al–Cu–Li–x alloys. Acta Materialia, 61, 2207–2218.

Dursun, T., Soutis, C., 2014. Recent developments in advanced aircraft aluminum alloys. Materials and Design, 56, 862-871.

Kashaev, N.,Chupakhin, S., Enz, J., Ventzke, V., Groth, A., Horstmann, M.,Riekehr, S., 2014. Fatigue and fatigue crack propagation of laser beam-welded AA2198 joints and integral structures, Advanced Materials Research, 1457-1462.

Kashaev, N., Riekehr, S., Erdmann, K., Carvalho, A.A., Nurgaliev, M., Alexopoulos, N.D., Karanika, A. 2015. Fracture mechanical behaviour of laser beam-welded AA2198 butt joints and integral structures, International Journal of Structural Integrity, 6, 787-798.

Li, H., Tanga, Y., Zenga, Z., Zhenga, Z., Zhenga, F., 2008. Effect of ageing time on strength and microstructures of an Al–Cu–Li–Zn–Mg–Mn–Zr alloy. Materials Science and Engineering, 498, 314–320.

Mou, Y., Howe, J.M., Strake, E.A., 1995. Grain boundary precipitation and fracture behavior of an Al-Cu-Li-Mg-Ag alloy, Metallurgical and Materials Transactions A, 26A, 1591-1595.

Prasad, E., Gokhale, A., Wanhill, R.J.H., 2013. Aluminum-Lithium Alloys Processing, Properties, and Applications, 1st ed.331.

Rioja, R.J., Liu, J., 2012. The evolution of Al-Li base products for aerospace and space applications, Metallurgical and Materials Transactions A, 43(9), 3325-3337.

Steglich, D., Wafai, H., Besson, J., 2010. Anisotropic deformation and damage in aluminium 2198 T8 sheets. International Journal of Damage Mechanics, 19, 131–152.

Steuwer, A., Dumont, M., Altenkirch, J., Birosca, S., Deschamps, A., Prangnell, P.B., Withers P.J., 2011. A combined approach to microstructure mapping of an Al-Li AA2199 friction stir weld, Acta Materialia, 59, 3002-3011.

Yoshimura, R., Konno, T.J., Abe, E., Hiraga, K., 2003. Transmission electron microscopy study of the evolution of precipitates in aged Al–Li–Cu alloys: the h' and T1 phases. Acta Materialia, 51, 4251–4266.