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The characteristics of plastic flow and a physically-based model for 3003 Al–Mn alloy upon a wide range of strain rates and temperatures

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ABSTRACT

The uniaxial compressive responses of 3003 Al–Mn alloy upon strain rates ranging from 0.001/s to about 10^4/s with initial temperatures from 77 K to 800 K were investigated. Instron servohydraulic testing machine and enhanced split Hopkinson bar facilities have been employed in such uniaxial compressive loading tests. The maximum true strain up to 80% has been achieved. The following observations have been obtained from the experimental results: 1) 3003 Al–Mn alloy presents remarkable ductility and plasticity at low temperatures and high strain rates; 2) its plastic flow stress strongly depends on the applied temperatures and strain rates; 3) the temperature history during deformation strongly affects the microstructure evolution within the material. Finally, paralleled with the systematic experimental investigations, a physically-based model was developed based on the mechanism of dislocation kinetics. The model predictions are compared with the experimental results, and a good agreement has been observed.

1. Introduction

3003 Al–Mn alloy is considered an important engineering material in cryogenic systems and in aerospace applications (Woodcraft, 2005). Compared with other aluminum alloys, it presents very high strength and very good corrosion resistance (Luan et al., 2004). To widen the application field and improve the performance, the mechanical properties of 3003 Al–Mn alloy have been widely studied in past decades (Fujii et al., 2002; Liu et al., 2004; Yeh et al., 2003; Barlat et al., 2002). In many practical applications, however, 3003 Al–Mn alloy is subject to high rates of straining with different temperatures, such as during the course of high speed machining, impact energy absorbing, rapid crack propagating, metal forming, and other scenarios. Therefore the corresponding mechanical responses under different strain rates and temperatures need to be well understood. In this work, the results of a series of quasi-static (less than 0.1/s) and dynamic (3200 and 9500/s) compression tests on 3003 Al–Mn alloy are first investigated. These tests are performed over a temperature range from 77 K to 820 K. Based on the observation of experimental results, and by considering the evolution of the microstructure and the effects of long-range and short-range barriers to the motion of dislocations, the flow stress of 3003 Al–Mn alloy under different strain rates and temperatures is modeled using a developed physically-based model. The corresponding model predictions are then compared with the experimental observations.

2. Experimental procedures

All tests are carried out on 3003 Al–Mn alloy base plates, which are commercially available with the specific chemical composition given in Table 1. Both the nominal diameter and height of the samples are designed to be 5 mm. Ends of samples are first polished using 1200- and 4000-grid waterproof silicon carbide paper to reduce end frictions during the low and high strain rate deformation, and then greased for low- and room temperature tests.

Compression tests at strain rates of 0.001/s and 0.1/s are preformed using an Instron hydraulic testing machine at temperatures ranging from 77 K to 600 K, with the maximum achieved true strain exceeding about 80%. Temperature elevation is achieved by using a high-intensity quartz-lamp in a radiant-heating furnace. The temperature is measured using a thermocouple arrangement. Constant temperatures can be maintained within ±2 °C. The deformation of the specimens is measured by LVDT mounted in the testing machine. The measuring facility is calibrated with standard

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Table 1
Major alloy content of 3003 Al–Mn alloy (wt %).

Mn	Fe	Si	Cu	Zn	Other	Al
1.0–1.5	0.7	0.6	0.05–0.20	0.1	<0.15	Remainder

extensometer before the tests. The low temperature of 77 K is achieved by immersing the specimen and testing fixture in a bath of liquid nitrogen. Typical true stress–strain curves of 3003 Al–Mn alloy at a constant strain rate of 0.001/s and with different temperatures are shown in Fig. 1.

Dynamic tests at a strain rate of 3200/s with different temperatures are performed using an enhanced split Hopkinson pressure bar (enhanced SHPB) (Nemat-Nasser and Isaacs, 1997). The configuration of the enhanced SHPB for compression testing is shown in Fig. 2. It consists of two identical elastic pressure bars of maraging 300 steel with the yield stress exceeding 2000 MPa. The dimensions of the bars are 12.7 mm in diameter and 1.2 m in length. For such high temperature dynamic tests, it is necessary to heat the sample to the desired temperature and, in the mean while, keep the incident and transmission bars at a suitable low temperature. In order to do this, the bars are kept outside the range of the heating wire in the furnace, and the specimen held by the thermocouple is positioned at the center of the furnace by a Cu sleeve. Once the specimen is heated to the target temperature, the bars are then brought into contact with the specimen right before the stress pulse reaches the end of the incident bar. This task is accomplished by the employment of a transmitter bar mover, which can be driven by synchro pneumatic pressure from an actuation assembly in the same time as the strike bar is fired. The temperature of specimen can be measured by thermocouple that is holding the specimen inside the furnace. The true stress–strain curves at a strain rate of 3200/s with different temperatures are shown in Fig. 3.

In order to ensure the validity of experimental data, all stress–strain curves are obtained by testing at least three samples. If the curves for three samples have remarkable scatter, more samples are needed to repeat the test until the experimental data are observed to possess good repeatability or less scatter. It turns out that good repeatability and consistency of the testing results is obtained, probably resulting from shear-glide domination during the plastic flow for metals.

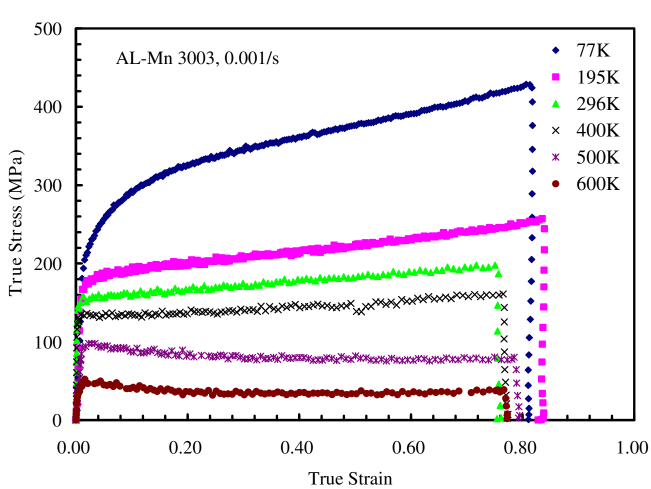

Fig. 1. True stress–true strain curves at indicted temperatures and a strain rate of 0.001/s.

3. Experimental results

3.1. Temperature effect on the flow stress

It has been noticed from Figs. 1 and 3 that the plastic flow stress of 3003 Al–Mn alloy remarkably decreases as the temperature increases from 77 K to 820 K, meaning that the flow stress is very sensitive to temperature change. For experimental data at strain rate of 0.001/s and temperature of 77 K shown in Fig. 1, the plastic strain is observed to be greater than 80%. It has been observed in Fig. 1 that the strain hardening rate slightly decreases as the strain increases for temperature above 500 K at the strain rate of 0.001/s. Such decrease is possibly caused by stress relaxation due to creep deformation under high temperatures and low strain rate. It is noticed as well in Fig. 3 that the strain hardening quickly decreases at strain rate of 3200/s and temperature of 77 K. This phenomenon is possibly due to the deformation localization or occurrence of shearband inside the sample for low temperature tests. The strained samples do not present visible crack or break in appearance. Uniform deformation has been observed through all tested samples, indicating excellent plastic formability and ductility even at low temperatures.

3.2. Strain rate effect on the flow stress

Fig. 4 shows the stress–strain curves of 3003 Al–Mn alloy at temperature of 296 K with various applied strain rates. It is noticed that the flow stress of 3003 Al–Mn alloy is strongly depending on the applied strain rate, especially when the strain rate is above the order of 10^3/s (see the result of 9.500/s for instance). The dependence of the flow stress on temperature at a fixed strain of 0.1 is presented in Fig. 5 for different applied strain rates. It can be seen that the strain rate effect increases with decreasing temperature for dynamic tests, and the greatest strain rate effect is observed around the temperature of 77 K. In Fig. 6, true stresses as a function of strain rates are plotted for a fixed strain of 0.2 and initial temperature of 296 K. It is noticed that the flow stress increases nonlinearly with increasing strain rate. The nonlinearity is more notable with strain rates higher than the order of 10^3/s. Such strain rate effect is usually attributed to the electron- and phonon-drag effect on the mobile dislocations (Follansbee and Weertman, 1982; Zerilli and Armstrong, 1992; Chiem, 1992; Regazzoni et al., 1987).

3.3. The 3rd dynamic strain aging phenomenon

Based on the observation of Figs. 1 and 3, it has been known that the plastic flow stress of 3003 Al–Mn alloy is strongly depending on temperature. To further reveal the temperature effect on flow stresses, the data in Figs. 1 and 3 are re-organized and plotted in Figs. 7 and 8. In these figures, the flow stresses are plotted as functions of temperature for given strains and certain strain rate. During the temperature increase from 77 K, the temperature of liquid nitrogen, to about 600 K, the flow stress first decreases rapidly, and then the decrease starts to slow down when the temperature is above 300 K. Actually for temperature above 300 K, there exist occasions that the temperature has very little effect on the flow stresses. Such unusual phenomenon is considered the 3rd dynamic strain aging (Guo, 2007; Guo and Nemat-Nasser, 2006; Nemat-Nasser et al., 1999).

Frequently dynamic strain aging (DSA), often called Portevin–Lechatelier effect, is defined as recurrent pinning (discontinuous or repeated yielding) of dislocations during plastic deformation (Kubin et al., 1992; Klose et al., 2003). The DSA is attributed to the additional resistance to dislocation motion produced by the mobility of solute atoms that can diffuse to dislocations above a certain temperature (Hong et al., 2005; Beukel and Kocks, 1982) while the