Split Hopkinson Pressure Bar compression testing of an aluminum alloy: Effect of lubricant type

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The Split Hopkinson Pressure Bar (SHPB), or Kolsky Bar, is widely used for studying the dynamic mechanical properties of metals and other materials. A cylindrical specimen is sandwiched between the incident and transmitter bars, Fig. 1, and a constant amplitude elastic wave is generated by the striker bar. Strain gages mounted on the incident and transmitter bars allow the compressive stress-strain response of the specimen to be established using uniaxial elastic wave theory [1]. A more detailed overview of SHPB testing is found in [2]. Lubricant is usually applied to the interfaces because the presence of any frictional effect on the specimen surfaces forms a multiaxial stress-state and invalidates one of the most important assumptions of the SHPB analysis, namely, a uniaxial stress state. This paper quantifies the effect for an aluminum alloy. The friction effect in a compression test may be estimated by Siebel's [3] analysis:

$$P = \left(1 + \frac{\mu D}{3L}\right)\sigma_\varepsilon \quad (1)$$

P is the applied mean pressure, μ is the coefficient of friction, D and L are the specimen diameter and length respectively, and σ_ε is the material flow stress at strain ε. For fixed specimen geometry, the measured stress value is the only parameter that is a function of μ. Using a specimen aspect ratio, $L/D \sim 0.5$, as proposed by Davies and Hunter [4] and their suggested friction coefficient (0.02–0.06), the error in the analysis is found to be between 1.3 and 4%. The flow stresses of many pure metallic materials, such as Cu and Al, typically increase at high strain rates by only 25% or less over the quasi-static values. Since alloying and thermal processing tend to reduce rate sensitivity of the metals significantly [5], the importance of measurement errors involved increases dramatically. Therefore, friction effects must be quantified, particularly for materials having relatively low strain rate sensitivities such as Al alloys. Better estimation of friction effects also allows more precise determination of a material's constitutive equation.

An Al 6061-T651 alloy was tested at approximately constant strain rate using no lubricant initially, followed by a range of solid and liquid lubricants. Small cylindrical specimens having an aspect ratio of 0.77 and length of 6.45 mm were core drilled from an alloy plate. Before testing, the surfaces of the alloy sample were diamond polished down to 3 μm. Other aspect ratios between 0.5 and 1 were tested to investigate any effect of aspect ratio but none was found. Multiple tests were conducted for each case. Detailed information on the SHPB used in this study can be found elsewhere [6].

Two lubricant types were used: (a) solid lubricants, (MoS_2 powder, graphite powder and Teflon tape) and, (b) liquid lubricants (light oil, grease, and silicone-oil). Unlubricated samples were also tested for comparison. For each test, the strain rate was maintained approximately constant. Additional tests were conducted for comparison purposes at quasi-static strain rate using grease as lubricant. After each test, the total strain imposed on the sample was measured using a micrometer to compare with the final strain values calculated from SHPB tests.

High strain rate ($\sim$1350 s^{-1}) flow stress values of the samples are shown in Fig. 2 at strain values of 5, 10, 15, 20 and 25%. The abscissa refers to the lubricant type as shown in the legend: the numbers were selected simply for convenience in illustrating the relative effects, and the trend lines have no numerical significance but are intended solely to make the analysis clearer.

Large differences in flow stress values are observed. The difference in stress values between non-lubricated and the best liquid lubricated samples was found to be 8% at 5% strain and 11% at 25% strain. This magnitude of difference cannot be neglected in the case of testing materials having relatively low strain rate sensitivity. For example, quasi-static testing of the same alloy showed flow stresses at 5, 15 and 25% strain of 332, 420 and 502 MPa respectively. Comparable figures for the grease-lubricated samples tested at high strain rate are 361, 440 and 517 MPa respectively, or approximately 9%, 5% and 3% greater than quasi-static values. Clearly, the potential uncertainty in dynamic flow stress for unsatisfactorily lubricated samples is of the same order of magnitude as the effect of strain rate sensitivity.

One of the common signs of frictional effects during compression loading of cylindrical specimens is barreling but in the present tests none of the specimens showed any significant barreling, even at 25% strain. This shows that lack of barreling alone is not an indication of the absence of frictional effects.

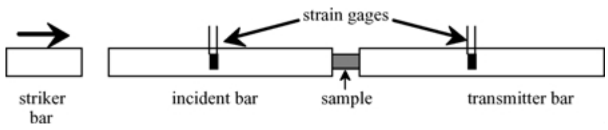

Figure 1 Schematic lay-out of Split-Hopkinson Pressure Bar apparatus.

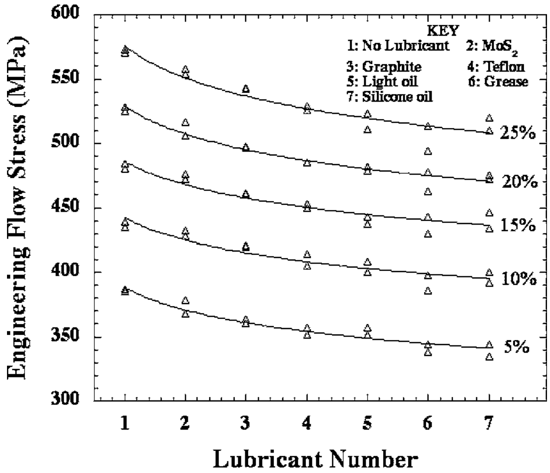

Figure 2 Flow stress at indicated strains for different lubricants.

The flow stress-strain curves of samples tested with liquid and solid lubricants are shown in Figs 3 and 4 respectively. Compared to the liquid lubricants, the solid lubricants resulted in more scattered flow stress values. Also the final strain values of the samples tested with liquid lubricants were between 31–32%, while they were 27–31.5% for the samples tested with solid lubricants. Like flow stress values, the final strain values in the case of solid lubricants are more scattered than those of the liquid lubricants. Since the incident wave amplitudes were essentially identical for each sample, the reduced final strain values (at the same strain rate) for samples tested with solid lubricants show the effect of friction, i.e., not all the pressure applied was used to deform samples.

The corresponding strain rate vs. strain curves of unlubricated, MoS_2-lubricated and grease-lubricated samples are shown in Fig. 5 as representative of each of

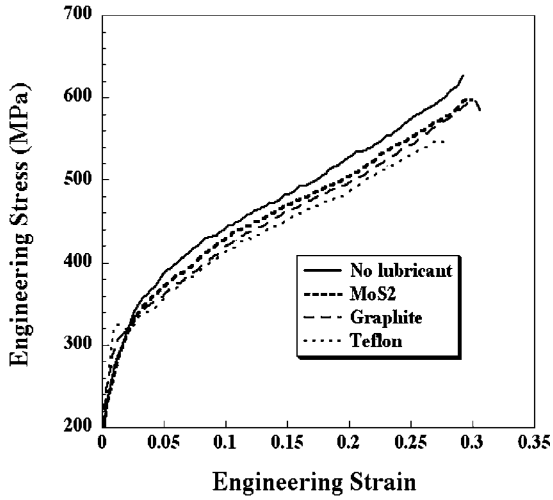

Figure 4 Stress vs. strain curves for unlubricated sample and several solid lubricants.

the 3 cases, no-, solid and liquid lubricants. An almost constant strain-rate of 1350 s^{-1} was attained in the case of grease-lubricated sample as shown in Fig. 5. Strain-rate in the case of solid- and no-lubricant was, however, observed to diminish slightly as the strain increased. The reduction in the strain rate in the case of no-lubricant was about 150 s^{-1} over the entire deformation.

Strain values calculated from SHPB data were compared with micrometer measurements and the percentage error was calculated as:

$$\%\text{Error} = \frac{(\text{calculated strain} - \text{measured strain})}{\text{measured strain}} \quad (2)$$

The percentage errors, shown in Fig. 6, show that the error values are between 1 and 3.5%, and liquid lubricants generally show less scatter. This confirms that conventional SHPB tests on homogeneous alloy specimens can be conducted with a reproducibility of $\sim$1% with an appropriate lubricant type well-polished specimens surfaces.

The above findings, however, apply to the case of only one strain-rate and a specific sample geometry.

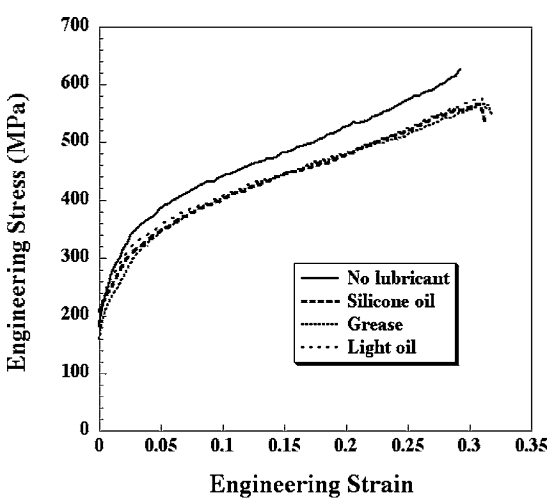

Figure 3 Stress vs. strain curves for unlubricated sample and several liquid lubricants.

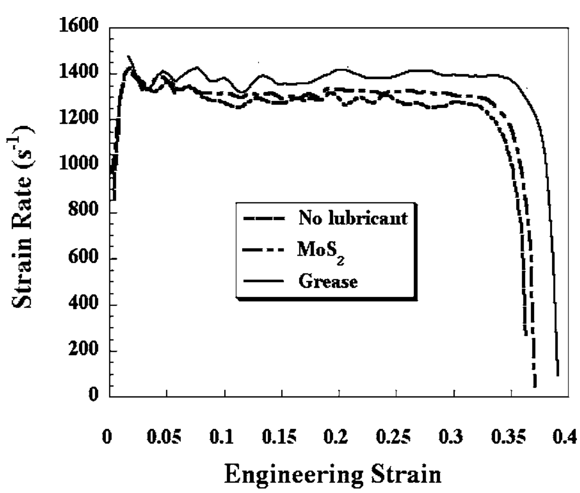

Figure 5 Strain rate vs. strain curves for typical unlubricated, liquid lubricated and solid lubricated samples.

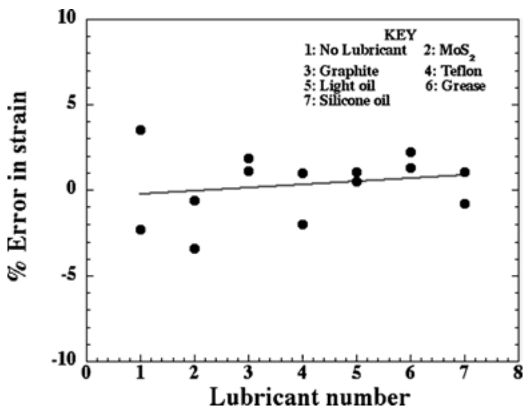

Figure 6 Percentage error in strain (measured vs. calculated from SHPB data) as a function of lubricant type.

A more rigorous and detailed analysis would call for investigation of the effects of strain rate, surface roughness and geometry of the specimen on the frictional constraining effects. When comparing the quasi-static flow stress data with the high strain rate flow stress data, one has, however, to be very careful, because differing degrees of frictional constraining effect would possibly occur in each test. That problem may possibly be solved using several tests of different aspect ratios so that frictional effects could be isolated and minimized.

The 6061-T651 Al alloy was compression tested at a constant strain rate with no-lubricant, solid, and liquid lubricants. It was found that liquid lubricants were more effective in reducing the friction effect resulting in lower flow stress values, increasing the final strain values and consequently increasing the accuracy of the test results. The range of stress values between aluminum alloy samples tested without lubricant and with various liquid type lubricants was found to be sufficiently high to hinder the determination of correct material response at high strain rates unless close attention is paid to adequate and consistent lubrication. Similar variability was found for the solid lubricants investigated.

References

1. H. KOLSKY, *Proc. Phys. Soc.* **B62** (1949) 676.
2. G. T. GRAY III, in "Methods in Materials Research" (Wiley, New York, NY, 1997).
3. E. SIEBEL, *Stahl u. Eisen* **43** (1923) 1295.
4. E. D. H. DAVIES and S. C. HUNTER, *J. Mech. Phys. Solids* **11** (1963) 155.
5. D. L. HOLT, S. J. BABCOCK, S. J. GREEN and C. J. MAIDEN, *Trans. ASM* **60** (1967) 152.
6. M. GUDEN and I. W. HALL, *Matls. Sci. and Eng. A* **A232** (1997) 1.

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