Data Article

Stress-strain and microscopy data for fire-damaged aluminum alloy 6061 subjected to multiaxial loading

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A B S T R A C T

Stress/strain data from mechanical testing of samples obtained from “as received” and fire damaged (400 °C and 500 °C) aluminum alloy 6061 plates is reported. Mechanical load information was obtained from load cells in the mechanical testing system while strain data was obtained from a digital imaging correlation system. For each plate condition (as received, 400 °C, 500 °C), four samples were machined along and across the rolling direction and subjected to four mechanical tests (tension, torsion, two combined tension/torsion tests) for a total of 24 unique combinations of condition, machining direction and loading path. Data from mechanical testing and digital imaging correlation systems was interpolated to generate stress/strain curves. Included data repository allows regeneration of stress/strain curves presented herein. Microscopy samples were obtained both from undeformed plates and deformed samples. Subsequent to polishing, EBSD was carried out and obtained microstructure and pole figures are reported.

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Specifications Table

Subject: Engineering
Specific subject area: Civil and Structural Engineering, Material Characterization, Materials
Mechanics, Metals and Alloys
Type of data: Table, Image, Graph, Figure
How data were acquired:
- Load Frame: MTS 858 Table Top System (25 kN axial and 250 N-m torsional loading capacity)
- Digital Imaging Correlation: Dual-camera Vic 3D™ system by Correlated Solutions
- EBSD: Zeiss EVO MA15 SEM microscope with Bruker eFlash EBSD detector
Data format:
- Raw, Analyzed, Filtered
Parameters for data collection:
- Dog-bone shaped specimens were machined along and across the rolling direction from Aluminum Alloy 6061 rolled plates in their as-received or fire-damaged conditions. Small sized specimens were obtained both from rolled plates and sections of dog-bone samples that had previously been subjected to mechanical testing.
Description of data collection:
- Stress/strain data was obtained from dog-bone samples subjected to mechanical loading. Subsequently microstructure and texture were obtained from subsections of plate and dog-bone samples.
Data source location:
- The University of Tennessee Knoxville
- Knoxville Tennessee
USA
Data accessibility: Public Access - Mendeley Data
https://doi.org/10.17632/vg3wkkb69t.1
Related research article:
S. B. Puplampu, A. Siriruk, A. Sharma, and D. Penumadu, “Multiaxial deformation behavior of aluminum alloy 6061 subjected to fire damage,” Mechanics of Materials, vol. 159, 2021.
https://doi.org/10.1016/j.mechmat.2021.103885 [1]

Value of the Data

- This data is useful as it contributes a complete characterization of the effects of fire damage on the response of AA6061 alloy to complex mechanical loading and microstructure evolution.
- This data can benefit design and safety engineers in the development of structural components operating in environments where fire exposure is a risk.
- This data can complement information for material modeling involving fire damage and plasticity.

1. Data Description

The chemical composition of the source material is described in Table 1. The geometry of samples for mechanical testing is shown in Fig. 1. Fig. 2 shows the setup for mechanical testing. The speckled pattern for strain measurements using a DIC system is shown in Fig. 3. Comparison of strain data obtained with various techniques is shown in Figs. 4–6. Strain distribution during combined axial/torsional loading of a sample with region of interest for strain measurements is shown in Fig. 7. Fig. 8 is a schematic representation of rolled aluminum plates indicating directions used to identify planes in EBSD images. Table 2 lists source material, mechanical testing, and observed planes of samples sectioned for EBSD. SEM images with grain structure and pole figures for samples listed in Table 2, are illustrated in Figs. 9–12. Files in the data repository are organized in folders according to sample identifiers. Samples are named according to the following convention SP_00XX where “XX” are two numerals. Some sample identifiers additionally include a “b” at the end indicating a repeated test subsequent to a failed test. Each folder contains Comma Separated Values (CSV) files from the MTS (DAQ_Running_Time_Timed.txt) and Vic3D systems (SP_00XX_data.txt), a MATLAB scripts for data interpolation (Analysis_script.m), and the CSV file that is generated from running the MATLAB script (SP_00XX_MTS_V3D.csv). For
Table 1
Chemical composition of aluminum alloy AA6061.

| Component | Weight %          |
|-----------|-------------------|
| Al        | 95.8–98.6         |
| Cr        | 0.04–0.35         |
| Cu        | 0.15–0.4          |
| Fe        | Max 0.7           |
| Si        | 0.4–0.8           |
| Ti        | Max 0.15          |
| Zn        | Max 0.25          |
| Mg        | 0.8–1.2           |
| Mn        | Max 0.15          |
| Other, each | Max 0.05        |
| Other, total | Max 0.15       |

Fig. 1. Sample schematics with dimensions (units: mm).

stress calculations it is necessary to input cross-section information for each sample. Sample dimensions (as well as machining direction, material condition, and mechanical test) are included in a descriptive excel file in the root folder named "samples.xlsx". A set of folders (SP_0001b, SP_0003, SP_0005b, SP_0006b, SP_0007b, SP_0009, SP_0010, SP_0011, SP_0012) has one CSV file from MTS and one CSV file from Vic3D (the timing data from the Vic3D cameras was manually added to the strain data file). Folders associated with subsequent tests.
Fig. 3. (a) Painted specimen and superimposed 25-pixel subset. (b) Detail of random speckle pattern on sample surface.

Fig. 4. (a) Comparison results from VIC3D and extensometer of fire-exposed sample subjected to tensile loading. (b) Axial strain distribution in the gage length.

Table 2
Observed planes according to sample condition and mechanical testing.

| Sample# | Sample condition | Mechanical Test | Observed Plane                  | Figure |
|---------|------------------|-----------------|---------------------------------|--------|
| 0p1     | As received      | –               | RD-TD                           | Fig. 9(a) |
| 0p2     | As received      | –               | ND-RD                           | Fig. 9(b) |
| 0p3     | As received      | –               | ND-TD                           | Fig. 9(c) |
| 4p2     | Fire exposed (400 °C) | –    | ND-RD                           | Fig. 9(d) |
| 7b      | As received      | Tension         | ND-RD                           | Fig. 10(a) |
| 12w     | Fire exposed (500 °C) | Tension | ND-RD                           | Fig. 10(b) |
| 70t     | As received      | Torsion         | TD-ND (Sample center)           | Fig. 11(a) |
|         |                  |                 | TD-ND (mid-point long side)     | Fig. 11(b) |
| 71t     | 400 °C           | Torsion         | TD-ND (Sample center)           | Fig. 11(c) |
|         |                  |                 | TD-ND (mid-point long side)     | Fig. 11(d) |
| 73t     | As received      | Beta 30         | TD-ND (Sample center)           | Fig. 12(a) |
|         |                  |                 | TD-ND (mid-point long side)     | Fig. 12(b) |
| 74t     | 400 °C           | Beta 30         | TD-ND (Sample center)           | Fig. 12(c) |
|         |                  |                 | TD-ND (mid-point long side)     | Fig. 12(d) |
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Fig. 5. (a) Shear strain distribution. (b) comparison of results from VIC3D and rosette strain gage for fire-exposed sample subjected to torsion.

(SP_0070-SP0082) contain two CSV files from Vic3D (SP_00XX_data.txt, SP_00XX.txt): strain data and data acquisition timing. Regardless, MATLAB scripts in each folder correctly read and interpolate the data as needed. Folders SP_0068 and SP_0069 contain single files because interpolation of MTS and Vic3D data was done manually in Excel prior to development of analysis script.

2. Experimental Design, Materials and Methods

2.1. Materials and specimen design

Source material consists of 9.9 mm thick AA6061 rolled plates obtained from Alcoa®. The chemical composition of AA6061 is shown in Table 1. While some plates were kept in their original as-received state, others were subjected to fire damage at temperatures of 400 °C and 500 °C. The fire damage was carried out in a controlled environment at the Extreme Environments and Materials Lab of the Virginia Tech Department of Mechanical Engineering [2,3]. Plates were subjected to an open flame for 30 min then water quenched to simulate fire suppressing agents. Thermal imaging ensured uniform plate temperature during fire exposure.

For mechanical testing, dog-bone shaped samples were machined from the aluminum plates; schematic sample model is shown in Fig. 1; dimensions were chosen according to ASTM standard E8/E8M for metal tensile testing [4]. Samples were machined along and across the plate rolling direction.

2.2. Mechanical testing: experimental setup

Mechanical testing was carried out on an MTS 858 Table Top System Load frame. This is a biaxial loading system with axial 25 kN, and torque 250 N-m capacities. Strain data for tensile tests was acquired using extensometer, strain gage, and digital imaging correlation (DIC) techniques as shown in Fig. 2. While the extensometer was integrated with the MTS, the strain gage and DIC systems were separate. Data acquisition at varying rates later required data interpolation to synchronize load cell and strain information.

The DIC system used for these measurements is Vic-3D from Correlated Solutions [5]. Vic-3D uses a dual-camera system to measure the shape of an object, displacements, and full-field
strains in three dimensions. The region wherein displacements are calculated for a single, central point is called a subset. Fig. 3(a) shows subsets used for strain calculations. The general motion of these subsets was tracked from image to image using numerical algorithms. For these measurements each camera acquired images at a rate of one image per second. The resulting displacement defined the motion of the center pixel in each subset. The software locates each subset center a specific number of pixels apart; this pixel distance is called the step size. The relative motion between steps is then used to calculate strain on the sample surface. Features required for mapping were introduced by careful painting of speckle patterns on the surface. Samples were first painted white using non-gloss paint and then lightly speckled with small
Fig. 9. (a) As received, RD-TD plane, (b) As received, ND-RD plane, (c) As received, ND-TD plane, (d) Fire damaged 400 °C, ND-RD plane.
Fig. 10. (a) As received, 3.4% axial strain, ND-RD plane (b) Fire damaged 500 °C, 6.6% axial strain, ND-RD plane.

black features in a random fashion as detailed in Fig. 3(b). A sharp black/white contrast combined with a random, appropriately sized, speckle pattern optimizes the algorithm for mapping.

On-specimen 3-D strain mapping for AA6061 samples subjected to tension or torsion was performed to study the development and possible localization of strains along the gage length as the extensometer only provides integral amount of deformation over the gage length. Fig. 4 shows that the average surface strain from Vic-3D on both sample width and thickness compares well with extensometer data and closely reproduced the stress strain curve. A similar observation was made under torsion when the surface strain at mid-height was compared with the rosette strain gage result in Fig. 5. The shear strain distribution under torsion is shown in Fig. 6(a) where a uniform strain profile plotted in Fig. 6(b) was found at the center of both width and thickness sides.

2.3. Testing parameters

Four samples were prepared from each category of damage level and machining direction. Four mechanical tests were then carried out: tension, torsion and two combined tensile/torsional loading tests with differing axial load to torque ratios. For tensile testing, axial deformation ranged from 1.5 mm to 2.5 mm. The deformation rate was 0.2 mm/min. For torsion tests, samples were twisted to 15° and vertical displacement was allowed to vary to maintain a 0 MPa axial stress to ensure the sample was subjected to pure torsion. The twist rate was 3°/min. For combined loading, a target axial displacement of 1.5 was chosen, and torsional loading was automatically applied to maintain a constant axial load/torque ratio. The axial deformation rate
Fig. 11. (a) As received cross-section center, 4.5% shear strain, TD-ND plane (b) As received, long side mid-point, 4.5% shear strain, TD-ND plane (c) Fire damaged 400 °C cross-section center, 4.4% shear strain, TD-ND plane (d) Fire damaged 400 °C, long side mid-point, 4.4% shear strain, TD-ND plane.
Fig. 12. (a) As received cross-section center, 8.6% octahedral shear strain, TD-ND plane (b) As received, long side mid-point, 8.6% octahedral shear strain, TD-ND plane (c) Fire damaged 400 °C cross-section center, 7.8% octahedral shear strain, TD-ND plane (d) Fire damaged 400 °C, long side mid-point, 7.8% octahedral shear strain, TD-ND plane.
was 0.2 mm/min. The data acquisition rate from the MTS system was 3 Hz while the Vic-3D data was acquired at 0.5 Hz or 1 Hz for varying tests. From the raw images, Vic-3D tracked displacements across the entire gage length painted with the speckle pattern. Strain data was then extracted from a 2 mm by 4 mm region at the center of the gage volume as show in Fig. 7.

Two Comma Separated Values (CSV) files were obtained from the MTS and Vic-3D systems, respectively. A MATLAB script was written to import data from the CSV files. Sample dimensions (width and thickness) are input for stress calculations. The data sets are linearly interpolated creating a new data set where tensile/torsional load and strain data are synchronized.

2.4. Stress calculations

Stresses (tensile, maximum shear, principal, and octahedral shear stresses) are calculated from axial load or torque values and sample dimensions. The engineering axial stress $\sigma_z$ is given by $\sigma_z = \frac{F}{A}$ where $F$ is the axial load measured by the load cell of the MTS system. In torsion, the highest shear stress $\tau_{\text{max}}$ at the midpoint of the long side of the rectangular cross-section depends on the applied torque $T$, the sample dimensions (short side $a$, long side $b$) and empirical parameter $\alpha$ whose value depends on the $b/a$ ratio [6].

$$\tau_{\text{max}} = \frac{T}{\alpha ba^2}$$

Principal stresses $\sigma_{1,3}$ are calculated based on axial and shear stresses and used to determine octahedral shear stresses which allow to plot multiaxial testing data on one plot accounting for both axial and torsional loads.

$$\sigma_{1,3} = \frac{\sigma_z}{2} \pm \sqrt{\left(\frac{\sigma_z}{2}\right)^2 + \tau_{xy}}$$

$$\tau_{\text{oct}} = \frac{1}{3} \left( \sigma_1^2 + \sigma_2^2 + (\sigma_1 - \sigma_3)^2 \right)^{\frac{1}{2}}$$

2.5. Microscopy

After mechanical testing, a selection of samples machined along the rolling direction was sectioned to examine the microstructure of the material. Reference samples were cut from the as-received and fire-damaged plates for comparison. Because of the uneven stress distribution in samples where some level of torsion was applied, the microstructure was examined at multiple locations of the cross-section; specifically, the center where the least stress is expected and close to the mid-point of the long side where the highest shear stresses were shown from calculations and DIC measurements. Observed planes are defined by Rolling Direction (RD), Transverse Direction (TD), and Normal Direction (ND) as shown in Fig. 8.

Polishing was carried out on a Buehler MetaServ® 250 Grinder-Polisher equipped with a Vector® power head. An initial grinding step was used to achieve a flat sample surface. Polishing steps with 9 μm, 3 μm, and 1 μm diamond pastes were carried out for five, four, and two minutes, respectively. The final surface finish was achieved with a ~0.05 μm colloidal silica polishing step lasting one and a half minutes.

A Zeiss Evo SEM microscope equipped with a Bruker eFlash EBSD detector was used to acquire maps identifying grain shape and orientation. Pole figures obtained from these maps gave grain morphology and texture information for various sample conditions and mechanical tests. A list of sectioned samples, mechanical tests, planes for microstructure characterization, and figure reference is reported in Table 2.
CRediT Author Statement

S.B. Puplampu: Conceptualization, Methodology, Analysis, Investigation, Writing – Original Draft; A. Siriruk: Methodology, Analysis, Investigation, Writing – Original Draft; A. Sharma: Investigation, Analysis, Writing – Review and Editing; D. Penumadu: Conceptualization, Resources, Writing – Review & Editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships which have or could be perceived to have influenced the work reported in this article.

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