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Experimental investigation and through process crystal plasticity-static recrystallization modeling of temperature and strain rate effects during hot compression of AA6063

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ABSTRACT

In this paper, a through process crystal plasticity-static recrystallization model to simulate hot compression in AA6063 is presented. A new temperature and strain-rate dependent hardening model is proposed and implemented in an in-house rate-dependent crystal plasticity framework. Using experimental Electron Backscatter Diffraction (EBSD) results, the modified crystal plasticity framework is calibrated, verified and further validated with experimental hot compression results from 400 °C to 600 °C and from 0.001 s^{-1} to 10 s^{-1} on AA6063. The proposed hardening model successfully captures the flow behavior from AA6063 hot compression results at various temperatures and strain-rates. Subsequently, the texture and resolved shear stress results from crystal plasticity framework are used as inputs to an integration point based static recrystallization (SRX) model. SRX model first finds possible nucleation sites and then grows them to reduce the stored energy in the system. SRX model is used to predict the recrystallized textures and grain size after hot compression in AA6063. Predicted texture and grain size at various temperatures and strain-rates are compared to experimental 2D XRD and optical microscopy results. The predicted results show good agreement with corresponding experimental data.

1. Introduction

Structural metals, like aluminum, are used extensively in automotive applications due to their light-weight and high strength [1]. Typical applications of aluminum alloys in the automotive industry include parts manufactured by drawing, stamping, extrusion etc. Unlike traditional forming operations such as sheet metal drawing and stamping, large strain processes such as extrusion are mostly performed at high temperatures and varying strain-rates to achieve maximum efficiency and output and cause huge deformation in the material resulting in flow, texture and grain size evolution [2].

Most aluminum alloys show little effect on the material stress-strain response near room temperature. For example, uniaxial tensile stress-strain results and shear results for aluminum alloys (5xxx) show little effect on the material stress-strain response [3,4]. However at higher temperatures, aluminum alloys show variability in the stress-strain response with temperature and strain-rate. Uniaxial stress-strain results from Hashemi et al. [5] show the temperature dependence of AA6xxx alloys from 323 K to 573 K and show that both, the yield and hardening-rate decreases with temperature. In addition, Hashemi et al. also show the strain-rate dependence of AA6xxx alloys at these temperatures from 0.001 s^{-1} to 1 s^{-1} and show that they exhibit positive strain-rate sensitivity. Similarly, Li et al. [6] have also shown that AA6xxx are positive strain-rate sensitive and soften with increasing temperatures and lowering strain-rates. Therefore it is important to incorporate the effect of temperature and strain-rate in modeling the material flow behavior during large strain processes in AA6xxx alloys.

There is very little experimental evidence on texture evolution during hot compression of AA6xxx under various temperatures and strain rates. However, there is some data on mild temperatures of AA5xxx which can provide a guideline to understand the effect of temperature and strain-rate on the texture evolution of AA6xxx alloys. Uniaxial tensile results for AA5xxx alloys have been shown to be temperature and strain-rate sensitive [7]. In addition, AA 5xxx alloys show little effect on the texture evolution [7]. Pandey et al. [7] studied AA5xxx at various temperatures (room temperature to 232 °C) and strain-rates (10° s^{-1} to 10^4 s^{-1}) and show that the overall texture trends do not change with different temperatures and strain-rates. However,

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the texture intensities are mildly affected. The effect of different temperatures and strain rates on texture evolution during hot compression of AA6xxx alloys, still remains unknown and is a topic which requires further investigation.

Crystal plasticity frameworks provide sufficient flexibility to capture the material stress-strain and texture evolution at room temperatures [8]. However, at high temperatures, materials undergo additional processes such as recrystallization. It is known that at high temperatures, AA6xxx alloys undergo static recrystallization [9]. This in-turn affects the final texture as well as the grain size in these alloys [10]. McQueen and Celliers [11] discuss static recrystallization in Al-Mg-Si (AA6xxx) alloys at high temperatures for extrusion. Sato and Kokawa [12] also observe static recrystallization in AA6063 at temperatures greater than 0.5 T_m. Therefore, in order to capture the correct material behavior in AA6xxx, it is important to capture the flow behavior as well as the texture and grain size evolution due to static recrystallization at various temperatures and strain-rates.

Various numerical methods have been proposed in the literature to capture the flow behavior of a given material subjected to different loading conditions (temperature, strain rate etc.). Phenomenological models have been shown to predict material response under different temperatures and strain-rates [13–15] however phenomenological models are unable to capture the texture evolution in the material during deformation. Crystal plasticity formulations provide the flexibility to predict the flow behavior as well as the texture evolution. Staroselsky et al. [16] proposed a rate-independent creep model to study the effect of extremely low strain-rates at various temperatures on single crystal octahedral slip system applied to Ni superalloys. Recent work by Cyr et al. [8] have modeled the effect of temperature to predict the stress-strain and microstructure evolution under shear and tensile loading for AA5754 using a rate-dependent crystal plasticity model. Dislocation based crystal plasticity simulations have been used to model large strain processes in literature and have been shown to predict the temperature effects in materials [17–19]. For example, Hansen et al. [19] have successfully implemented a high strain-rate and temperature dependent single crystal model for Copper but the authors have not validated it for polycrystalline materials. Thus, a polycrystal crystal plasticity model is needed that is able to capture the bulk stress-strain response under various temperatures and strain-rates.

As mentioned earlier, large deformations at high temperatures in AA6xxx alloys involve static recrystallization (SRX). Even though Crystal Plasticity models can capture the flow behavior and texture evolution to a certain extent, they are unable to capture the change in microstructure in subsequent recrystallization that can take place at these elevated temperatures. There are different methods used, in literature, to model recrystallization problems and can be divided into analytical and numerical models. Analytical approaches based on the Johnson-Mehl-Avrami-Kolmogorov (JMAK) model such as the texture-component model [20], can only simulate the recrystallized volume fraction in the material. In addition, JMAK based models assume site-saturated nucleation and constant growth. Non-homogenization models (full field models) like Potts Monte-Carlo [21–23] and Cellular Automata [17,24,25] are widely used to model SRX and have been used to simulate different kind of annealing conditions including texture and grain size evolution during static recrystallization. It is important to be able to predict the correct texture after SRX as it affects the material performance after subsequent forming operations. Undesirable forming effects such as earing [26], roping [27] etc. are directly related to texture and can only be avoided by predicting the texture correctly. In addition, capturing the correct grain size after SRX is also important as many mechanical properties are directly related to grain size. For example, it is commonly known that a smaller grain size improves the strength (Hall-Petch effect) [28] and toughness of the material [29,30].

Potts Monte-Carlo and Cellular Automata models are very similar as they both use a grid/mesh to describe the current and future state of the material [31]. The main difference lies in the state update of each material point during recrystallization. Monte-Carlo models use random sites for updating the states whereas Cellular Automata model update all the states thus increasing their efficiency. Caleyo et al. [32] and Kobayashi et al. [33] have simulated recrystallization in Fe-50%Ni and pure aluminum respectively using the Monte-Carlo model. While Raabe [34] and Raabe and Becker [35] have used cellular automata model to model SRX in single and polycrystal aluminum respectively. Rollett and Raabe [36] have also proposed a hybrid Monte-Carlo and Cellular Automata model to model recrystallization.

The purpose of this work is two-fold. Firstly, a comprehensive experimental study is performed to understand the flow behavior and texture evolution of AA6063 under hot compression at various temperatures and strain rates. Hot compression experiments were carried out on an as-cast AA6063 billet. Hot compression leads to texture evolution in the material which was characterized using Electron Backscatter Diffraction (EBSD) and 2D X-Ray diffraction (XRD). To the best knowledge of the authors, this is the first work presenting and analyzing texture evolution and stress-strain response of AA6xxx at various temperatures and strain-rates during hot-compression. Secondly, an in-house, Taylor-type polycrystal model [37] was used to simulate hot compression for AA6063 at various temperatures and strain-rates. A new temperature and strain-rate dependent hardening model was proposed to predict the flow behavior and texture evolution. Flow behavior and texture from hot compression simulations were validated with experimental AA6063 hot compression results. Lastly, as AA6063 undergoes static recrystallization at high temperatures, a simple and robust in-house integration point based static recrystallization model was developed to predict the final textures and grain sizes at various temperatures and strain-rates. The model used as input the resultant texture and resolved shear stress data from crystal plasticity simulations to predict the recrystallized texture and grain size. Simulated textures and grain size were compared to the corresponding 2D XRD and optical microscopy data and the results show good agreement at various temperatures and strain-rates. This paper presents a through process model to simulate hot deformation of AA6063 at different temperatures and strain-rates. The significance of this paper lies in the fact that it serves as a stepping stone for modeling high temperature forming operations like extrusion, ECAP, hot rolling etc. to predict material performance and save costs by reducing full-scale experiments.

2. Experimental data

In this work, stress-strain and texture evolution of AA6063 under hot compression is investigated. Experimental characterization at high temperatures was performed to understand the material stress-strain response and texture evolution under hot compression. Table 1 shows the chemical composition of AA6063 used in this work. Hot compression tests were performed using Gleeble® 3500 thermal-mechanical testing system. AA6063 compression samples were machined from homogenized cast billet with dimensions shown in Fig. 1. Initial as-cast texture for AA6063 was captured using Electron Backscatter Diffraction (EBSD). Whereas texture for deformed AA6063 samples was captured using 2D X-Ray Diffraction (XRD). Results and experimental procedures for EBSD and XRD are provided in Sections 2.1.1 and 2.1.2 respectively whereas results from hot compression experiments are presented in Section 2.2.

Table 1
AA6063 chemical composition by wt%.

Mg	Fe	Si	Cu	Mn	Al
0.49	0.16	0.4	0.01	0.03	Bal.