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Thermo-mechanical response of Al 6061 with and without equal channel angular pressing (ECAP)

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ABSTRACT

The thermo-mechanical responses of Al 6061 before and after equal channel angular pressing (ECAP) at different strain rates and temperatures were measured. Al 6061 was solution heat treated before ECAP pressing at room temperature and subjected to up to three passes. After pressing, the billets were aged at 100 °C for 2 days. An as-received Al 6061-T651 was studied similarly to investigate the differences between processed and non-processed specimens. The responses of ECAP material were determined at −30, 22, 125 and 250 °C, and at strain rates from 10^{-5} to 2530 s^{-1}; the 6061-T651 specimens were subjected to uniaxial compressive loading at −31, 22, 85, 150, 230 and 315 °C, and strain rates ranging from 10^{-5} to 2200 s^{-1}. It was found that, the ECAP process increases the strength versus the T651 condition. Additionally, the Al 6061 ECAP is not sensitive to strain rate at room and lower temperatures, but the sensitivity increases as the number of passes and/or temperature are increased and this is the same for the non-processed material. Increasing the number of passes increases the flow stress at room and lower temperatures, has almost no effect at 125 °C and decreases at 250 °C. For both materials, the dynamic flow stress is higher than the stress at quasi-static strain rates even when the quasi-static strain rate regime is insensitive to strain rate. The Al 6061 has strong texture after one pass but steadily increases as the number of passes are increased. This is the first study that reports on the thermo-mechanical responses of ECAP and non-ECAP Al 6061 at such a wide range of strain rates, including dynamic, and temperatures.

1. Introduction

Aluminum alloys, like Al 6061, are some of the most widely used materials today which spans the entire range of industries. They are used in consumer products and military applications. The aircraft and aerospace industry uses aluminum alloys because it is much lighter than steel and every kilogram of weight reduction results in greater fuel savings and higher payloads. The car industry has increased its use of aluminum over the years as the price of gasoline has increased and the need to reduce vehicle weight has been of paramount importance. Today, much of aluminum's use is to reduce the weight of the item being produced, but it has always been popular because it is easy to machine, cast, extrude, roll, etc. and many alloys are age-hardenable (like 6061).

Because of the widespread use of this alloy, it is important to understand their mechanical behavior when exposed to different loading conditions, strain rates and temperatures, and to be able to model the behavior and later, to predict the behavior for *any* of these conditions. There have been many experimental studies on the mechanical behavior of this alloy at different temperatures and strain rates, with many being performed in the 1960s. A study by Holt et al. (1967) concluded

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that Al 6061-T6 was effectively strain rate insensitive for strain rates between 0.009 and 910 s^{-1} in compression. The dynamic experiments were performed on a split-Hopkinson Pressure Bar (SHPB). An earlier study (Barker et al., 1964) came to a different conclusion when their experiments showed that Al 6061-T6 is slightly strain rate sensitive from quasi-static to dynamic strain rate regimes. The flow stress was only slightly higher for the shock loaded material but they suggested that a "different stress–strain curve exists for each strain rate." They used a high speed plate impact setup and only gave an approximate strain rate of 10^5 s^{-1}. Several dynamic studies on Al 6061-T6 in tension have shown that the yield strength only increases slightly in the dynamic regime but the ultimate strength rises more significantly (~20%) (Austin and Steidel, 1959; Steidel and Makerov, 1960; Smith, 1963). Hoge (1966) observed a significant strength increase between 4.8×10^{-5} and 65 s^{-1} that the others did not report and an increase in strain rate sensitivity with temperature. The main weaknesses of these studies are that each only investigated a narrow range of strain rates and temperatures (or no range at all), for one dimensional stress and strain conditions, and experiments were performed using dissimilar equipment and loading directions (i.e. tension or compression).

Equal channel angular pressing (ECAP) is a technique using severe plastic deformation to produce ultra-fine grain sizes in the range of hundreds of nanometers to bulk course grained materials (Segal et al., 1981; Valiev et al., 1993; Segal, 1995; Iwahashi et al., 1996; Furukawa et al., 1998). ECAP is performed by pressing a billet of material through a die that has two channels which intersect at an angle. The billet experiences simple shear deformation, at the intersection, without any precipitous change in the cross section area because the die does not allow for lateral expansion. This means the billet can be pressed more than once and can be rotated about the pressing axis during subsequent pressings. A single pass with channels 90° to each other, induces approximately 1.15 equivalent strain in the billet. Depending on the billet rotation, different deformation routes can be applied. Route A has no rotation of the billet, route B_A is rotated counterclockwise 90° on even number of passes and clockwise 90° on odd number of passes, route B_C is rotated counterclockwise 90° after every pass, and route C is rotated 180° after every pass (Furukawa et al., 1998). This technique can be applied to commercial pure metals and metal alloys, with FCC, BCC and HCP crystal structures, with coarse grains to fabricate ultra-fine grained materials that have no porosity and higher strength than the non-processed material (Valiev et al., 1997; Shin et al., 2000; Valiev et al., 1999; Nemoto et al., 1999; Stolyarov et al., 2001; Mukai et al., 2001; Kim et al., 2002a,b). A number of high strain rate experiments on ultra-fine grained and nanocrystalline materials subjected to different processing methods, in addition to ECAP, have been performed by Gray et al. (1997), Jia et al. (2001), Wei et al. (2004), Meyer et al. (2007) and Farrokh and Khan (2009). Constitutive modeling of UFG materials has been achieved by Farrokh and Khan (2009), Alexandrov et al. (2008), Beyerlein and Tomé (2007), Beyerlein et al. (2007), and Muszka et al. (2006).

Al 6061 can be heat treated to greatly improve its strength and because of this, Al 6061 has been studied by other researchers to determine pre- and post-ECAP heat treatments to optimize the increase in strength. Ferrasse et al. (1997) studied the effects of pre- and post-pressing heat treatments of Al 6061 and concluded that after a solution heat treatment and aging at 170 °C for 8 h before pressing (and no post-pressing heat treatment), the material exhibited peak strength and elongation in tension. Additionally, pressing temperatures from 110 to 170 °C showed the highest strengths at the lowest temperature. Kim et al. (2002a,b) modified the above heat treatment approach by applying only the solution treatment before pressing at 125 °C and varying the aging temperature and the time after pressing. The hardness was maximized at an aging temperature of 100 °C for 48 h. The subsequent ultimate tensile strength and elongation values were 13% and 51% higher than those reported by Ferrasse et al. (1997). Kim et al. (2005) investigated the cooling rate of the solution treatment and the pressing temperature on the tensile strength of Al 6061 ECAP. Water quenching produced higher strength versus furnace cooling, following the solution heat treatment. Interestingly, pressing at 125 °C showed higher tensile strength than pressing at 70 °C for no post-press aging and with post-press aging, probably due to greater dynamic precipitate hardening at the higher temperature (Roven et al., 2008). Only a couple of investigations have been published when ECAP of Al 6061 was performed at room temperature. Horita et al. (2001) studied the strength in tension of fully annealed Al 6061 and no post-press heat treatment. The resulting yield strength was 42% lower and the material exhibited lower elongation as compared to Kim et al. (2002a,b). Another study at room temperature (Chang and Shan, 2003) was forced to perform intermediate annealing at 200 °C for 1 h after each pass to prevent failure of the billet. This resulted in no strength increase from the first to the second pass and caused a reduction in strength after two passes. Hockauf et al. (2008) successfully processed, via ECAP, Al 6082 without cracking for up to eight passes at room temperature using backpressure. They reported a yield strength, in tension, of 405 MPa after subjecting the billet to eight passes.

Studies on aluminum alloys have concluded that ECAP can be an effective processing method to control texture evolution because of the many different processing parameters of the technique. Two of the most important are the number of passes and the deformation route. Many different texture orientations with all types of texture strength can be produced at many different numbers of passes. But the initial texture has a limited role in the outcome (Ferrasse et al., 2004). Additionally, as the number of passes increase, the strength of the textures tends to decrease (Ferrasse et al., 2004; Wang et al., 2005; Chowdhury et al., 2008) due to the creation of ultra-fine grains with high angles of misorientation which limit slip (Ferrasse et al., 2004).

This study is the first reporting the thermo-mechanical behavior of Al 6061 processed via ECAP (at room temperature) subjected to such a wide range of temperatures and strain rates. In this study, ultra-fine grained Al 6061 specimens were processed by ECAP for up to four passes at *room temperature*. The texture is observed without ECAP and at one, two, three and four passes to determine the evolution due to the ECAP process. Further, the temperature and strain rate (quasi-static to dynamic) sensitivities of the material under uniaxial *compressive* loadings were investigated to elucidate their changes as the