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THE YOUNG'S MODULUS OF 1018 STEEL AND 6061-T6 ALUMINIUM MEASURED FROM QUASI-STATIC TO ELASTIC PRECURSOR STRAIN-RATES

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Abstract. The assumption that Young's modulus is strain-rate invariant is tested for 6061-T6 aluminium alloy and 1018 steel over 10 decades of strain-rate. For the same billets of material, 3 quasi-static strain-rates are investigated with foil strain gauges at room temperature. The ultrasonic sound speeds are measured and used to calculate the moduli at approximately 10^4 s^{-1}. Finally, 1D plate impact is used to generate an elastic pre-cursor in the alloys at a strain-rate of approximately 10^6 s^{-1} from which the longitudinal sound speed may be obtained. It is found that indeed the Young's modulus is strain-rate independent within the experimental accuracy.

Keywords: modulus, metal, strain-rate
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INTRODUCTION

It is an implicit assumption in structural engineering and materials science that the elastic moduli of metals is a weak function of temperature [1, 2] but strain-rate invariant. The authors performed an extensive literature search to show that this assumption had been tested and the results published. Nothing relevant was found for common metallic elements or alloys. It was therefore decided to determine the Young's modulus of two pedigreed metals at strain-rates from quasi-static up to elastic precursor rates and show that the value was indeed constant when tested at room temperature and corrected for conditions such as the difference between isothermal and adiabatic compression. The strain-rates used cover approximately 10 decades.

For the study, two common structural alloys were chosen, a 0.17% carbon steel, 1018 and 6061-T6 aluminium. The specific billets used have both been previously characterized for prior research [3, 4, 5].

EXPERIMENTAL

Four methods were used to measure the moduli at different strain-rates. Strain gauges were bonded to ASTM compliant compression samples to make quasi-static measurements (9.3×10^{-5} and 9.2×10^{-4} s^{-1}). Compression measurements were also made in a high-speed servo hydraulic machine (0.52 (1018) and 1.8 s^{-1} (6061)).

Two pairs of 5 MHz ultrasonic transducers were used to make time of flight measurements of the longitudinal and shear wave-speeds at strain rates of approximately 10^4 s^{-1}.

Finally an 80mm light gas gun was used to perform symmetric 1D plate impacts on samples to generate an elastic precursor ahead of the plastic wave. The strain-rate of the elastic precursor was measured to be approximately 10^6 s^{-1}.

The density (ρ) of the two materials were measured using a helium gas pycnometer (Micromeritics Accupyc 1330). The densities are shown in table 1.

For the strain-gauge experiments, 9.525 mm diameter right cylinders that were 19.05 mm tall had two Measurements Group CEA-13-062WT-120 strain gauges bonded to the circumference forming a half bridge arrangement. These particular gauges have two foils at 90 degrees allowing the Poisson ratio and Young's modulus to be simultaneously measured. Using the supplied manufactures gauge factor information and calibrated shunt resistors the strains measured are estimated to be significantly better than 1% of the absolute measured value. The repeatability is expected to be significantly better than 0.2%.

The speed of sound in the alloys was measured using a time of flight method. Room temperature samples 12.7 mm thick were tested using longitudinal and shear wave inducing heads[1]. The measured times were suitably correcting for triggering and coupling medium delays. Values for Young's modulus (E), Poisson ratio (ν) and shear modulus (G) are obtained using the material densities quoted above and the following expressions,

$$\nu = \frac{C_l{}^2 - 2C_s{}^2}{2(C_l{}^2 - C_s{}^2)}, \quad (1)$$

$$E = 2\rho C_s{}^2(1+\nu), \quad (2)$$

where C_l and C_s are the longitudinal and shear wave-speeds respectively and ρ is the density. These expressions are only valid for isotropic solids however it has been shown that elastic constants for most engineering materials are relatively insensitive to crystallographic size and modest texture[1, 2]. Estimating the strain rate imposed by this method is difficult since the displacement imposed by the transducer is unknown and difficult to measure. Private communication with the manufacturer suggests that the likely strain-rate is approximately 10^4 s^{-1}.

To generate an elastic precursor to a 1D plane strain plastic wave, an 80 mm light gas gun was used to perform symmetric impacts at 671.6 ± 2.0 m s^{-1} for 6061-T6 and 591.7 ± 2.0 m s^{-1} for 1018 steel. Assuming the shock speed versus particle relation ship shown in table 1, the impacts generated peak pressures of 5.29 GPa for 6061 and 11.7 GPa for 1018. The pressure in 1018 was below the $\alpha - \varepsilon$ phase transition. Both targets had a step on the rear surface to generate information at two target thicknesses (nominally 5 mm and 12.7 mm) and were large enough that release fans from the step did not reach the diagnostics until late in the experiment. The free surface velocity was measured using a PDV system [6]. The assumption that the particle velocity is half the measured free velocity has been used. Referring to [7], the authors calculated a correction to half the free surface velocity approximation for an aluminium alloy at pressures between 14.6 and 33.1 GPa. At the lowest pressure they reported the correction factor was only -0.06% increasing to -0.35% at the highest. Because the pressures reported here at significantly lower than in [7], the assumption is therefore a valid one.

TABLE 1. Material data required for shock pressure calculation. Data from [8, 9]

Material	Density / kg m^{-3}	C_0 / m s^{-1}	S
6061-T6	2714.0 ± 0.7	5350	1.34
1018	7839.7 ± 1.9	4632	1.385

At the impact velocities used, the longitudinal sound speed is faster than the plastic wave resulting in a measurable HEL. Using the exact distance between the target steps and the time to free surface breakout at each thickness, the longitudinal sound speed was calculated. Owing to the modest target thicknesses used and difficulty estimating the exact time of particle motion at the rear surface, the plate impact sound velocity is known to 2% of the measured values. Because the 1D strain modulus is proportional to the wave-speed squared this will increase the error to 4% for this measurement.

The elastic moduli of metals differs if the measurement is made under isothermal or adiabatic conditions[10][2]. Using easily found literature values for the materials, it is found that for the metals considered here the correction factor is only +0.02% for the Young's modulus and +0.11% for Poisson ratio from isothermal to adiabatic. It is assumed that the tests at 10^{-5} and 10^{-4} s^{-1} are isothermal and the remainder are adiabatic.

[1] Panametrics 5077PR Pulser/Receiver, Panametrics V155 & V109 transducers. Timing obtained from a Tektronix TDS 754D Oscilloscope

[2] In the 3rd edition there are typographical errors in this section. a 9 should be a ρ while in eqn. 6.7 the denominator should be ρC_p

TABLE 2. Isothermal elastic moduli.

Material Strain-Rate / s^{-1}	E / GPa	ν
6061, 9.3×10^{-5}	70.10 ± 0.7	0.3370 ± 0.0034
6061, 9.2×10^{-4}	70.22 ± 0.7	0.3316 ± 0.0033
1018, 9.3×10^{-5}	208.5 ± 2.1	0.2750 ± 0.0028
1018, 9.2×10^{-4}	208.3 ± 2.1	0.2719 ± 0.0027

TABLE 3. Intermediate strain-rate elastic moduli.

Material Strain-Rate / s^{-1}	E / GPa	ν
6061, 1.8	70.6 ± 0.7	0.337 ± 0.003
1018, 0.52	208.3 ± 2.1	0.274 ± 0.0027

RESULTS

Between 3 and 6 tests at each rate were undertaken to establish the quasi-static Young's modulus (9.3×10^{-5} and 9.2×10^{-4} s^{-1}) in each material. The Young's modulus is designated, E, and the Poisson ratio, ν. The results are presented in table 2. Table 3 contains the results for intermediate strain rates obtained on the high-speed servo-hydraulic load frame. The data from three samples were averaged to obtain the results.

The results from ultrasonic testing are shown in table 4. As previously described, from a knowledge of the sample density and the longitudinal (C_l) and shear (C_l) wave-speeds, the elastic moduli may be calculated.

Owing to the 1-D strain present in plate impact experiments, the axial modulus measured is not Young's modulus but the longitudinal modulus (L).

$$L = \rho C_l^2. \qquad (3)$$

It may be shown that E is related to L by the following expression,

$$E = \frac{L(1+\nu)(1-2\nu)}{(1-\nu)}. \qquad (4)$$

To calculate the Young's modulus from the shock data the assumption is made that the Poisson ratio is constant with respect to strain-rate and the value from the ultrasonic results is used. The strain-rate was measured from the PDV rise times and the fact that the strain is just U_p/U_s where U_p is the particle

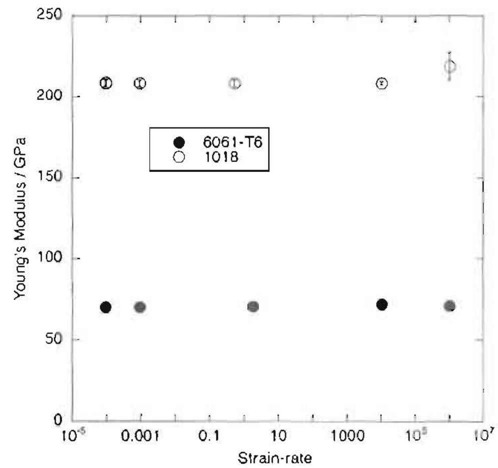

FIGURE 1. A summery of the room temperature Young's modulus as a function of strain rate for both materials. Error bars for modulus are plotted but with only one exception they do no extend outside the symbol

velocity (half the impact velocity in a symmetric impact) and U_s is the measured sound speed. The results from the shock experiment are shown in table 5.

The results from all of the above moduli calculations are summarized in figure 1

DISCUSSION

The elastic modulus of 1018 has been previously studied at intermediate strain-rates ($\approx 10^3 s^{-1}$)[11]. The reported density of their 1018 was 7833.5 ± 5.78 kg m^{-3} which compares favorably with the value of 7839.7 ± 1.9 kg m^{-3} reported here. Averaging over 276 measurements, the Young's modulus was 207.1 ± 2.75 GPa which again compares favorably with the values reported here. The ultrasonic wave properties of 1018 have also been previously reported[12]. The density was again measured at 7833 kg m^{-3} and C_l was 5857 m s^{-1} and C_s can be calculated as 3280 m s^{-1}. These values are comparable to those measured by the authors.

The wave-speed properties of 6061 have been previously measured[8, 1]. The reported densities were 2703 and 2700 kg m^{-3} respectively which are approximately 0.18% lower that measured here. The

TABLE 4. Ultrasonic wave speeds and calculated elastic moduli. Strain-rate $\approx 10^4$ s^{-1}

Material	C_l m s^{-1}	C_s m s^{-1}	E / GPa	ν
6061	6398 ± 30	3142 ± 15	71.86 ± 0.59	0.3411 ± 0.0028
1018	5890 ± 30	3210 ± 15	208.2 ± 1.1	0.2887 ± 0.0042

TABLE 5. Gas-gun longitudinal sound speed. Young's modulus calculated assuming Poisson ratio from ultrasonic results. Measured strain-rate $\approx 1 \times 10^6$ s^{-1}

Material	C_l m s^{-1}	E GPa
6061	6359 ± 127	71.0 ± 2.8
1018	6040 ± 120	218.8 ± 8.6

sound speeds quoted in [8] are $C_l = 6400$ m s^{-1} and $C_s = 3150$ m s^{-1} while reference [1] reports $C_l = 6350$ m s^{-1} and $C_s = 3210$ m s^{-1}. The later paper reports some variation in wave-speeds with respect to forging direction of the sample and some difficulty getting accurate shear wave-speeds owing to experimental concerns.

It is clear that the calculated room temperature Young's modulus for 6061-T6 and 1018 is independent of strain-rate over nearly 8 decades when it is directly measured. In the case of 6061-T6, the calculated Young's modulus is constant over 10 decades if the assumption of a constant Poisson ratio is valid. The error bar for shock loaded 1018 does not quite reach the rest of the data when calculated, however, it is not thought that this anomaly is real and that it is caused by the relatively poor velocity sensitivity of the shock experiment.

In summary, for the metal alloys studied here the Young's modulus is found to be strain-rate independent to better than the resolution of the experiments (generally 1% or better).

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