



A new crystal plasticity framework to simulate the large strain behaviour of aluminum alloys at warm temperatures



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ABSTRACT

To improve metal formability, high temperature forming has become a desired manufacturing process. Phenomenological plasticity models are widely used in this application, however lack good predictive capability concerning microstructure evolution during forming. Many crystal plasticity hardening models have been developed to predict deformation phenomena of metals during high temperature forming; however, few have thermodynamic self-hardening formulations based on deformation mechanisms. This work presents a crystal plasticity based analysis with a Taylor polycrystal averaging scheme of warm forming employing a new microstructure and dislocation based strain hardening model to simulate deformation behaviour. The hardening model is derived from energy balance between dislocation storage, dislocation accumulation, and dislocation recovery, based on remobilization of immobile dislocations, due to thermal activation. The constitutive formulation is extended to include alloying effects due to solute strengthening of Mg. The material hardening properties of AA5754 are characterized for a range of temperatures at constant strain-rates. A formulation for the kinematics of dynamic strain aging is presented and employed for room-temperature simulations. The hardening characterization is then used to predict stress-strain behaviour of AA5182 for similar conditions. The model shows excellent predictability of experimental results. An analysis on the microstructural connection between temperature and stress-strain response is presented.

1. Introduction

For decades, mass reduction has been a priority in the automotive sector for improving fuel economy [26]. Many manufacturers have opted for substituting typical steel components for lighter aluminum alloys. An application of particular interest in this study is the use of 5xxx series aluminum-magnesium sheet alloys in panel components. The difficulty with aluminum sheet, in the replacement of panel components, is the lower formability at room temperatures than in steels [7]. In addition, surface quality of formed parts at room temperature is undesirable due to the Lüder's lines and serrated flow behaviour of Al-Mg sheet alloys (dynamic strain aging/PLC effect) [66]. However, poor formability and surface finish can be greatly improved by warm forming [73] without expensive production costs of refining microstructure to achieve the same outcome. Hot deformation processing is a desirable method for shaping in industry due to the ability to refine microstructure, which significantly influences the mechanical response and can increase formability [43,83]. Elevated temperature forming corresponds to a decreased flow stress and increased ductility of the

sheet, which can allow deep drawing and stretch in panels competitive with steels without design modifications. The understanding of high temperature deformation behaviour for warm forming and the constitutive relations describing the material flow are two of the fundamental prerequisites for the advancement of forming technology in industry.

Dynamic softening mechanisms, such as dynamic recovery (DRV) often occur in aluminum alloys with high-stacking fault energies during deformation at elevated temperatures. Numerous reports on the high-temperature deformation behaviour and dynamic softening of aluminum alloys (and other FCC metals) have shown that the mechanisms contributing to softening, recovery, and microstructure evolution during high-temperature deformation are highly sensitive to temperature and strain-rate [1,13,19,58]. Determination of the effects of temperature and strain rate on high-temperature deformation in metals has been a topic of discussion for decades [36–39,4,40,41,45,5,78]. Flow stress is the most basic and useful measure for characterizing plastic deformation properties of metals and provides a means to determine the energy required to plastically deform a metal. The balance between

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energy storage and plastic strain accommodation by mechanisms of slip-deformation can be evaluated with the aid of governing constitutive equations to provide good predictability. The improvement of these constitutive models over recent decades have given rise to an incredible understanding of material behaviour on a fundamental level; however, in many cases at the expense of great complexity and subsequently increased difficulty in application.

Available research for simulation of warm forming processes focuses only on the effect of elevated temperature on the evolution of the flow stress or hardening (Li and Gosh, 2003; [52,77,80]), rather than the effect of elevated temperature on microstructural parameters that lead to this behaviour. Confidence in numerical analysis of plasticity of materials depends greatly on the accuracy of the constitutive model describing the behaviour of the material [12]. This is of particular importance when the material exhibits anisotropy caused by texture, for example, in rolled sheets. The importance of an appropriate material model for predicting even simple monotonic loading strain paths has been demonstrated [11].

Plasticity theories are widely used in research and industry covering a broad field of applications ranging from crash and extrusion simulations to modeling and optimization of material microstructures. However, empirical phenomenological plasticity theories fail to predict the mechanical behaviour of micro-components and the corresponding material response. The methods of crystal plasticity have been successfully used to fill this gap in modeling local non-homogeneous mechanical behaviour, and has been applied extensively to study plastic deformation and texture evolution [64]. The material hardening, however, is usually empirical, or is based on dislocation models relying on many fitting variables or complex special gradient/misorientation determinations for dislocation density. These models are usually only adequate at ambient temperature up to bulk failure strain deformation. It is essential for the investigation of complex deformation features during forming, such as temperature dependent and geometric softening, strain localization, and microstructure evolution, etc., that the material hardening models are derived from physical deformation mechanics.

Crystal plasticity has been successfully used in modeling non-homogeneous mechanical behaviour and has been applied extensively to study both heterogeneous plastic deformation and texture evolution [64]. The collectives of crystal plasticity with the finite element method (CPFEM) and Taylor polycrystal analysis have proven a very powerful tool for the investigation of such plastic phenomena as the Bauschinger effect [33], formability [31,47,82], cyclic loading [27,49], surface effects [67], texture evolution [34,61] and high rate deformation [13], to list a few. However, little physical information is directly involved in the well-established crystal plasticity hardening models as most hardening laws are empirical fits, or require complex and computationally expensive calculations of strain gradients to predict dislocation contents [18,23]. Phenomenological models are satisfactory for the intended use of room temperature deformation, but are typically only able to predict material response up to the specimen failure strains. This is exaggerated when these hardening laws are used to predict large deformation at high temperatures. Large strain predictability is essential for the investigation deformation behaviour during forming. The ability to model phenomena such as thermal softening, geometric softening, strain localization, and microstructure evolution, etc., require material hardening models be derived from physical deformation mechanics.

In first part of this study, a physical theory for temperature dependent strain hardening in FCC polycrystals is developed based on dislocation accumulation and recovery. The model is then fit with available pure aluminum uniaxial stress-strain data [36] and temperature dependent hardening parameters are identified and investigated. Finally, the resulting temperature dependencies and theory are used to predict the stress-strain curves at a new strain rate and a parameter sensitivity analysis is completed. Then the developed model is implemented in a Taylor-type crystal plasticity model to simulate the

deformation behaviour of Al-Mg aluminum alloys (AA) 5754 and 5182 at elevated temperatures. The material hardening properties of AA5754 sheet are characterized for a range of temperatures from 25 °C to 260 °C at constant strain rates using experimental data obtained from literature. The available experimental data was reported to be at constant low strain rate such that thermal straining effects can be neglected. A kinematic formulation to capture dynamic strain aging at room temperature is also implemented to accurately represent the temperature dependency of the material hardening. Finally, the hardening characterization is used to predict stress-strain behaviour of AA5182 sheet over the same temperature and strain rate ranges.

2. Temperature dependent single crystal hardening model

Work hardening has always been a topic of great interest for scientists and engineers studying plastic deformation in metals. The work-hardening reflects the way in which networks of stored dislocations, both geometrically-necessary and statistically-stored, impede the passage of moving dislocations. Individual dislocations may act as point obstacles causing short-range interactions, or can form junctions. The collective network, a source of long-range internal stresses. Following the discovery of dislocations and dislocation theory, many concentrated efforts by the scientific community led to the description of the three stages of work hardening in single crystals: primary slip (stage I), multiple slip (stage II), and cross slip and recovery (stage III). The first stage is only observed in single crystals at low strain where hardening is governed by statistically-stored dislocations. Although flow stress theory and strain hardening is derived from single crystals, most metals strained in application are polycrystalline, characterized by yield followed by a low-strain high-hardening stage II that transitions, often rapidly, into a lower hardening stage III. The theory on the initiation of stage III began with the work of Seeger and coworkers [71,72] which begins because cross-slip occurs upon sufficient local pile-up stresses. The model predicts an exponential variation of the onset of stage III with temperature, however, was met with controversy [15]. Much debate exists on the high-strain transition from a stage III to a stage IV hardening, where the stress-strain curve begins to plateau or become nearly linear, however this is typically not observed under uniaxial conditions due to localization.

Single crystal work hardening theories based simply on the concept of hardening stages have been employed in crystal plasticity framework and can successfully be tuned to match the polycrystal behaviour; however, there still exists a significant gap in the connection between physical properties and mechanisms of deformation in explaining work hardening through the use of hardening laws. This is even more obvious at high temperatures, where conventional stage II to stage III transition broadens and the region of the stress-strain curve corresponding to each becomes unclear. In addition, the extremely low stage III hardening relative to the high stage II cannot be predicted with conventional crystal plasticity hardening models. Therefore, a hardening relationship based on the dislocations themselves, rather than the behaviour that manifests as multiple “stages” of hardening, must be developed in order to predict temperature dependent hardening.

The relationship between material strength and the square root of total dislocation density is well known as

$$\sigma = \sigma_0 + M\alpha\mu b\sqrt{\rho} \quad (1)$$

where M is the Taylor factor relating shear and normal stresses in polycrystals ($\sigma = M\tau$), α is a measure of the strengthening effect of dislocations, μ is the shear modulus, and b is Burgers vector [42]. Initial material strength σ_0 is due greatly to alloying, precipitates, particles, and grain size. The significance of this equation is that all work hardening models from earlier theories attributing work hardening to dislocation pile-ups, tangles, jogs, and forest dislocations and newer statistical theories and models of decreasing mean free path all predict this proportionality of strength and the square root of dislocation density.

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