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Description of a Micro-Mechanical Testing System

David T. Schmale, Roy J. Bourcier, Thomas E. Buchheit

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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DESCRIPTION OF A MICRO-MECHANICAL TESTING SYSTEM

David T. Schmale
Roy J. Bourcier
Thomas E. Buchheit

Materials and Process Sciences Center
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185

Abstract

A mechanical test system has been designed and assembled to facilitate the study of small scale specimens with characteristic dimensions between 0.001 in and 0.750 in. The system was designed to utilize many off-the-shelf items including an MTS Systems Corporation 3000 pound 1.0 inch travel hydraulic actuator and can accommodate an Interface 10 lb., 100 lb. or 250 lb. load cell. Load, stroke and displacement control is provided by an MTS TestStar system and two 0.100 inch LVDT displacement gages situated in a parallel arrangement at the specimen. Load resolution is on the order of 50 μ oz. and displacement resolution is less than 45 μ inch. The system can test dynamically up to 100 hz at 0.005 inch actuator displacement and loads of 100 lb., statically at up to 250 lb. (limited by the load cell). The scope and flexibility of the microscale test system extends far beyond simply testing LIGA synthesized parts. A detailed description of the machine and a diverse set of results are presented in the following sections of this report.

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Introduction

In recent years, technological advances have significantly enhanced the capability to produce milli- and micro- sized components which may be incorporated into the design of small, less costly, reproducible and more reliable nuclear weapons components. Two promising micro-scale processing technologies are Silicon surface micromachining (SMM), [1-3] a process derived from microelectronics fabrication, and LIGA, [1-2] a process involving electrodeposition of metals into a polymeric mask containing very fine, sharp features. Complicated SMM structures with micron sized features such as microengines, gears and pop-up mirrors have already been successfully developed. However, the mechanical properties of the structural material, polysilicon, used in SMM devices is not well characterized. In the case of the LIGA process, metal structures are produced at a slightly larger size scale than the polysilicon SMM structures. In addition, LIGA has the capability to produce parts with very high thickness aspect ratios. [4] Nickel and some binary nickel alloys are common structural materials in this process. However, methods for characterizing the mechanical properties of SMM and LIGA synthesized structural materials have only recently been developed [5-6] and a comprehensive database of material properties does not yet exist. Furthermore, the influence of processing and microstructure on MEMS materials properties has not yet been well characterized. Optimized performance of future micromachines, such as use control devices for nuclear weapons, will require a detailed understanding of mechanical response at these size scales.

As part of an overall broad effort to develop mechanical test capability of millisized and microsized structures, a mechanical test system has been designed and assembled with the primary goal of characterizing the mechanical properties of LIGA synthesized structures and materials. The current system utilizes many off-the-shelf items including an MTS 3000 pound 1.0 inch travel hydraulic actuator and an Interface 100 pound load cell. Load, stroke and displacement control is provided by an MTS TestStar system and two 0.100 inch LVDT displacement gages situated in a parallel arrangement at the specimen.. Load resolution is on the order of 50 μ oz. and displacement resolution less than 45 μ inch. The system can test dynamically up to 100 hz at 0.005 inch actuator displacement and loads of 100 lb., statically at up to 250 lb. (limited by the load cell). The scope and flexibility of the microscale test system extends far beyond simply testing LIGA synthesized parts. A detailed description of the machine and a diverse set of results are presented in the following sections of this report.

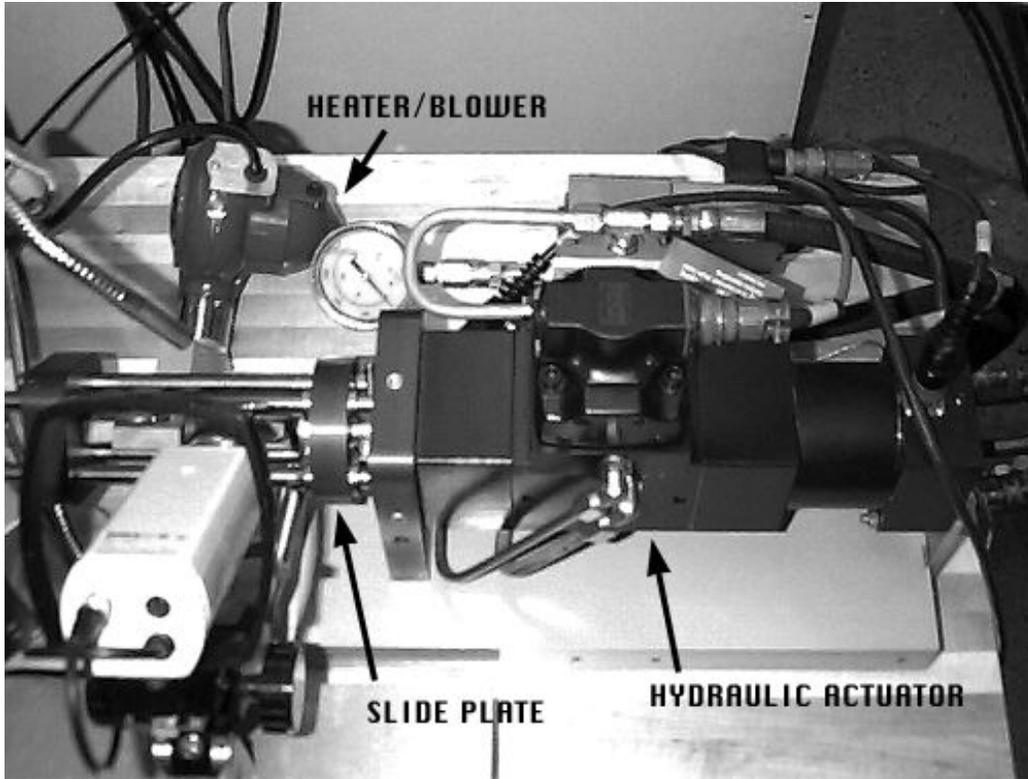


Figure 1: Photographs of the test system. The system is horizontally mounted and situated on a mobile wooden “butcher-block” table.

Description of the Test System

The development of the micro-mechanical test system was intended to accomplish two major design goals. First was the development of a capability to perform standard static and dynamic mechanical tests, i.e. tensile and fatigue tests, on specimens of a size typical of those used in micromachine applications. A typical specimen tested in the system would require a maximum load of < 200 lb., a minimum deformation measurement resolution near 45 μ inch, and capabilities to apply $\pm 0.5\%$ strain at a rate of 100 hz. The second design goal was to construct a flexible system capable of a broad spectrum of microscale testing applications not necessarily definable at the time of design.

An examination of the existing technical product literature revealed no suitable commercial systems. Since that time, MTS Systems has developed a magnetic system capable of applying up to 25 lb. at 50 hz, but this system does not possess the necessary higher load testing and dynamic loading capabilities for tensile and fatigue testing of LIGA materials. To fit within the available mechanical test lab infrastructure, which includes a 3000 psi hydraulic oil power supply, the choice was made to use a standard MTS 3000 lb. hydraulic actuator with 1.00 inch total displacement. The actuator allows testing up to 200 hz at displacement levels below 0.001 inch. Diagnostic tests on the micro-mechanical test system have shown that at 0.003 inch displacement, the actuator cycles up to 100 hz and at 0.060 inch displacement the actuator cycles up to 15 hz. The frequencies could all be increased with a larger displacement and/or high performance servovalve. The short 1.00 inch maximum displacement minimizes the mass of the piston, reducing inertial effects and permitting lower reversing times and higher frequencies. MTS manufactures actuators with less load capacity, but this size actuator

minimizes motion effects from seal stiction and a provides a system capable of applying higher loads with future design of larger grips and the installation of a larger capacity load cell.

The components of the micromechanical test system, shown in figure 1, include:

- The load frame (shown schematically in **figure 2**), consisting of:
 - MTS 3000 pound hydraulic actuator ± 0.50 inch displacement and 1 gallon/minute servovalve.
 - Four Thomson 0.500 inch diameter hardened steel precision shaft posts.
 - Four Thomson high precision linear ball bushings.
 - Sandia designed anodized aluminum alloy support plate, slide plate and load cell plate.
 - Interface load cell.
 - Two Schaevitz 0.100 inch ac LVDT's.
 - Sandia designed micro specimen gripping system.
- A heating system to run tests at up to 482°F (250°C) and control to $\pm 2^\circ\text{F}$ ($\pm 1^\circ\text{C}$).
- 60X Bausch & Lomb stereo scope and 200X video system with b&w camera and microscope lens.
- MTS TestStar digital control system.

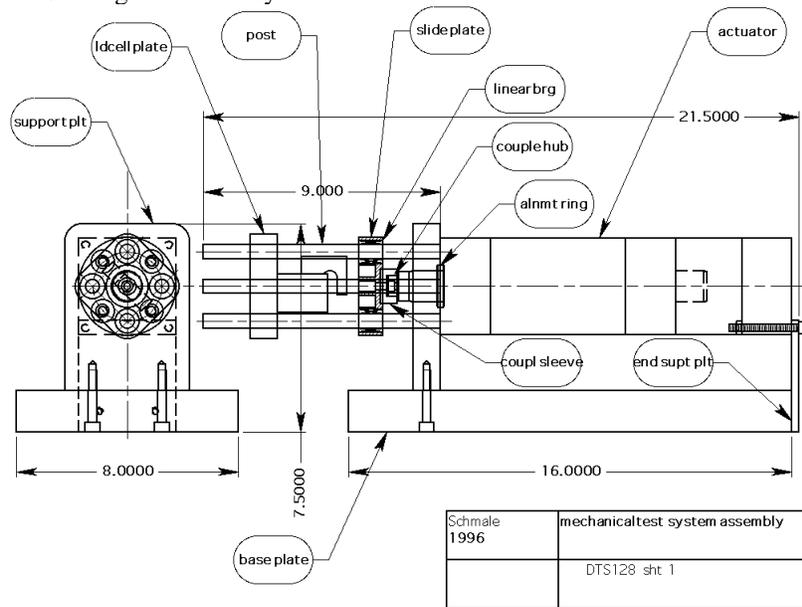


Figure 2. Schematic of test actuator and frame. The steel base plate rests on rubber feet. Dimensions are in inches.

The load frame was designed for maximum rigidity and simplicity. Four hardened steel posts allow loads up to the limits of the actuator while the over-design minimizes compliance. The system operates horizontally for ease of hand loading of the small fragile test specimens and minimization of errors in zeroing the load before tests.

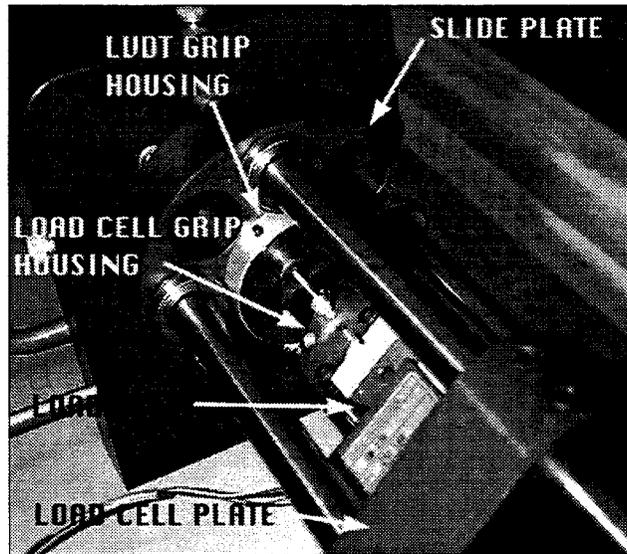


Figure 3. Photograph of grip housings. The grip housing mounted on the slide plate also holds dual high resolution LVDT's. The grip housing mounted on the load cell also holds the LVDT core rods. The load cell plate slides on the posts allowing coarse adjustment of the frame for different size specimens.

One specimen grip is mounted on the slide plate, illustrated in figure 3, which slides centered on the posts on 4 precision linear ball bearings similar to the operation of a precision stamping die. The die-like design ensures accurate axial alignment of the tensile specimen, and is necessary to resist lateral motion during fatigue testing of specimens rigidly coupled to the actuator ram. A sleeve is attached to the slide plate and a hub is attached to the ram. For most tensile testing a dowel pin slides through the sleeve into the hub. For extremely low load tensile testing and fatigue testing two set screws are tightened in the sleeve against the hub to rigidly fasten the lower grip to the ram.

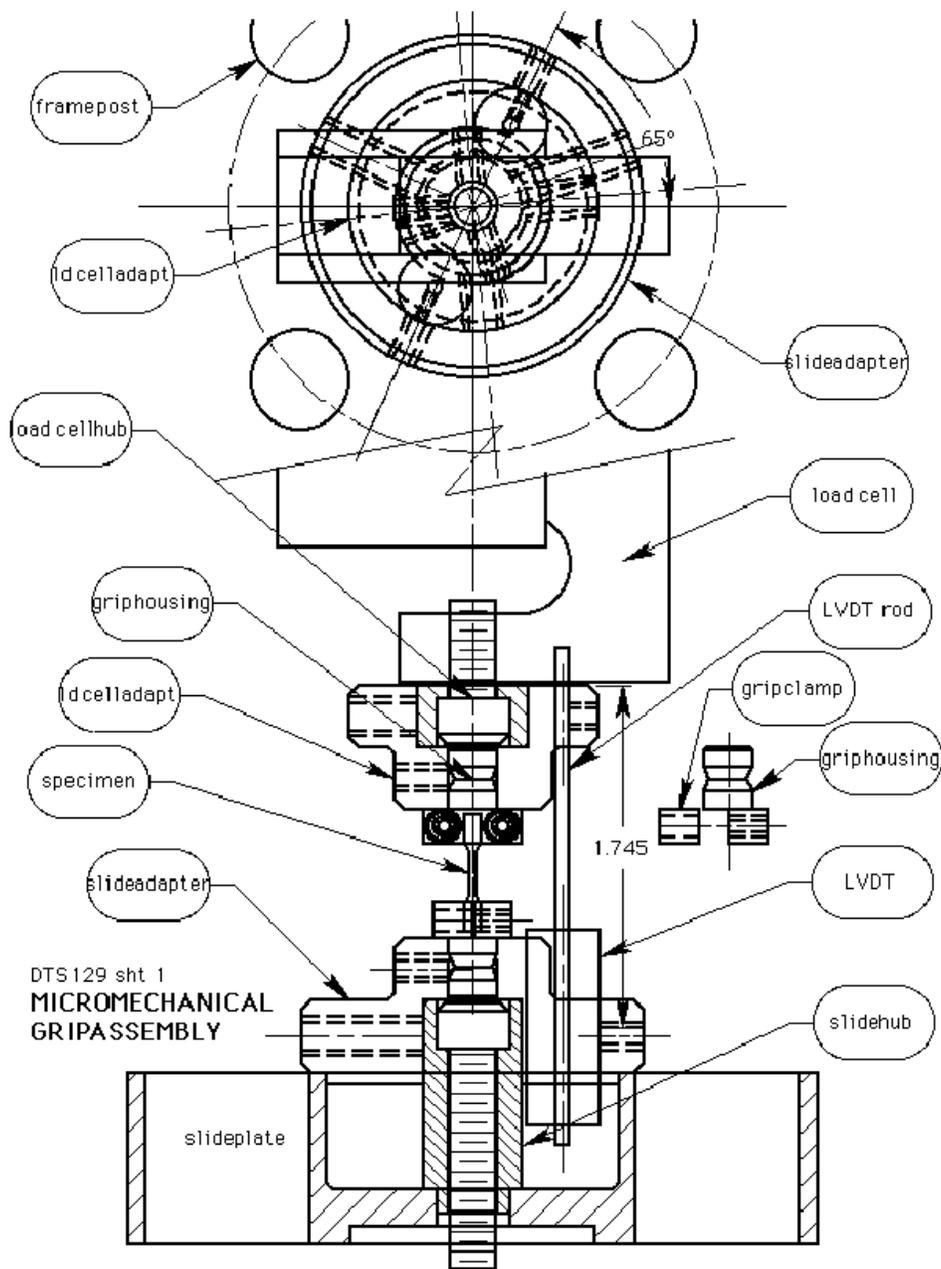


Figure 4. Schematic of gripping system. The slideplate attaches to the ram and moves relative to the load cell. Only one of the 2 LVDT's is shown. Specimen is flat "dog-bone" type. The grips (shown schematically in figure 4, photograph figure 5) are two screw clamps designed to hold dog-bone shaped specimens. The grips slip into the housings and are held in place with two set screws that engage the groove in the grip shaft.

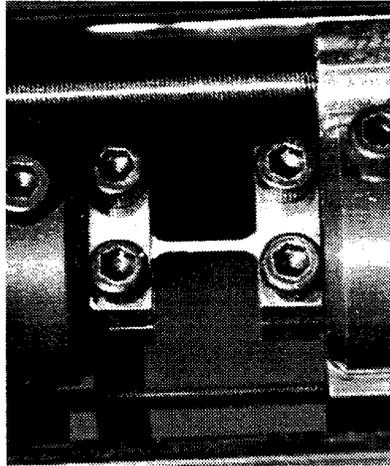


Figure 5. Photograph of flat tensile specimen mounted in test frame. Distance between radii is 0.200 inch. The load cell is to the left, the actuator to the right. Note 2 LVDT threaded core rods and set screws used to hold the grips in the housings. This photograph was taken with the video camera and captured to digital format.

Load frame compliance is minimal, but to further mitigate compliance and aid in accurate testing of specimens with short gage sections (where a small amount of compliance distorts test results), a displacement measuring system including two high resolution LVDT's was designed into the grips. The signals are averaged to eliminate the effects of any nonperpendicularity with respect to the axial centerline.

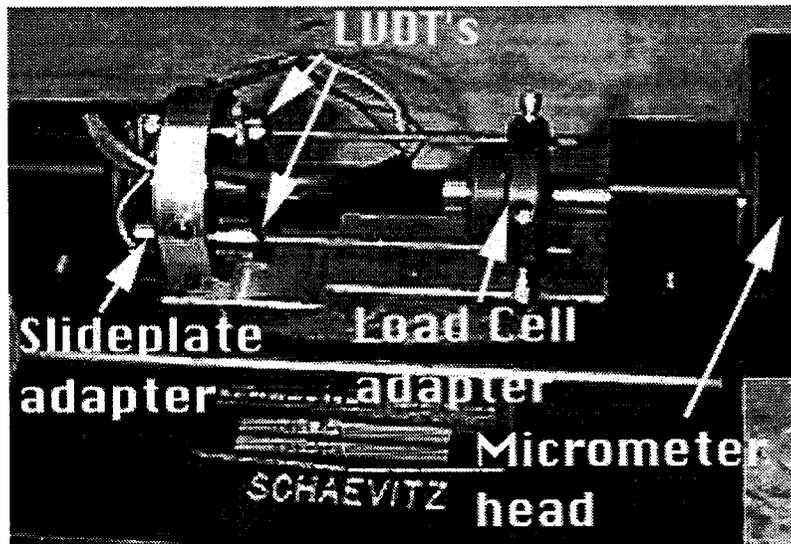
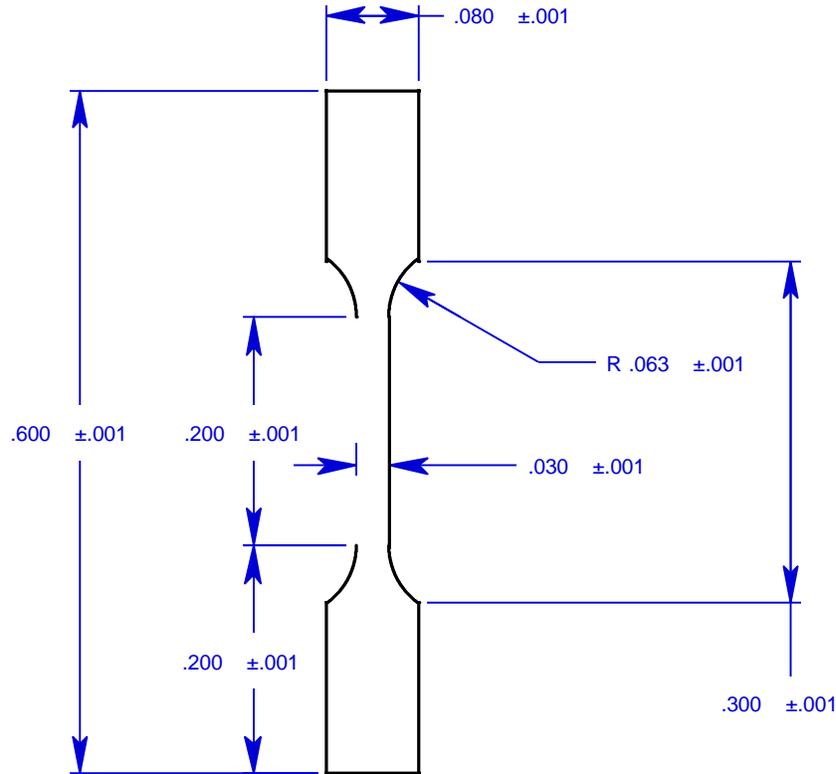


Figure 6. Micro LVDT calibration fixture. Grip housings are taken from the load frame and mounted in a modified Schaevitz micrometer head calibration fixture. The LVDT's are housed in the slide plate grip housing (which in the load frame moves with the actuator ram) on the left. The LVDT core rods are secured with set screws in the load cell grip housing on the right. The use of this system for displacement measurement eliminates compliance of the frame posts and the load cell from the displacement data. The temperature control system uses a modified Master heat gun to direct heated air on the specimen. The heated air is not recirculated and is directed through a 0.375 inch diameter tube containing a type K thermocouple at the tip approximately 0.75 inch from the specimen. The thermocouple output is used as feedback and readout for a Red Lion

Test Procedure

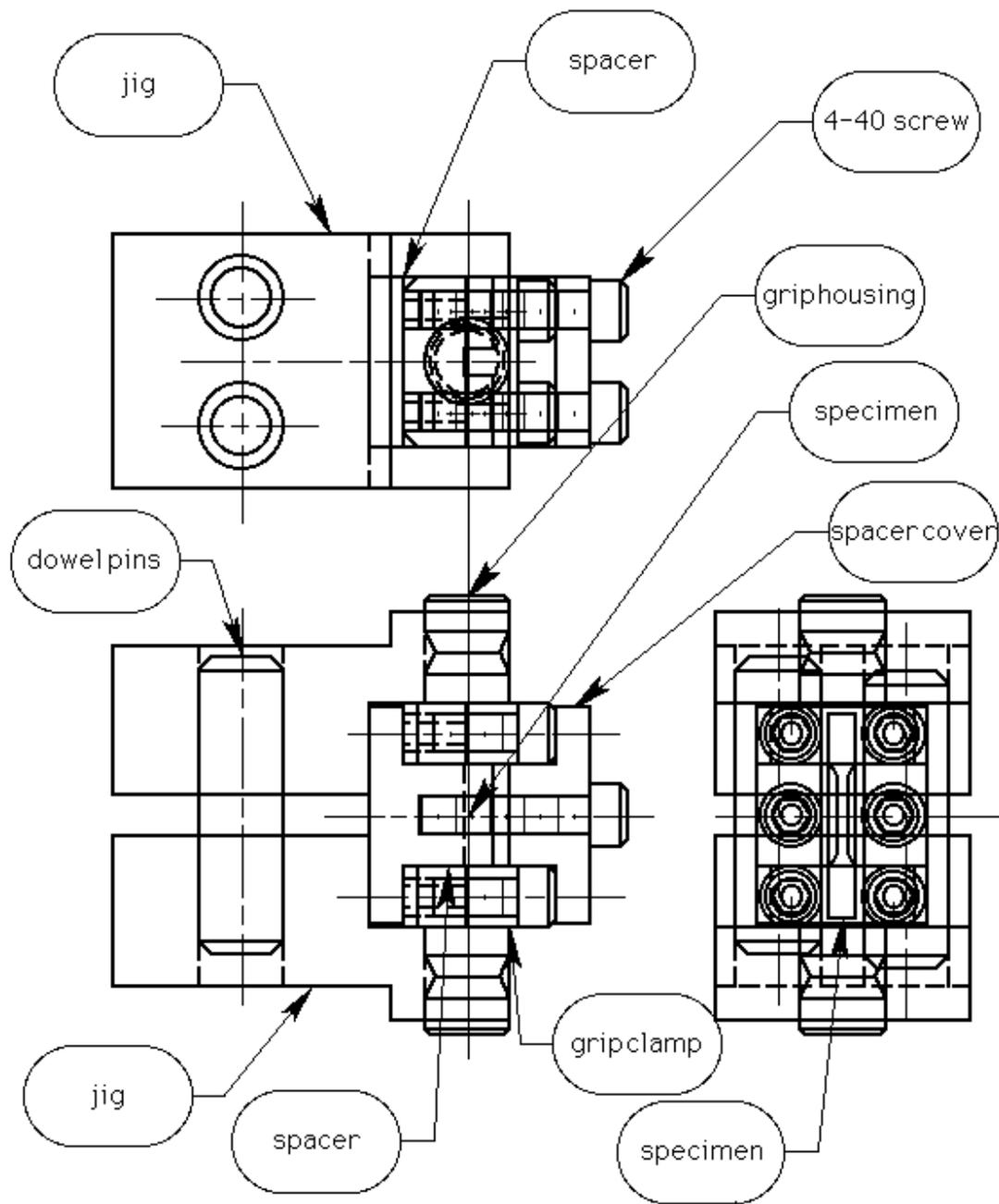
Calibration of the micro LVDT's is done by mounting the entire grip housings in a modified Schaevitz calibration fixture as shown in **figure 6**. The LVDT's are calibrated in several ranges from ± 0.0100 inch to ± 0.100 inch.



DTS129 sheet 2 SPECIMEN

Figure 7. Flat tensile specimen designed to fit into mounting fixture (dimensions in inches). Specimens with gage sections as little as 0.010 inch wide x 0.050 inch long x 0.0006 inch thick have been tested.

Specimens tested in this system are extremely small and fragile (**figure 7**) with material thickness as little as 0.001 inch. A fixture was designed (schematic, **figure 8**) to allow specimen insertion with no deformation to the specimen before testing. **Figure 9** is a photograph of the specimen mounted in the fixture.



DTS129 sheet 9

JIGASS'Y

REQ'D 1

MAT'L steel alloy RC 45+
FINISH 32 or better

Figure 8. Schematic of the specimen mounting jig assembly designed to protect fragile specimens before testing begins.

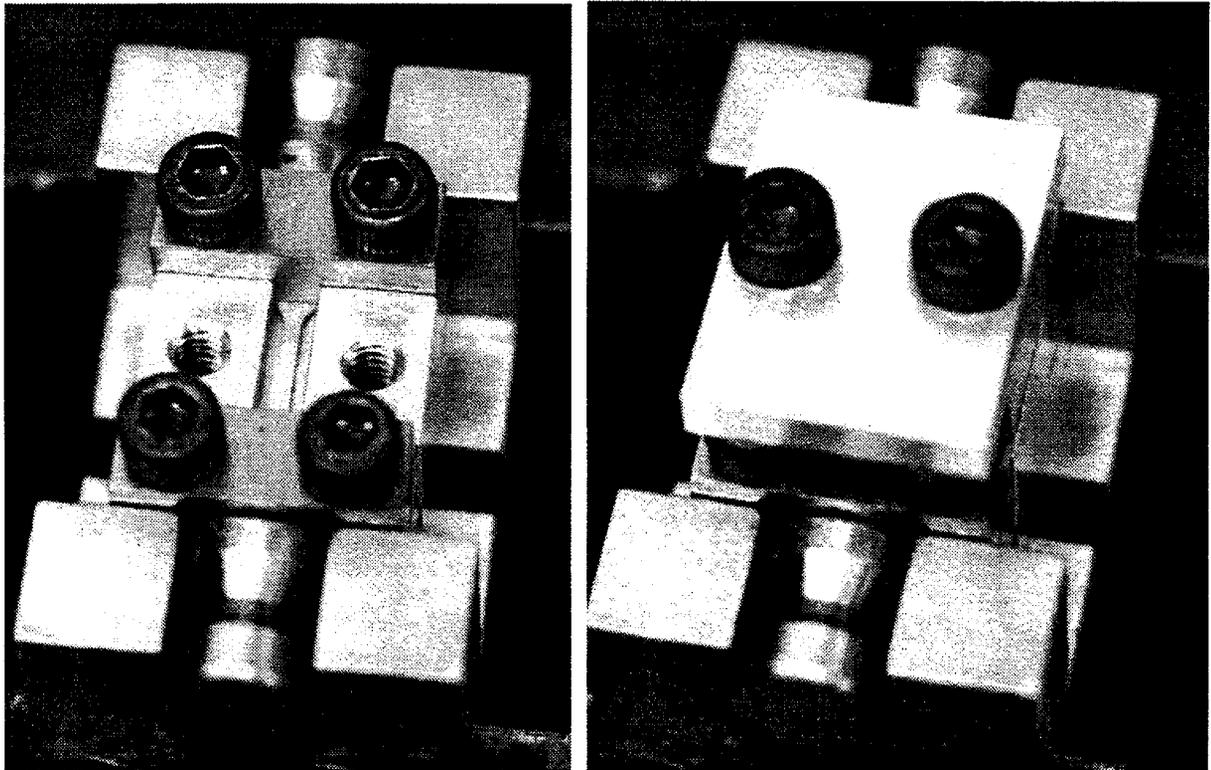


Figure 9. Specimen mounting jig. The jig is placed into a small vice and the grips and specimen are assembled (left). The spacer cover is then installed (right) and the grip/specimen assembly can be removed from the jig and installed in the load frame grip housings.

To conduct a tensile test, the specimen is first mounted in the specimen mounting jig. The ram and slide plate are moved away from the load cell to allow clearance for the specimen/spacer assembly. The specimen/spacer assembly is inserted into the load cell grip housing and the slide plate is manually moved toward the load cell so that the other grip slips into the slide plate grip housing. The load is then zeroed and the set screws tightened. With the spacer and spacer cover still protecting the specimen, the ram is moved toward the load cell so that the ram hub slips into the slide plate sleeve. The pin is inserted and with the system stable at zero load the protecting spacer and spacer cover can be removed and testing can begin.

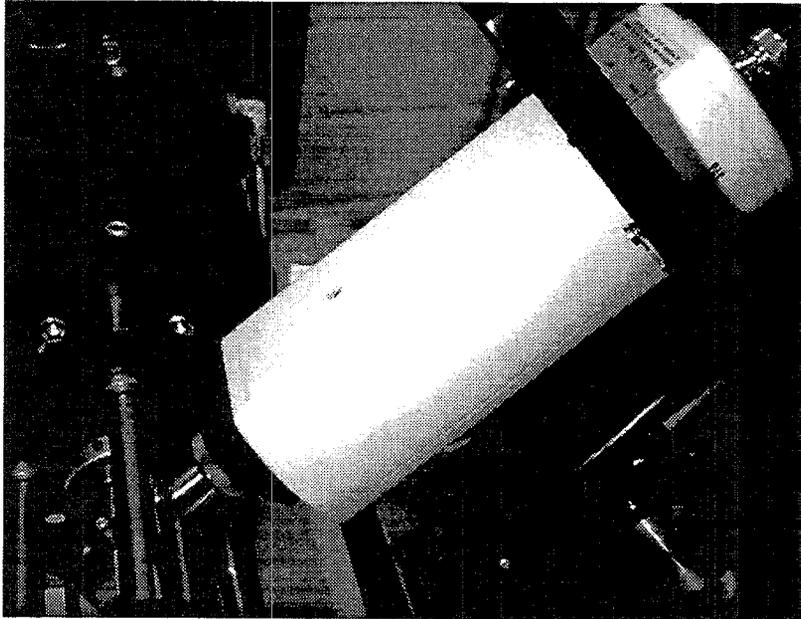


Figure 10. Video camera with microscope lens focused on tensile specimen. When video coverage is not required the camera is replaced, in the same fixture, with a Bausch & Lomb 60X adjustable stereoscope.

The video camera (**figure 10**), a recorder and digital time display system are used to obtain more complete data. Strain measurements are taken from the video data and, since the exact time is known, the corresponding load can be used to gain an accurate indication of Young's modulus. **Figure 11** is a video capture photograph, through the microscope lens, of the gage section of tensile specimen being used in a plastic flow study of copper.

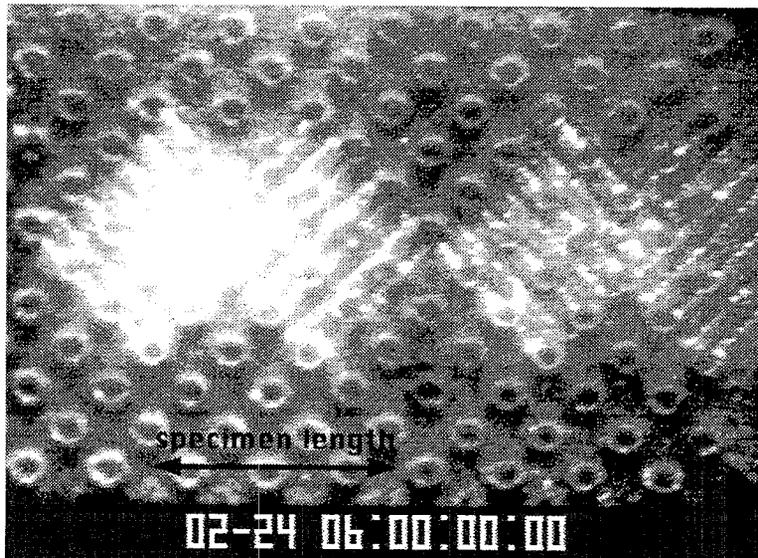


Figure 11. Video capture photograph of 0.030 inch wide gage from copper tensile specimen. The holes are 0.0033 inch diameter. The computer sends a pulse to start the clock when the test begins. The video record can be used for later modulus calculation and, in this case, study of flow behavior around holes.

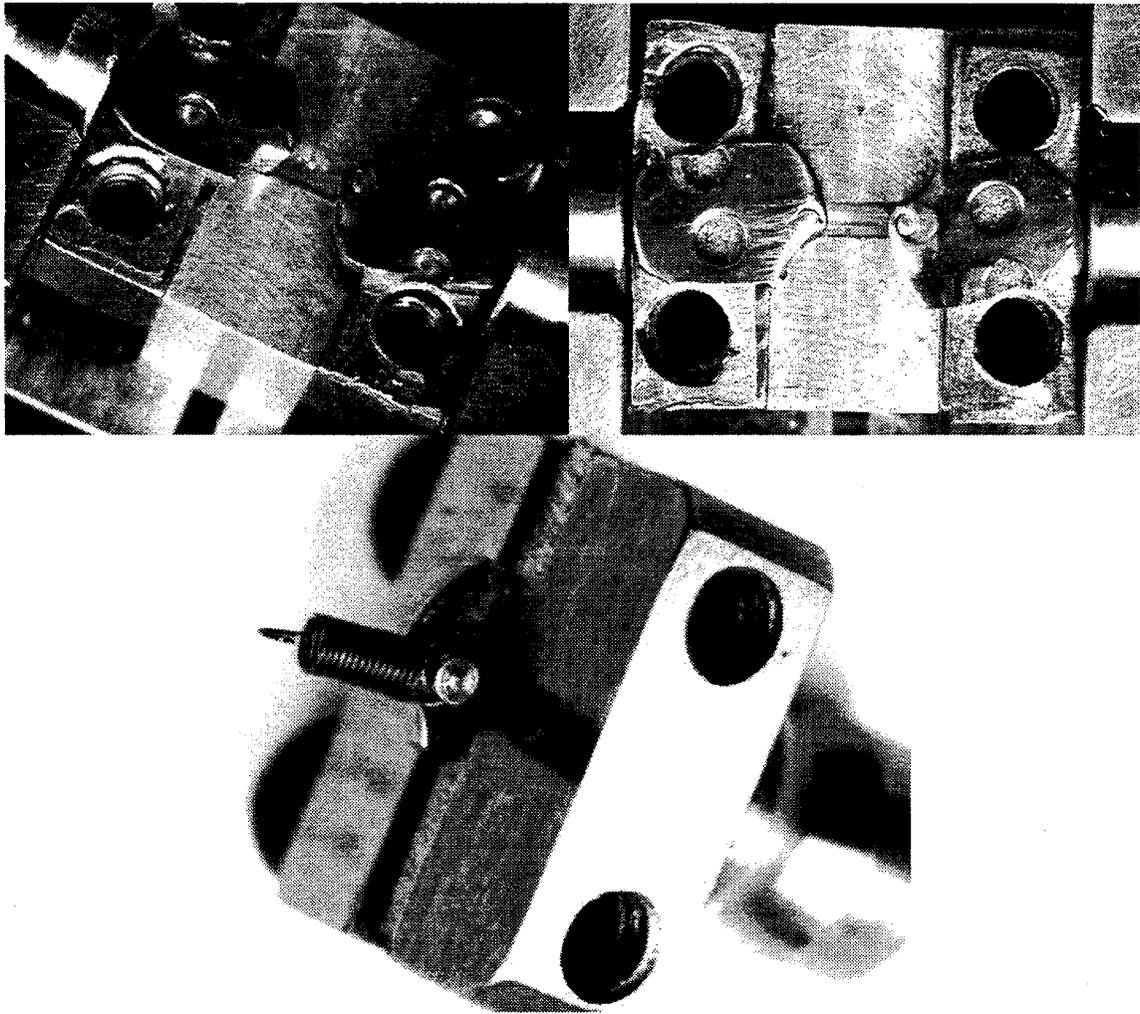


Figure 12. Top: Arms cut from stronglink parts are mounted in tensile specimen clamping grips. A block with a groove and spacers allow axial alignment of the pins. Bottom: Spring ready for testing mounted on part with pin cut from stronglink arm and clamped in grip.

In the special case of stronglink springs testing, pins fabricated from stronglink parts were mounted in the clamping grips to house the springs during testing as shown in **figure 12**. For non-isothermal springs testing, the temperature controller was programmed to run simultaneously with the MTS TestWare SX. The springs were cycled mechanically at a temperature and during a pause in the mechanical cycling the temperature was automatically ramped to the next level and the mechanical cycling continued.

Test Results

LIGA Electroplated Specimen Tensile Tests

Several series of tensile tests were performed on specimens fabricated utilizing the LIGA process with final dimensions near those specified in **figure 7**. These specimens were pre-mounted in the handling fixture, loaded into the frame, and the tests were run at a strain rate of 10^{-3} /second. **Figure 13** illustrates results from two tensile tests on as-deposited Nickel. **Figure 14** illustrated results on as-deposited and annealed Permalloy, 80-Ni/20-Fe. The material is much stronger in the as deposited condition, the yield strength reduced by 88 and 94%, respectively for the 800 and 1100°C anneals. Reproducibility is good.

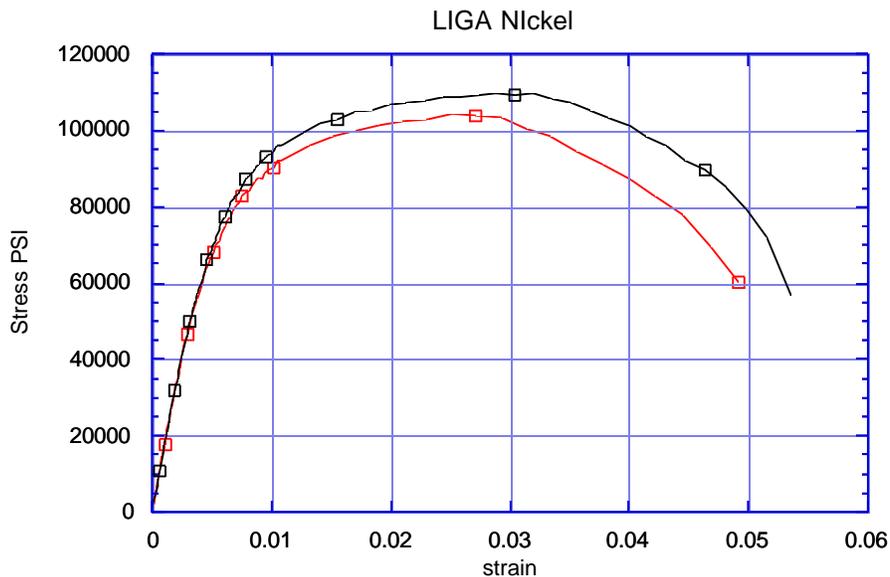


Figure 13. Engineering stress-strain curves from LIGA deposited Nickel tests. The strain data is the output of the LVDT's averaged and divided by the gage length of the specimen.

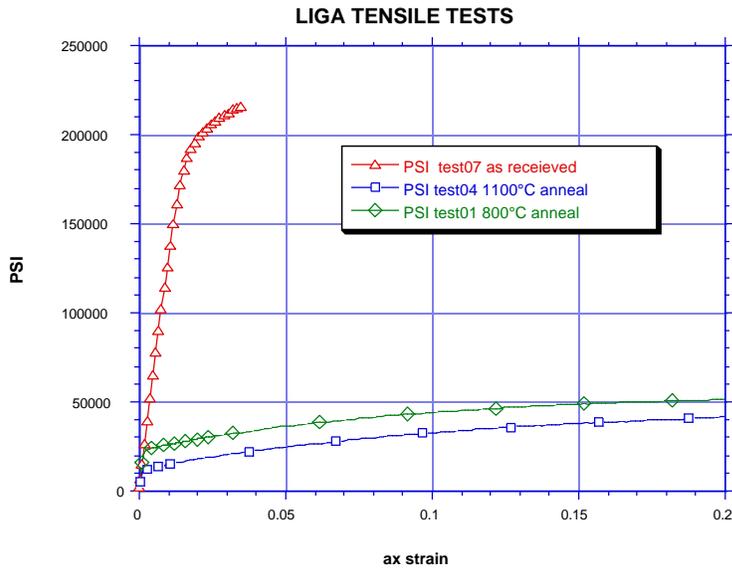


Figure 14. Engineering stress-strain curves from LIGA 80Ni/20Fe tensile tests. Note drop in strength of annealed specimens.

Figure 15 shows the results of another binary Nickel alloy, Ni-60/Co-40. These results showed trends in strength vs. annealing temperature which are quantitatively similar to those observed in the Permalloy test results. These specimens were fabricated at Electroformed Nickel, Inc. in Huntsville, Alabama using poly methyl methacrylate molds fabricated at Sandia Laboratories.

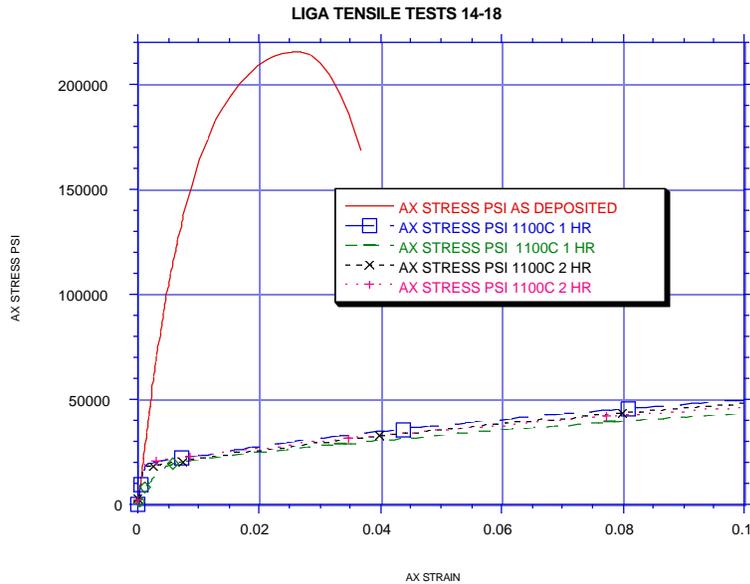


Figure 15. Engineering stress-strain curves from LIGA Ni-60/Co-40 tensile tests. Note drop in strength of annealed specimens. The “ax strain” data is the output of the LVDT’s averaged and divided by the gage length of the specimen.

An additional series of Ni-60/Co-40 specimens were fabricated at Sandia Laboratories using LIGA processing. Results from testing of these samples is shown in **figure 16** and is consistent with earlier results.

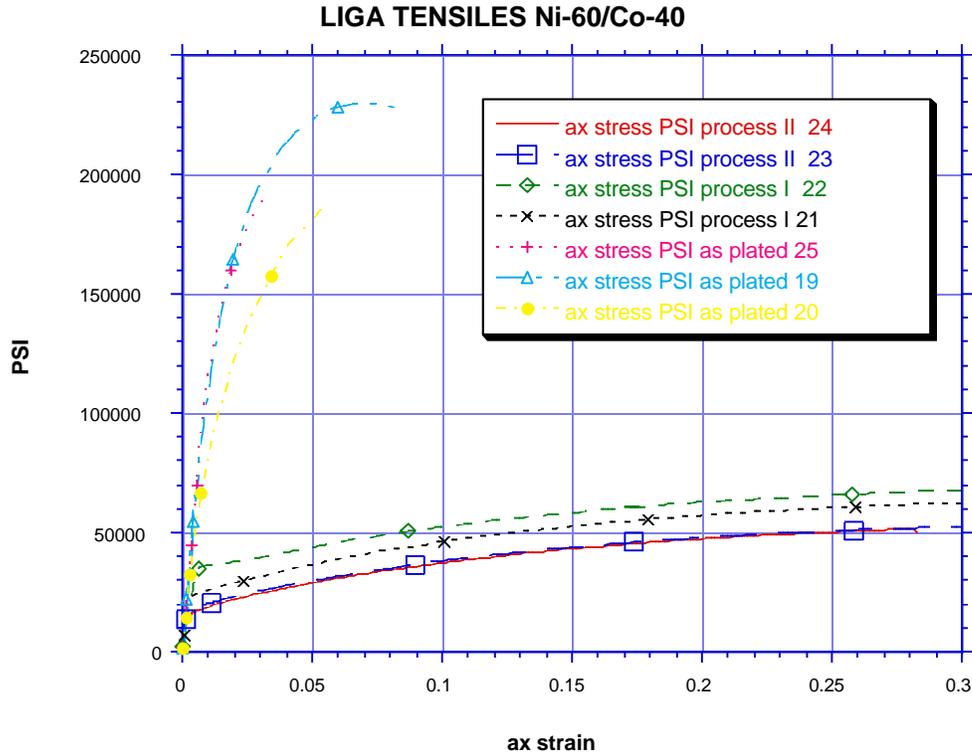


Figure 16. Engineering stress-strain curves from LIGA 60-Ni/40-Co tensile tests. Note drop in strength of annealed specimens. Process I specimens were annealed in dry H₂ at 800°C for 3 minutes. Process II specimens were annealed in dry H₂ at 1100°C for 3 minutes.

Test Results
Wrought Sheet Specimen Tensile Data

Specimens of molybdenum, permalloy and kovar sheet (0.29 mm thick) were electro discharge machined (EDM) from foil stock into the specimen geometry shown in **figure 7**. These specimens were tested in various conditions of heat treat and orientation to the rolling direction (**figure 17**).

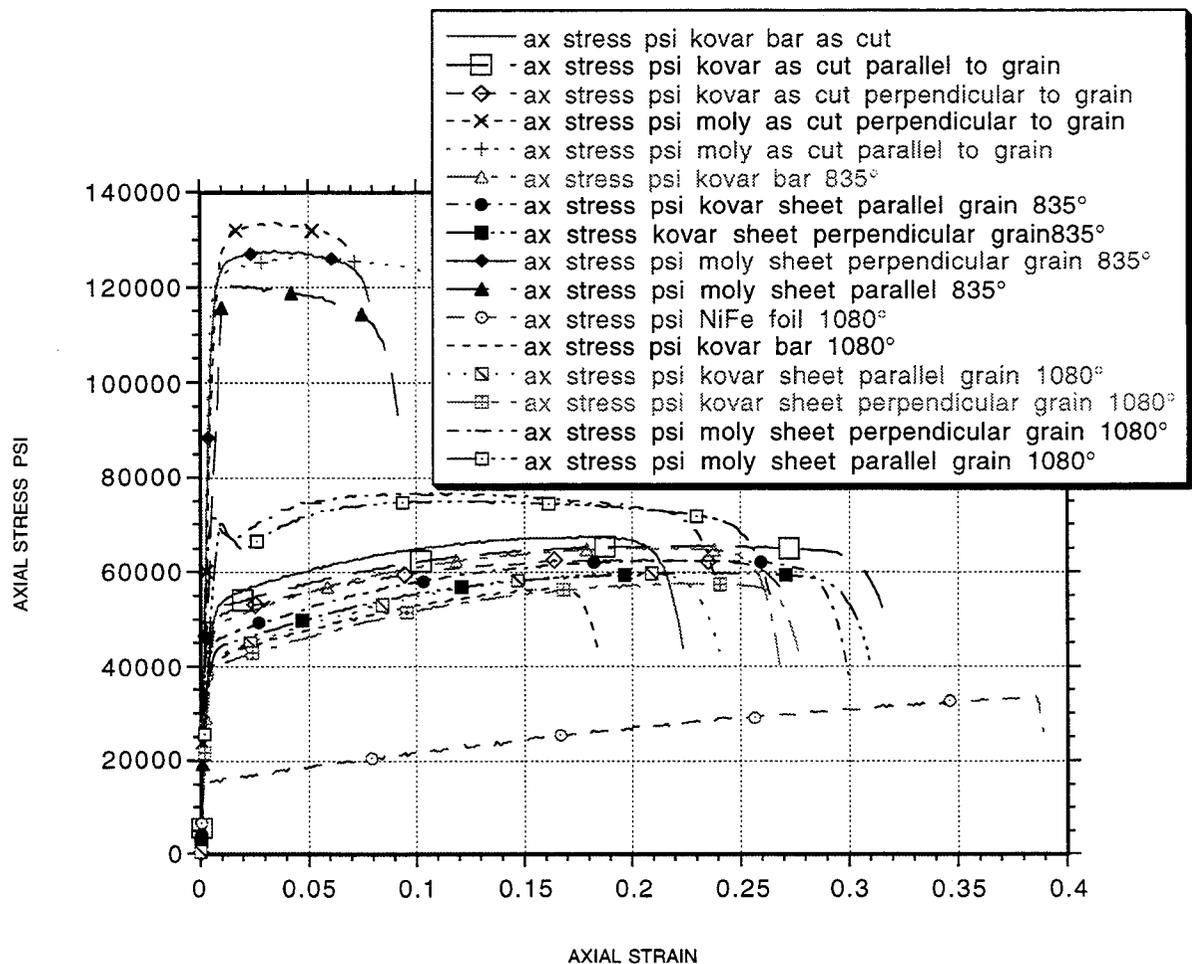


Figure 17. Engineering stress-strain curves from foil & thin sheet miniature tensile tests. The “grain” refers to rolling direction. Heat treated specimens were held for 3 minutes in vacuum at 835°C and for 3 minutes in dry hydrogen at 1080°C.

Test Results

Plastic Flow Study in Perforated Copper Tensiles

A series of tensile tests on perforated and solid foil specimens was performed for a study by Dan Mosher (Department 8746, Sandia National Laboratories, Livermore, Ca.) to characterize strain gradient and size scale effects of plastic flow. Three different sizes of the 99.95% pure OFHC copper specimens were produced having identically proportioned dimensions with size ratios of 1:3:10. The cross sections of the gage lengths were 0.001 inch thick by 0.011 inch wide, 0.003 inch by 0.033 inch and 0.010 inch by 0.110 inch. Respective hole diameters were 0.00033, 0.001 and 0.0033 inches. Chemical etching was used to cut the specimen boundaries, and an Excimer laser was employed to produce 30 rows of holes with 6 holes per row in the perforated specimens (**figure 11**). These specimens could not be mounted in the special fixture (**figure 9**). A different procedure was used that included mounting the specimen in one of the grips outside the frame (in the fixture) and then completing the attachment with both grips rigidly mounted inside the frame and the slideplate setscrews tightened to the actuator hub. The specimens were extremely fragile, and the smallest failed at loads less than 0.25 pounds. **Figure 18** is a compilation of representative data which can be used to estimate bounds for parameters in nonlocal plasticity models.

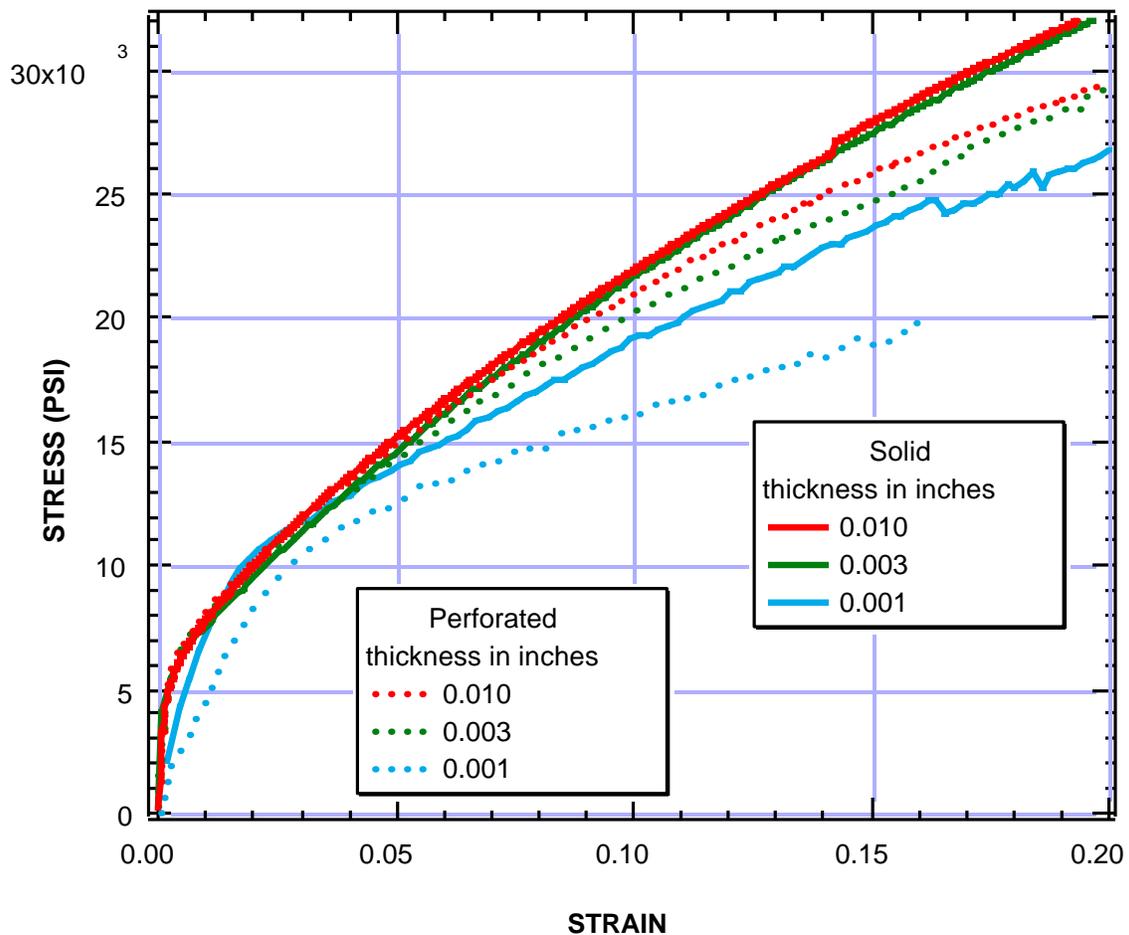


Figure 18. True stress-strain curves from copper tensile specimens. Holes were 0.00033, 0.001 and 0.0033 inches diameter respectively in the 0.001, 0.003 and 0.010 inch thick specimens.

Test Results
Stronglink Spring Fatigue

The mechanical stronglinks used in nuclear weapons contain many small springs. A study was requested to characterize the mechanical response of these springs through several activation cycles subject to a range of different operating temperatures. Five springs were taken from each of 3 stronglinks subjected to different preliminary conditions. Three tests were conducted on each spring -- 100 and 150% of the actual in

Table I
100% Displacement Table

	BBN 6684	BBN 6236	BBN 8150
322849	0.134 - 0.266 in	0.134 - 0.266 in	0.134 - 0.266 in
309364	0.148 - 0.210 in	0.148 - 0.210 in	0.148 - 0.210 in
309368	0.104 - 0.188 in	0.104 - 0.188 in	0.104 - 0.188 in
309367	0.112 - 0.138 in	0.112 - 0.138 in	0.112 - 0.138 in
309365	0.066 - 0.092 in	0.066 - 0.092 in	0.066 - 0.092 in

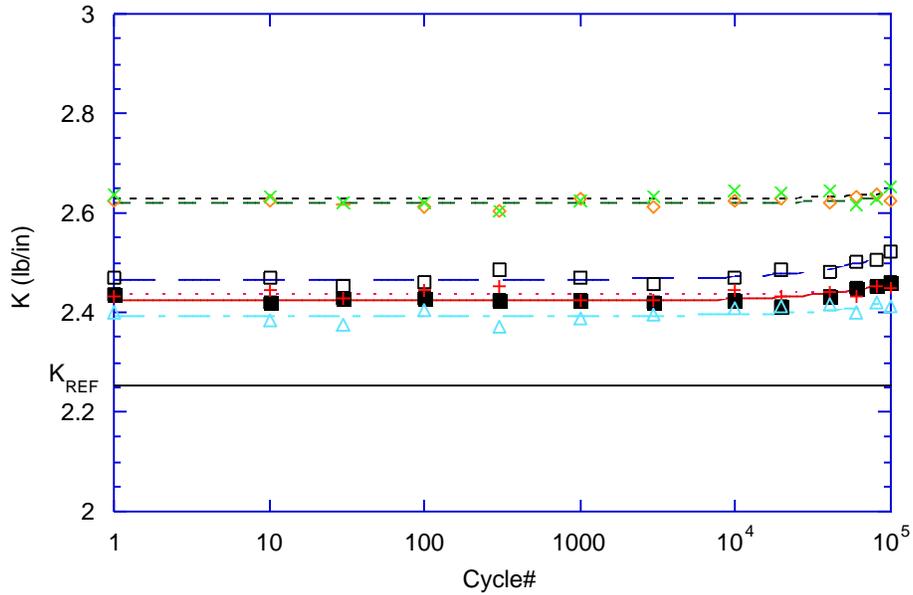
service displacement and a test to characterize the effect of temperature on the mechanical behavior of the springs. The 150% displacement tests were conducted immediately after the 100% displacement tests. Data to reconstruct the waveform and monitor the spring constant K during the tests were taken periodically throughout the test duration to isolate any variation in K. The tests which characterized the effect of temperature were conducted at 39°C (102°F), 115°C (239°F), 196°C (385°F), and 279°C (534°F). Each spring was cycled at the 150% displacement specified in Table II and data

Table II
150% Displacement Table

	BBN 6684	BBN 6236	BBN 8150
322849	0.134 - 0.332 in	0.134 - 0.332 in	0.134 - 0.332 in
309364	0.148 - 0.241 in	0.148 - 0.241 in	0.148 - 0.241 in
309368	0.104 - 0.230 in	0.104 - 0.230 in	0.104 - 0.230 in
309367	0.112 - 0.151 in	0.112 - 0.151 in	0.112 - 0.151 in
309365	0.066 - 0.105 in	0.066 - 0.105 in	0.066 - 0.105 in

were taken to determine the spring constant K at each of these temperatures. The purpose of these tests was to characterize changes of the mechanical response of the spring over a range of temperatures. Results from the 100 and 150% displacement tests

Spring: 309364



Spring: 309365

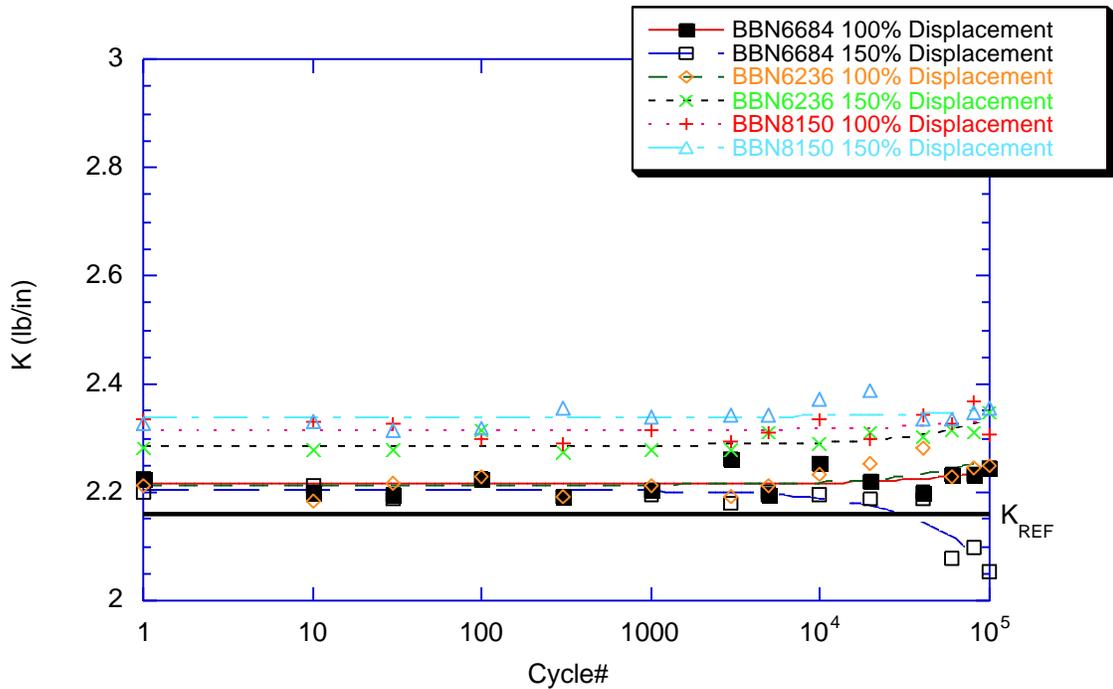


Figure 19A. Spring constant (K) vs. cycles.

are given in **figure 19**. The variation of the spring constant K with the number of cycles is plotted separately for each of the five spring types. Each plot contains displacement data for springs from each of the three stronglinks. When possible, a linear fit was

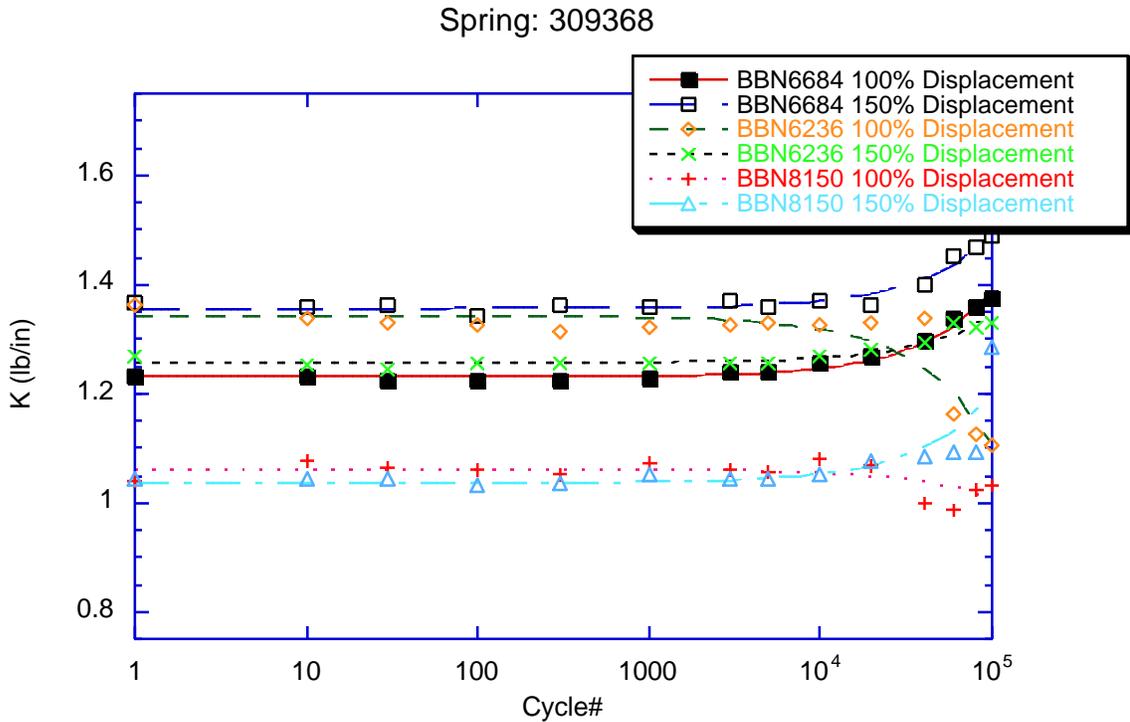
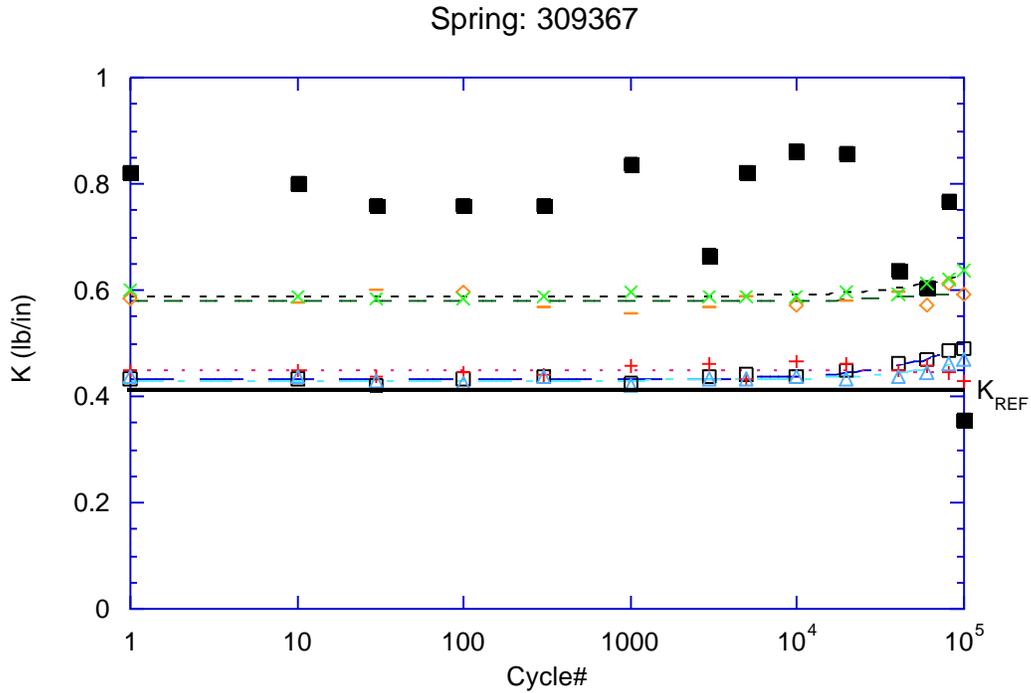


Figure 19B. Spring constant (K) vs. cycles.

applied to the data. The curvature of the fitted data in **figure 19** results from plotting a straight line with a non-zero slope on a semi-logarithmic plot. The reference spring constant taken from the drawings is also illustrated in **figure 20** for each spring. The change in spring constant K over 100,000 cycles was negligible or within the noise of the data.

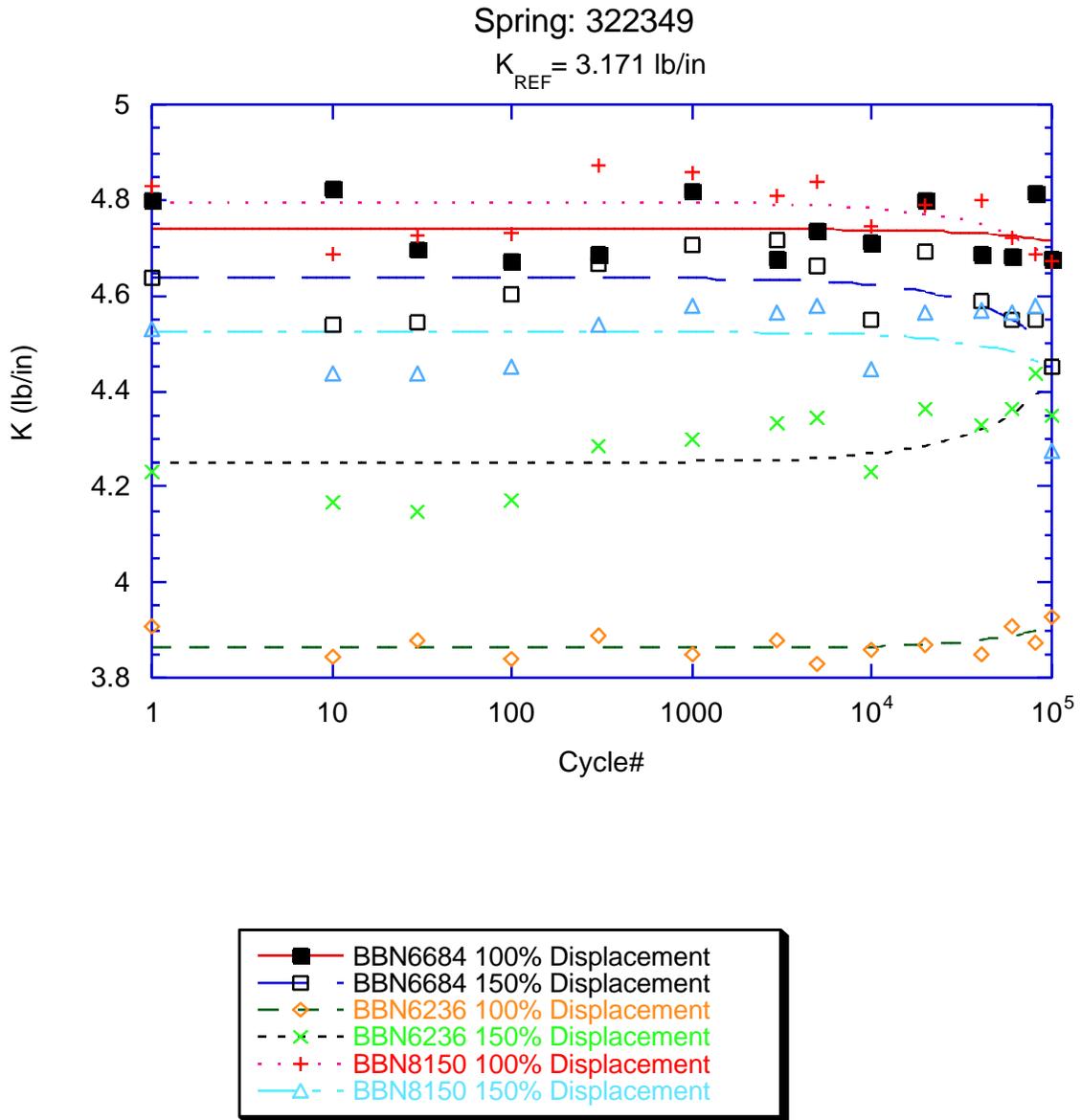


Figure 19C. Spring constant (K) vs. cycles.

The variation of spring constant vs. temperature up to 300 C for four different spring types taken from three stronglinks is given in **figure 20**. Note that the series 309367 springs and the 309365 spring from stronglink BBN8150 were not subjected to the

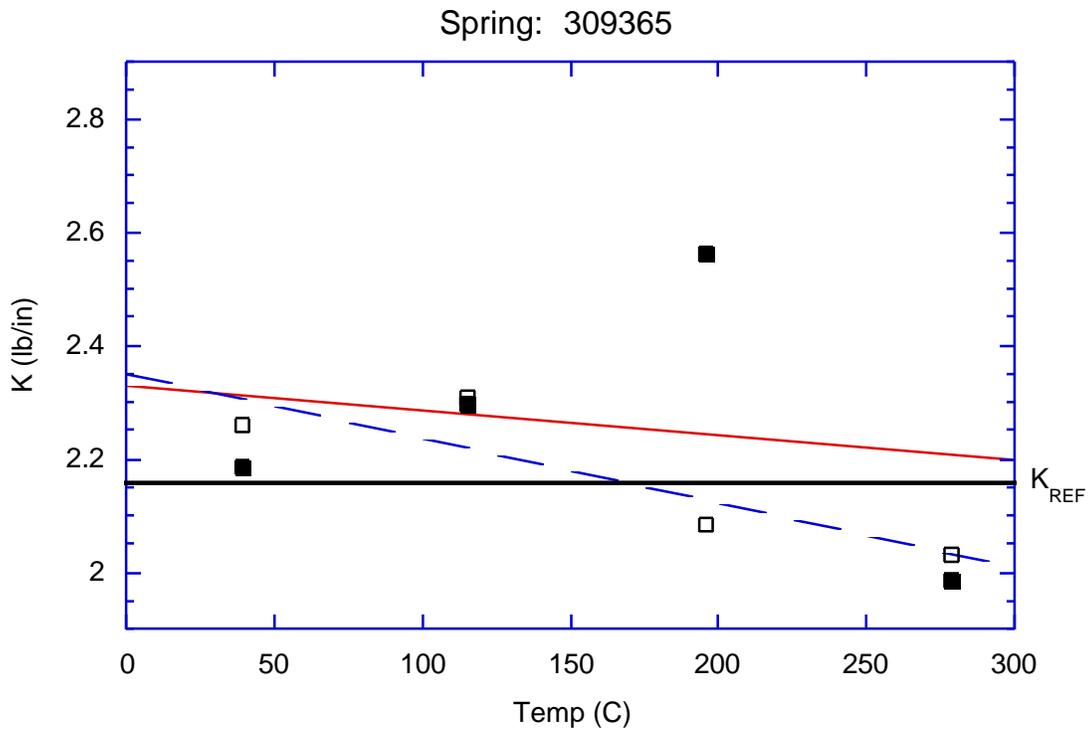
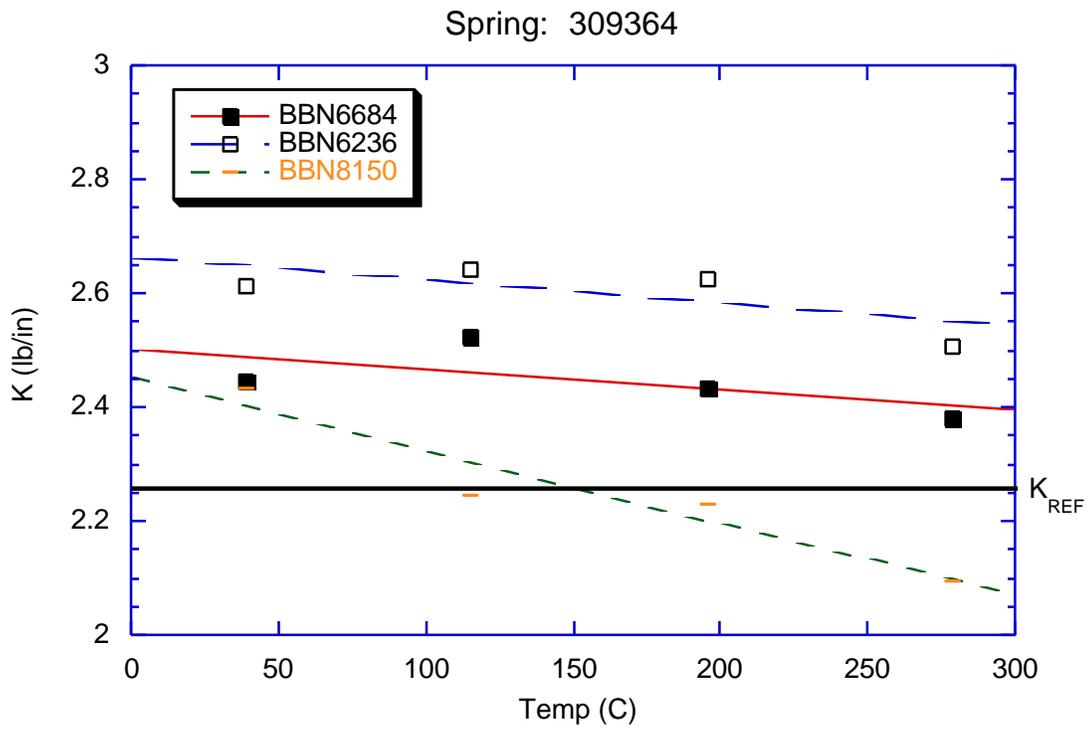


Figure 20A. Spring constant vs. temperature, stronglink spring.

temperature test. A linear fit was applied to each set of data, when possible. Small variations in spring constant K vs. temperature were noted -- usually a small decrease in K with an increase in temperature.

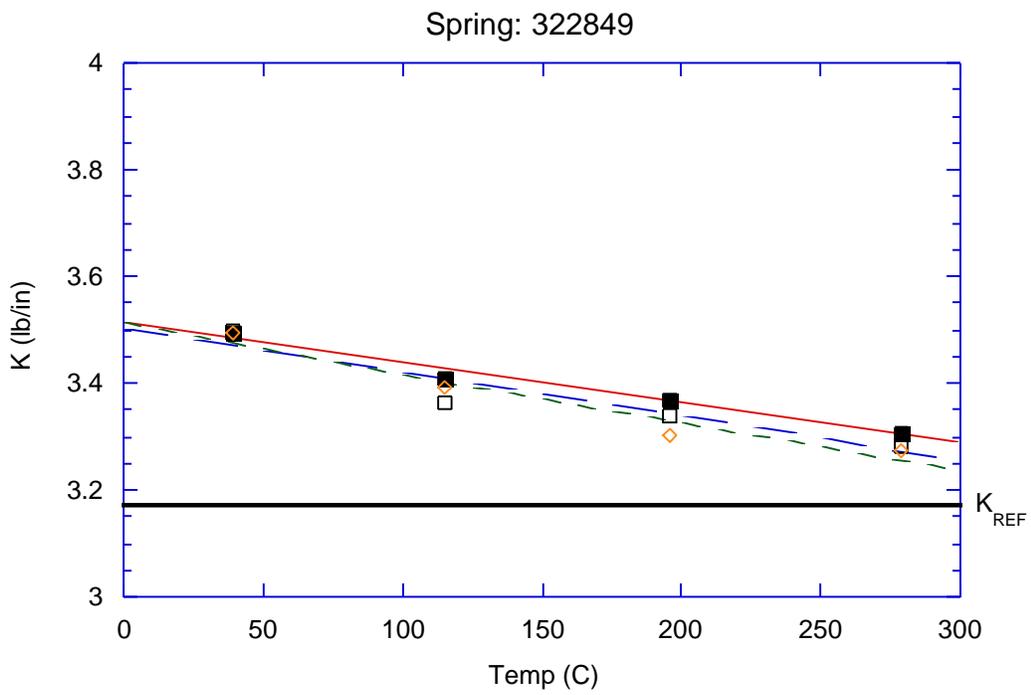
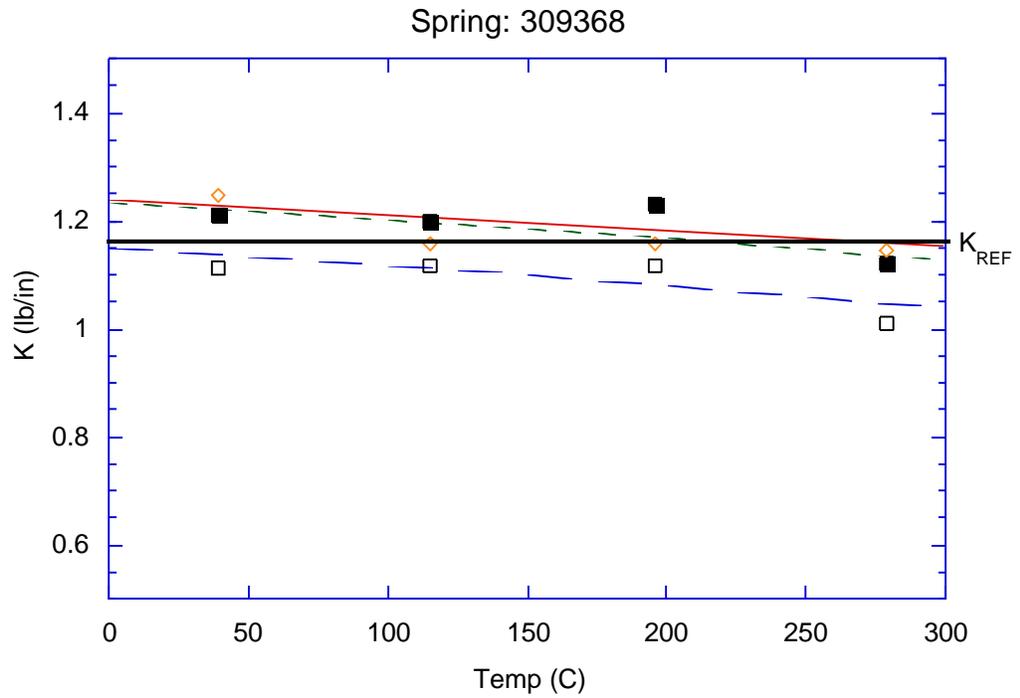


Figure 20B. Spring constant vs. temperature, stronglink spring.

Test Results

Low Cycle Fatigue

One of the primary technical drivers in the development of this test system was to provide the capability to perform fatigue testing of LIGA produced test articles. **Figure 21** illustrates the first such result obtained using this load frame. Due to the lack of

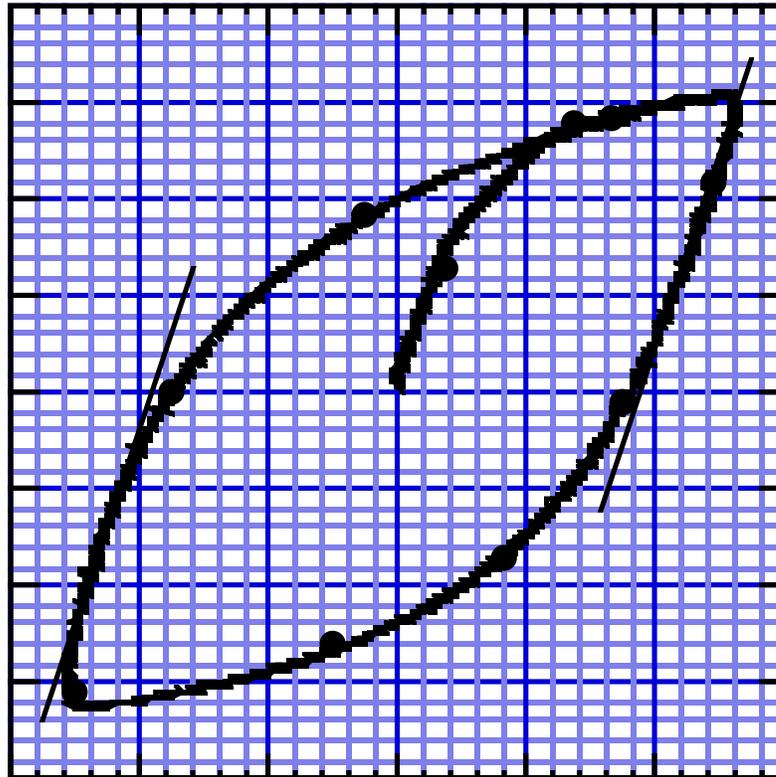


Figure 21. Fatigue test, compliance corrected first cycle from LIGA material. Specimen gage dimensions .022 inch wide, .044 inch thick x .054 inch long.

available contacting extensometry and the extremely short gage length of the test specimen (to avoid compressive buckling) it was necessary to compliance correct the raw experimental results. This was done by comparing a calibrated digital image of the deformed test specimen with the LVDT readout. The resulting hysteresis loop possesses the expected shape and symmetry typical of a well aligned, fully reversed test of an annealed polycrystalline specimen.

Conclusion

As part of an overall broad effort to develop mechanical test capability of millisized and microsized structures, a mechanical test system has been designed and assembled with the primary goal of characterizing the mechanical properties of LIGA synthesized structures and materials. The current system utilizes many standard as-manufactured items including an MTS 3000 pound 1.0 inch travel hydraulic actuator and an Interface 100 pound load cell. Load, stroke and displacement control is provided by an MTS TestStar system and two 0.100 inch LVDT displacement gages situated in a parallel arrangement at the specimen.. Load resolution is on the order of 50 μ oz. and displacement resolution less than 45 μ inch. The system can test dynamically up to 100 hz at 0.005 inch actuator displacement and loads of 100 lb., statically at up to 250 lb. (limited by the load cell). Presented here were a detailed description of the machine and a diverse set of results -- demonstrating that the scope and flexibility of the microscale test system extends far beyond simply testing LIGA synthesized parts..

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