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Experimental analysis and constitutive modeling for the newly developed 2139-T8 alloy

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ABSTRACT

Mechanical behavior of recently emerged 2139-T8 aluminum alloy, which is based on an Al–Cu–Mg–Ag system, has been characterized by uniaxial compression and tension experiments over a wide range of strain rates from 10^{-4} to 10^{4} s^{-1} and for temperatures from −60 to 300 °C. Driven by experimental results, modifications to widely used Johnson–Cook constitutive model has been proposed, and model parameters have been determined. It has been shown that modified Johnson–Cook (MJC) model satisfactorily captures rate- and temperature-dependent variations in flow stress through enhanced coupling between temperature and strain hardening as well as temperature and strain-rate sensitivity. The modified model also provides flow stress prediction over the entire range of quasi-static and dynamic regimes by a single continuous function.

1. Introduction

In today's performance driven world many damage critical components are designed with severe weight and volume constraints. As a result of the need for lighter materials that can still survive extreme loading conditions such as encountered in blast and impact events there is a continuous search to improve manufacturing processes and materials properties that could reduce weight and/or increase efficiency.

One such material is a recently developed aluminum alloy designated as 2139. Aluminum 2139 is an Al–Cu–Mg–Ag alloy registered with the Aluminum Association in 2004 [1]. This new alloy has emerged as a result of four decades of research on the effects of trace amount of alloying elements in age hardenable Al-alloys. A recent study in 2006 [2] showed that 2139-T8 alloy has higher strength, fracture toughness, fatigue life and better ballistic properties than other high performance aluminum alloys. For example, the ballistic performance of 2139-T8 is better than that of 2519-T87, which is currently the alloy of choice for modern armored vehicles in its class. Fracture toughness values of 2139-T8 are also superior to those of 2324-T39 and 7475-T7351, which are the alloys commonly used for most damage critical applications such as the lower wing skin plate for airplanes. Limited experimental results show that new 2139 alloy is an excellent candidate alloy for a wide range of damage tolerance critical applications.

The prediction of dynamic response, damage initiation, progression, and failure of material is crucial for the design and development of components against extreme loading conditions such as blast and impact, which are characterized by very high strain rates, large deformations, high pressures, and rapid changes in temperature. The main motivation of this paper is to contribute to ongoing efforts in exploring the potential of 2139 aluminum alloy for damage critical applications. Our objective is to fully characterize the mechanical response of this new alloy in a wide range of strain rates (from 10^{-4} to 10^{4} s^{-1}) and temperatures (from −60 to 400 °C).

2. Background

It is well known that the addition of trace amounts (<0.1 at.%) of an alloying element to selected age hardenable Al-alloys can have a marked effect on mechanical properties [3]. One such trace element to receive considerable attention is silver, Ag. The effect of Ag was first reported in 1960 by Polmear [4] where its addition to Al–Zn–Mg based alloys enhanced the response to age hardening through a refinement of the precipitate dispersion. Further work on the addition of Ag to other precipitation hardened Al-alloy systems generalized the beneficial influence of Ag to all Al-alloys containing Mg [5,6]. The phenomenon was attributed to an interaction between Ag and Mg atoms and the subsequent effect on the nucleation of intermediate precipitates. By 1980s it was shown [7,8] that in alloy systems such as Al–Cu–Mg with high Cu:Mg ratios (e.g., 10:1), the addition of Ag not only enhanced the hardening response but also totally changed the precipitation processes

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Table 1
Chemical compositions of selected aluminum alloys (balance is Al) by wt.%.

Alloy	Cu	Mg	Ag	Zr	Mn	Si	Fe	Cr	Zn	Ti	V
2519[a]	5.3–6.4	0.05–0.4	–	0.10–0.25	0.1–0.5	0.25	0.30	–	0.10	0.02–0.1	0.05–0.15
C415[b]	5.0	0.8	0.5	0.13	0.6	0.04	0.06	–	–	–	–
C416[b]	5.4	0.5	0.5	0.13	0.3	0.04	0.06	–	–	–	–
2139[a]	4.5–5.5	0.2–0.8	0.15–0.6	–	0.2–0.6	0.10	0.15	0.05	0.25	0.15	0.05
2139[c]	4.9	0.46	0.38	0.002	0.32	0.03	0.04	–	–	0.09	–

[a] Composition limits given by the Aluminum Association from [1].
[b] Exact compositions from [11].
[c] Exact composition from Cho and Bes [2].

usually observed in these alloys. The Ag addition promoted the formation of a fine and uniform dispersion of hexagonal-shaped plate-like precipitates on the $\{1\,1\,1\}_\alpha$ planes of the matrix at the expense of the precipitation of $\theta'(Al_2Cu)$ which is usually observed in Al–Cu–Mg alloys. It is the fine and uniform distribution of this new precipitate (designated as Ω) and its good thermal stability that lead the alloys to have superior strength and creep resistance at temperatures up to 250 °C [9,10].

Following the pioneering research of Polmear [4–9] on Al–Cu–Mg–Ag systems and a number of work on experimental alloys based on this system, recent studies on a NASA program [11–13] showed that small additions of Ag and Mg to 2519 could increase the peak aged tensile yield strength by 10%. Aluminum alloy 2519 was originally developed by Alcoa and the U.S. Army (registered with the Aluminum Association in 1985) as a weldable material with ballistic penetration resistance superior to Al–Mg (5xxx) alloys, and without the susceptibility to stress corrosion cracking (SCC) that has limited the use of Al–Zn–Mg (7xxx) armor alloys [14].

Studies based on 2519 chemistry in NASA program [10,11] confirmed that the addition of small amounts of Ag and Mg stimulate the precipitation of a plate-like Ω precipitates on {1 1 1} in addition to the θ′ precipitates that form on {1 0 0} planes of the matrix. Using computer simulations, Zhu et al. [15,16] have shown that an optimum balance of {1 1 1} and {1 0 0} precipitates can increase the strength compared to alloys that contain similar volume fractions of only one type of precipitate. A number of alloys based on 2519, but with variations in Cu, Mg, and Mn and with 0.5%Ag and 0.13%Zr were examined on the NASA program with the objective of developing a damage tolerant aluminum-based material. Two alloys developed by Alcoa for the NASA program looked particularly attractive with respect to mechanical properties and were designated C415 and C416. Tensile yield strengths and creep resistance of these alloys have been found to be significantly better than 2519-T87 and 2618-T61.

The chemical composition ranges of these aluminum alloys are presented in Table 1, which clearly indicates the compositional differences between aforementioned aluminum alloys. Like 2519, aluminum C415 is an Al–Cu alloy and, therefore, maintains the enhanced mechanical properties imparted by precipitation hardening behavior. The composition of major solute elements and the amount of solute additions, however, are different between the two alloys. In particular, C415 and C416 contain 0.5% Ag not present in the 2519 composition.

Building on previous research, Alcan recently developed a new aluminum alloy designated 2139, which was registered with the Aluminum Association in 2004 [1]. As can be seen from Table 1, the major difference between Alcan's 2139 and Alcoa's C415 is the absence of Zr in 2139 alloy. The most recent and only work in open literature, to the best of author's knowledge, on the mechanical properties of 2139 alloy is the one due to Cho and Bes [2]. In this study, Cho and Bes particularly focus on the relative influence of dispersoid forming elements Zr and Mn, and compare the mechanical properties of 2139 based alloys in T8 temper with (i) only Zr, (ii) only Mn (as in 2139, see Table 1), and (iii) Zr + Mn (as in C415) in chemical composition.

They report that the removal of Zr from chemical composition (i.e., 2139 composition) further improves both strength and fracture toughness values. A particularly interesting result in their study is the comparison of plane-stress fracture toughness values at room temperature and −54 °C for different dispersoid compositions. Fracture toughness of 2139-T8 (with only Mn) slightly increases at −54 °C while the alloy with only Zr shows a significant reduction in fracture toughness with the same temperature decrease. SEM studies on fracture surfaces reveal that the difference is associated with an increase in propensity to intergranular fracture by Zr addition. Closer examination of microstructures by TEM suggests that Zr-containing dispersoids (Al_3Zr particles and $\theta'(Al_2Cu)$ phase nucleated around them) are likely to be located at the boundaries, where they exacerbate the detrimental effect of subgrain and grain boundary precipitation during artificial ageing process. This further compromises grain boundary strength in the temper and makes the alloy even more prone to intergranular fracture than alloys not containing Zr. This is particularly true at low-temperatures where thermally activated cross-slip mode becomes less favored and planar slip mode becomes more pronounced.

Another striking result from Cho and Bes' work [2] is that the ballistic performance of alloy 2139 is superior to that of 2519, which is currently the alloy of choice for modern armored vehicles.

In conclusion, alloy 2139 formulated by adding Mn and completely excluding Zr in Al–Cu–Mg–Ag system (last row in Table 1) offers new potentials in damage tolerance critical applications as recently demonstrated by higher fracture toughness and ballistic performance characteristics than other high performance aluminum alloys currently in use. In this study, its quasi-static and dynamic response will be investigated for a wide range of temperatures.

3. Experimental

3.1. Materials and microstructure

The material, 2139-T8 aluminum alloy, was provided in plate form with the dimensions of 22 in. × 6.75 in. × 2 in. The chemical composition of alloy is as given in the last row of Table 1, i.e., the same composition and temper as in the work of Cho and Bes of Alcan [2]. In order to investigate the extent of grain texture in as received 2139-T8 plates, microstructural characterization with optical microscopy was performed on the surfaces of undeformed specimens. Cylindrical specimens were cut out from the plate in order to evaluate the degree of grain texture in L–T, L–TT and T–TT planes; where L, T and TT represents longitudinal (i.e., longest), transverse and through-thickness directions of the plate, respectively. Specimens were embedded in a thermosetting mounting material and cured at 140 °C under pressure for 30 min. Then, the specimens were polished using a series of successively finer grinding papers and finally diamond paste. After each step in polishing the specimens were washed and/or sonically cleaned. Polished