Infrared Imaging of Thermo-Elastic Isentropic Cooling and Heating During Uniaxial Tensile Tests

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Abstract. In order to identify thermal phenomena during the elastic portion of the stress-strain curve, tensile strength testing was imaged by a Telops FAST M3k broadband infrared camera. Both steel and aluminum samples were imaged while being pulled to fracture by an MTS Criterion Model 43 system, which provides complementary engineering stress and strain measurements. The primary goal of this campaign was to reveal a difficult to capture data point, thermo-elastic stress cooling and heating from fully reversible elastic stresses. The Telops system deployed collected a detailed thermal profile for the duration of each tensile test, which successfully captured a full thermal profile for both elastic and plastic deformations, including thermo-elastic stress cooling and heating. After analysis, thermo-elastic stress cooling was detected and quantified at a rate of -1.69K/GPa for aluminum and -0.61 K/GPa for steel. Additionally, thermos-elastic stress heating was detected and quantified at a rate of -1.8K/GPa for aluminum and -1.2 K/GPa for steel. Utilizing the high radiometric accuracy and low NETD offered by Telops broadband cameras, the authors are proud to present these measurements, which we believe to be the first of their kind reported in literature.

Possible Sessions

1. Infrared & Thermal Methods 2. Model Validation

Introduction. An adiabatically compressed gas heats; a rapidly expanded gas cools. A solid tensile bar quickly and elastically stressed also changes temperature. The quantitative measurement of temperature changes due to elastic, reversible stresses and deformation in uniaxial stressed, solid, tensile bars is the subject of this paper. The isentropic thermal stress measurements reported are new measurements. The measured thermo-elastic stress cooling and heating processes in tensile bars reported are adiabatic and reversible i.e., fully elastic, and are isentropic. At the very end of the tensile tests, the specimen fractures and relieves the applied stress. This elastic stress relief changes the temperature by heating the bar. Both experimental temperature measurements of deformed tensile specimens are compared to predicted isentropic temperature changes from a thermodynamic energy balance first proposed by Lord Kelvin in 1853 and equations of state tables. The materials tested are an aluminum alloy and a structural steel, both are well understood engineering materials. The analytic thermodynamic descriptions are based on isotropic thermo-elastic mechanical properties.

Thermodynamic analysis of a tensile test bar. The engineering strain is small in the elastic range and may be ignored compared to 1. This yields a thermodynamic expression connecting changes in T to the elastic stress:

$$\left.\frac{\partial T}{\partial \sigma_e}\right|_S = -\frac{\alpha T}{c_p \rho} \qquad (1)$$

Eq. 1 was derived and published by Lord Kelvin [2]. Experimental measurements from the IR camera and from the MTS instrument have both been asynchronously recorded in our experiments. The temperature and stress changes and their ratio are both recorded versus time, t. Asynchronous records use T and σ_e directly measured by eliminating t. The spike in the temperature when the sample fractures is measured from the middle term in the expression below:

$$\left.\frac{\Delta T}{\Delta t}\right|_S \Big/ \left.\frac{\Delta \sigma_e}{\Delta t}\right|_S = \left.\frac{\Delta T}{\Delta \sigma_e}\right|_S = -\frac{\alpha T}{c_p \rho} \qquad (2)$$

The experimental expression is on the left and in the middle equation while the theoretical value is on the right in Eq.2. This equation permits a direct comparison of the concept of temperature changes due to elastic uniaxial stresses to measured values. Eq. 2 is the isentropic thermo-elastic stress cooling or heating for uniaxial tensile stresses. The system measurements have been restricted to the reversible or elastic region of the tensile loading curve and fracturing curve, so values are isentropic properties.

Thermal Cooling Measurements. The Telops FAST M3K IR camera was used for radiometric temperature mesurements during the tensile test. The thermal data is processed from each image to obtain thermal maps. The recording array is 320x256 pixels, and each pixel has a thermal sensitivity of 20 mK. The Telops IR camera utilizes a framing rate of up to 3,000 frames per second in full window mode. The camera's image has been software selected to look only at the thermal response from outside of the necked area on the tensile bar. The selected area feature of the Reveal IR software allows this image without the neck to be selected. The MTS Criterion Model 43 as configured collected stress and strain measurements at a rate of 100hz. Though capable of much faster speeds, the M3k was set to match this acquisition rate asynchronously with a framerate of 100hz to ensure simplicity of post processing. The M3K and MTS system as arranged during the collection can be seen in Figure 1.

Figure 1. Left: The experimental setup described in this abstract including the MTS tensile test unit, and the Telops FAST M3k. Right: Fractured aluminum (center) and steel (upper right) samples imaged after testing.

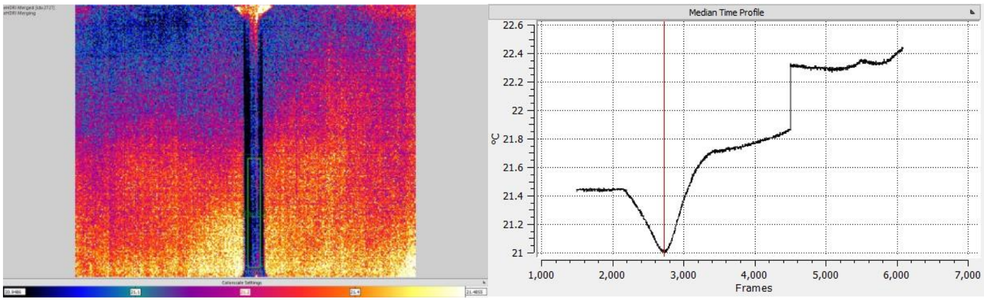

Figure 2. a) A sequence in infrared imaging acquisition software Reveal IR depicting a sample experiencing maximum thermo-elastic cooling, the region of interest (ROI) placement seen is for a sample which will eventually fracture closest to the upper threaded connection. b) Median radiometric temperature time profile plot for the sequence and ROI shown in 2a. Note that at 100Hz, we can assess the elastic cooling for this particular sample to have been ~0.5K in magnitude about 5 seconds after initiation of the test.

Table I is a summary of the experimental and analytic values of thermo-elastic stress cooling expressions for aluminum and steel. The experimental data are from the left side of Eq.2. The data for aluminum and from steel are taken from figures just like Fig.2 from multiple samples. Table I also shows the right side of Eq.2 evaluated using the data contained in ASM Materials Web. Finally, Table I also has expressions evaluated using the published data in Sesame and LEOS studies [3,4]. An analysis of the role of shear stress in cooling and heating will also be presented in this work.

Table I. Thermo-Elastic Stress Cooling and Heating experimental and theoretical values

Material	Experimental Cooling: Measured	Experimental Heating: Measured	Equation 13 Predictions*	Sesame #3720 Aluminum†	Sesame #2140 Iron†	LEOS #260 Iron†
Aluminum	-1.7 K/GPa	-1.56 K/GPa	-2.8 K/GPa	-2.7 K/GPa	NA	NA
Steel	-0.61 K/GPa	-1.16 K/GPa	-0.97 K/GPa	NA	-1.2 K/GPa	-0.93 K/GPa

Conclusion

Direct temperature changes due to uniaxial stress have been measured and analyzed as a first of its kind. We call the effect the isentropic thermo-elastic stress cooling or heating depending on the stress sign. The comparisons between the experimental and theoretical predictions are very encouraging. The experimental values were below the theoretical table predictions, however the tables have been developed for applications in hydro-codes and are (maybe inappropriately) applied to solids.

References

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