Stress-strain data for aluminum 6061-T651 from 9 lots at 6 temperatures under uniaxial and plane strain tension

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1. Data

Stress-strain curves for two kinds of test specimens are presented as csv files in a public data repository on Mendeley Data [3]. The csv files in the repository are labeled with the specimen type, temperature of the test, lot, and specimen number within the lot.

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https://doi.org/10.1016/j.dib.2019.104085
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The two types of test specimens used are shown in Figs. 1 and 2. Fig. 3 shows the stress state in the plane strain test specimen obtained from finite element analysis. Figs. 4–6 show the test setup, specimen attachment to the loading machine, and speckle pattern used to facilitate digital image correlation respectively. Figs. 7 and 8 show the gauge section used for strain measurements. Fig. 9 shows the distribution of stress across the cross section of the plane strain specimen, from finite element analysis. Table 1 shows the number of specimens from each lot tested at each temperature. Table 2 shows the available data about chemical composition of the material from the lots.

2. Experimental design, materials, and methods

The following sections describe the design and material selection of the tested specimens, the test setup and experimental procedure, a brief appraisal of errors in the test measurements, and the methodology used for computing stress-strain curves.

2.1. Specimen design

Two types of specimens were tested: a standard “dogbone” type uniaxial tension coupon and a custom plane strain tension specimen. Design of the uniaxial tension specimens followed the guidelines in ASTM E8 [4], with the exact geometry of the specimen shown in Fig. 1. Using digital image correlation (DIC), different gauge lengths can be considered for strain measurement. In keeping with established standards, a 2 in. gauge length is used to calculate strains in uniaxial tension.

Unlike uniaxial tension, standard geometries (e.g. ASTM E8) do not exist for plane strain tension specimens. The specimens here were designed to achieve a condition as close as possible to plane
strain and were derived from [5]. The geometry of the plane strain specimens is shown in Fig. 2. Finite element modeling was conducted to verify the approximately plane strain stress state within the gauge section of the specimen as illustrated in Fig. 3, which shows contours of equivalent plastic strain, von Mises stress, and stress triaxiality \( \eta \) at a given point during the inelastic response. The specimen, however, is not under a uniform stress state throughout the reduced section. The stress state at the edges is approximately uniaxial tension \( \left( \eta = \frac{1}{3} \right) \) while only approximately the center third of this cross-section is in plane strain \( \left( \eta = \frac{1}{\sqrt{3}} \right) \). To account for this, a region of height 0.25 inch and width 0.25 inch at the center of the specimen, as shown in Fig. 3, was chosen as the gauge section to calculate stresses and strains.

2.2. Material

Specimens were prepared from nine lots (denoted Lots A – I) of AA6061-T651 bars procured off-the-shelf. Specimens from all 9 lots were tested in uniaxial tension and specimens from four of these lots (Lots F – H) were tested in plane strain tension. The nine material lots were intentionally procured from different suppliers/manufacturers in an effort to test an accurate cross-section of commercially available aluminum. Table 1 shows a detailed breakdown of the number of tests conducted, sorted according to the lot, specimen type, and temperature. A total of 154 tests were conducted: 100 uniaxial tension tests and 54 plane strain tension tests. Note that testing of plane strain specimens at 100 °C was not possible given the 10 kip capacity of the load frame (see below). Also, material from Lot F was tested
**Fig. 3.** Contour plots of equivalent plastic strain (top), von Mises stress (middle), and stress triaxiality (bottom) during plastic deformation in the reduced section of the plane strain specimen from finite element simulation. Also shown on the contour plots is the square region selected to be the gauge section for this specimen.

**Fig. 4.** Test setup showing image acquisition equipment, data acquisition system, temperature control setup, and loading mechanism.
in plane strain at 150 °C and 200 °C but exceeded the frame’s load capacity. The chemical composition of the material was available for a few lots and it is shown in Table 2.

2.3. Experimental setup and procedure

The test setup and experimental procedure were identical for the two specimen types. The test specimens were loaded through pins by a 10 kip capacity MTS 810 load frame inside an MTS 651.06E-03 environmental chamber as shown in Fig. 4. A Eurotherm Process Controller Model 2404 was used to control temperature inside the furnace. For tests at elevated temperature, the temperature inside the chamber was raised to the desired value and the specimen temperature was allowed to equilibrate for at least 20 min, as described in [6] before loading. K-type thermocouples were attached to the top, center, and bottom of the test specimen to obtain three temperature readings as shown in Fig. 5. A fourth thermocouple located near the center of the chamber was used to measure the temperature inside the chamber. From the three thermocouples attached to the specimen, it was observed that the temperature gradient between the center and the ends of the reduced section was within ±1 °C. At
equilibrium, the average of the three temperature readings from the specimen was within ±1 °C of the test temperature. Temperature measurements were obtained at a rate of 100 Hz using a NI9211 data acquisition card, averaged over every second and recorded throughout the experiments to ensure temperature consistency.

During the heating phase, force-control was adopted with zero force on the specimen to allow thermal expansion without stressing the material. After the specimen temperature reached

Fig. 7. Gauge section and strain measurement locations for typical uniaxial tension specimen.
equilibrium, loading was displacement-controlled at a rate of 0.01 in/min until material failure (corresponding to a nominal strain rate of 0.005/min over a 2 inch gauge length) for the uniaxial tension specimen, as specified in [4]. Loading was displacement-controlled at a rate of 0.00125 in/min (corresponding to a nominal strain rate of 0.005/min over a 0.25 inch gauge length for the plane strain specimen. Load and displacement readings from the load frame were acquired using NI9209 data acquisition hardware at a rate of 100 Hz, averaged over every second and recorded in a csv format using a custom LabVIEW program.

Table 1
Number of specimens tested according to lot and temperature. A total of 100 uniaxial tension specimens and 54 plane strain tension specimens were tested.

| Specimen type        | Temperature | 20 °C | 100 °C | 150 °C | 200 °C | 250 °C | 300 °C |
|----------------------|-------------|-------|--------|--------|--------|--------|--------|
| Lot                  |             |       |        |        |        |        |        |
| Uniaxial tension     |             |       |        |        |        |        |        |
| A                    | 3           | 3     | 0      | 3      | 0      | 3      |
| B                    | 3           | 3     | 2      | 3      | 2      | 3      |
| C                    | 3           | 3     | 2      | 3      | 2      | 3      |
| D                    | 3           | 3     | 2      | 3      | 2      | 3      |
| E                    | 3           | 3     | 2      | 3      | 2      | 3      |
| F                    | 1           | 1     | 1      | 1      | 1      | 1      |
| G                    | 1           | 1     | 1      | 1      | 1      | 1      |
| H                    | 1           | 1     | 1      | 1      | 1      | 1      |
| I                    | 1           | 1     | 1      | 1      | 1      | 1      |
| Plane strain tension |             |       |        |        |        |        |        |
| F                    | 3           | 0     | 0      | 3      | 3      |        |
| G                    | 3           | 0     | 3      | 3      | 3      | 3      |
| H                    | 3           | 0     | 3      | 3      | 3      | 3      |
| I                    | 3           | 0     | 3      | 3      | 3      | 3      |
Displacements were obtained using a custom digital image correlation (DIC) system. By using DIC, not only is it possible to obtain full-field measurements of the kinematics but also to choose multiple gauge lengths around the region of strain localization to compute average strains over different length scales. The DIC code utilized for the analysis was developed by the Hemker research group at Johns Hopkins University and is available through the MATLAB file exchange site [7]. This program computes the normalized cross-correlation between a subset of the image (here the subset size was $20 \times 20$ pixels) around the point of interest in the reference image and subsets of the same size within a search window of size twice the subset size in the current image. The peak of the normalized cross-correlation function is chosen to be the current location of the point of interest. To obtain sub-pixel resolution in the computed displacements, the DIC interpolates a continuous surface between pixel intensity values. In the program used in this study, a quadratic polynomial interpolation function is employed. More details about DIC can be found in [8].

The surface of each specimen was painted with flat white paint and a random speckle pattern of Temperkote flat black paint was then applied using an airbrush, resulting in a speckle pattern as shown in the Fig. 6. To ensure that the paint adhered to the surface for all the tests, it was necessary to use two different white paints. Krylon flat white paint, which could resist temperature exposure up to 200 °C, was used for the lower temperature tests, and Zynolyte Hi-Temp flat white paint, which hardened during the heating of the specimen, was used for tests at 250 °C and higher. The target feature size was 0.1mm - 0.4mm, which is optimal for the magnification used in the tests. 8-bit images of the deforming specimen were captured at three-second intervals during loading using a high resolution (2824 × 4240 pixel i.e., 12 megapixel) PointGrey Grasshopper3 monochromatic 1” ccd camera with a 35 mm fixed focal length Edmund Optics HP Series high performance lens attached.

A grid of points within the gauge length was chosen in the first image (the step size used was 10 pixels, which corresponded to a spatial resolution of about 350 μm) and the location of these points was tracked by the DIC algorithm. In this way, the displacement of several material points in the region of interest was obtained. The strain over the gauge length was taken to be the average of the strains computed between 35 pairs of points lying on the ends of the gauge section for the uniaxial tension specimen and between 18 pairs of points on the ends of the gauge section for the plane strain specimen.

3. Error analysis

Nine measurements each were made of the thickness and the width of every test specimen. Using this data, uncertainty in the measured cross-sectional area of the test specimen was computed by the procedure in [9]. The average measurement error in the cross-sectional area was 0.0092 mm² (approximately 0.07%) resulting in $\pm 0.01\%$ error in stress, which we consider negligible.

Forces were recorded at 1 s intervals by computing the average of 100 force readings over that 1 second interval. Two load cells were used during the test program. Most tests were conducted on a 10 kip (44,482 N) load cell with measured force standard deviation 0.65 N. The 12 plane strain tests at room temperature required a load cell of larger capacity, so a 100 kip (444,820 N) load cell was used with measured force standard deviation 7 N. Again, these small variations in force measurement were considered negligible.

Temperature was likewise recorded at 1 s intervals by computing the average of 100 temperature readings obtained during that 1 second. The standard deviation of the measured temperature by each thermocouple was 0.22 °C resulting in very small errors even at room temperature.

| Lot | Chemical composition (%) |
|-----|--------------------------|
|     | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti |
| A   | 0.56 | 0.23 | 0.18 | 0.07 | 0.86 | 0.06 | 0.02 | 0.01 |
| D   | 0.67 | 0.28 | 0.23 | 0.05 | 0.90 | 0.05 | 0.03 | 0.02 |
| G   | 0.61 | 0.15 | 0.17 | 0.02 | 0.88 | 0.05 | 0.01 | 0.01 |
| I   | 0.68 | 0.23 | 0.20 | 0.04 | 0.87 | 0.05 | 0.02 | 0.02 |

Table 2
Chemical composition of aluminum alloy AA6061-T651 specimens for select lots.
Displacements were measured using DIC, as discussed above. Errors in DIC displacements may be caused by random noise in the pixel intensities, by sub-pixel level interpolation for the current position of the point being tracked, by out-of-plane motion of the specimen, or by loss of tracking caused by non-adherence of the paint to the surface of the specimen at large deformations. The final source of error was eliminated by using the two different flat white paints as mentioned above to ensure adhesion of the paint to the specimen at high strain regions. Integrating the other sources of error, the maximum measurement errors in the location of each point were estimated to be approximately 5e-3 mm, which leads to a maximum error of 1e-2 mm over the gauge length. This corresponded to a maximum error of 2e-4 in the strain measurements over the gauge section for the uniaxial tension specimen and 1.6e-3 in the strain measurement over the gauge section for the plane strain specimen.

4. Stress-strain calculation

4.1. Uniaxial tension

The engineering stress is calculated as $\sigma = \frac{P}{A}$ where, $P$ is the force measured from the load cell and $A$ is the measured cross-sectional area of the specimen. Strains were calculated as the average of 35 displacement measurements across the width of the gauge section, as illustrated in Fig. 7.

4.2. Plane strain tension

For the plane strain specimen geometry, it is not straightforward to compute the stress because stress is both multiaxial and is not uniformly distributed over the cross-section of the specimen. To approximate stress in the gauge section, finite element analysis was adopted to estimate the fraction of the total load resisted by the gauge section. Fig. 9 shows the distribution of von Mises stress in the cross-section from FE analysis during initial elastic deformation and after material yielding. This analysis reveals that the gauge section takes approximately 12.5% of the total force during elastic deformation, which then increases to approximately 13.0% after yield at room temperature. Note that a uniform distribution of stress corresponds to 12.5% of the force being applied over the gauge length. Meanwhile, at high temperature the gauge section continues to take approximately 12.5% of the force (again corresponding to an approximately uniform distribution of stress over the cross-section) until strains in the gauge become very large. It is also observed from Fig. 9 that stress on the gauge section is nearly constant. Given that the stress is approximately constant and the proportion of force in the gauge section does not deviate considerably from 12.5%, stresses are computed as follows: $\sigma = \frac{F_g}{A_g}$ where $A_g$ is the area of the gauge section and $F_g$ is the force being uniformly applied to the gauge section, which is estimated as $F_g = \alpha F$ where $\alpha = 0.125$ throughout. Strains are computed as the average of 18 measurements over the gauge section, as shown in Fig. 8.

Acknowledgments

The authors gratefully acknowledge the advice of Dr. Pawel Woelke from Thornton Tomasetti – particularly as it related to design of the plane strain specimens. This material is based upon work supported by the National Science Foundation under Grant No. CMMI -1400387 with Dr. Y. Grace Hsuan as program officer.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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