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A modified Johnson-Cook model of as-quenched AA2219 considering negative to positive strain rate sensitivities over a wide temperature range

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Abstract

In order to establish the constitutive model to predict deformation behavior during quenching process, uniaxial tension behaviors of an as-quenched AA2219 sheet were investigated over a wide temperature range (298-773K) at different strain rates (0.001-1s^{-1}) in quasi-static regime. The experimental results show that the flow stress is closely related to temperature and strain rate. The material exhibits negative strain rate sensitivity (SRS) that the flow stress decreases with increase of strain rate below a critical temperature of T_c. A model established by Kabirian et al. (Kabirian, F., Khan, A.S., Pandey, A. Int. J. Plast. 2014, 55) based on the KHL model considering the negative to positive SRS shows successful prediction of the flow stress in a temperature range of 296-473K. However, at higher temperatures (473-773K) the measured SRS deviates from the calculated values of Sigmoidal function given by Kabirianet al. with the increase of temperature. Therefore, in this paper, based on an extended Sigmoidal function and a proposed relation between flow stress and the coupling effects of strain and temperature, a modified Johnson-Cook model is proposed to describe the quasi-static stress-strain responses over a wider temperature range. Correlations using the modified model show good agreement with the experimental results.

Keywords: As-quenched AA2219; Modified Johnson-Cook model; KHL model; Strain rate sensitivity; Dynamic strain aging.

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1. Introduction

AA2219 (Al-Cu-Mn alloy) has wide application in spacecraft industry to produce large structures due to its excellent performances such as stress corrosion resistance and weldability[1, 2, 3]. As one of heat-treatable Al alloys, mechanical properties of this alloy are largely influenced by the heat treatment processes. Quenching is a very important process to improve the mechanical properties but also easily leads to quenching distortion and residual stress. Thus, prediction of the quenching distortion and residual of large-scale structures is a significant work that should be investigated[4, 5]. Therefore, an appropriate constitutive model should be founded for obtaining accurately prediction of thermal stress and corresponding strain during the quenching process.

The Johnson-Cook (JC) model[6] is one of the most famous temperature, strain rate, and strain-dependent material constitutive models, for its simple implement, few parameters, and suitability for wide temperature range[7]. However, the JC model assumes that thermal softening, strain rate hardening and strain hardening are three independent phenomena and can be isolated from each other, which result in inadequate prediction to describe some flow behaviors especially in dynamic softening stage[8, 9]. Based on the original JC model, some researchers replaced the parameters with functions of temperature, strain, or strain rate, to consider the coupled effects of them. The predicted results show that the modified JC model can track the deformation behavior more accurately[10, 11].

In a certain temperature and strain rate range, the mechanical properties of alloy materials are also influenced by Dynamic strain aging (DSA), a strengthening mechanism that leads to Portevin-Le Chatelier (PLC) effect and negative strain rate sensitivity (SRS)[12]. This mechanism is considered to relate to the interaction of the mobile dislocations and solute atoms[13, 14]. The DSA phenomenon is observed in AA5xxx-O, and a proposed modified KHL model considering negative to positive strain rate sensitivity was established in a temperature range of 296-473K[15, 16]. However, materials are cooled from solution temperature (773K for 2219 aluminum alloy) to room temperature during quenching process, and the modified KHL model should be extended for describing the stress-strain relation in a higher temperature range. Because the strengthening mechanisms (DSA, work hardening) and softening mechanisms (dynamic recovery (DRV) and dynamic recrystallization (DRX)) are variable in low temperature range (298-473K) and high temperature range (473-773K), which makes the competition between work hardening and the softening mechanisms more complex, it becomes more difficult to capture the variation of the SRS and the relation between temperature and flow stress over the whole temperature range.

In this paper, based on the original JC model and the approach utilized to predict negative to positive SRS by Kabirian and Khan[14], a modified JC model considering negative to positive SRS over a wide temperature range (298-773K) has been established to predict stress-strain response of the as-quenched AA2219.

2. Experiments

A 2219 aluminum alloy (AA2219) plate with 2 mm thickness has been examined in this research. Before tensile tests the experimental samples machined to have the coincident axis with the rolling direction were heated at 808K for 4 hours and quenched in water. Then, uniaxial tensile tests were conducted in a MTS810 material testing machine at different strain rates (0.001-0.1 s^{-1}), and temperatures (298-773K) to obtain stress-strain curves of as-quenched AA2219 at different loading conditions. During tensile testing process the samples were firstly heated up to test temperatures in 15 minutes and hold for 5 minutes for temperature homogeneity. Because the heating time was short enough, the material state at different experimental temperature was able to simulate the material conditions during quenching process. Finally, samples holding at different test temperatures were stretched to the same strain.

3. Results

Fig. 1 shows the stress-strain curves for as-quenched AA2219 at different strain rates ($0.001s^{-1}$, $0.01s^{-1}$, $0.1s^{-1}$) in a temperature range of 298-773K. At low experimental temperatures (298-373K), the flow stress increases with the decrease of strain rates showing obvious negative SRS (Fig. 1 (a)-(b)). However, negative SRS phenomenon was not observed in annealed 2xxx aluminum alloys[17]. When deformation temperature equals to 416K, the flow stresses at all strain rates ($0.001s^{-1}$, $0.01s^{-1}$, $0.1s^{-1}$) are almost the same (Fig. 1 (c)). Therefore, the critical temperature (T_c)