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HIGH STRAIN-RATE RESPONSE OF HIGH-PURITY ALUMINUM AT TEMPERATURES APPROACHING MELT

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Abstract. High-temperature, pressure-shear plate impact experiments were conducted to investigate the rate-controlling mechanisms of the plastic response of high-purity aluminum at high strain rates (10^6 s^{-1}) and at temperatures approaching melt. Since the melting temperature of aluminum is pressure dependent, and a typical pressure-shear plate impact experiment subjects the sample to large pressures (2 GPa - 7 GPa), a pressure-release type experiment was used to reduce the pressure in order to measure the shearing resistance at temperatures up to 95% of the current melting temperature. The measured shearing resistance was remarkably large (50 MPa at a shear strain of 2.5) for temperatures this near melt. Numerical simulations conducted using a version of the Nemat-Nasser/Isaacs [1] constitutive equation, modified to model the mechanism of geometric softening, appear to capture adequately the hardening/softening behavior observed experimentally.

INTRODUCTION

Frutschy and Clifton [2] modified the pressure-shear plate impact experiment in order to test OFHC copper at elevated temperatures. The results of that work show that the shearing resistance decreases with increasing temperature and increases with increasing strain rate over the full range of temperatures (500 - 700°C) and strain rates (10^5 and 10^6 s^{-1}) examined. However, the flow stress at the highest temperatures and highest strain rates was substantially greater than predicted by models based on rate-controlling processes involving the thermally activated motion of dislocations past obstacles. While conclusive evidence of a change in rate-controlling mechanism was not obtained, the response suggests that the influences of temperature and strain rate may be changing at the highest temperatures. The current study was undertaken to examine whether or not these trends observed by Frutschy and Clifton [2] persist at still higher fractions of the melting temperature. Larger fractions of the melting temperature are accessible in the current study due to the lower ambient melting temperature of aluminum, 660°C.

In pressure-shear plate impact experiments, the sample is subjected to large pressures and undergoes large plastic deformations. The sample temperature is increased by both the increased pressure and the plastic work done to the sample. A full thermodynamic analysis of these experiments is provided in Reference [3] and can be used to estimate the change in temperature of the sample throughout the test. Also, since the melting temperature for aluminum is pressure dependent, it is relevant to think of the sample temperature as a percentage of the current melting temperature and not the ambient melting temperature.

TABLE 1. Shot summary for tests on high purity aluminum.

Shot name	SG0402	SG0504	SG0602	SG0703	SG0802
Initial sample temp. ($^{\circ}$C)	Rm. Temp.	495	591	584	582
Approx. final temp. ($^{\circ}$C)	137	657	627	753	609
Approx. final temp. (% of melt)	31	67	82	77	95
Shear strain rate (s^{-1})	1.19×10^6	1.85×10^6	1.29×10^6	1.41×10^6	1.52×10^6
Peak shear stress (MPa)	230	112	130	163	163
Maximum pressure (GPa)	5.35	6.76	2.37	5.66	6.13
Impact velocity (*m/s*)	118.8	159.6	52.9	131.4	127.5
Aluminum purity (%)	99.999	99.999	99.0	99.999	99.999
Sample thickness (μm)	25	25	10	25	25

EXPERIMENTAL RESULTS

For this study, high-temperature, pressure-shear plate impact experiments [2,3] were conducted on thin (10 – 25 μm) aluminum samples, which were sandwiched between tungsten carbide target plates and impacted by a tungsten carbide flyer plate. It is essential to the interpretation of these experiments that the dynamic response of the tungsten carbide plates be known for the temperatures and stresses that these plates experience during the experiments. Therefore, symmetric impact tests, where the flyer and target are both tungsten carbide, were conducted at temperatures up to 643°C in order to characterize the response of the tungsten carbide under stresses and temperatures that result in the sandwich tests on aluminum. Those results can be found in Reference [3] and are used to analyze the results of the tests on aluminum.

Five experiments were conducted on high-purity, polycrystalline aluminum at nominally similar strain rates and at starting temperatures ranging from room temperature up to 591°C. The shot summaries for these tests are given in Table 1. An important consideration in these experiments is the large increase in the melting temperature of the sample when the sample is subjected to the large pressures of pressure-shear plate impact experiments. A pressure-release technique [3] was utilized for Shot SG0802 in order to measure the flow stress while the sample is at the ambient melting temperature and therefore at larger fractions of the current melting temperature.

Fig. 1 shows the dynamic shear-stress versus shear-strain curves for all five tests performed on polycrystalline aluminum. As predicted by models

based on rate-controlling processes involving the thermally activated motion of dislocations, the shear flow stresses for the tests at elevated temperatures are significantly lower than the flow stresses obtained at room temperature (shot SG0402). However, the shearing resistance does not decrease monotonically with increasing temperature. This result is evidenced by shots SG703 and SG0802, which were tested at a higher temperature than shot SG0504, yet displayed a higher shear resistance.

Shots SG0703 and SG0802, which have similar testing and loading conditions until the pressure release occurs in shot SG0802, exhibit similar responses while under pressure. Thus, there appears to be good repeatability in the high-temperature, pressure-shear plate impact experiments.
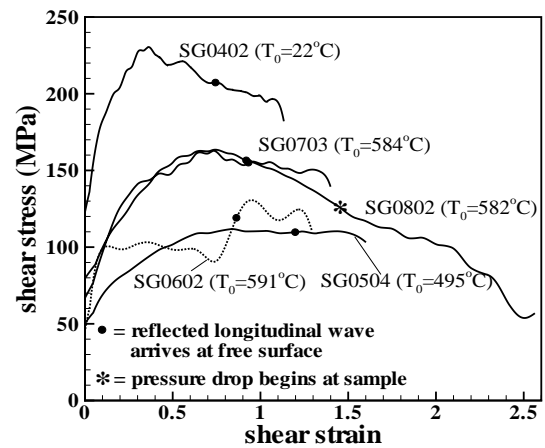

Figure 1. Shear stress vs. shear strain curves for shots on polycrystalline aluminum.
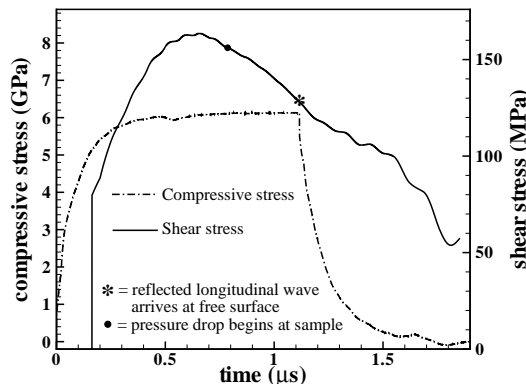
Figure 2. Compressive and shear stresses from shot SG0802 plotted against time at the sample.

The shear-stress versus shear-strain curve for the test on 99.0% pure aluminum (shot SG0602) displays a unique structure. Due to the difference in purity, direct comparisons to the other results are not appropriate.

The normal and shear stress histories for shot SG0802 are plotted in Fig. 2. When the pressure begins to drop, the shear stress is decreasing steadily. After the pressure drop the shear stress decreases less quickly. The pressure drops is accompanied by a drop in sample temperature [3] and a larger drop in melting temperature. This temperature jump can be viewed as either a decrease in absolute sample temperature or an increase in absolute temperature as a fraction of the melting temperature at the current pressure. In either case, the continuous response of the shear stress suggests that a temperature jump does not have a direct effect on the flow stress, but may influence the subsequent flow stress through a change in hardening rate.

COMPUTATIONAL RESULTS

Three constitutive models were used in finite difference simulations of the experiments on aluminum [3]. The Johnson/Cook model [4] was used with a modification to include the pressure dependence of the melting temperature. The Nemat-Nasser/Isaacs [1] model and a version of the Nemat-Nasser/Isaacs model [3], modified to incorporate the mechanism of geometric softening were also used.
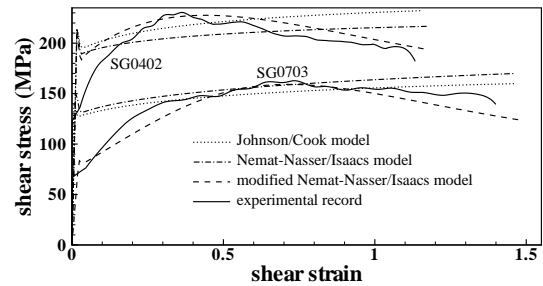

Figure 3. Experimental and simulated shear responses for shots SG0402 and SG0703.

The shear stresses for the simulations of shots SG0402 and SG0703 are plotted against the nominal shear strain with the experimental results in Fig. 3 for all three constitutive models. Both the Johnson/Cook and Nemat-Nasser/Isaacs models can predict the approximate shear stress levels of the room temperature (SG0402) and elevated temperature (SG0703) tests with empirically fit parameters. However, neither model can capture the hardening/softening observed in the experimental results. The modified Nemat-Nasser/Isaacs model, with the addition of geometric softening, provides the best fit.

The shear stress versus nominal shear strain curves computed for all three constitutive models in the simulations of Shot SG0802 are plotted with the experimental response in Fig. 4. The Johnson/Cook and Nemat-Nasser/Isaacs models roughly predict the shear stress level prior to the pressure drop (at a strain ~1.4), but fail to capture the hardening/softening observed experimentally.

The modified Nemat-Nasser/Isaacs model, using empirically fit hardening and softening parameters, can accurately predict the experimental
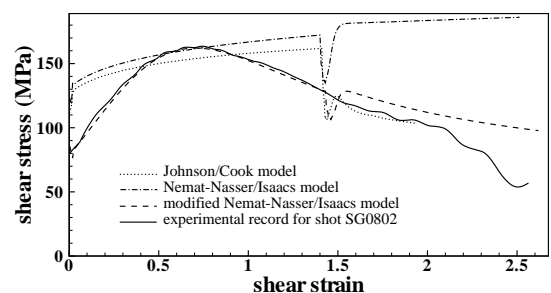

Figure 4. Experimental and simulated shear responses for shot SG0802.

result prior to the pressure drop. After the dip in shear stress associated with the pressure drop, the simulated shear stress rebounds to a slightly higher stress level and then continues decreasing, but at a rate slower than observed prior to the pressure drop. After reaching a peak, the experimental shear stress decreases until the time of the pressure drop (corresponding to a strain ~1.4). The experimental result does not show a discontinuous change in stress at the time of the pressure drop; however, the shear stress does begin to decrease less quickly after the pressure drop. That response is predicted using the modified Nemat-Nasser/Isaacs model.

The dip observed in all three of the simulated responses of Shot SG0802 is a byproduct of modeling the tungsten carbide plates to respond linearly [3].

DISCUSSION

Shot SG0504 was conducted at a starting temperature of 495°C, which is between the starting temperatures of shots SG0402 (T_0=22°C) and SG0703 (T_0=584°C). This shot displayed a lower shearing resistance than the other shots while being deformed at a nominally similar strain rate (Fig.1). All of the models presented here produce a monotonic decrease in flow stress with increasing temperature. Therefore, none of these models can predict the stress levels of shots SG0402 (T_0=22°C), SG0504 (T_0=5495°C) and SG0703 (T_0=584°C) with a single set of parameters.

In order for a constitutive model to predict an increase in flow stress with increasing temperature it is helpful to consider the motion of dislocations as involving both thermally activated motion past obstacles and phonon-drag-resisted glide between obstacles. At sufficiently high stress levels and/or sufficiently high temperatures the obstacles can be overcome quickly and the rate controlling mechanism becomes phonon drag, which increases with increasing temperature. If such a model is used for the high shearing rate experiments reported herein, the dependence of the flow stress on temperature has the form shown in Fig. 5. While the qualitative behavior of the model is consistent with the observed non-monotonic change in flow stress with increasing temperature,
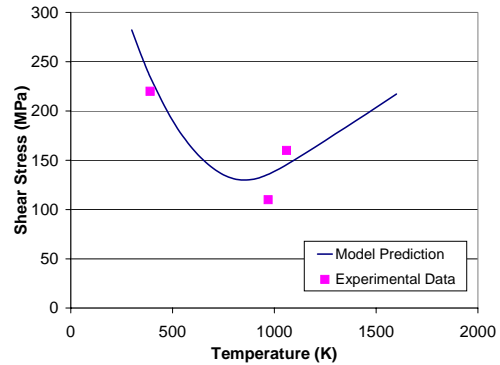

Figure 5. Comparison of the measured flow stresses in high purity aluminum at very high strain rates with predictions of a dislocation dynamics model (e.g. [5]) that includes both thermal activation and phonon drag.

the sharpness of the increase at high temperatures suggests that further consideration of rate controlling mechanisms in this regime is required.

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