Dynamic Flow Stress Measurements of 6061-T6 Aluminum under Rapid Heating for Machining Studies

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ABSTRACT
The flow stress of aluminum alloy Al6061-T6 produced by conventional thermomechanical methods has been investigated under the application of strains up to 80 % at a strain rate of the order of 10^3 1/s, and temperatures ranging from ambient to near melting. The high strain and strain rate deformation was imposed using a Kolsky bar apparatus equipped with a fast pulse-heating system to reach the target temperatures at high heating rates. The flow stress was measured to provide a constitutive model under strains, strain rates, temperatures and heating rates that match thermomechanical conditions developed in the primary shear zone for specially-designed comparative machining tests. It is expected that these measurements will enable the formulation of realistic machining models for Al6061-T6. Temperature measurements were obtained using non-contact infrared (IR) full field imaging together with embedded micro-thermocouple (TC) point probing, the latter being used to estimate the emissivity of the aluminum sample via separate, *in situ* calibration tests. Type-K TC measurements were made using the separated junction principle by embedding the TC wires into two micromachined holes in the specimen. The temperature measurement technique is discussed in detail, and temperature uncertainties are estimated. The technique will be used going forward to study the effect of heating time on the dynamic thermal softening behavior of Al6061-T6, which has been shown to be time-sensitive under quasi-static loading when temperatures exceed 200 °C due to Mg-Si precipitate growth.

KEY WORDS: Aluminum, Plastic Behavior, Kolsky Compression, Machining, High Strain, High Strain Rate, High Temperature, High Heating Rate.

INTRODUCTION

Manufacturing processes impose extreme strains, strain rates and temperatures [1]. Because these processes are designed to transform materials, it is important to understand material behavior under such extreme conditions. In particular, for machining, accurate information about the mechanical response of the workpiece material is required to obtain predictive models to optimize performance measures such as surface roughness, energy expenditure and tool wear [2]. One well-known experimental approach that provides accurate information about mechanical response (flow stress) under extreme thermomechanical conditions is the Kolsky bar compression technique. With this technique, dynamic compression (high strain and strain rate) that is similar, in terms of peak strains and strain rates, to deformation imposed by machining may be produced. The Kolsky compression tests may be performed under elevated temperature. However, the heating rates commonly employed in this kind of material testing are quite low compared to those occurring during machining. As a result, the flow stress data obtained may reflect equilibrium material conditions that are quite different than the transient conditions present during machining if the material transforms under heating. For example, in aluminum alloy Al6061, Mg-Si precipitates can grow above 200 °C, causing a significant change in flow stress depending on the time-at-temperature [3].

This work presents results from dynamic compression experiments performed on a model, precipitation treatable alloy (aluminum alloy Al6061-T6), with a special Kolsky bar apparatus equipped with an electric pulse heating element. The compression was performed at high strains and strain rates (up to 80 % and 10^3 1/s, respectively), and at elevated temperatures (up to 500 °C) under rapid heating (of the order of 1000 °C/s). These conditions were selected to match strain, strain rate, temperature and heating rate achievable by special machining tests, where the strains were lowered to less than 100 % by the combined application of highly-positive rake angles and chip pulling [4]. The work is aimed at the generation of material models that include contributions from non-equilibrium, time-sensitive, phase transformations that might be more suitable for simulating machining processes compared to models developed from more conventional high temperature Kolsky bar techniques.

EXPERIMENTAL

An extruded 6061-T6 aluminum block purchased commercially was used as the specimen source. The specimens were cut from this block using electrical discharge machining (EDM). Disk-shaped specimens measuring 4 mm in diameter and 2 mm in thickness were dynamically compressed with a Kolsky bar system under both ambient temperature conditions and with rapid pre-heating using a pulse-direct current heating method [5]. Dynamic compression experiments were conducted with a 375 mm striker launched pneumatically at a gage pressure of 205 kPa (30 psi), which produced plastic strains up to 80 % at strain rates of the order of 10^3 1/s. For smoothing the incident pulse, copper pulse shapers, measuring 6.35 mm diameter and 0.0254 mm thick (¼ inch diameter and 0.01 inch thick), were placed in between the striker bar and the incident bar. The strain pulses were measured by metal foil strain gages connected to a battery-powered bridge circuit. The output was sampled at 2 MHz using a digital oscilloscope.

For carrying out the heated Kolsky bar experiments, a single short direct current pulse, produced by a low voltage, high current capacity battery bank (12 V), was passed through the specimen and the bars. Samples were heated using controlled current pulses of 35 A to 90 A with the times ranging from several seconds down to 0.2 s in order to obtain a range of temperatures and heating times prior to impact. With 35 A being the lowest controllable current for the equipment and specimen size used in this study, the minimum achievable steady-state temperature was about 360 °C. Since precipitate growth becomes an issue at temperatures as low as 200 °C, it was of interest to explore lower temperatures, which were achieved by short, ramped current pulses with durations less than 1 second. Because of the very high thermal conductivity of aluminum, the temperature uniformity of the specimens was good even during these very short ramped experiments.

Temperature measurements were obtained using an *in situ* calibrated mid-wave infrared (MWIR) thermal camera, with operating wavelengths between 1.5 µm to 5 µm, a sensor integration time of 150 µs, a frame rate of 870 Hz, and a sensor resolution of 160 pixels by 128 pixels with a magnification yielding 38 µm/pixel. The camera was first calibrated using a blackbody furnace, followed by a second *in situ* calibration that consisted of imaging heated aluminum samples while simultaneously measuring the temperature with a fine-wire (0.127 mm, 0.005 in diameter) type-k thermocouple embedded within the sample. Embedding the thermocouple was necessary because the individual wires were too fine to be reliably spot-welded onto the surface. Embedding the wires involved carefully drilling two small holes into the side wall of the sample using a #80 drill mounted on a linear micrometer stage (Figure 1, left). Each thermocouple wire was press-fit into a hole using a second, small piece of the same thermocouple wire as a wedge. An installed thermocouple can be seen in Figure 1, right. With this distributed-junction thermocouple technique, sample temperature measurements were obtained during the *in situ* thermal camera calibration tests to determine the effective surface emittivity (emissivity plus scattering) for the aluminum samples in the Kolsky bar measurement environment. While it was also determined that the thermocouple holes did not significantly affect the flow stress measurement by comparing identical compression tests on samples with and without holes, it was decided to use the calibrated thermal camera to determine impact temperatures for heated compression tests to avoid having to drill each sample.

The stress-strain curves were analyzed using the usual wave analysis methods [5] with two exceptions. First, because graphite foil was used as a lubricant in the heated tests as well to avoid electrical arcing during heating, the mechanical contribution of the foil was subtracted from the total mechanical response to obtain the specimen response. The complete method of graphite foil correction can be found in the work done by Mates et al. [5]. The other correction implemented was the correction of the elastic indentation of the bars during the dynamic compression, using the method described by Safa and Gary [6]. However, this correction is almost negligible for aluminum.

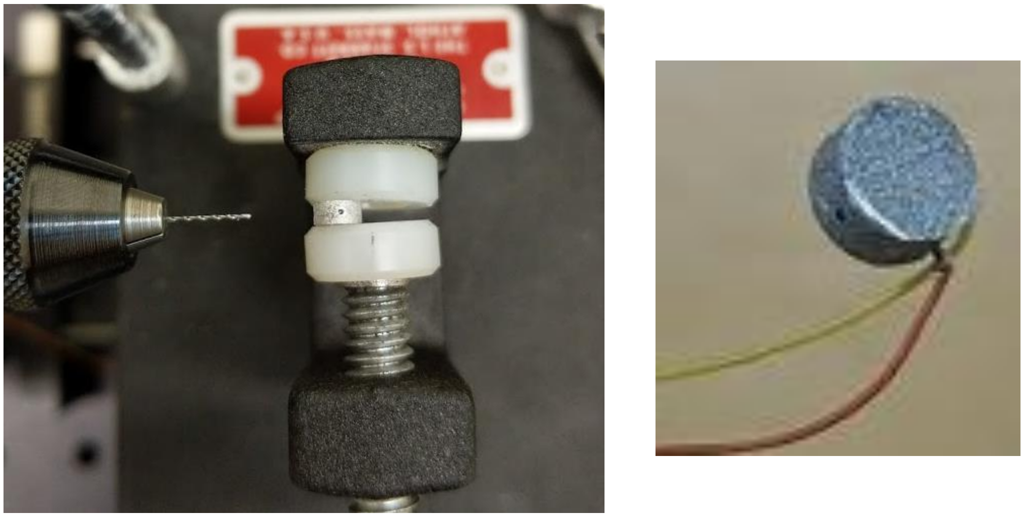

Figure 1. Procedure for drilling holes for the micro-thermocouple point probing installation on a 2 mm thick by 4 mm diameter aluminum sample.

RESULTS

Figure 2 illustrates the flow stress of Al6061-T6 at essentially ambient temperature, without any current going through the sample prior to or during the test. Any temperature rise during this test is only from dissipation of plastic work arising from the compression. Estimates based on temperature measurements using the embedded thermocouple indicate this temperature rise to be no more than 50 °C. In these experiments, grease lubricant was used instead of the foil, and therefore the stress-strain analyses were performed with only the elastic indentation correction applied. The drop-off in the flow stress for strains close to 0.8 is caused by the release-wave, which is produced at the end of the experiment, and does not represent material failure. Also, the upturn in the curve starting from strain about 0.7 may be attributed to friction. The curve shown in the figure represents the mean flow stress of 9 experiments performed under identical impact conditions. The error bars correspond to three times the standard deviation of the flow stress at each strain point. The flow stress observed corresponds well to previous studies of aluminum alloys [7]. The values measured also correspond well with flow stress estimates from special machining tests performed with the intention of matching the strain and strain rate of our Kolsky bar tests performed at ambient temperature [4]. These machining tests were designed to match strains and strain rates in the Kolsky bar tests. The machining tests performed at strain of 0.6, strain rate 10^2 1/s and essentially ambient temperature resulted in flow stress of 383 MPa [4]. This value is within the measurement error in flow stress shown in Figure 2. The agreement between the machining test and the Kolsky bar data is good despite the differences in stress states between the two types of test. The strain rate produced by the machining test was an order of magnitude lower than that produced by the Kolsky bar test. Future machining tests will be performed at faster cutting speeds to improve the strain rate match. However, flow stress estimates are not expected to change significantly, as it is known that the strain rate sensitivity of Al6061-T6 is low at strain rates less than 10^4 1/s [7].

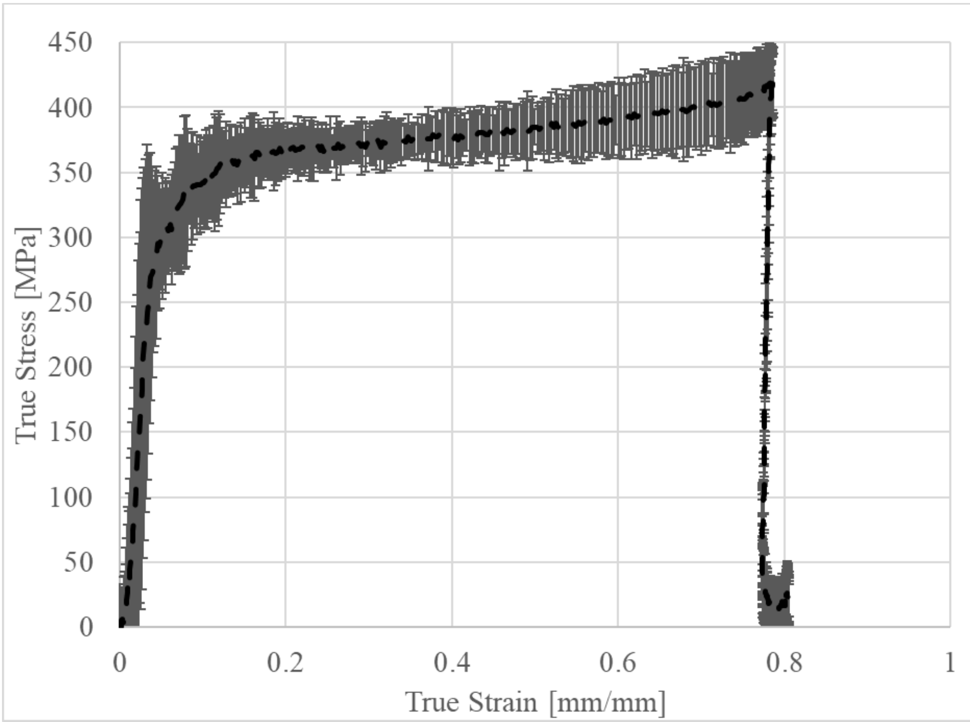

Figure 2. Flow stress as a function of strain. The flow stress is estimated by an average based on 9 repeated experiments. The error bars correspond to ± 3 standard deviations.

Figure 3 shows the plastic flow stress at several temperatures up to about 500 °C at a fixed level of plastic strain (50 %). The heating was performed by applying current pulses of different dwell times (heating times). However, the heating time was always very short – with a maximum of 7.5 s. The higher the temperature and the longer the heating time, the smaller the flow stress (Figure 3). This result is generally reflective of what has been shown at lower strain rates, where time-sensitive thermal softening is likely caused by precipitate growth [3], although grain growth may also play a role as well. In reference [3], a significant reduction in flow stress was reported when a test was performed after subjecting the material to a thermal treatment. The thermal treatment had for target temperature 400 °C. The heating rate was 200 °C/s, and the cooling rate was of the order of 10 °C/s. Therefore, the total time under temperature above 275 °C/s was about 15 s. In Figure 3, points of flow stress and specimen temperature for a given dwell time are assigned a unique color (see the legend in the figure). For the two tests with impact temperatures just below 300 °C and heating times of 3.5 and 7.5 s (one orange point and one red point in Figure 3), the specimens were heated to a steady temperature of about 360 °C and then allowed to cool prior to impact by delaying the striker impact slightly. With a cooling rate of several hundred degrees per second, the striker delay to achieve the final temperature was of the order of 0.1 s. Experiments above 360 °C for heating times longer than 1 s were heated continually until impact, while experiments heated for 0.3 s were obtained with no dwell time or cooling by using a ramped current pulse. For the temperature range from 250 °C to 350 °C, Figure 3 shows a significant difference in the flow stress between sub-second heating times (green and blue points) and the longer heating times (red and orange points). This temperature range matches that over which precipitate growth is promoted by heat energy (see ref. [3]). It is compelling to think that the effects observed herein are due to the dependency of the size and distribution of the Mg-Si precipitates on heating time. This hypothesis needs to be verified by direct observation of the precipitates. In any case, for applications such as machining, where temperature easily rises several hundred degrees Celsius over a fraction of a second, the elevated-temperature Kolsky compression testing developed for this study may provide thermal softening parameters over applicable, high heating rates. Thermal softening parameters derived from slow heating Kolsky compression tests may not be valid for such problems. Further work will focus on developing a more extensive data set from dynamic compression tests obtained under a wider range of thermal histories, and on the characterization of precipitate growth as a function of thermal history using advanced metallography techniques.

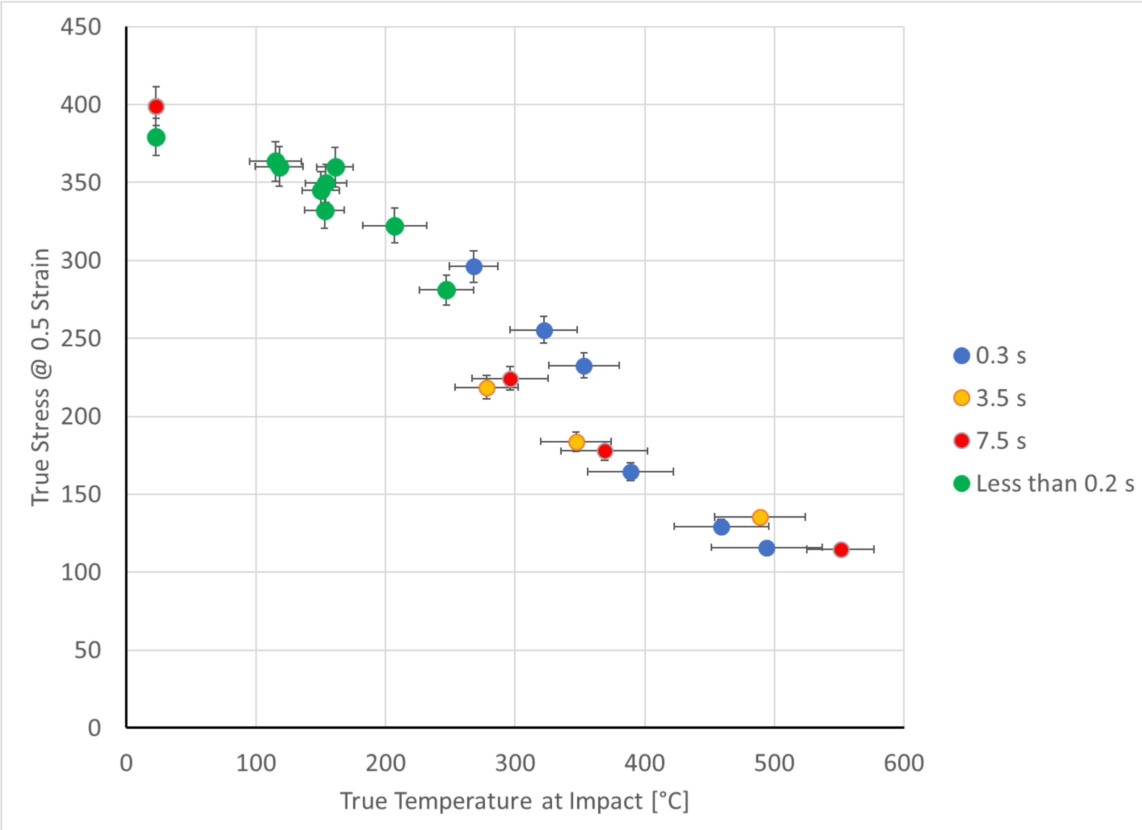

Figure 3. Flow stress of 6061-T6 at several temperatures using the short-pulse-heating method with temperatures determined from the thermal camera. Temperatures are those just prior to impact (within 1.6 ms (=1/614 s)). Error bars on stress are computed from error propagation (95 % confidence interval) and error bars on temperature are computed from thermal gradient measurements obtained during each experiment. The legend shows applied temperature dwell times (heating times).

CONCLUSIONS

At strains of 50 %, strain rates of about 10^3 1/s and near ambient temperature, the flow stress of Al6061-T6 derived from dynamic Kolsky compression tests matches the flow stress derived from machining tests. As the temperature increases, the flow stress decreases. However, differences in thermal softening rates are observed depending on the heating time, owing perhaps to the time-dependent growth of Mg-Si precipitates. The high heating rate, elevated-temperature Kolsky compression test developed for this study offers a unique platform to investigate the effects of time-sensitive material transformations on mechanical response. Future work will expand exploration of time-sensitive material behavior in this model alloy. It will also provide direct observations of the effect of precipitate growth over very short times (of the order of seconds or less) on flow stress, which can be used to develop material models that are better-suited to model machining processes.

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REFERENCES

[1] S. Kalpakjian and S. R. Schmid, Manufacturing Processes for Engineering Materials, Upper Saddle River, New Jersey: Pearson, 2007.

[2] J. S. Strenkowski and J. T. Carroll, "A Finite Element Model of Orthogonal Metal Cuting," *Journal of Engineering for Industry*, vol. 107, no. 4, pp. 349-354, 1985.

[3] D. Maisonnette, M. Suery, D. Nelias, P. Chaudet and T. Epicier, "Effects of Heat Treatments on the Microstructure and Mechanical Properties of a 6061 Aluminium Alloy," *Materials Science and Engineering A*, vol. 528, pp. 2718-2724, 2011.

[4] C. Cui, P. Bhavsar, H. Lopez-Hawa, V. Madhavan and W. Moscoso-Kingsley, "Comparison of Flow Stress of Aluminum Alloy 6061-T6 Obtained From Chip-Pulling Orthogonal Cutting and Kolsky Bar Testing," in *SME North American Manufacturing Conference*, Ohio, 2020 (submitted for review).

[5] S. P. Mates, R. Rhorer, B. Timothy and D. Basak, "A Pulse-Heated Kolsky Bar Technique for Measuring the Flow Stress of Metals at High Loading and Heating Rates," *Experimental Mechanics*, vol. 48, pp. 799-807, 2008.

[6] K. Safa and G. Gary, "Displacement Correction for Punching at A Dynamically Loaded Bar End," *International Journal of Impact Engineering*, vol. 37, pp. 371-384, 2010.

[7] A. Manes, L. Peroni, M. Scapin and M. Giglio, "Analysis of strain rate behavior of an Al 6061 T6 alloy," *Procedia Engineering*, vol. 10, pp. 3477-3482, 2011.