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Effect of tempering conditions on dynamic deformation behaviour of an aluminium–lithium alloy

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ABSTRACT

The deformation behaviour of an aluminium–lithium alloy heat treated to different tempering conditions was investigated at high strain rate in compression using a direct impact Hopkinson Pressure bar. Detailed microstructural investigation was carried out using electron back scatter diffraction and bulk crystallographic texture was determined using X-ray diffraction. All the impacted samples showed presence of adiabatic shear bands irrespective of the prior ageing condition, however, the extent of grain fragmentation and strength of ⟨101⟩ parallel to compression direction texture component was strongly dependent on the tempering condition of the alloy. The naturally aged sample showed less propensity to adiabatic shear band formation and therefore, highest toughness, compared to artificially aged samples. This can be attributed to higher resistance to instability by prolonged strain hardening from dislocation–precipitate interaction in the underaged sample compared to peak and over aged samples under dynamic loading conditions. The single stage peak-aged sample provides the best combination of high toughness with stable microstructure amongst the differently aged samples.

1. Introduction

The new generation light weight aluminium–lithium alloy AA 2099 (Al–Cu–Li–Mg–Zr) is the preferred structural component material over other aluminium alloys in the AA 2000 (Al–Cu), 6000 (Al–Mg–Si), and 7000 (Al–Zn) series that are used for high performance aerospace applications. AA 2099 exhibits excellent mechanical properties like high specific modulus, excellent fatigue resistance and cryogenic toughness which are suitable for critical aerospace applications in statically and dynamically loaded fuselage structures, lower wing stringers, and stiffness dominated designs [1]. But these components of the aircraft are often exposed to dynamic impact loading in service where strain rate can be of the order of $\sim 10^{+3}$ s^{-1} due to sudden impact of foreign object like birds. Though catastrophic failures are rare, damages due to impact of foreign objects can cause considerable economic cost in terms of aircraft repair and downtime per year. Therefore, deformation and failure behaviour of such aerospace materials under dynamic loading condition is of paramount importance. In addition, it is desired to tailor the microstructure of aerospace materials to obtain high shock absorbing capacity and to ensure good damage tolerance on exposure to sudden impact. The deformation and failure behaviour of materials under dynamic shock loading is different from that under quasi static loading conditions. During dynamic loading at high strain rate, highly localised adiabatic heating of the material occurs along narrow paths which causes severely localised plastic deformation. These narrow paths of intense localised strains known as adiabatic shear bands (ASBs) act as precursors to catastrophic failure of materials at high strain rate by promoting initiation of cracks and facilitating crack propagation [2–10]. In addition, novel micro-mechanisms like continuous dynamic recrystallization, geometric dynamic recrystallization and twinning have been reported at high strain rate deformation [11–13,17].

Age hardenable aluminium alloys are the most common structural aerospace materials which are used in different ageing conditions to obtain different functionality. The naturally aged T4 alloys are known to have higher toughness than the artificially aged T6 and cold worked and artificially aged T8 temper alloys under quasi-static loading conditions. However, the naturally aged samples have unstable microstructure and rarely find use in aerospace applications and hence peak aged or over-aged samples with stable microstructure are used in aerospace applications. Quasi-static deformation behaviour of differently aged samples has been reported but effect of temper condition on the dynamic deformation behaviour of aluminium alloys in general and aluminium–

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Table 1
Elemental composition of AA 2099 aluminium alloy.

Alloy	Al	Li	Cu	Mg	Si	Zn	Mn	Zr	Cr
Elemental composition (%)									
AA 2099	>95	1.6–2.0	2.4–3.0	0.1–0.5	–	0.4–1.0	0.1–0.5	0.05–0.12	–

lithium alloys in particular is yet to be explored. Few studies have been carried out on microstructure–property correlation in AA 2099 alloy under quasi-static [14,15] and dynamic loading condition [16,17].

Adesola [14] have reported the compressive strength of AA 2099 alloy under different tempering condition under quasi-static and dynamic loading while Lin et al. [15] have reported the effect of solutionising temperature on the tensile strength property of the alloy. The study carried out by Odeshi et al. [16] compared the relative deformation resistance of the alloy under different impact momentum for different tempering condition. Gurao et al. [17] discussed the effect of different impact momentum during dynamic loading condition on the mechanism of deformation in AA 2099-T8. They showed that the dynamic deformation was characterised by heterogeneous evolution of microstructure comprising of submicron grains of the matrix phase and small spherical precipitates in the adiabatic shear band that can contribute to final failure. A novel mechanism of continuous dynamic recrystallization assisted geometric dynamic recrystallization mechanism was proposed by the authors [17]. However, the effect of tempering or ageing condition on damage evolution has not been fully investigated. The aim of the present investigation is to study the mechanical behaviour of AA 2099 under different tempering conditions at high strain rate loading and decipher micro-mechanisms of deformation using state of the art electron backscatter diffraction and X-ray bulk texture measurement facilities.

2. Experimental

The AA 2099 aluminium alloy used in the present investigation with nominal chemical composition given in Table 1, was obtained from Alcoa Inc. in the form of hot rolled plate in T8 temper condition. The details of T8 heat treatment and different temper conditions to which the alloy was subjected are described in Table 2. Cylindrical specimens with 10.5 mm height and 9.5 mm diameter were machined in the rolling direction and subjected to dynamic impact loading using an instrumented direct impact Hopkinson bar. The cylindrical specimens were impacted with a blunt projectile fired by a light gun at impact momentum of 39 kg m/s. On impact, elastic waves were produced, which propagated through the cylindrical sample to the output bar. The elastic waves, captured by strain gage attached to the bar, were used to generate dynamic stress–strain curves for the impacted specimens. The deformed samples were ground, polished and metallographically prepared to one micron diamond polishing. Bulk texture measurements were carried out on a Bruker D8 Advance diffractometer with Cu Kα radiation and a 2D Hi-star detector. Incomplete (1 1 1), (2 0 0), (2 2 0) and (1 1 3) pole figures were measured for all the samples. Resmat software [18] was used to calculate the complete Orientation Distribution Function and determine the complete pole figures as well as volume fraction of important texture fibres. The impacted samples were then subjected to colloidal silica polishing using Vibromet automatic polisher for 6 h. Orientation Imaging Microscopy was carried out on field emission gun scanning electron microscope (FE-SEM) Hitachi SU 6600 with Oxford Instruments electron backscatter diffraction set up. Data analysis was carried out using *hkl* Channel 5 data acquisition and analysis software.

Table 2
Temper designation of AA 2099 aluminium alloy.

T4	ST + aged (naturally)
$T6_{1'}$	ST + aged (naturally) for 48 h + aged at 120 °C for 12 h
$T6_{2''}$	ST + aged (naturally) for 48 h + aged at 120 °C for 12 h + aged at 160 °C for 18 h
$T8_{1'}$	ST + aged (naturally) for 48 h + 9.5% CW[b] under compression + aged at 120 °C for 12 h
T8 (AR)	ST[a] + 6% stretched + aged

[a] Solution treated,
[b] Cold worked, ′ single step ageing, ″ double step ageing.

3. Results and discussion

3.1. Initial microstructure

The optical micrograph of as-received AA 2099 in T8 aged condition (Fig. 1a) is characterised by elongated grains and second phase particles that are evenly distributed throughout the matrix. The SEM micrograph of the sample shows presence of tiny white precipitates (Fig. 1b). Microstructures of the differently aged samples obtained from SEM are depicted in Fig. 2. AA 2099-T4 sample (Fig. 2a) shows small size incoherent dispersoids of various shapes while AA 2099-$T6_1$ sample (Fig. 2b) reveals fine uniform dispersion of spherical shaped incoherent dispersoids along with few tiny white coherent precipitates in the grain matrix. In AA 2099-$T6_2$ sample, precipitates are coarser and higher in volume fraction compared to AA 2099-T4 and AA 2099-$T6_1$ samples (Fig. 2c). SEM image of AA 2099-$T8_1$ sample (Fig. 2d) shows presence of irregular shape dispersoids that nucleated preferentially at the dislocation sites in the matrix after straining prior to the ageing treatment. Small white precipitates are not observed in this case.

The exact phase(s) present in Al–Li alloys vary depending on the alloy additions and the kind of ageing treatment namely natural ageing, artificial ageing and cold work followed by artificial ageing, that is carried out after solutionising. In Al–Li alloys, δ' (Al_3Li) phase is precipitated immediately after quenching which remains coherent and ordered with the parent matrix even after extensive ageing [19]. The other coherent phases are δ (AlLi) and β' (Al_3Zr) while T1 (Al_2CuLi), T2 (Al_6CuLi_3), θ' (Al_2Cu) and S (Al_2CuMg) are either semi-coherent or incoherent phases. Due to the presence of alloying elements like copper, magnesium and zirconium in AA 2099 alloy, the solubility of lithium in aluminium is lowered and co-precipitation of the above-mentioned phases alongside δ' phase occurs during artificial ageing [19]. The dislocations generated during plastic deformation prior to ageing, contribute to precipitation hardening due to T1 (Al_2CuLi) and S (Al_2LiMg) precipitates [19,20]. In the case of T4 sample, only coherent precipitates of δ' phase are present due to natural ageing that corresponds to underaged condition. Whereas in the case of $T6_1$ and $T6_2$ samples which are subjected to artificial ageing, formation of semi-coherent co-precipitates of above mentioned phases are observed along with the δ' phase. Similar phases are observed in $T8_1$ and T8 samples which were subjected to straining prior to ageing.