May 2016

Effect of Thermal Treatment on High Temperature Deformation of Alloy EP-~823

Martin Milburn Lewis
University of Nevada, Las Vegas

EFFECT OF THERMAL TREATMENT ON HIGH TEMPERATURE DEFORMATION OF ALLOY EP-823

by

Martin Milburn Lewis

Bachelor of Science in Engineering – Mechanical Engineering
University of Nevada, Las Vegas
2000

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science in Engineering – Mechanical Engineering

Department of Mechanical Engineering
Howard R. Hughes College of Engineering
The Graduate College

University of Nevada, Las Vegas
May 2016

UNLV | GRADUATE COLLEGE

Thesis Approval

The Graduate College
The University of Nevada, Las Vegas

February 19, 2016

This thesis prepared by

Martin Milburn Lewis

entitled

Effect of Thermal Treatment on High Temperature Deformation of Alloy EP-823

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Engineering – Mechanical Engineering
Department of Mechanical Engineering

Brendan O'Toole, Ph.D.
Examination Committee Chair

Mohamed Trabia, Ph.D.
Examination Committee Member

Zhiyong Wang, Ph.D.
Examination Committee Member

Robert Schill, Ph.D.
Graduate College Faculty Representative

Kathryn Hausbeck Korgan, Ph.D.
Graduate College Interim Dean

ABSTRACT

The objective of this research topic is to determine mechanical properties of Alloy EP-823 and to provide a mechanistic understanding of its sensitivity to both thermal treatment and performance temperature. EP-823 is a leading target material for accelerator-driven waste transmutation applications. Overall, the tensile test results of Alloy EP-823 indicated a general trend of decreasing mechanical performance with an increase in tempering time. An increase in tempering time had a statistically significant inverse relationship with ultimate tensile strength (UTS) and yield strength (YS). An increase in tempering time did not have a significant effect on elongation and reduction in area. Performance temperature effects, however, were more noticeable, trending UTS and YS values downward with increasing temperature. Elongation values experience a slight reduction up to 300°C then ramped upwards for increasing temperatures. Reduction of area values appeared unaffected by an increase in temperature up to 400°C but did experience an increase with greater temperatures beyond 400°C. With increasing temperature the mechanical properties changed gradually and predictably up to 400°C, but at 500°C they changed drastically, implying that a critical temperature can be found between 400°C and 500°C. This temperature could be important to design integrity. At performance temperatures beyond this critical temperature the material experiences unstable deformation shortly after reaching the yield strength value, exhibiting severely truncated uniform plastic deformation characteristics.

Keywords: martensitic alloys, tensile properties, elevated temperatures, EP-823

ACKNOWLEDGMENTS

At times the pursuit of wonderful things in life can take much longer than originally planned. Often this can lead to a situation where it becomes increasingly more difficult to keep moving - or in some cases start moving again, requiring a great force to overcome one's own static inertia. When facing these situations it is always a blessing to have people who care and offer their support and guidance to help push through all barriers. This thesis would certainly not have been completed without these key people in my life.

I would like to thank Dr. Brendan O'Toole, Dr. Ajit Roy, and Dr. Anthony Hechanova for offering me this research opportunity. So much knowledge and understandings were gained from this research that has been applied throughout my academic and professional engineering career. Dr. O'Toole, my committee chair, has always been a great mentor and a North Star for me during the last couple of decades. His support and advice has been crucial in my development and success as an engineer.

I would like to thank my other committee members Dr. Mohamed Trabia, Dr. Zhiyong Wang, and Dr. Robert Schill. Dr. Trabia has always been a trusted advisor since my freshman year, and he has helped me make some important decisions in life. Dr. Wang has philosophically changed my perspective of mechanical engineering, defining mechanical engineering as *artwork that is practical*. Because of this, everything I design or engineer must be beautiful and beautifully functional. Dr. Schill has been a great engineering professor to look up to in the college and a great black belt to look up to in the taekwondo dojang. It was an honor to have these gentlemen as part of my committee.

I am grateful to have Mark Jones and Ray Kozak as my research partners. We spent many long days, nights, and weekends in the lab designing and building the test system, performing tests, and processing data. Mark (SIUYA) is by far the finest machinist and machine designer that I have ever known. He is the machine whisperer among machine whisperers and has a way of making things work perfectly. Many of our equipment parts were fabricated by him and even today I still marvel at his ability. My other partner Ray was a dear mentor to me and looked out for me throughout college. He was the guy anybody could turn to and get help from to create anything and was instrumental in setting up the tensile testing machine and its test software. I miss him dearly, and because of him I strive to help others the way he did.

I am truly blessed and lucky to have such wonderful family and friends to get me through this program. My parents have always been supportive in all my endeavors and always made sure that I knew that they were proud of me. I am thankful for their love. My three offspring, Aziz, Asiya, and Aysha gave me their love, their humor, and the motivation to keep moving. They are all gifts and there is not a single day that goes by that I do not think of how lucky I am to have them.

Finally my beautiful wife, Sarah, is both my best friend and soul mate. I have and always will trust in her and her counsel for all of life's defining moments and big decisions. She provided me the love and the size five-and-half shoe print permanently indented on my backside to get this thesis written and defended. Sarah is an inspiration to all that know her, including myself, and I will forever wonder at my good fortune to have married her.

I thank God for all of these blessings. Life is good.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1:

INTRODUCTION

1.1. Objective

The driving objective of this research topic is to determine mechanical properties of Alloy EP-823 for a mechanistic understanding of its sensitivity to both thermal treatment and performance temperature.

1.2. Background

Spent nuclear fuel and high-level radioactive waste are hazardous to the environment and deadly to almost all forms of life. This creates a demand for safe and secure means for disposal. To dispose of this waste properly and safely carries a tremendous challenge due to the extremely high radioactive levels and long half-lives of these waste forms. This type of waste can remain radioactive for thousands of years.

In light of this serious problem a research program was initiated in an effort to reduce the radioactivity and half-lives of these nuclear by-products through a process called transmutation. Transmutation causes changes in the nuclear structure of the elements in these waste forms by exposing such elements to high speed collisions from neutrons. These neutrons are produced when protons from an accelerator or reactor bombard a target neutron source, such as molten lead-bismuth-eutectic.

Using molten lead-bismuth-eutectic as a target material requires a structure to contain it. This container could be fabricated from several ferritic-martensitic steel options. Alloy EP-823 was recommended by the project's collaborator at Los Alamos National Laboratory (LANL) for the

alloy's irradiation creep properties, resistance to irradiation void swelling, and low thermal expansion coefficient [1]-[2].

EP-823 was specifically developed for nuclear reactor facilities that used lead-bismuth coolant [3]. It exhibits good corrosion resistance by creating a protective oxide layer when exposed to the lead-bismuth coolant [4]. The material also has good mechanical performance before and after irradiation [5]. However, there are losses in ductility and increases in yield stress values post-irradiation, suggesting embrittlement of the material. This embrittlement is attributed to the material's high content level of silicon [6]. The alloy has a silicon content between 1.0 and 1.3 percent by weight.

The target container will be subjected to high tensile stress at temperatures ranging between 400°C and 600°C (752°F and 1110°F).

1.3. Research Plan

Since the target container will be subjected to high tensile stress in temperatures ranging from 400°C to 600°C (752°F to 1110°F), this project scope encompassed this temperature range with tensile tests performed at room temperature up to 600°C (1110°F). At different temperatures the mechanical properties were determined of which included ultimate tensile strength, yield strength, elongation, and reduction of area. With a goal of enhancing the ductility parameters, the material was thermally treated with varied tempering times to determine the effect on mechanical properties.

1.4. Develop Test Apparatus and Test System

Conducting this study required outfitting a tensile testing machine with elevated temperature test equipment, including a furnace, laser extensometer, custom high temperature grips, and

automated nitrogen and cooling systems. The use of this system was not only intended for the researchers of this topic but was also developed for use by independent researchers outside of this topic as well. Because of this, the system hardware was developed with automation and system safeguards to aid other researchers.

1.5. Determine Material Properties

To help process data, a spreadsheet template was developed for data reduction, complete with user instructions. This data reduction tool processed the tensile test output files and test specimen dimensional characteristics to determine ductility parameters, such as ultimate tensile strength, yield strength, elongation, and reduction of area. This tool featured an algorithm to systematically and numerically determine the yield point on a stress-strain curve to mitigate human error typically attributed to visual inspection. It also provided a means for data conditioning to correct for system compliance.

This thesis presents the results of tensile testing with respect to testing temperature across three thermal treatments. It also details the system set-up and experimental method to accurately determine these results.

CHAPTER 2:

MATERIALS DESCRIPTION

All tensile specimens were made from a single alloy heat to accurately gage the sensitivity of heat treatment on mechanical properties of Alloy EP-823 ferritic-martensitic steel. This heat was processed into bars, thermally treated, and ultimately machined into the tensile specimens used for this thesis.

2.1. Raw Material

A single heat of Alloy EP-823 ferritic-martensitic steel was melted by vacuum induction melting and further processed by forging and hot rolling into 13-mm (half-inch) hot rolled bars 46 cm (18 in) in length. Eighteen bars from this heat were used to address all eighteen test variable combinations used for this research. This raw material production was performed at Timken Research Laboratory with the chemical composition provided in Table 1. The bar material was subsequently subjected to thermal treatment as described in Section 2.2.

Table 1. Alloy EP-823 Chemical Composition

Element	Weight Percent (%)
Chromium (Cr)	10-12
Molybdenum (Mo)	0.6-0.9
Nickel (Ni)	0.5-0.8
Manganese (Mn)	0.6-0.9
Vanadium (V)	0.2-0.4
Tungsten (W)	0.5-0.8
Niobium (Nb)	0.2-0.4
Carbon (C)	0.14-0.18
Silicon (Si)	1.0-1.3
Iron (Fe)	Balance

2.2. Bar Material Thermal Treatment

The bar material was thermally processed to produce a fully tempered and fine grained martensitic microstructure without any retained austenite. For the first part of the thermal process the bars were austenitized for one hour at 1010°C (1850°F) immediately followed by oil quenching. To study the effects of tempering time on the alloy's ductility parameters, the material was subsequently tempered at 621°C (1150°F) for three different tempering times, specifically 1.25, 1.75, and 2.25 hours, and was followed by air-cooling. These material test lots were identified as 2054S, 2054T and 2054U, respectively. Table 2 provides a heat treatment summary of the raw material.

Table 2. Alloy EP-823 Material Heat Treatment Summary

Test Lot	Austenitizing Process			Tempering Process		
	Temperature (℃ / ℉)	Time (Hours)	Cooling Method	Temperature (℃ / ℉)	Time (Hours)	Cooling Method
2054S	1010 / 1850	1	Oil Quench	621 / 1150	1.25	Air Cooling
2054T	1010 / 1850	1	Oil Quench	621 / 1150	1.75	Air Cooling
2054U	1010 / 1850	1	Oil Quench	621 / 1150	2.25	Air Cooling

The measured hardness value of the quenched and tempered materials ranged between 24 and 28 HRC as measured on the Rockwell C hardness scale. Hardness values decreased with longer tempering time as indicated in Table 3. As a reference, the untempered parent heat lot 2054 measured 39 HRC but was not subjected to mechanical testing for this paper. These quenched and tempered bars were machined into the tensile specimens used to determine the mechanical properties.

Table 3. Hardness Values Resulting from Heat Treatment

Test Lot	Tempering Time (Hours)	Rockwell C Hardness (HRC)
2054	0	39
2054S	1.25	28
2054T	1.75	26
2054U	2.25	24

2.3. Tensile Specimens

Subsequent to thermal processing the round bars from the three material test lots were machined in the longitudinal rolling direction to form the cylindrical dog-bone shaped tensile specimens as specified in Figure 1. The specimens had a smooth gage section 25.4 mm (1 in) in length by 6.35 mm (.25 in) in diameter. Both ends of the dog-bone specimens had external threads for mating with the high temperature adaptor grips. To help protect data integrity both ends of all specimens were engraved with the material lot number and a sequential specimen identification number. Specimen machining was performed by fellow researcher Mark Jones.

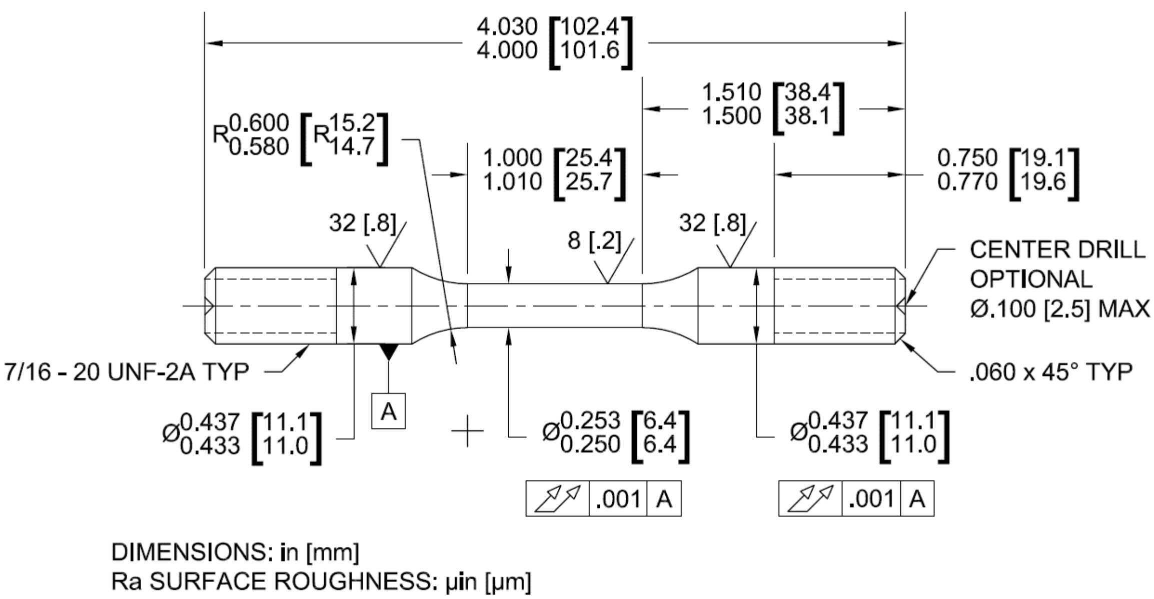


Figure 1. Dog-Bone Tensile Specimen Drawing

It was mentioned by Jones that extra care was required during the machining operation of the tensile specimens due to extensive warping in the round bar stock, pointing out that each 45-cm

(18-in) stick typically had between 3.81 to 6.35 mm (0.150 to .250 in) of bowing from end to end. Instead of bar straightening via bending, which would induce stresses into the material, Jones elected to true smaller pieces of each stick by rough machining prior to machining the tensile specimens. The bar stock diameter was 14.0 mm (0.550 in) and the finished diameter was 11.1 mm (0.435 in), allowing for rough machining. Each specimen was machined within tolerances specified by Figure 1.

CHAPTER 3:

EXPERIMENTAL METHODS

In addition to studying the effects of tempering time, the ductility parameters of each material lot were determined at various temperature intervals, ranging from ambient room temperature to 600°C (1112°F). To perform this a computer-controlled material testing system (MTS) machine, outfitted with high temperature testing equipment, performed the tensile testing in accordance with ASTM E8, *Standard Test Methods for Tension Testing of Metallic Materials* [7]. To prevent ambient atmospheric contamination, all tests were conducted in a nitrogen atmosphere, created by a constant overpressure inside the confines of the ceramic chamber of the high temperature furnace. This chapter details the test matrix, the set-up of the testing apparatus, the test procedure, and data reduction method.

3.1. Experiment Testing Matrix

The goal for this research was to develop a mechanistic understanding of Alloy EP-823 with regard to both tempering time and testing temperature. To accomplish this a comprehensive battery of tests was methodically conducted, varying a single independent variable to determine the sensitivity of that particular variable. The data recorded from each test condition generated mechanical property performance curves and ductility parameters. With three material tempering times at six test temperatures there were eighteen test variable combinations. These variable combinations are tabulated in Table 4. Each combination was limited to three test samples due to material availability and the required duration of each test. In total there were 54 tensile tests.

Table 4. Experiment Test Matrix

Heat Lot	Tempering Time [1] (Hours)	Number of Tensile Tests Performed (Samples)					
		Testing Temperature					
		RT [2]	100°C (212°F)	300°C (572°F)	400°C (752°F)	500°C (932°F)	600°C (1112°F)
2054S	1.25	3	3	3	3	3	3
2054T	1.75	3	3	3	3	3	3
2054U	2.25	3	3	3	3	3	3

[1] Tempering thermal treatment is detailed in Section 2.2.

[2] RT is ambient room temperature, generally approximated to 25°C (77°F).

3.2. Set-Up of Testing System

To facilitate high temperature mechanical testing, a material testing system (MTS brand) was outfitted with high temperature components, many of which were custom built by the researchers of this study. This section describes the components used to create the testing environment, to provide accurate data acquisition, to protect the testing apparatus, and to safeguard data integrity.

During the design of this testing apparatus, strong consideration was given to the idea that other graduate students and faculty would use this testing system to conduct their own research [8]-[13], theses [14]-[24], and dissertations [25]. Being mindful of this, the elevated temperature testing apparatus, data acquisition system, and data reduction software was developed with automation and safeguards to mitigate human error. The complete testing system is shown in Figure 2. The following subsections will further describe the integral systems components that were necessary for high temperature testing for this thesis.

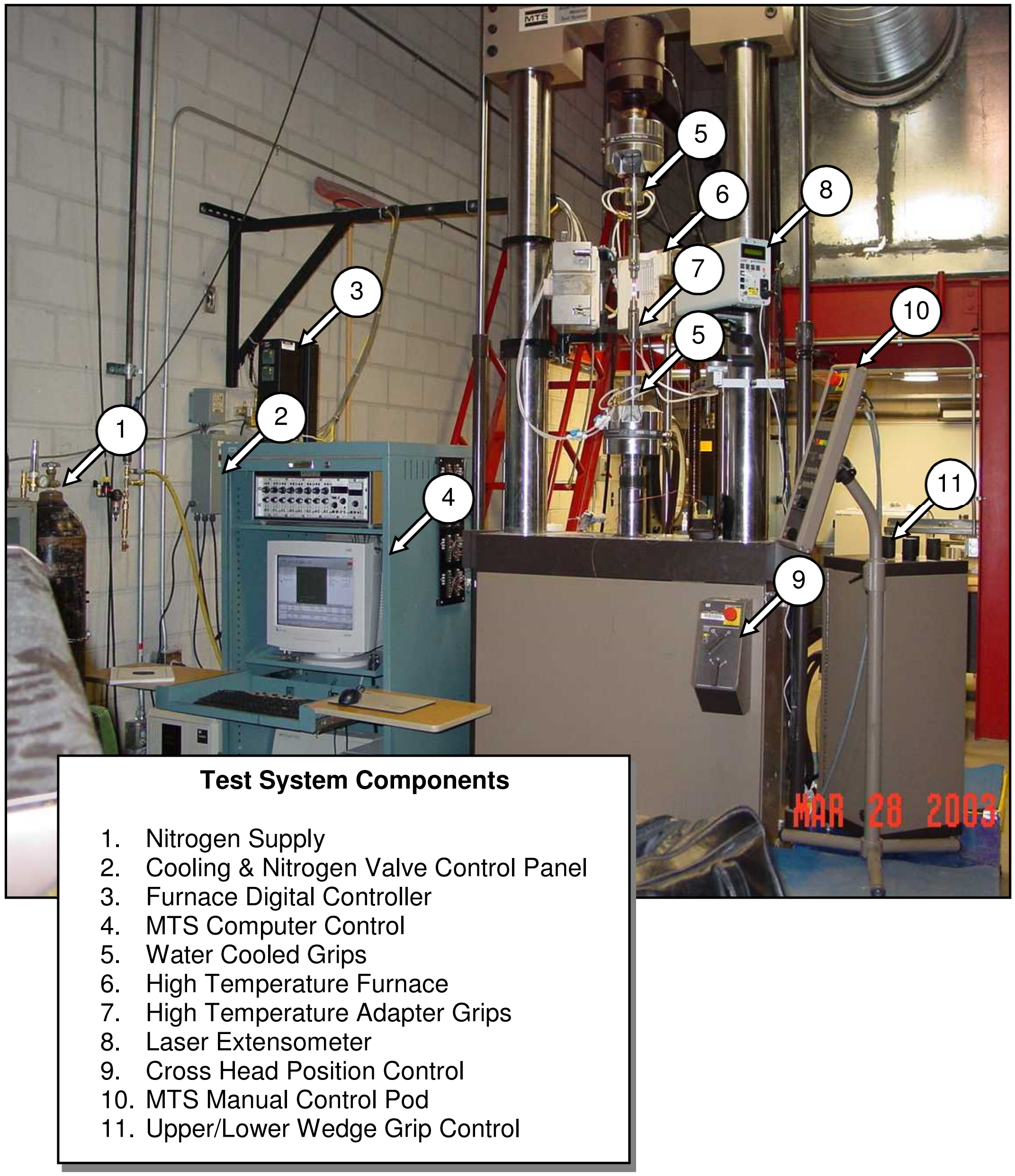


Figure 2. Elevated Temperature Material Testing Apparatus Set-up

3.2.1. Material Testing System Machine (MTS)

The test equipment shown in Figure 3 is a servo-hydraulic-actuated material testing system machine (MTS brand, Model 319.25), capable of providing 250 kN (55 kip) of tension loads and

2200 N-m (20,000 lbf-in) torsion loads. On board sensors include a linear variable displacement transducer (LVDT), angular displacement transducer (ADT), axial load transducer, and torsional load transducer. The cross head height is adjustable for set-up purposes and contains the axial and torsional load transducers. The linear actuator is integral to the base and features a 15-cm (6-in) actuator dynamic stroke length. The upper and lower wedge grips are hydraulically actuated and have cylindrically shaped interfaces for gripping the circular rod stems of the high temperature grip assembly.

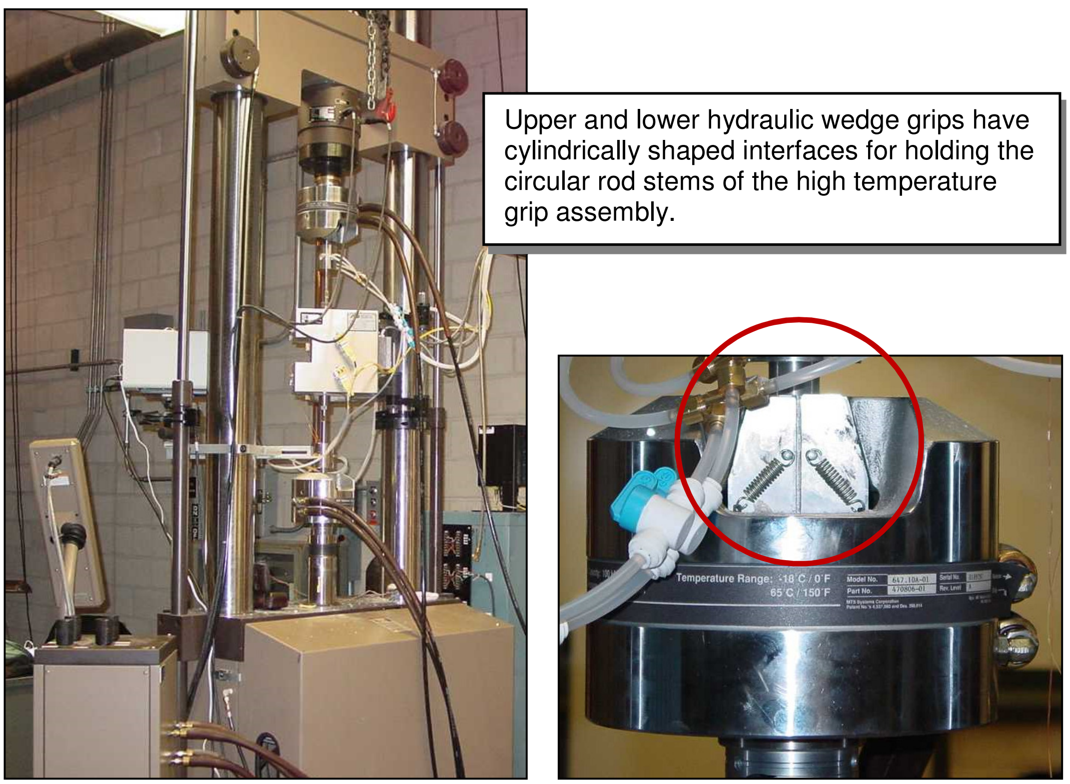


Figure 3. Material Testing System Machine (MTS) with Wedge Grips

MTS TestStar-790.00 Version 4.0E software provides a graphical user interface and controls all functions of the MTS machine. The axial loads, torques, linear displacements, and rotation can be applied manually with the MTS digital control pod (Figure 4). They can also be controlled by software programming. Load application can be load-controlled, displacement-controlled, or controlled by an external signal from a sensor device such as an extensometer or load cell. MTS TestWare-SX Version 4.0D software allows the user to create programmed test templates for running each experiment. For this research topic the load is applied by controlled displacement, which is discussed later in Section 3.2.10.

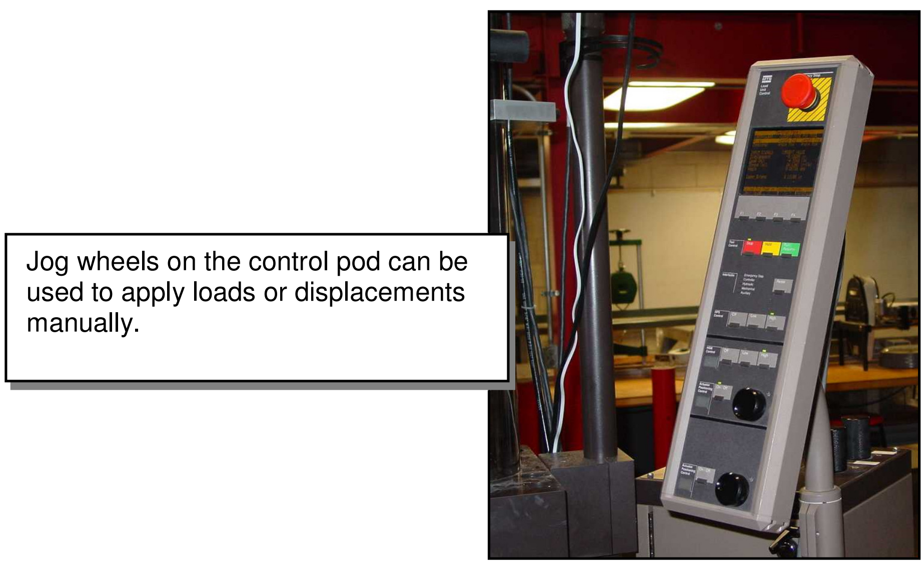


Figure 4. Digital Control Pod with Jog Wheel Controls

3.2.2. High Temperature Furnace and Controller

The elevated temperature environment was provided by an insulated, ceramic-lined clamshell type furnace, employing dual zone resistance heaters, capable of providing temperatures up to

1000°C (1832°F). The MTS brand (model 409.83) temperature controller, shown in Figure 5, has dual digital temperature controllers and features signal input and output connections. These connections can be used for safety interlocks and for automatically activating system safeguards such as water and air cooling systems and to activate a nitrogen atmosphere when the temperature controller unit is enabled. Two thermocouples, embedded in the heating elements, provide temperature feed-back of the elements but do not provide the temperature of the test environment inside of the furnace chamber. There is an entry port, located at the furnace clamshell part line, allowing an extensometer device to provide vertical measurement. The furnace was also equipped with a horizontally-oriented view port which was replaced by a custom plate for mounting a thermal couple probe to measure the surface temperature of the tensile specimens.

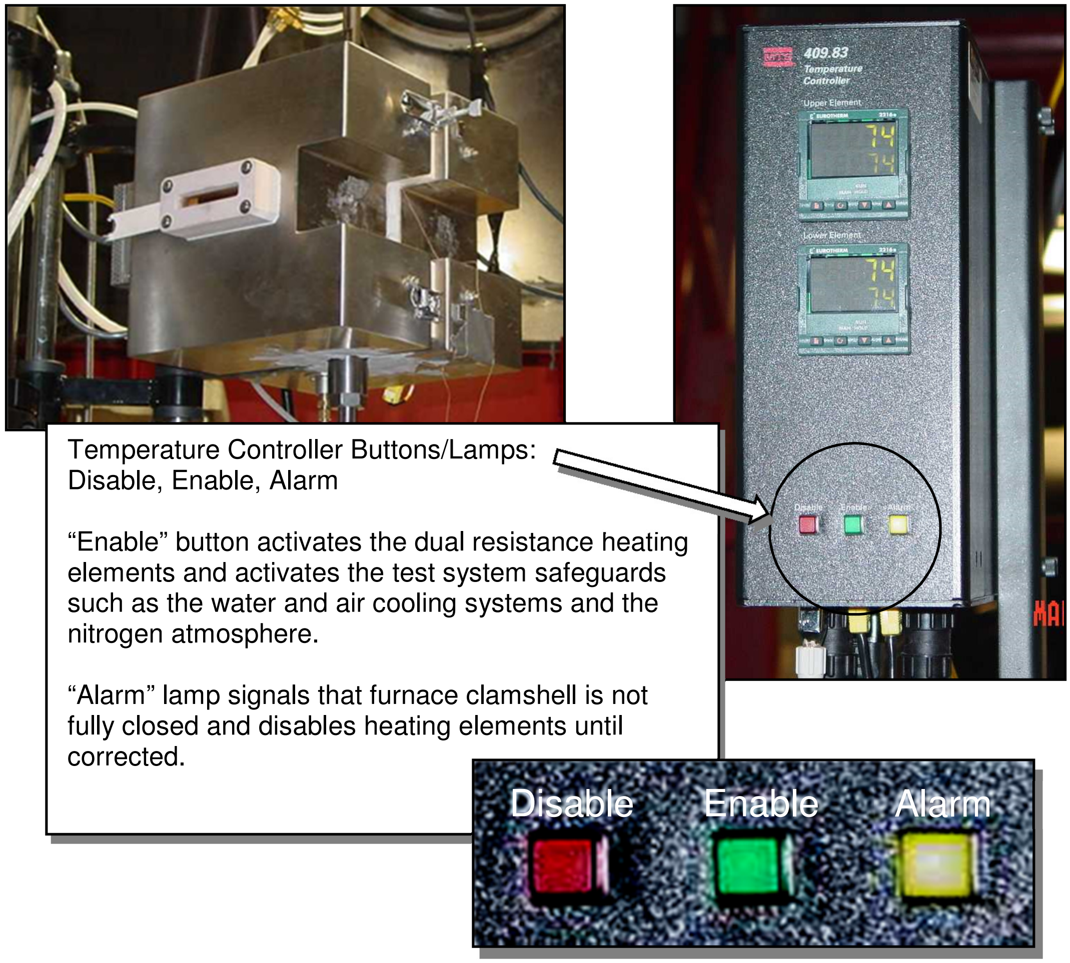


Figure 5. High Temperature Furnace and Digital Temperature Controller

The furnace is equipped with a cantilevered two-link mounting arm for positioning the furnace around the tensile specimen. This arm has two large split rings, designed for attaching to one of the two main support columns on the MTS machine. Counting the furnace itself as a link, this design provides three degrees of freedom for positioning the furnace around the test grips. See Figure 6.

Figure 6. Furnace Mount

3.2.3. Laser Extensometer

To collect accurate tensile specimen extension data during each experiment, the EIR brand (model LE-01) laser extensometer shown in Figure 7 was incorporated into the set-up. This laser extensometer provided direct extension measurement of the gage length, thereby removing any compliance errors caused by elastic deformation of grip components and machine structure. This laser has a measurement range of 0.3-3.2 in (8-80 mm) and a measurement resolution of 0.0001 in (0.001 mm) with ±0.0001 in (±0.0025 mm) repeatability. Extension data is provided at 100 scans per second via an analog output port for connection to the test system computer.

A major advantage gained by using this laser extensometer instead of other extensometer types is being able to monitor a test for its entirety, up to and including specimen rupture. Other extensometer types, such as ceramic-arm extensometers, require contact with the tensile specimen and must be removed prior to specimen failure or risk damage from a violently snapping specimen. This suddenly released load can be in excess of 18 kN (4,000 lbf). However, using a laser, this

extensometer device requires only a line of sight to the gage portion of the specimen and is positioned safely away from specimen movement and elevated furnace temperatures.

Laser Extensometer
Brand: EIR
Model: LE-01

Specifications	
Measurement Range	0.3-3.2 in (8-80 mm)
Non-Linearity	± 0.0002 in (±0.005 mm)
Resolution	0.0001 in (0.001 mm)
Nominal Target Distance	10 in (250 mm)
Max. Target Distance	20 in (500 mm)

Figure 7. Laser Extensometer

There are, however, limits to the effective usage of this laser extensometer system. The laser relies on reflective strips that must be affixed to the tensile specimens as shown in Figure 8. These aluminum-backed adhesive strips can withstand temperatures up to 482°C (900°F). Consequently,

the laser system is limited to performing up to the 400°C tests, falling short of accommodating the 500°C and 600°C tests.

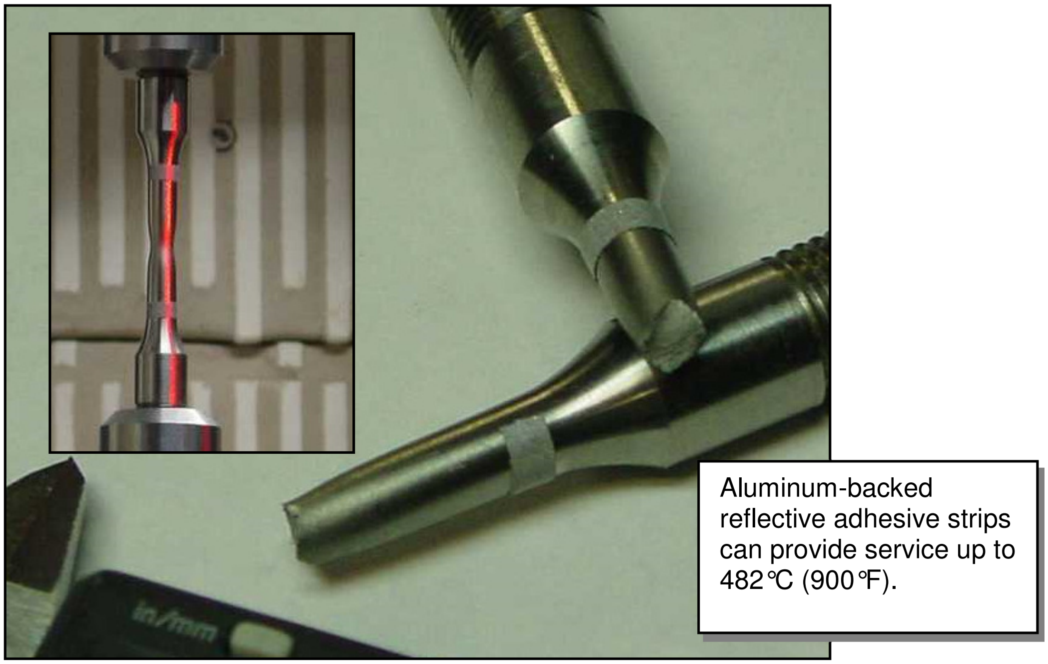


Figure 8. Aluminum-Backed Reflective Adhesive Strips

The manufacturer of the laser extensometer specifies a nominal target distance of 10 inches (250 mm) from the specimen. To position the laser at the specified distance, a customized adjustable mounting arm supported the laser and was attached to a main support column on the MTS machine. This mount was used as an alternative to a floor standing tri-pod that had proven cumbersome for set-ups and was inherently subject to bumping. It was imperative that the laser line was perfectly aligned with the axis of the tensile specimen to ensure extension measurement

accuracy. To facilitate this, a fully adjustable camera mount with dual-axis bubble indicators was installed on the mounting arm as shown in Figure 9.

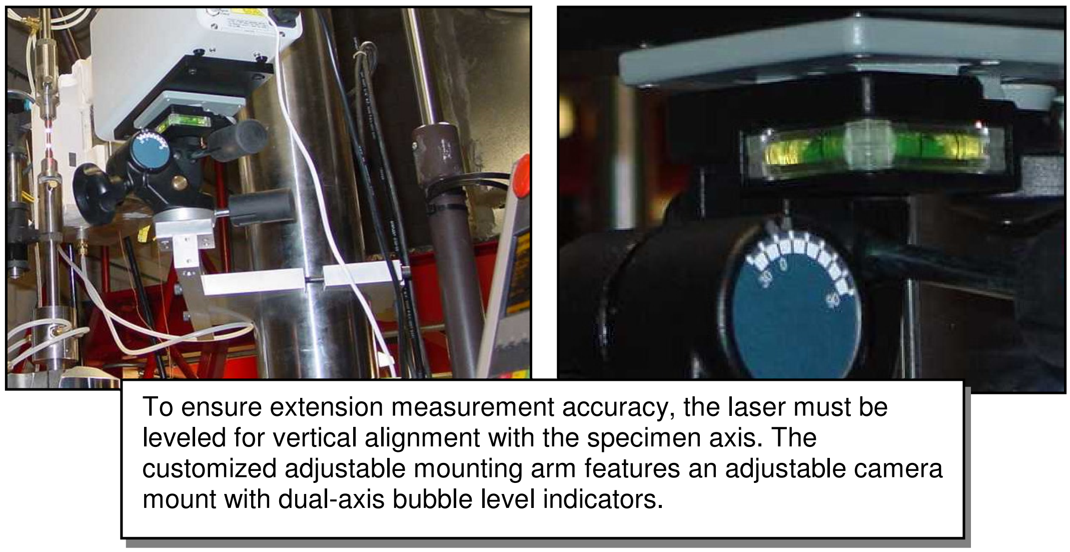


Figure 9. Customized Laser Extensometer Mount

3.2.4. High Temperature Adaptor Grips

To accommodate the large number of elevated temperature tests from this research topic and from others as well [8]-[25], special Adaptor grips were designed and fabricated for repeated use, requiring robust material properties to withstand the elevated temperatures of the test environment. 18Ni (250) maraging steel was selected for its high yield strength of 1800 MPa (260 ksi) and hardness of 52 HRC. Furthermore, this material lends itself well to machining operations.

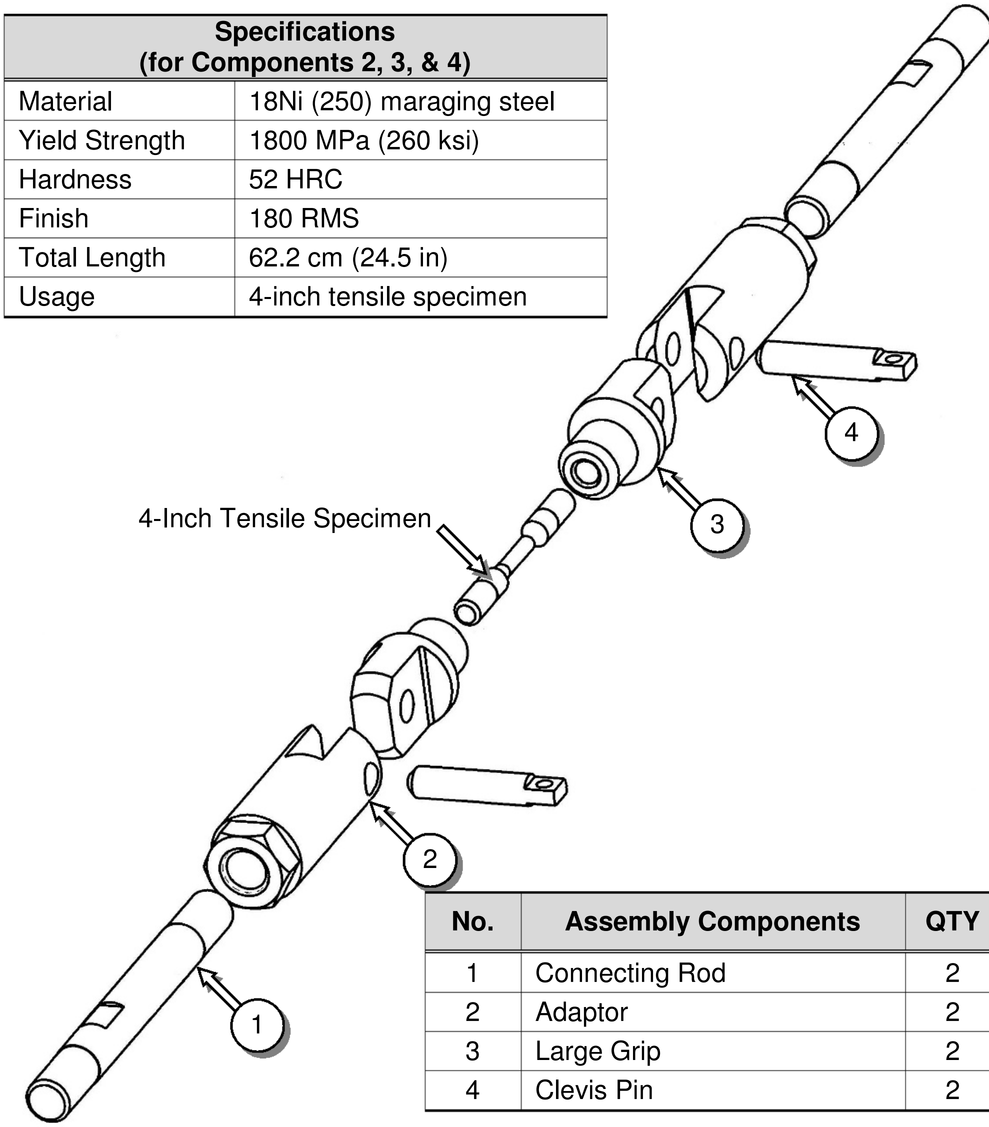
The material was purchased as 1.5-inch and .5-inch bar stocks and arrived in its thermally treated condition according to the material specification. With regard to thermal treatment, the material specification of 18Ni (250) maraging steel [26] calls firstly for solution-annealing for 1

hour at 820°C (1500°F) followed by air cooling. Secondly, it calls for solution-annealing, for 3 hours at 480°C (900°F).

It is this second thermal treatment for the grip assembly that was of particular importance, since at least a third of all experiments in this study (see Table 4, test matrix) had test temperatures above the minimum aging temperature, which has an aging range of 480°C to 540°C (900°F to 1000°F). In essence, the cumulative overaging effect on the performance of the grip material had to be considered, since these grips were repeatedly subjected to elevated temperatures for many cumulative hours beyond the optimal aging duration. Fortunately, even with 200 hours there should only be a minor decrease in the material's high strength performance from overaging [26], making this steel alloy an ideal grip assembly material.

The grip assembly has clevis joints with removable pins above and below the specimen for connecting the specimen grips to the adaptors, allowing for quick installation and removal of the specimens. Additionally, the tensile specimens have external threads and therefore, must be threaded into the grips. Once threaded onto the tensile specimen, the grip components can easily be connected to the rest of the grip assembly with the clevis pins. See Figure 10 for an illustration. See APPENDIX A for the entire drawing of this grip assembly. Component machining was performed by Mark Jones.

Specifications (for Components 2, 3, & 4)	
Material	18Ni (250) maraging steel
Yield Strength	1800 MPa (260 ksi)
Hardness	52 HRC
Finish	180 RMS
Total Length	62.2 cm (24.5 in)
Usage	4-inch tensile specimen



No.	Assembly Components	QTY
1	Connecting Rod	2
2	Adaptor	2
3	Large Grip	2
4	Clevis Pin	2

Figure 10. High Temperature Tensile Grip Assembly for 4-Inch Specimens

The Adaptor component's body is 3.8 cm (1.5 in.) in diameter and by its design is the same diameter as the furnace upper and lower entrance ports for the grip assembly. This design keeps the furnace entrance ports plugged throughout the entire motion of the grip assembly during a tensile test. There is a slight clearance at the port interface, but this clearance was kept to a minimum to protect the test environment from external atmospheric contamination. This interface

is illustrated in Figure 11. The design allows for 2.5 cm (1 in) of specimen extension before contact occurs between the lower clevis pin and furnace lining.

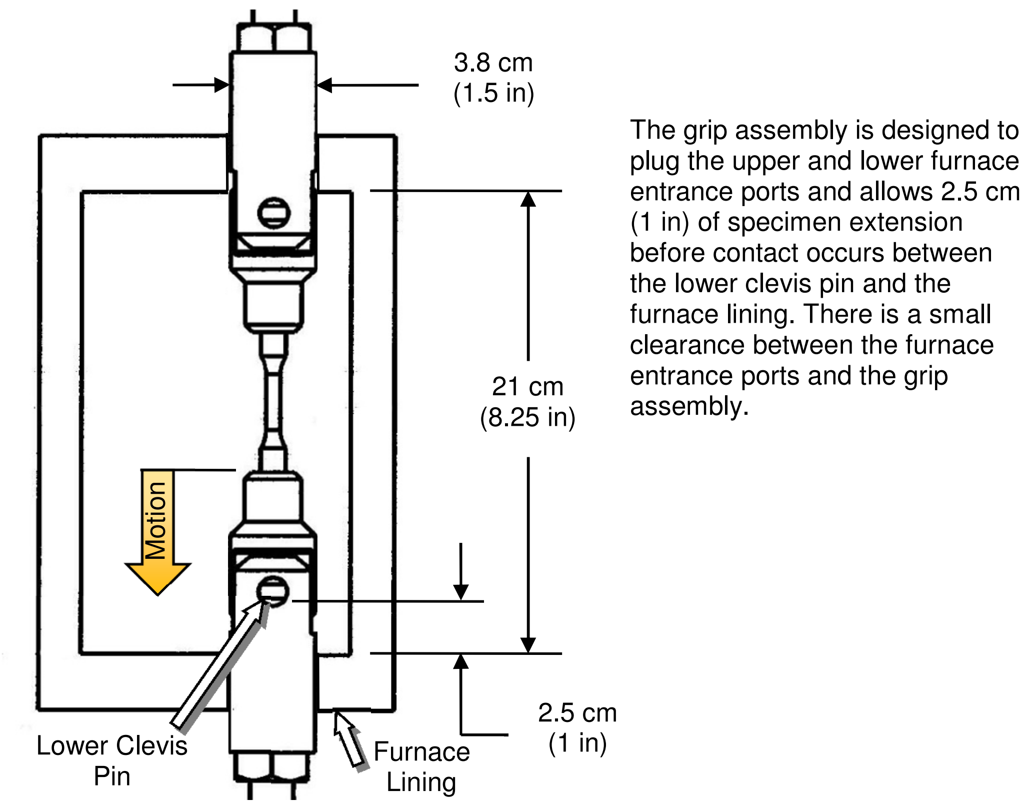
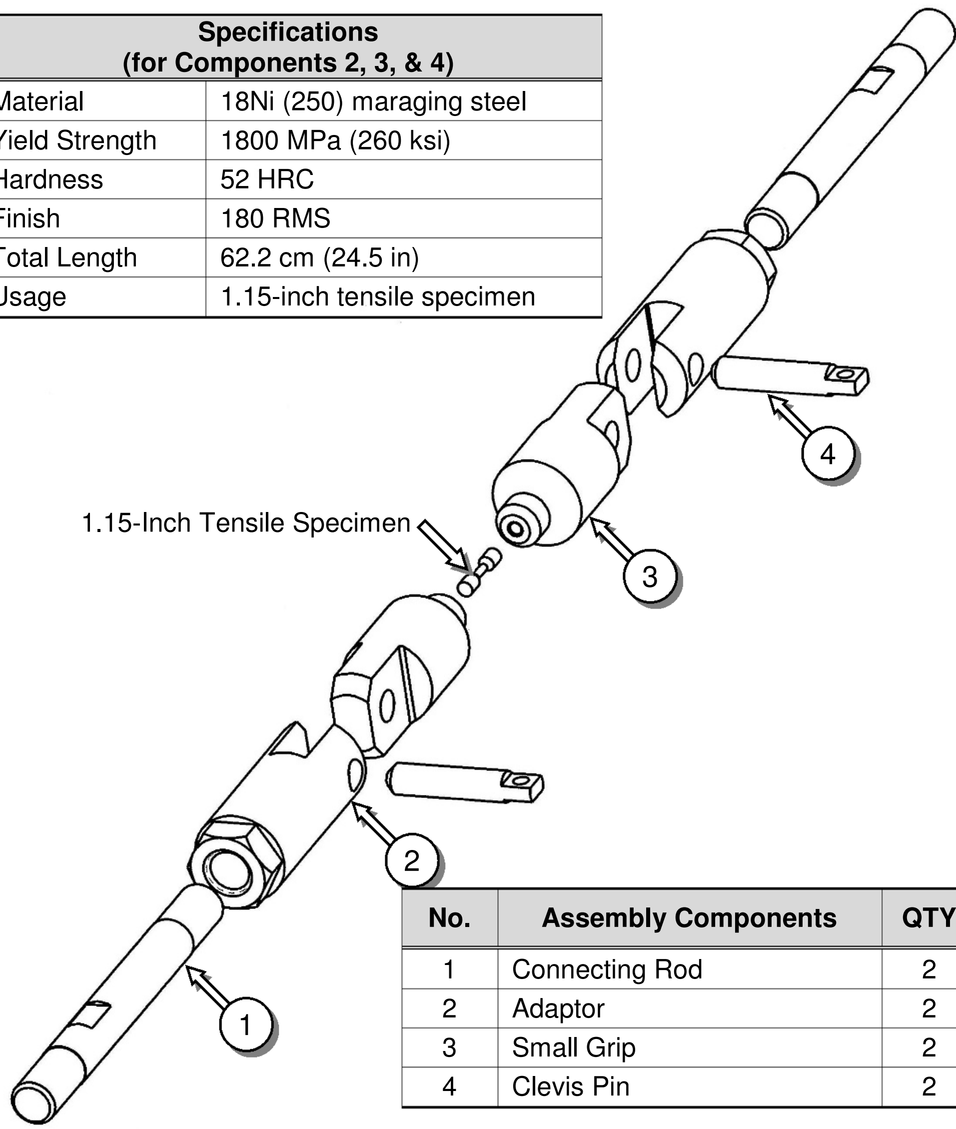


Figure 11. Furnace and Grip Assembly Interface

This grip assembly was also designed to accommodate shorter 29.2-mm (1.15-in) length specimens for separate research topics [27]-[28] outside the scope of this thesis. These tests were to occur concurrently with testing of the longer 101.6-mm (4.00-in) specimens used for the research of this document. Hence, design consideration was made to facilitate easy changeovers with minimum set-up steps, switching from one specimen length to the other. The specimen grips

for the shorter specimens, shown in Figure 12, were designed to easily replace the longer specimen grips without requiring any physical adjustments to the test system apparatus.



Specifications (for Components 2, 3, & 4)	
Material	18Ni (250) maraging steel
Yield Strength	1800 MPa (260 ksi)
Hardness	52 HRC
Finish	180 RMS
Total Length	62.2 cm (24.5 in)
Usage	1.15-inch tensile specimen

No.	Assembly Components	QTY
1	Connecting Rod	2
2	Adaptor	2
3	Small Grip	2
4	Clevis Pin	2

Figure 12. High Temperature Tensile Grip Assembly for 1.15-Inch Specimens

The grip assembly overall length in either configuration was designed to be the same for allowing easy changeovers between 4-inch and 1.15-inch specimens set-ups. These two configurations are shown in Figure 13.

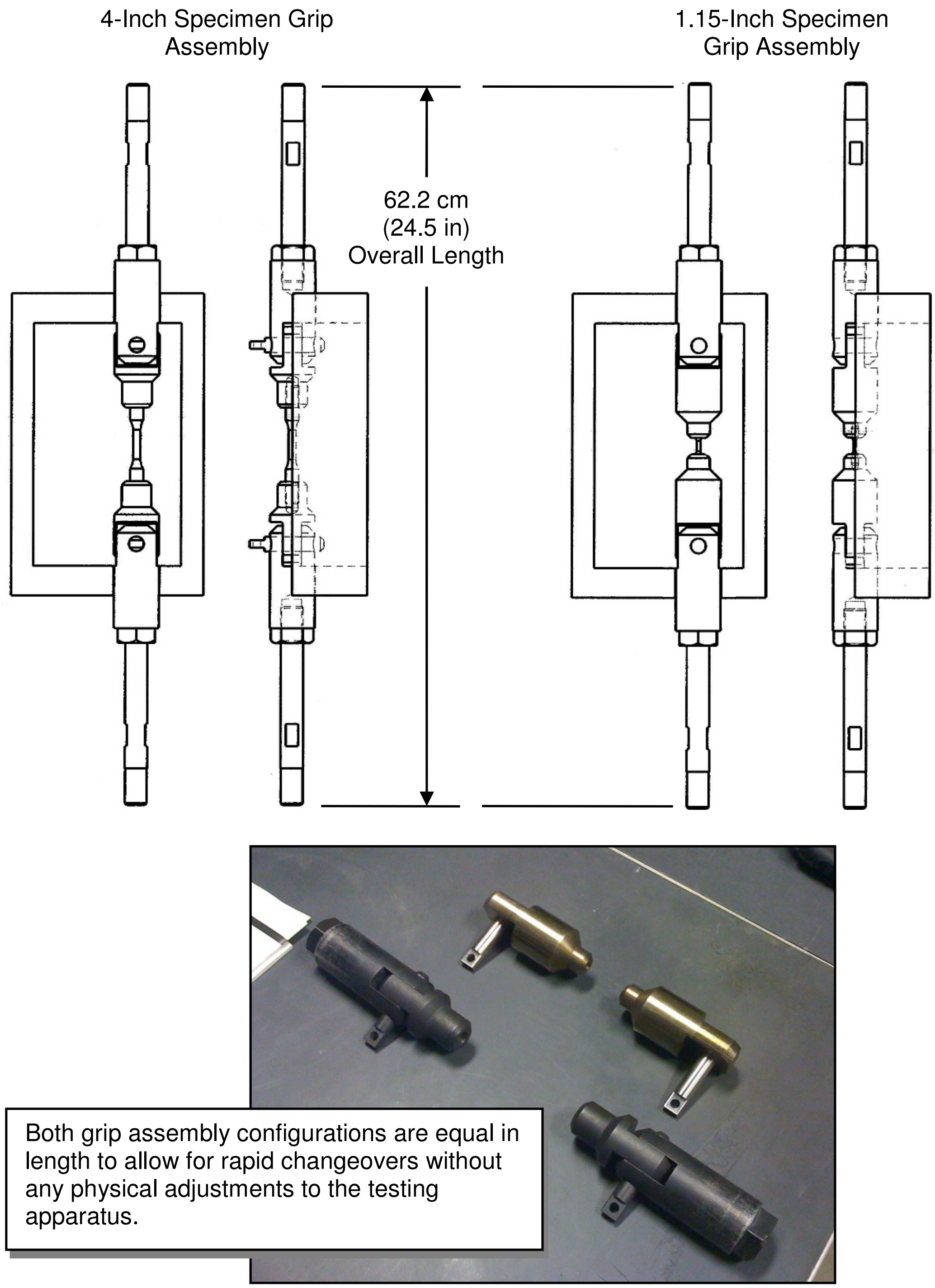


Figure 13. Dual Grip Assembly Configurations

3.2.5. Nitrogen System

A nitrogen system was installed to purge oxygen from the environmental chamber throughout the entirety of each test, including temperature ramp up, load application, and cool down. The system employs compressed nitrogen, supplied by T-size steel tanks delivered with 49 l (2990 cu. in) of compressed nitrogen at 165 bar (2400 psi).

A flow meter, shown in Figure 14, was set to deliver nitrogen at a calculated rate to sufficiently purge the furnace cavity with four volume replacements per minute, creating a slight overpressure. This overpressure was essential, since the furnace was not hermetically sealed. From the flow meter a hose carries the nitrogen to a solenoid control valve for automation control. From the control valve another hose delivers the nitrogen to a threaded access port in the bottom of the furnace.

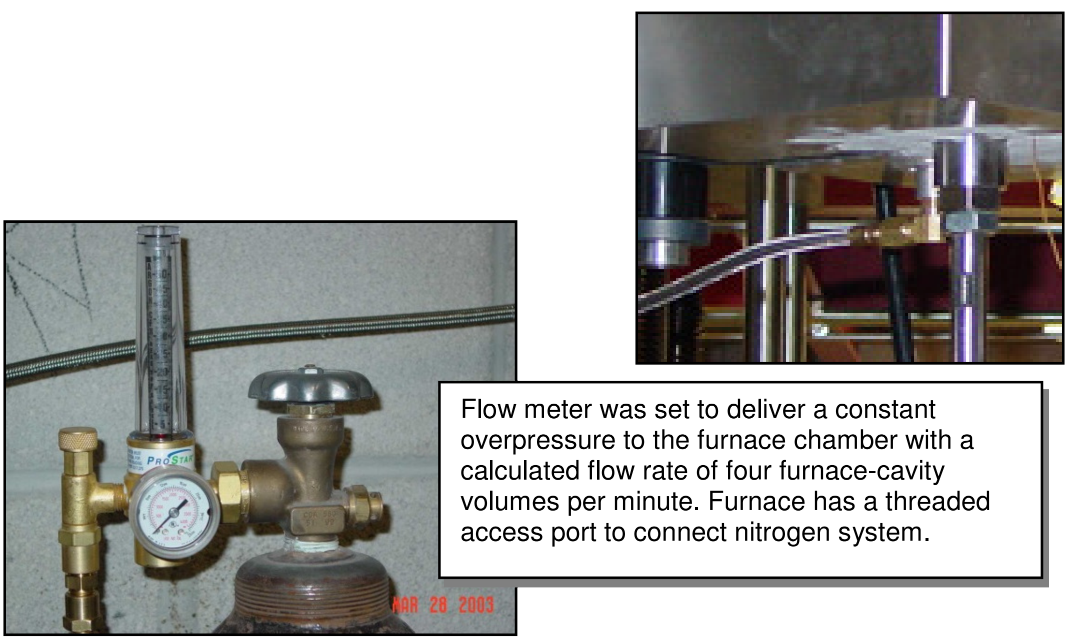


Figure 14. Nitrogen System

3.2.6. Water Cooling System

To insulate the MTS machine and its electronics from the elevated temperatures of the furnace, water cooled cylinders were installed between the MTS machine wedge grips and the specimen grip assembly as shown in Figure 15. The system uses tap water as the coolant, flowing from a solenoid control valve, through the cooling cylinders, and then flushed to a drain. The cooling cylinders are threaded onto the circular rod stems, which are gripped by the MTS wedge grips. The grip assembly connecting rods shown in Figure 10 and Figure 12 are threaded into the other end of the cooling cylinders.

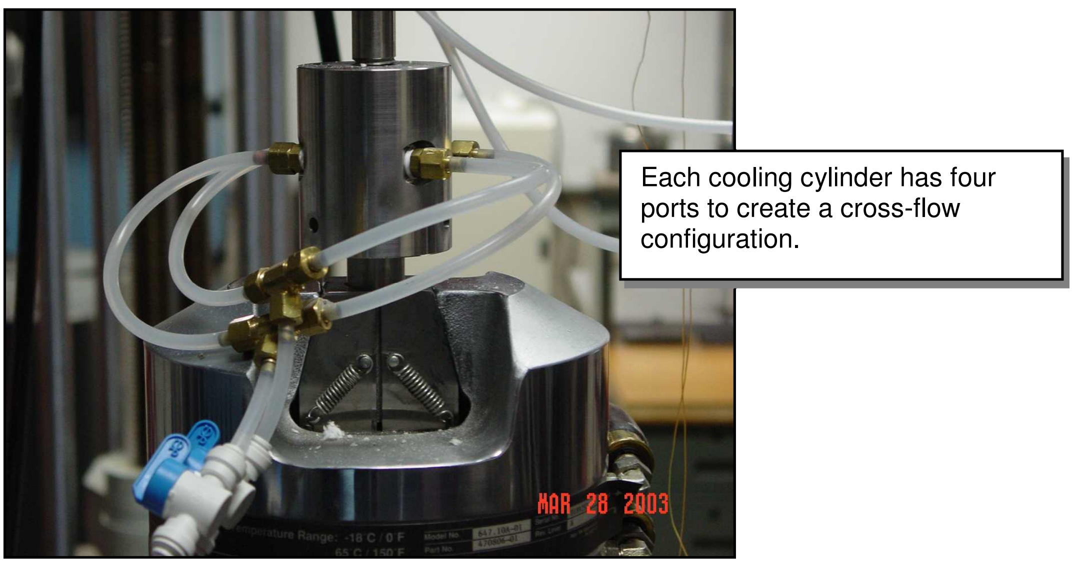


Figure 15. Water Cooled Cylinders to Insulate MTS Equipment

3.2.7. Automation Controls

To ensure that the protection systems are activated during each test, the nitrogen atmosphere, the water coolant, and an air cooling systems were automated. These systems were important for

protecting the MTS machine and safeguarding data and were activated when the furnace digital temperature controller (Figure 5) was enabled. The operator needed only to input the temperature set point and press the furnace enable button to activate all protections.

The control panel shown in Figure 16 was created to house the relays and wiring for controlling the normally-closed solenoid valves for the water, nitrogen, and air systems. Although not used for this research study, the air cooling system was put into place for air cooling high temperature ceramic-arm extensometers. The solenoid valves required 24V to function, so a transformer was added to step down the 120V service voltage from the laboratory. The panel also provided a manual means to deactivate the control valves.

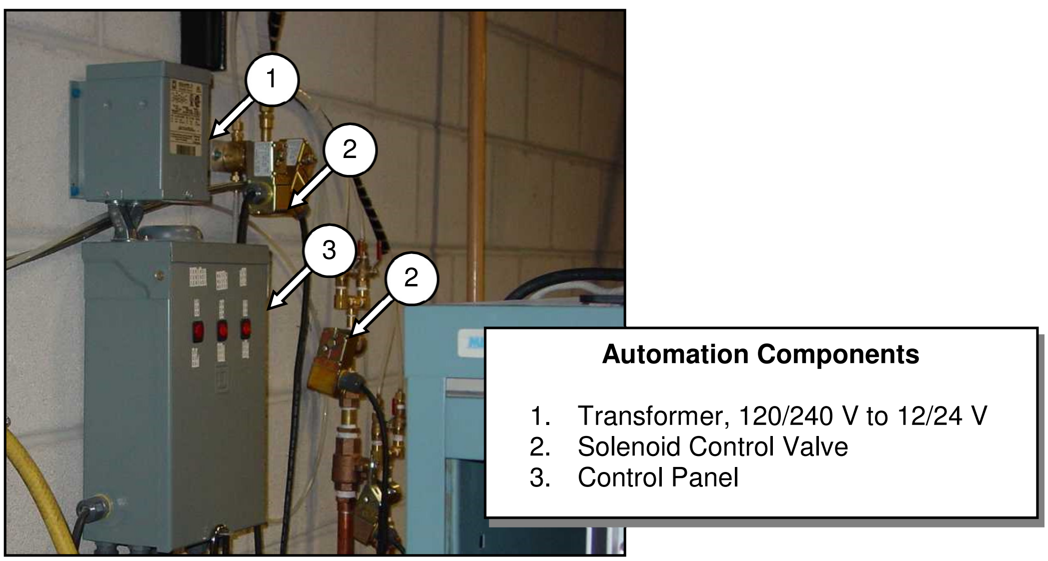


Figure 16. Automation Components

An overall schematic of the control system and plumbing is shown in Figure 17. This figure includes only the system components employed for high temperature capability, excluding the MTS machine controls.

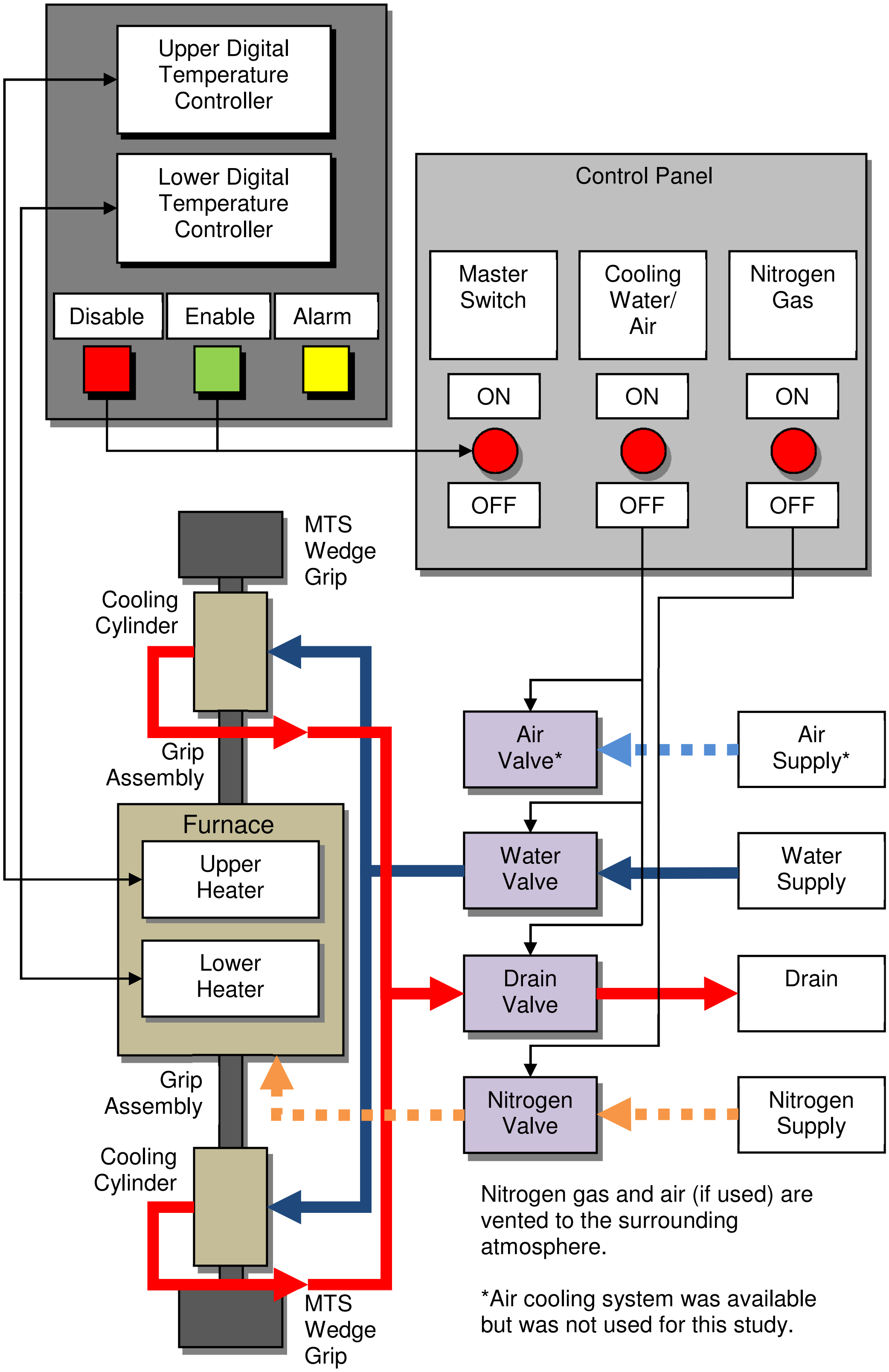


Figure 17. Control System and Plumbing Schematic

3.2.8. Modified Specimen with Internal and External Thermocouple

An extra tensile specimen was modified to incorporate an internal and an external thermocouple for providing actual internal and surface temperatures during furnace calibration. This furnace calibration will be discussed later in Section 3.3.1. For external readings a K-type thermocouple probe was looped around the specimen gage diameter to ensure contact between the probe tip and specimen surface. To measure internal temperatures at the specimen centroid a second K-type thermocouple probe tip was installed internally. To facilitate this a sixteenth-inch (1.59-mm) diameter hole was drilled into one end of the specimen with a channel machined into the threads. The thermal couple probe was then shaped and inserted into this channel and hole as illustrated in Figure 18. This modified specimen was not subjected to tensile testing.

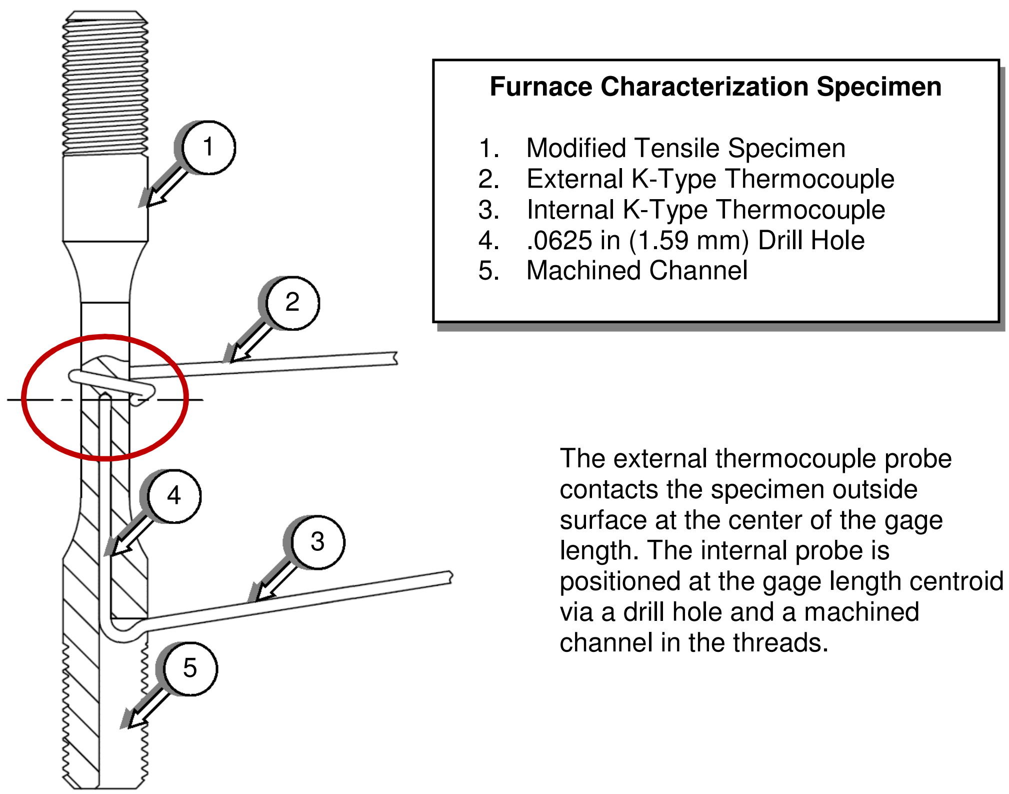


Figure 18. Modified Specimen with Internal and External Thermocouple

This configuration provided a method to determine the temperature gradient from axis to surface, during furnace temperature characterization. To realistically represent the actual test environment during furnace calibration it was important to include all components of the test equipment, installed as they would be during a tensile test. Thus this modified specimen was threaded into the grips and properly installed inside of the furnace. Figure 19 shows the modified specimen installed into the tensile grips with thermocouple probes in place.

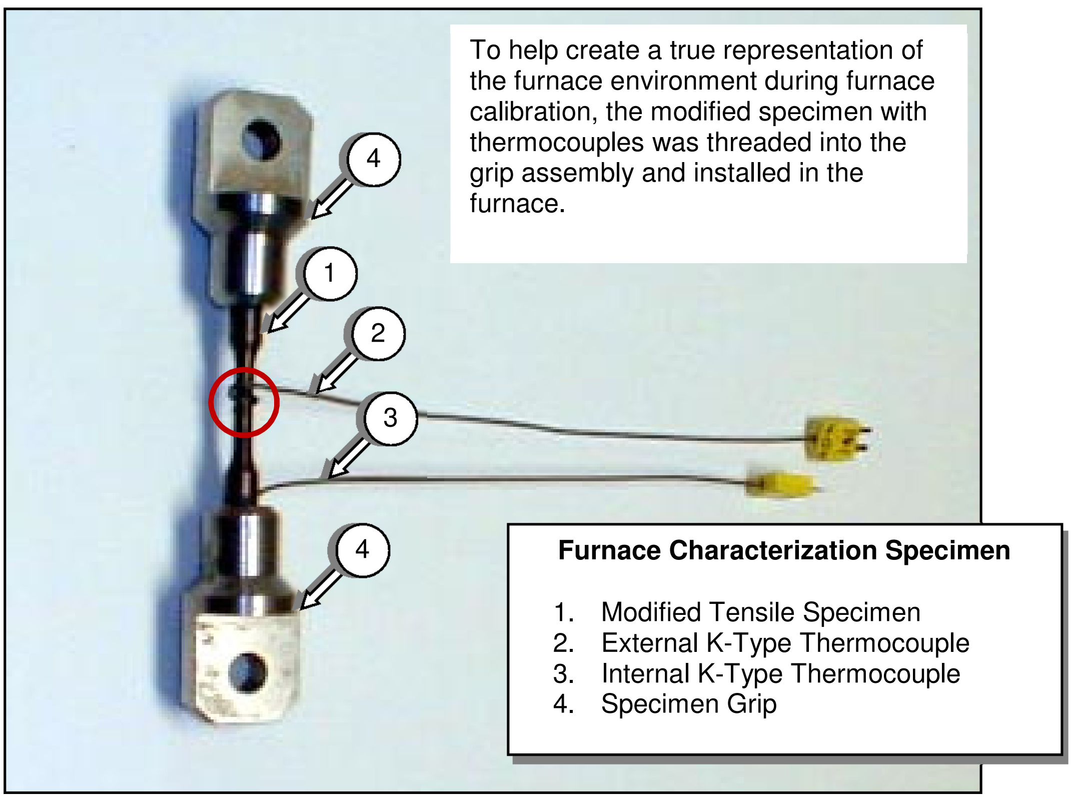


Figure 19. Modified Specimen Threaded into Specimen Grips with Thermocouples

3.2.9. Clamping Block for Measuring Broken Specimens

Elongation and reduction of area are determined by the overall lengths and diameters before and after each test. The two broken pieces after each test must be held together to make the final length and diameter measurements. Holding the two pieces together and taking measurements had proven to be cumbersome without an effective means for securing the pieces. Research partner, Jones, created the clamping block shown in Figure 20 for holding the two broken pieces together during measurements. Once the two pieces were clamped into position, the whole block could be picked up and oriented for ease of measurement.

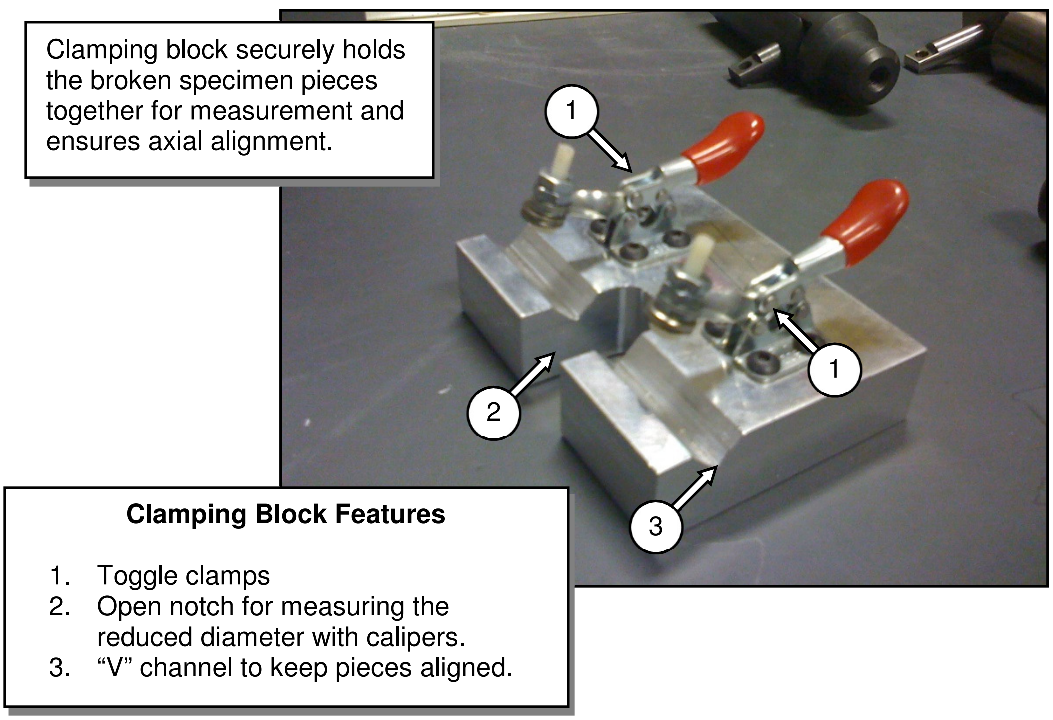


Figure 20. Clamping Block for Measuring Broken Specimens

3.2.10. Testing Template Software

TestWare-SX Version 4.0D software was used to create the testing template for controlling the loads and displacements and recording test data. The template was programmed to first zero the load on the specimen, hold for five seconds, and then apply a displacement rate of .0005 in/sec. (0.0127 mm/sec.) for load application. It recorded cross-head displacement, load, temperature, and specimen extension as a function of time. Recorded data was output to a data file. Data was recorded ten times per second. The data was tab-delimited and could be opened with standard commercially-available spreadsheet software. Figure 21 provides a portion of the information header that accompanies each test data file. Fellow researcher Raymond Kozak created the test template. See APPENDIX B for the complete test template set-up.

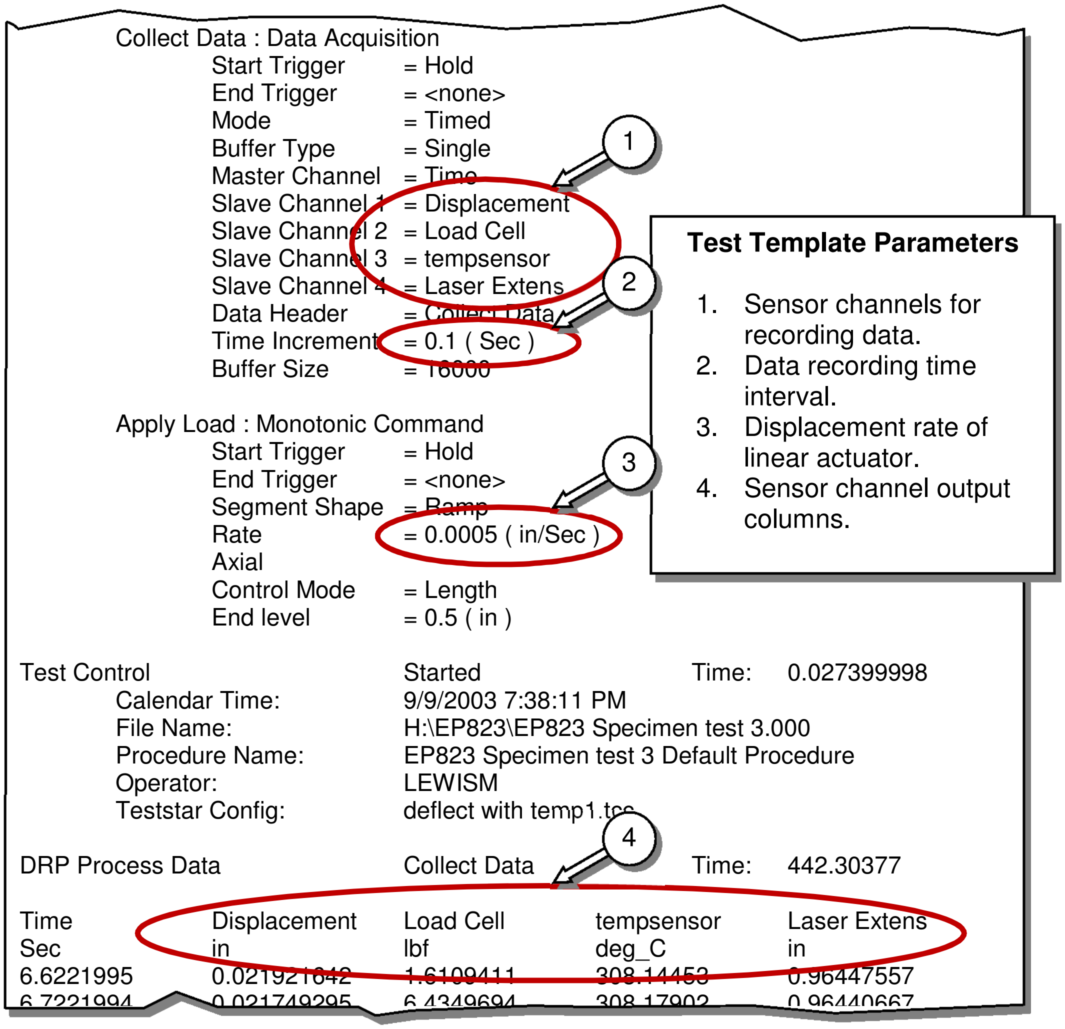


Figure 21. Portion of Set-up Header from Data File

3.3. Experimental Procedure

This section discusses the procedure used to determine the effects of tempering time on mechanical properties throughout a range of temperatures. It will first address furnace set point calibration, and then it will present the tensile testing procedure.

3.3.1. Furnace Temperature Set Point Determination

When using a closed-loop temperature controller such as the one described in Section 3.2.2, it is important to understand what exactly the temperature display is representing. The controller's thermocouple probes are embedded in the heating elements and thus are only reporting the temperature of that region within the furnace – not necessarily the specimen temperature. If the furnace was sealed and did not have any external influences, then perhaps at a steady-state, homogeneous temperature condition, a specimen's temperature may be represented by the display.

With regard to this set-up, this was simply not the case. The user could just simply enter the desired specimen temperature into the controller and expect that the specimen would be at that displayed temperature over time. There were external heat fluxes within the furnace that would lower the temperature in the region of the specimen. These heat fluxes were caused by the constant flow of nitrogen gas and heat conduction by the water-cooled grip assembly. There was also a small amount of radiative heat loss that occurred through the laser extensometer's view port and user view port.

A heat transfer analysis of the system could have been performed, but reliable thermal data was not available and these calculations were beyond the scope of this project. Instead, an instrumented specimen with attached thermocouples was created to measure the internal and surface temperature of the specimen during heat-up. Using the modified specimen presented in Figure 18, the internal and external thermocouples report the temperature gradient across the specimen gage section radius during the set point calibration exercise. During this calibration, the temperature gradient between the internal and surface temperatures varied by as much as 30 degrees on the Celsius scale with the internal values lagging behind the surface values. As the specimen surface temperature neared the target temperature this gradient decreased to the

differential shown in Table 5. This table specifies the set point temperatures and the minimum times required to reach the specimen testing temperatures.

Table 5. Furnace Set Point and Heat Time for Desired Specimen Temperature

Test Temperature (°C / °F)	Furnace Set Point (°C / °F)	Minimum Heating Time (Minutes)	Specimen Surface Temperature (°C / °F)	Internal & Surface Temperature Differential (Degrees on Celsius Scale)
100 / 212	143 / 289	60	107 / 225	8
300 / 572	363 / 686	60	309 / 588	3
400 / 752	467 / 873	55	408 / 767	4
500 / 932	563 / 1045	50	505 / 941	5
600 / 1112	658 / 1216	50	600 / 1112	6

It is important to understand that the conditions listed in Table 5 are at near steady state conditions. Initial calibration efforts with lower set point temperatures resulted in lesser gradients at more steady state conditions but after preheat times in excess of three hours. The actual tensile tests, however, requires a relatively short duration, generally reaching specimen tensile failure between eight and sixteen minutes, depending on test temperature. The higher set point temperatures specified in Table 5 decreased the required preheat time to approximately one hour. Each test took place in a near steady state condition where the change in specimen surface temperature during the test was less than three degrees on the Celsius scale.

3.3.2. Performing Tensile Tests

Implementing procedure IPLV-061 [29] provides detailed instruction for operating the MTS machine controls and TestStar software, which was described in Section 3.2.1. TestWare-SX

software (Section 3.2.10) was used to record and output tensile test data. This output data in addition to the specimen initial and final dimensional characteristics were input into a spreadsheet data reduction tool that was developed to process the data and ultimately calculate the mechanical properties of the material. The details of this spreadsheet template are provided in Section 3.4

3.3.2.1. Measuring Initial Conditions

The initial overall length and gage diameter of each specimen were measured using digital calipers and digital micrometers. Calipers were used to measure the overall length, and micrometers were used for the initial gage diameter. For each characteristic three measurements were taken at 120° apart and recorded in the spreadsheet template for averaging.

3.3.2.2. Preparing Laser Extensometer

After the tensile specimen was installed into the grip assembly (Figure 10) the reflective adhesive strips (Figure 8) were affixed on the gage section of the specimen. The specimen manufacturing drawing (Figure 1) specifies that the gage length blends seamlessly into both fillets, making it difficult to discern the exact starting and ending points of the gage section without using an optical comparator. Consequently, the reflective strips were intentionally placed with a small margin away from the fillets to avoid inadvertently placing the reflective strips in the fillet region. To be deemed correctly affixed the reflective strips were required to have registered an initial length between 23.6 and 24.6 mm (0.930 and 0.970 in) as read by the laser extensometer as shown in Figure 22. This measurement is performed at room temperature as a check but is not used as a factor to determine ductility parameters. This step was only applicable to test temperatures up to 400°C (752°F).

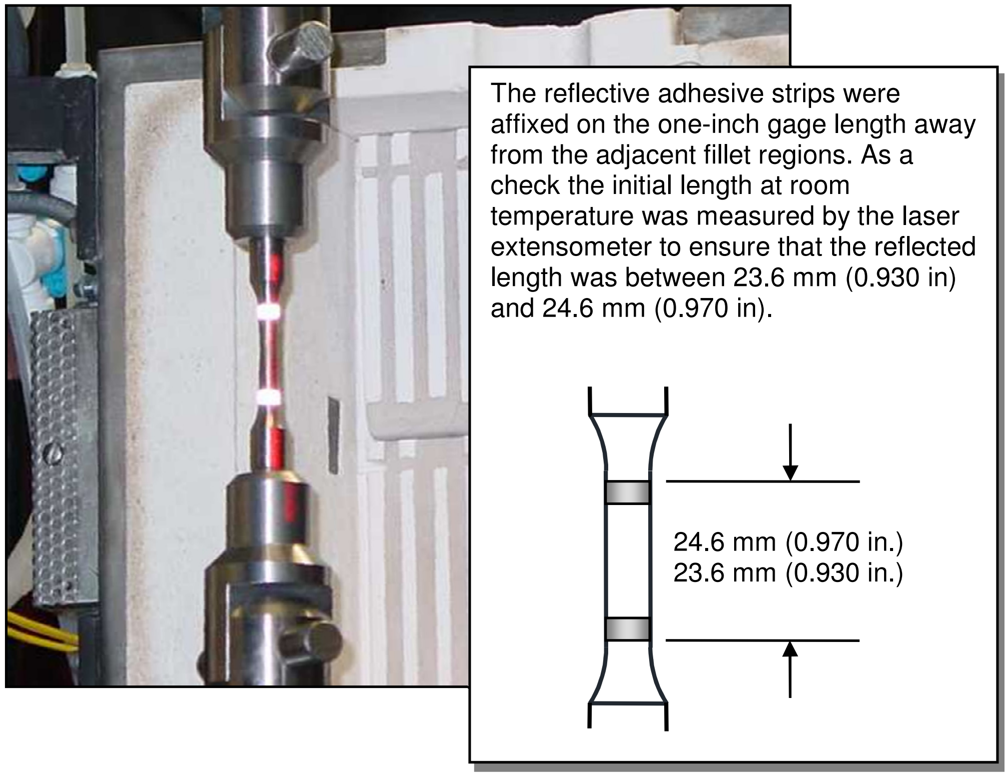


Figure 22. Properly Placed Reflective Adhesive Strips

3.3.2.3. Heat Furnace

Prior to the start of tensile testing the specimen was preheated to the specified test temperature. Table 5 provided the set point temperatures for the furnace temperature controller. When the controller was enabled the nitrogen atmosphere and cooling systems were automatically activated. Once the prescribed time and specimen surface temperature was met, the tensile test could begin.

3.3.2.4. Perform Tensile Test

The TestWare-SX template described in Section 3.2.10 provided sequenced instructions for the MTS machine controller. Instructions included first zeroing the load on the specimen, holding

for five seconds, and then applying a displacement rate of .0005 in/sec. (0.0127 mm/sec.) for load application. Cross-head displacement, load, temperature, and specimen extension were recorded and output to a data file with a sampling rate of ten times per second. See APPENDIX B for the complete test template set-up. The specimens were loaded to failure, ending the test. Upon test completion the enabled temperature controller was reset to room temperature and nitrogen flow was increased to aid specimen and furnace cooling.

3.3.2.5. Measure Final Conditions

The final dimensional characteristics at room temperature were measured using calipers and entered into the data reduction spreadsheet template as done previously for the initial conditions. To help with measuring the final overall length and the reduced diameter at the fracture location the specimen pieces were secured in the clamping block shown in Figure 20. The reduced diameter was measured in the necked region of the specimen. Similarly three measurements were taken at 120° apart and recorded in the spreadsheet template for averaging.

3.4. Data Reduction Methods

Making sense of the copious amounts of data is just as important as the methods for acquiring the data. This data helps to characterize a material's performance and applicability for engineered solutions. This section discusses the methods for determining the mechanical properties from the data. The desired output are engineering stress-strain curves, ultimate tensile strength, yield strength, elongation, and reduction of area.

3.4.1. Engineering Stress-Strain Curves

Both the stress and strain at each data point must be calculated to generate an engineering stress-strain plot. For engineering stress at any given load, engineering stress s is equal to the load P divided by the initial cross-sectional area A_0 as in Equation (3.1) and is related to the initial gage diameter D_0 by Equation (3.3).

$$s = \frac{P}{A_0} \tag{3.1}$$

$$A_0 = \frac{1}{4}\pi {D_0}^2 \tag{3.2}$$

$$s = \frac{P}{\frac{1}{4}\pi {D_0}^2} \tag{3.3}$$

Where:
s = Engineering Stress
P = Load
A_0 = Initial Cross-Sectional Area
D_0 = Initial Gage Diameter

With any given extended length, engineering strain e is equal to the difference between the extended gage length L and the initial gage length L_0 divided by the initial gage length L_0, represented by Equation (3.4).

$$e = \frac{L - L_0}{L_0} \tag{3.4}$$

Where:
e = Engineering Strain
L = Extended Gage Length
L_0 = Initial Gage Length

Plotting the calculated engineering stress with respect to the calculated engineering strain generates a curve similar to the example shown in Figure 23.

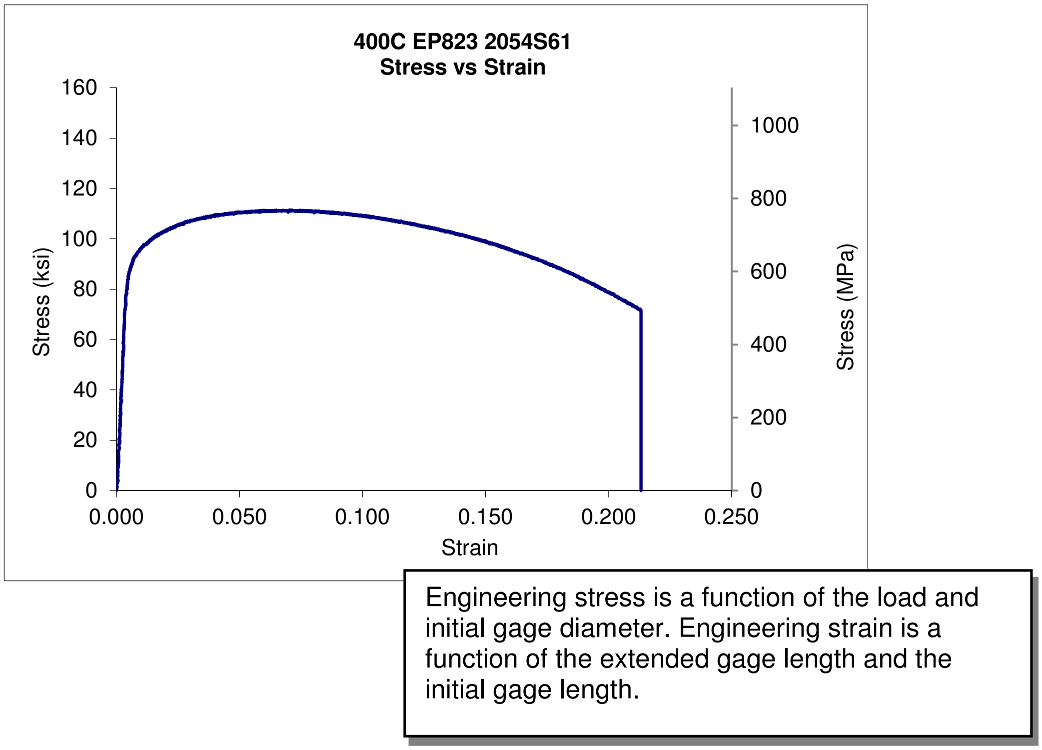


Figure 23. Engineering Stress-Strain Curve Example

3.4.2. Ultimate Tensile Strength

The ultimate tensile strength *UTS* is equal to the maximum engineering stress s_u. This maximum stress is found by evaluating load *P* in Equation (3.3) with the maximum load P_{max} from tensile testing. Maximum engineering stress s_u is given by Equation (3.5).

$$UTS = s_u = \frac{P_{max}}{\frac{1}{4}\pi {D_0}^2} \qquad (3.5)$$

Where:
UTS = Ultimate Tensile Strength
s_u = Maximum Engineering Stress
P_{max} = Maximum Load
D_0 = Initial Gage Diameter

Graphically the maximum engineering stress s_u is located at the top of the engineering stress-strain curve where the slope is zero, occurring just prior to the onset of necking in the specimen gage section as illustrated in Figure 24. At this point the material deformation changes from uniform to unstable plastic deformation, where necking occurs in the gage section.

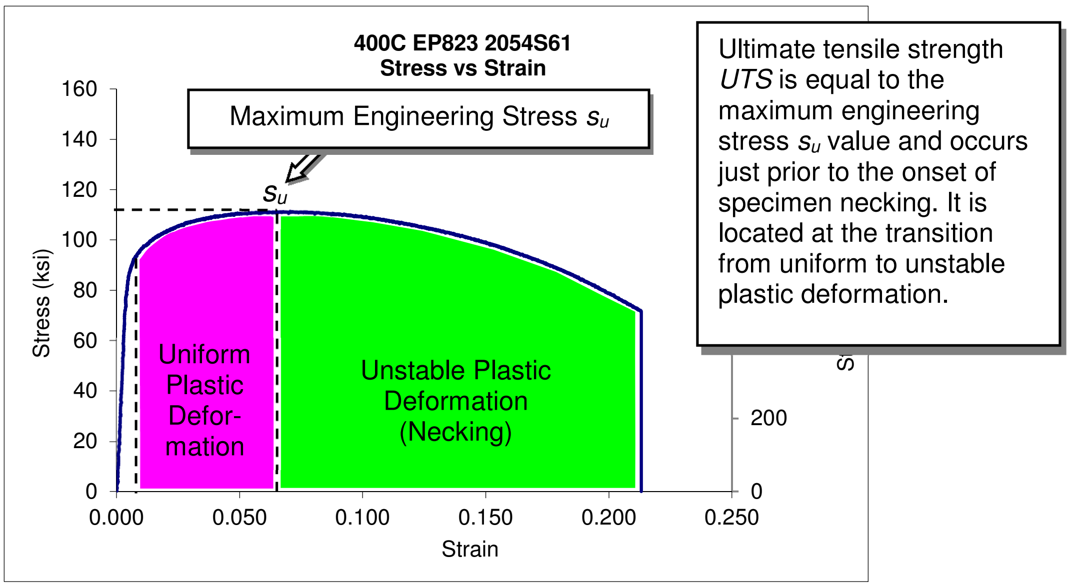


Figure 24. Maximum Engineering Stress Location

3.4.3. Yield Strength

The yield strength is determined through inspection of the engineering stress-strain curve and is equal to the stress point where the material yields or deforms permanently. This yield stress must be deciphered graphically and is found at the stress point along the curve where the stress deviates from the elastic deformation region of the curve at the onset of plastic deformation. Prior to this yield stress, the material deforms elastically and returns to its unstressed form when the applied

stress is released. This elastic region is represented by the linear set of data points at the start of the stress-strain curve. The exact yield point is not distinctly obvious because of the smooth transition curve from the elastic to plastic deformation sections of the curve. See Figure 25 for illustration.

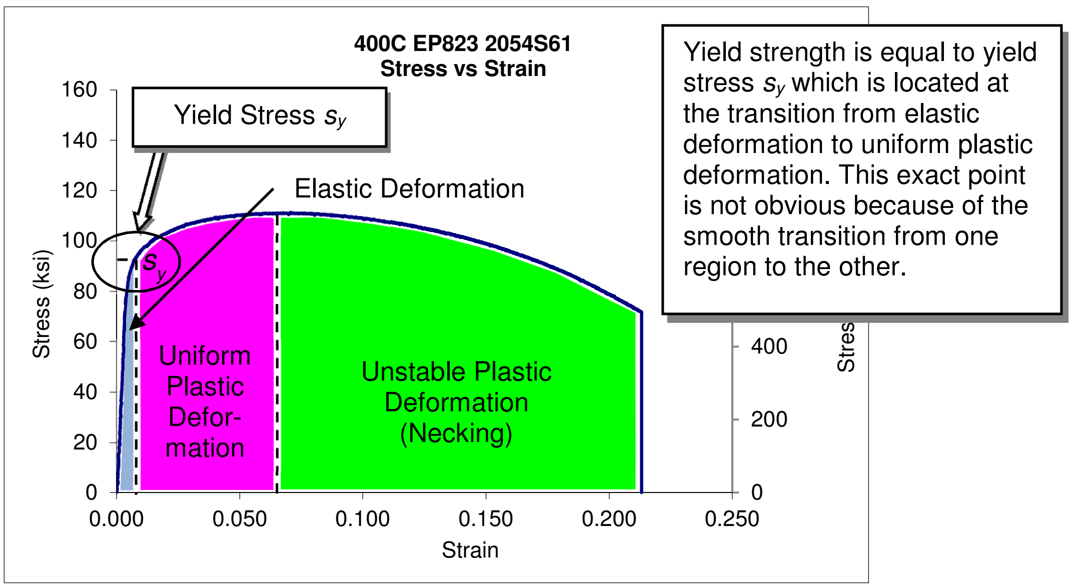


Figure 25. Yield Stress Location

Since the elastic region of the stress-strain curve flows smoothly into the plastic region without a discernible feature to mark the point of yielding, a commonly accepted method for identifying this point is to draw an intersecting line representing a 0.2% offset from the elastic portion of the stress-strain curve. This is illustrated in Figure 26.

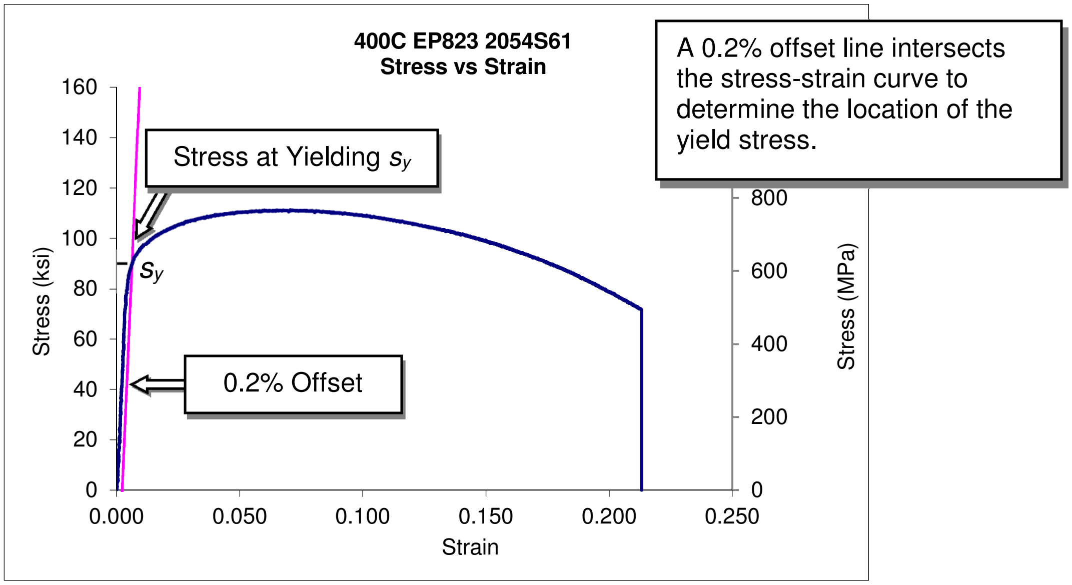


Figure 26. Yield Stress Point Identified by 0.2% Offset Line

3.4.4. Reduction of Area

Reduction of area RA is equal to the difference between the final cross-sectional area A_f at tensile failure and the initial cross-sectional area A_0, divided by the initial cross-sectional area A_0. This is represented by Equation (3.6). A_0 is dependent upon the gage section initial diameter D_o, whereas A_f is dependent upon the final diameter D_f which is measured at the smallest diameter of the necked portion of the specimen.

$$RA = \frac{A_f - A_0}{A_0} \tag{3.6}$$

$$A_o = \frac{1}{4}\pi {D_o}^2 \tag{3.7}$$

$$A_f = \frac{1}{4}\pi {D_f}^2 \tag{3.8}$$

Where:
RA = Reduction of Area
A_0 = Initial Cross-Sectional Area

A_f = Final Cross-Sectional Area
D_0 = Initial Diameter
D_f = Final Diameter

Substituting Equations (3.7) and (3.8) into Equation (3.6) relates reduction of area *RA* to the initial and final diameters D_o and D_f, provided in (3.9). Reduction of area *RA* is often referred to as "percent reduction of area" and is presented as a percentage decrease.

$$RA = \frac{{D_f}^2 - {D_0}^2}{{D_0}^2} \tag{3.9}$$

3.4.5. Elongation

Elongation *El* is equal to the maximum engineering strain e_f at tensile failure and is often referred to as "percent elongation," presented as a percentage increase. Based on Equation (3.4), maximum engineering strain e_f, shown graphically in Figure 27, can be determined by evaluating engineering strain *e* with the final extended length L_f at tensile failure as presented in Equation (3.10).

$$El = e_f = \frac{L_f - L_0}{L_0} \tag{3.10}$$

Where:
El = Elongation
e_f = Maximum Engineering Strain
L_f = Final Extended Length
L_0 = Initial Gage Length

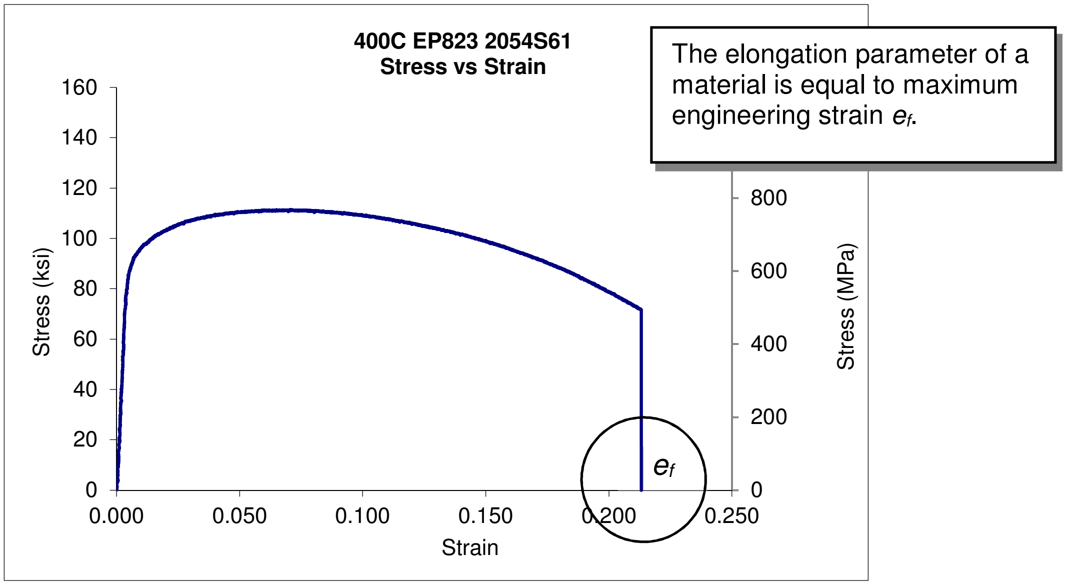


Figure 27. Location of Maximum Engineering Strain

The elongation values reported in this thesis were based on the overall specimen lengths measured before and after tensile testing. Instead of measuring the gage section length directly, the overall length of the specimen was measured. The reasoning behind this is that the gage section blends smoothly into the adjacent fillets, making it difficult to distinguish the exact end points of the gage section length without the use of an optical comparator. Figure 1 provides the specimen drawing to illustrate this.

The tensile specimens were machined on a CNC lathe that repeatedly provided accuracy to less than half of a thousandth of an inch, ensuring that the initial gage length L_0 was indeed 1.000 in (25.4 mm) in length. The remaining regions outside of the gage length had greater diameters and consequently only experienced elastic deformation. Thus, plastic deformation was confined to the specimen gage section only. Based on this rationale, the difference between the final extended

length L_f and the initial gage length L_0 is equal to the difference between the final overall length OAL_f and the initial overall length OAL_o, represented by Equation (3.11).

$$L_f - L_0 = OAL_f - OAL_0 \tag{3.11}$$

Where:
L_f = Final Extended Length
L_0 = Initial Gage Length
OAL_f = Final Overall Length
OAL_0 = Initial Overall Length

Substituting Equation (3.11) into (3.10) yields Equation (3.12).

$$El = \frac{OAL_f - OAL_0}{L_0} \tag{3.12}$$

Where:
El = Elongation
OAL_f = Final Overall Length
OAL_0 = Initial Overall Length
L_0 = Initial Gage Length

3.4.6. Data Reduction Tool

A spreadsheet tool was developed as a vehicle to standardize recording and processing test data, calculate ductility parameters, and output graphs. This data reduction tool was developed for use with this project and other research projects that required tensile testing. It was written with the end user in mind and provided instructions for entering data and for extracting key properties. Input for the data reduction tool included the MTS data output file and initial and final specimen dimensions. Output include mechanical properties and stress-strain plots.

With all data entered, the data reduction tool calculated the ultimate tensile strength, yield strength, elongation, and reduction of area, using the equations and methods previously described in Sections 3.4.1 through 3.4.5. It also output an engineering stress-strain curve. Additionally, the tool provided a data correction algorithm, addressing system compliance to accurately plot stress-

strain data for 500°C and 600°C tests, which solely depended upon the LVDT for displacement data. Data from the LVDT is biased by the testing machine's compliance

3.4.7. Determine Yield Strength with Data Reduction Tool

Material yield strength is equal to the stress at yielding s_y, which occurs at the onset of plastic deformation. As described in Section 3.4.3 a 0.2% offset line is used to intersect the stress-strain curve and define the yield stress at that intersection as shown Figure 28.

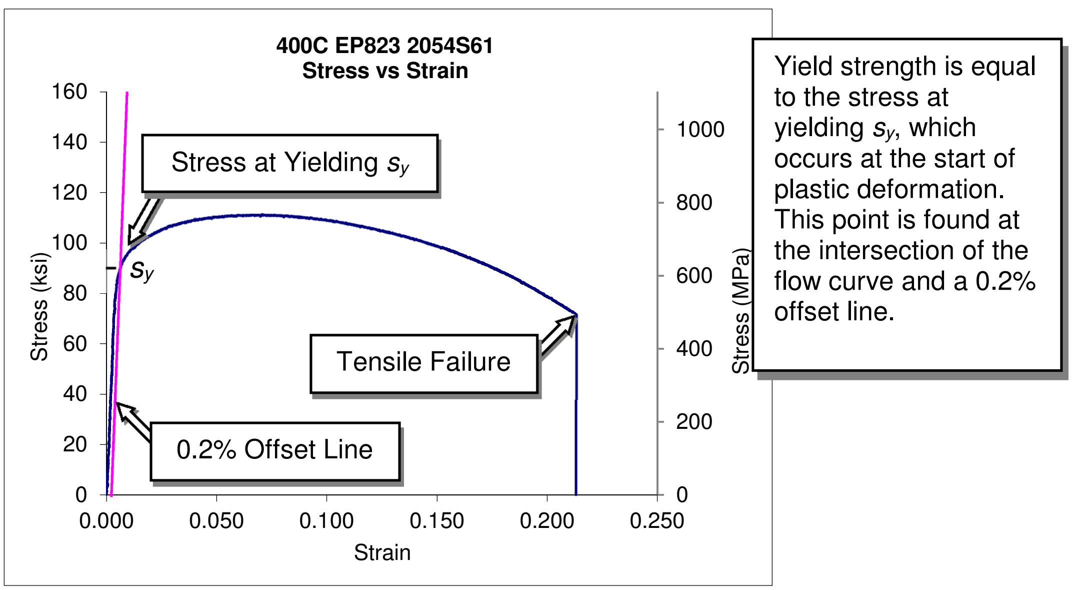


Figure 28. Yield Stress Point Identified by 0.2% Offset Line

There are several methods for creating the 0.2% offset line. One way involves hand drawing a parallel line onto the graph at that crosses at 0.002 along the *Strain* axis (x-axis). Another way is to numerically shift the elastic region stress-strain data, which is indicated in Figure 25, by 0.002 along the *Strain* axis. This offset line would have to be extended to intersect the stress-strain data.

Additionally, data noise would make distinguishing the exact intersection of the data and offset line subjective. Figure 29 offers an example of this.

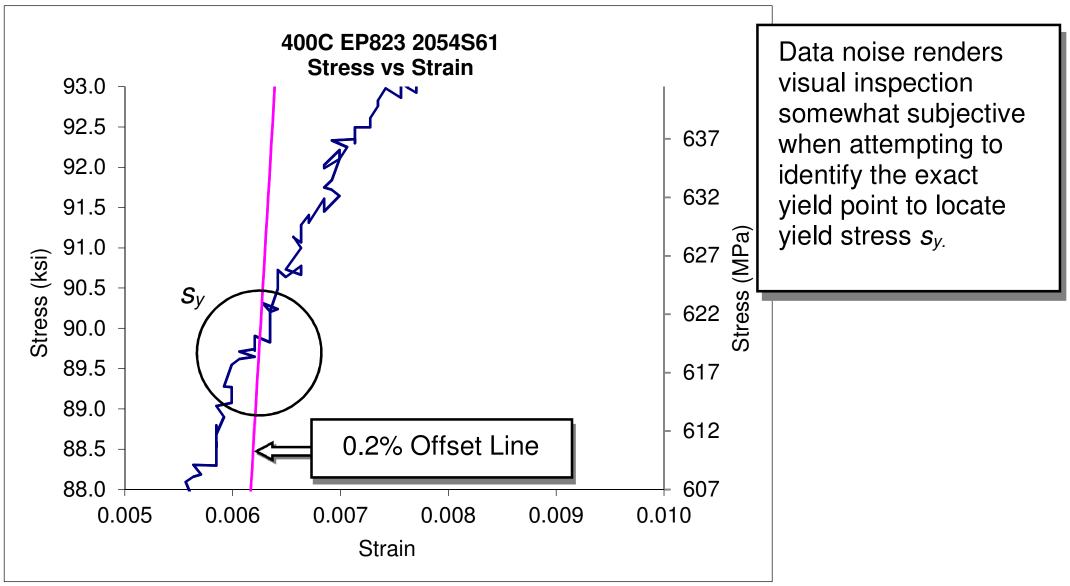


Figure 29. Visual Inspection to Determine Yield Strength

Instead of relying on visual inspection by the user, the data reduction tool was written with an algorithm to systematically calculate the yield strength through numerical analysis. This was accomplished by generating two polynomial equations to represent both the elastic-plastic transition and the elastic region of the stress-strain plot, which was offset by 0.2%. The numerical intersection of these two curves determines the yield strength.

First, to represent the elastic region of the plot, the data reduction tool performed a linear regression on the data points in that region. In a similar fashion, a second-order curve fit was

performed on the data points along the elastic-plastic transition. Both equations are displayed on the plot, as shown in Figure 30. Their corresponding trend lines are shown as heavy lines.

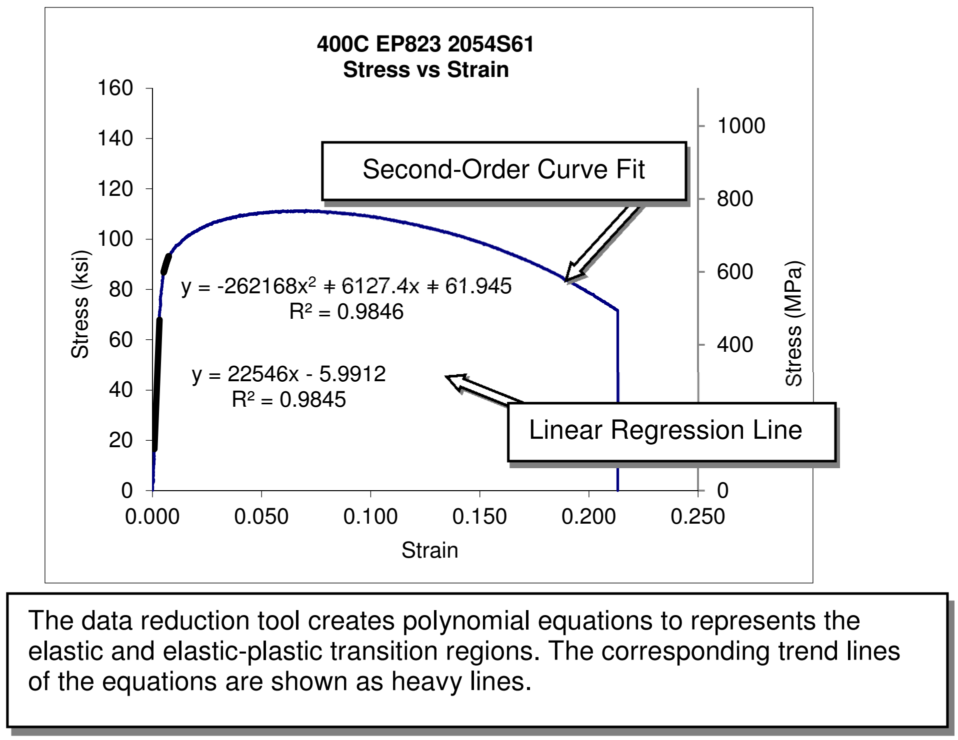


Figure 30. Polynomial Equation Representations

With the elastic portion represented by a polynomial equation, the data reduction tool numerically translated the equation with a 0.002 positive shift along the x-axis, defining a new equation. This new equation represented the 0.2% offset line. The offset line and elastic-plastic transition trend line are superimposed on the stress-strain plot in Figure 31 to graphically illustrate a data noise filtering effect. The tool calculates the intersection of the two equations to determine the stress at yielding s_y, reporting this as the specimen yield strength.

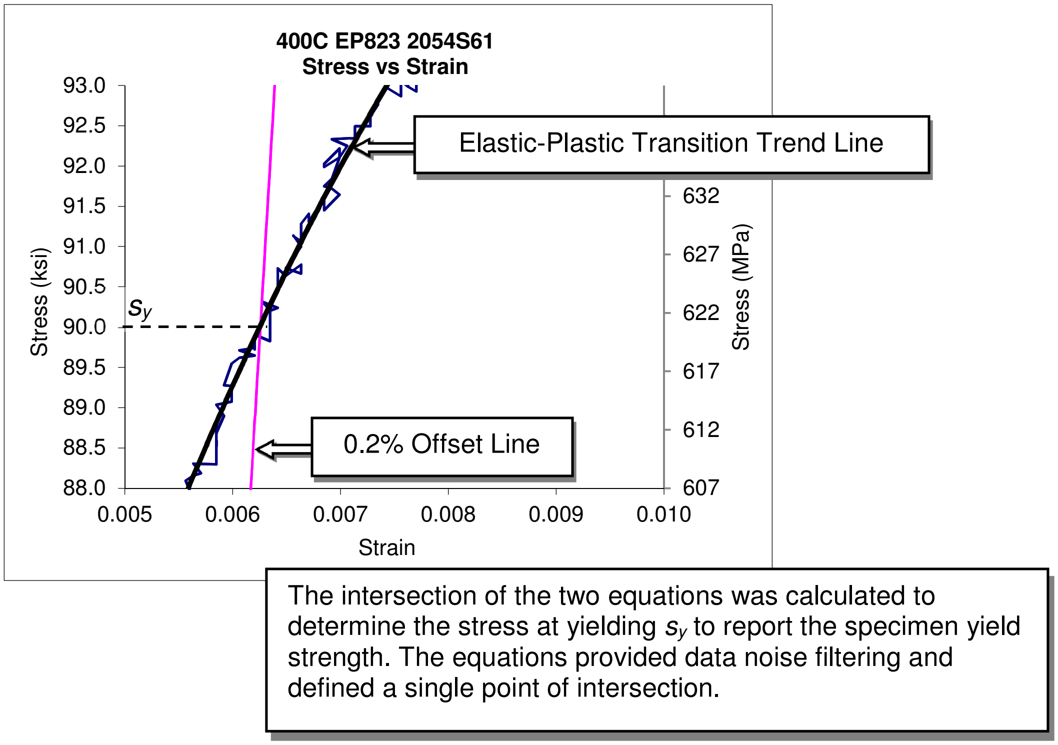


Figure 31. Yield Stress Found at Intersection of Equations

3.4.8. Stress-Strain Curve Correction

As presented in Section 3.2.3 the laser extensometer was functionally limited to the temperature tests 400°C (752°F) and cooler. To collect specimen extension data, the MTS machine's LVDT was used in absence of the laser extensometer. The LVDT was capable of measuring displacement to tensile failure without risk of damage, unlike other extensometers that require contact with the specimen.

However, using the tensile machine's LVDT carries one major disadvantage. The LVDT reports displacement values of the linear actuator – not the extension of the tensile specimen gage section, and if not compensated, the stress-strain curve generated with LVDT data will be distorted. This bias is caused by the combined compliance of the machine and component stack between the

LVDT and the specimen gage section. In essence, the MTS machine and component stack act as a series of springs with varying compliance characteristics when applying the tensile load to the specimen. Systems with low stiffness characteristics will flatten the true slope of the elastic region, potentially resulting in a lower yield strength determination when performing a 0.2% offset. This may provide conservatism - but lower, nonetheless. To demonstrate the effect of machine compliance Figure 32 presents an example tensile test that is represented by two engineering stress-strain plots. One plot displays strain data derived from the laser extensometer, representing the baseline condition, and the other displays strain data derived from the LVDT.

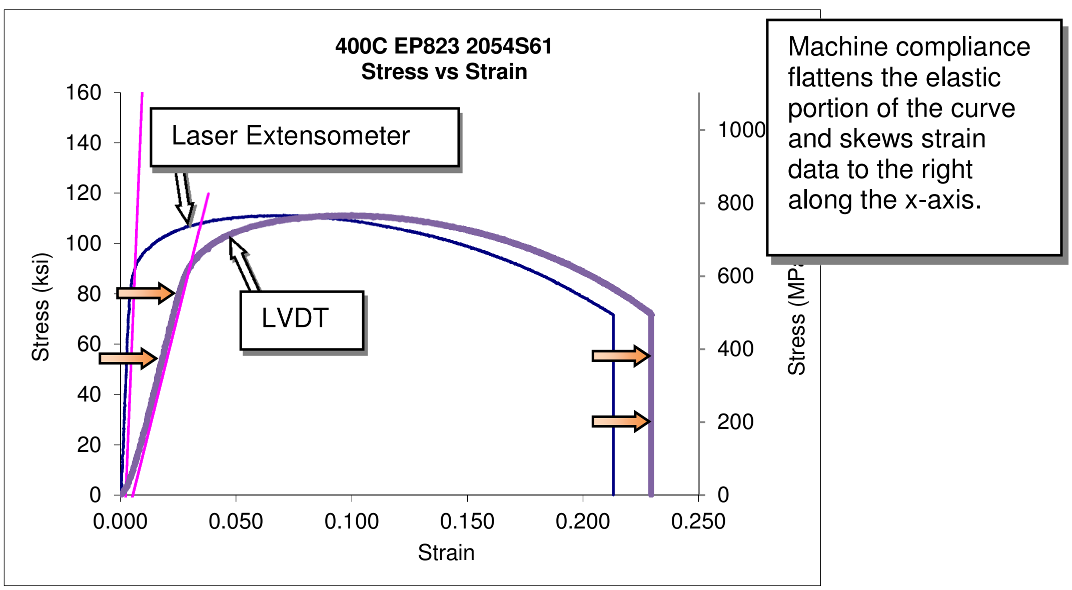


Figure 32. Effect of Machine Compliance on Strain Data

There are several methods for correcting skewed LVDT data to compensate for system compliance. Each method has its own limitation. One method involves applying a modulus

correction factor to align the elastic region of the data; however, as depicted in Figure 33 the plastic region is drastically overcompensated.

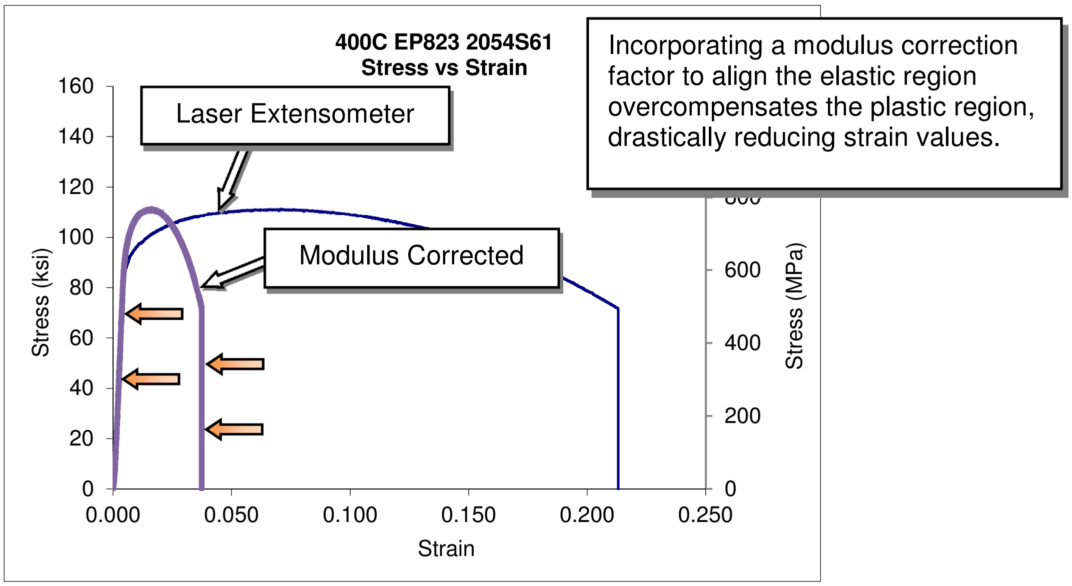


Figure 33. Applying Modulus Correction Factor

Another method involves applying a failure strain correction factor to align the tensile failure point with the specimen maximum engineering strain e_f, which is derived from dimensional measurements. Figure 34 shows that this method corrects the overall length of the plot but severely falls short of correcting the elastic region.

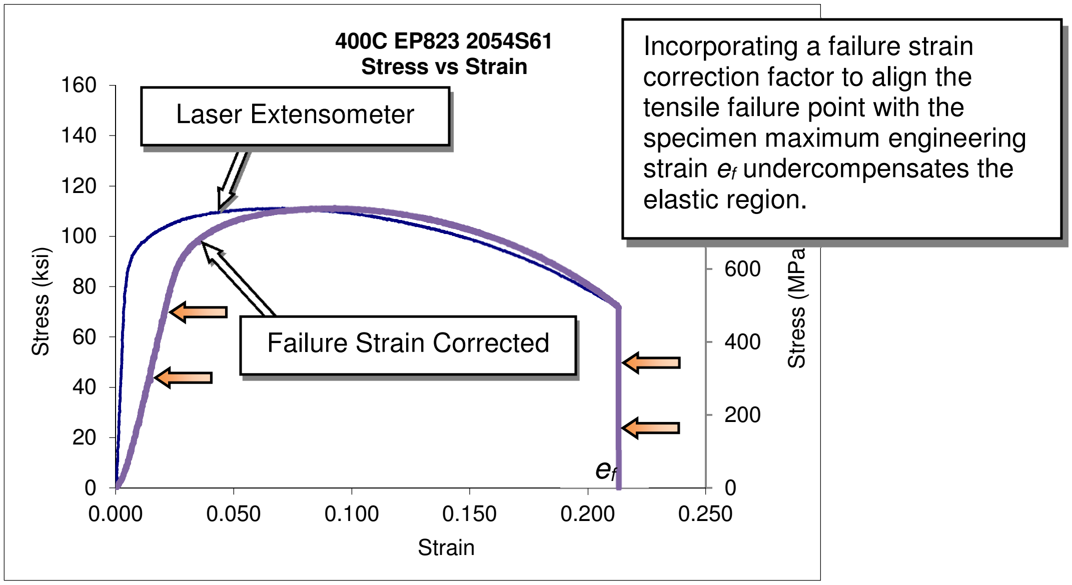


Figure 34. Applying Failure Strain Correction Factor

The two aforementioned correction methods are only effective when the deformations are elastic for the entire system, including the specimen itself. With a perfectly elastic system the relationship between LVDT response and extensometer response is proportional. However, introducing plastic deformation into the system renders these two correction methods ineffective for providing a comprehensive correction to the stress-strain plot. The relationship between the LVDT data and the laser extensometer data is not linear throughout the entire stress-strain curve. This becomes evident when the laser extensometer strain data is plotted against the LVDT strain data as in Figure 35. Fortunately, elongation values were determined by direct dimensional measurements of the tensile specimen as detailed in Section 3.4.5. On the other hand, the accurate representation of the engineering stress-strain curve was dependent upon accurate strain data.

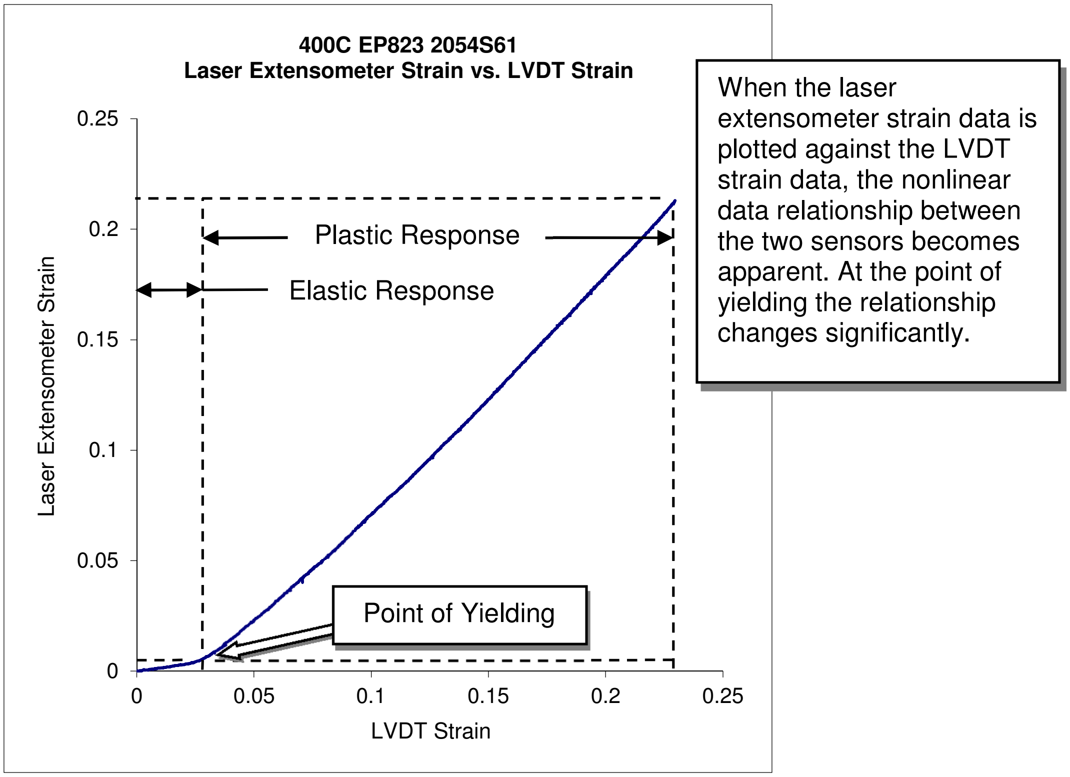


Figure 35. Extension Sensor Relationship Plot

For tests that rely on the LVDT exclusively for calculating strain data, specifically the 500°C (932°F) and 600°C (1112°F) tests, the data reduction tool incorporated a strain correction algorithm to provide realistic stress-strain plots. To do this, two second-order curve fits were applied to represent the strain data relationship between the laser extensometer and LVDT. The resulting polynomial equations are provided on the plot in Figure 36.

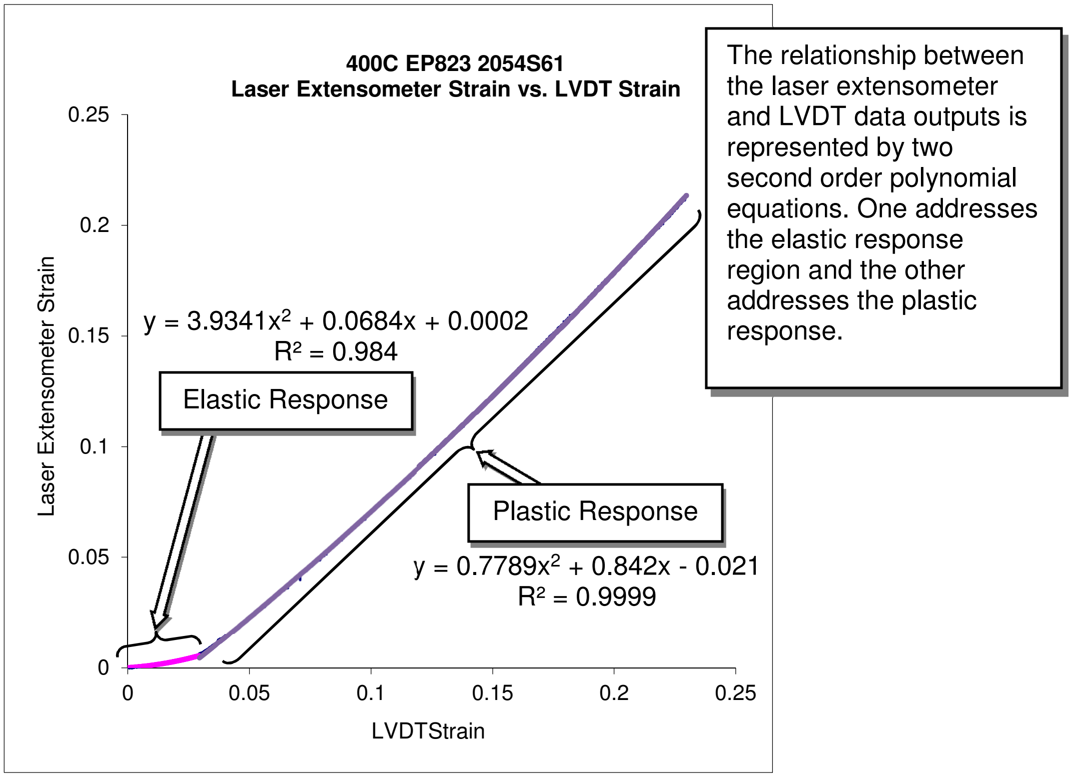


Figure 36. Polynomial Equation Representation of the Sensor Relationship

The data reduction tool conditions the LVDT strain data by applying the second-order polynomial equations provided in Figure 36. The elastic data points are conditioned by the elastic response polynomial equation, and likewise, the plastic data points are conditioned by the plastic response equation. Figure 37 displays the result of this data shift.

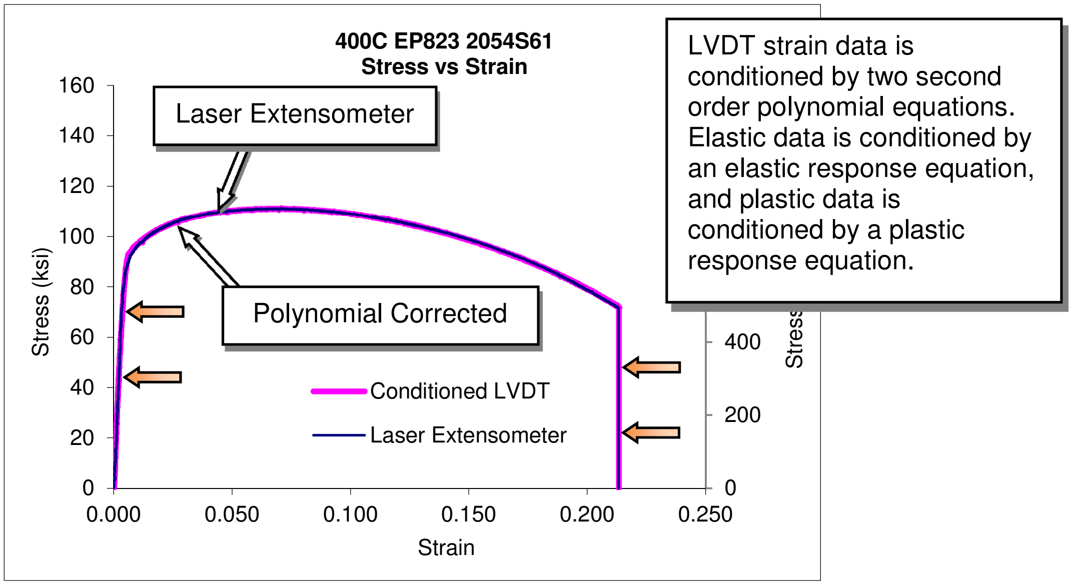


Figure 37. Applying Correction Polynomial Equations

In Figure 37 the resulting conditioned LVDT curve tightly matches the benchmark laser extensometer curve. Before applying this correction algorithm to the 500°C and 600°C elevated temperature tests, this exercise was performed on three known quantities, i.e., tests that had both laser extensometer and LVDT data. This was done to develop the coefficients for the elastic and plastic response equations used for data conditioning. The three pairs of resulting equations were then averaged to provide the final pair of polynomial equations for addressing system compliance. Table 6 provides the resulting averaged coefficient values.

Table 6. Correction Polynomial Equation Coefficients

Data Set	Elastic Response			Plastic Response		
	x^2	x	Constant	x^2	x	Constant
400C 2054S60	4.2344	-0.0131	0.00005	0.7323	0.8465	-0.0259
400C 2054S61	3.9341	0.0684	0.00020	0.7789	0.8420	-0.0210
400C 2054S63	5.8006	0.0145	0.00030	0.6904	0.8663	-0.0212
Averaged Coefficients	4.6564	0.0233	0.00018	0.7339	0.8516	-0.0227

The data reduction tool used Equations (3.13) and (3.14) to condition the LVDT strain data for the 500°C and 600°C tests.

Equation to Correct Elastic LVDT Data Response

$$y = 4.6564{x_e}^2 + 0.0233x_e + .00018 \tag{3.13}$$

Equation to Correct Plastic LVDT Data Response

$$y = 0.7339{x_p}^2 + 0.8516x_p - 0.0227 \tag{3.14}$$

Where:
y = Conditioned LVDT Strain
x_e = Elastic LVDT Strain
x_p = Plastic LVDT Strain

Figure 38 shows the conditioning effects on the LVDT data, using Equations (3.13) and (3.14). The original LVDT data curve, shown in green, is shifted to the conditioned LVDT data curve, shown in pink. For comparison the baseline laser extensometer data is shown in blue. This conditioned LVDT data curve tightly follows the baseline data curve, attenuating the effect of the tensile machine's compliance.

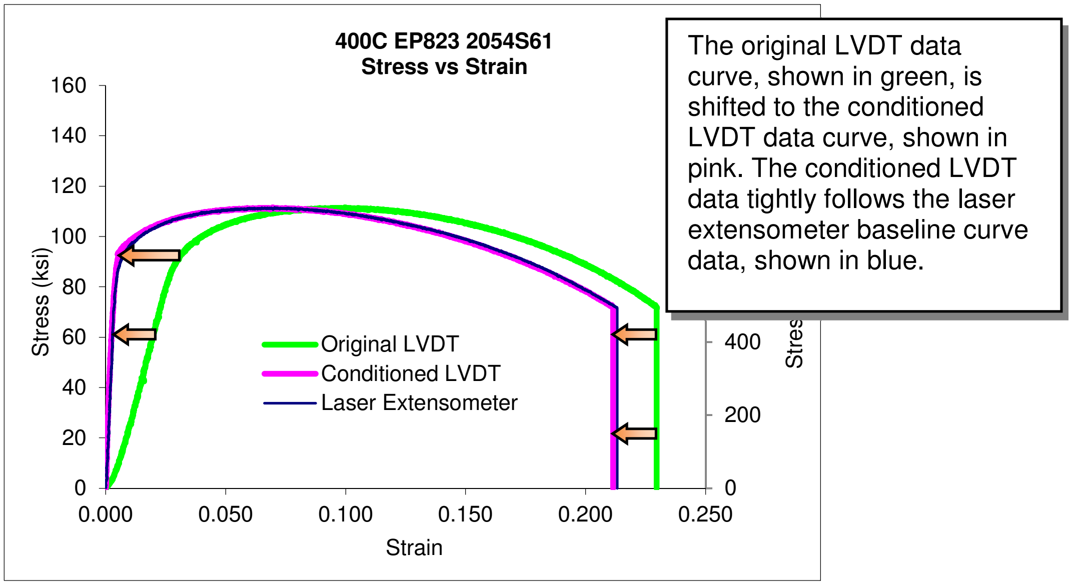


Figure 38. Conditioning Effects from Applying Correction Polynomial Equations

As with other correction methods this method has limitations as well. In order to calibrate a nonlinear unknown system with a measurable known system, it is generally good practice to calibrate over a bounding range to encompass all possible output. Without a bounding calibration an extrapolation can be used but entails uncertainty. Since the laser extensometer had a temperature limitation, the calibration was limited to the 400°C test temperatures and cooler. To safely use the conditioning equations requires an understanding that the 500°C and the 600°C tests generally have greater elongations. Consequently, some LVDT strain data was conditioned with an extrapolated portion of the correction polynomial equation (Equation (3.14)), which could skew the position of the strain point at tensile failure. However as mentioned earlier, instead of using this strain value at tensile failure, the elongation reported for this thesis is based on the direct measurements of the specimen.

For additional information of the data reduction tool and its data conditioning algorithms, refer to APPENDIX C.

CHAPTER 4:

RESULTS

Following the experimental test matrix presented in Table 4, all 54 tests were completed successfully. For each test scenario, three tensile tests were performed according to the experimental procedure presented in Section 3.3. All data was processed according to the data reduction methods detailed in Section 3.4. The resulting ductility parameters are presented in this section. Individual tensile test results are available in APPENDIX D, APPENDIX E, and APPENDIX F segregated by tempering time. CHAPTER 5 provides the discussion of results.

The following list briefly describes how the data is presented in this section.

- Section 4.1, Tabulated Tensile Test Results - The individual results are tabulated among their peers for a given material tempering time according to testing temperature.
- Section 4.2, Stress-Strain Curve Composite Plots - For each test temperature all three stress-strain curves are plotted on one graph to illustrate the repeatability of the tensile tests.
- Section 4.3, Individual Specimen Statistics, SI Units - The mean and standard deviation for each parameter are calculated to better describe the average values and spread of the data in SI units.
- Section 4.4, Individual Specimen Statistics, US Customary Units - The mean and standard deviation for each parameter are calculated to better describe the average values and spread of the data in US customary units.

- Section 4.5, Mean Ultimate Tensile Strength (UTS) – The mean at each temperature and tempering time combination is presented in tabular and graphical format with its corresponding standard error of the mean.
- Section 4.6, Mean Yield Strength (YS) – The mean at each temperature and tempering time combination is presented in tabular and graphical format with its corresponding standard error of the mean.
- Section 4.7, Mean Elongation – The mean at each temperature and tempering time combination is presented in tabular and graphical format with its corresponding standard error of the mean.
- Section 4.8, Mean Reduction of Area – The mean at each temperature and tempering time combination is presented in tabular and graphical format with its corresponding standard error of the mean.
- Section 4.9, Temperature Effects on Mechanical Performance – Composite graphs show test temperature effect on the stress-strain curves for each tempering time.
- Section 4.10, Tempering Time Effects on Mechanical Performance – Composite graphs show tempering time effect on the stress-strain curves for each test temperature.

4.1. Tabulated Tensile Test Results

For each tempering time the tensile test results are presented in Table 7 through Table 12 in both SI units and US customary units. Mean and standard deviation values for each data set can be found in Section 4.3 and 4.4.

Table 7. 1.25-Hour Tempering Time Specimen Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S50	RT	901.1	758.4	23.55	23.89	62.59
2054S51	RT	918.4	777.7	23.47	23.75	63.40
2054S52	RT	919.8	777.7	24.38	23.54	65.02
2054S53	100	852.2	713.6	22.42	22.51	63.85
2054S54	100	853.6	720.5	22.48	22.80	63.57
2054S55	100	852.2	717.1	22.72	22.64	63.50
2054S56	300	805.3	661.2	20.22	19.75	61.26
2054S57	300	806.0	663.3	19.98	19.74	62.42
2054S59	300	808.1	663.3	19.75	19.78	62.93
2054S60	400	754.3	610.9	22.25	21.86	63.15
2054S61	400	768.8	620.5	21.30	21.31	63.74
2054S63	400	759.8	615.0	21.97	22.13	63.09
2054S64	500	618.5	583.3	29.08	-	76.46
2054S65	500	607.4	577.1	26.92	-	75.15
2054S67	500	602.6	569.5	28.05	-	74.86
2054S68	600	410.2	406.8	42.22	-	87.40
2054S69	600	421.3	420.6	45.37	-	87.98
2054S71	600	408.2	406.8	48.63	-	88.14

Table 8. 1.25-Hour Tempering Time Specimen Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S50	RT	130.7	110.0	23.55	23.89	62.59
2054S51	RT	133.2	112.8	23.47	23.75	63.40
2054S52	RT	133.4	112.8	24.38	23.54	65.02
2054S53	212	123.6	103.5	22.42	22.51	63.85
2054S54	212	123.8	104.5	22.48	22.80	63.57
2054S55	212	123.6	104.0	22.72	22.64	63.50
2054S56	572	116.8	95.9	20.22	19.75	61.26
2054S57	572	116.9	96.2	19.98	19.74	62.42
2054S59	572	117.2	96.2	19.75	19.78	62.93
2054S60	752	109.4	88.6	22.25	21.86	63.15
2054S61	752	111.5	90.0	21.30	21.31	63.74
2054S63	752	110.2	89.2	21.97	22.13	63.09
2054S64	932	89.7	84.6	29.08	-	76.46
2054S65	932	88.1	83.7	26.92	-	75.15
2054S67	932	87.4	82.6	28.05	-	74.86
2054S68	1112	59.5	59.0	42.22	-	87.40
2054S69	1112	61.1	61.0	45.37	-	87.98
2054S71	1112	59.2	59.0	48.63	-	88.14

Table 9. 1.75-Hour Tempering Time Specimen Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T50	RT	897.7	750.8	23.85	23.72	61.79
2054T51	RT	905.3	756.4	23.35	24.03	62.88
2054T52	RT	895.6	750.1	23.62	23.76	62.47
2054T53	100	846.0	707.4	22.48	22.58	64.20
2054T54	100	844.6	697.7	22.35	22.59	63.66
2054T55	100	848.7	706.0	22.63	23.05	63.33
2054T57	300	803.2	646.0	19.90	19.93	62.40
2054T58	300	797.0	646.0	20.42	20.13	62.99
2054T59	300	795.0	649.5	19.78	19.20	61.88
2054T60	400	757.7	619.8	21.32	21.32	64.26
2054T62	400	756.4	615.7	21.38	21.18	64.26
2054T63	400	749.5	607.4	21.47	21.40	63.01
2054T64	500	597.8	562.6	27.42	-	75.57
2054T65	500	595.0	562.6	26.68	-	75.64
2054T66	500	595.7	561.2	27.42	-	75.46
2054T67	600	399.2	395.8	36.53	-	85.65
2054T68	600	402.7	397.8	44.47	-	86.32
2054T69	600	418.5	415.8	40.77	-	86.24

Table 10. 1.75-Hour Tempering Time Specimen Result, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T50	RT	130.2	108.9	23.85	23.72	61.79
2054T51	RT	131.3	109.7	23.35	24.03	62.88
2054T52	RT	129.9	108.8	23.62	23.76	62.47
2054T53	212	122.7	102.6	22.48	22.58	64.20
2054T54	212	122.5	101.2	22.35	22.59	63.66
2054T55	212	123.1	102.4	22.63	23.05	63.33
2054T57	572	116.5	93.7	19.90	19.93	62.40
2054T58	572	115.6	93.7	20.42	20.13	62.99
2054T59	572	115.3	94.2	19.78	19.20	61.88
2054T60	752	109.9	89.9	21.32	21.32	64.26
2054T62	752	109.7	89.3	21.38	21.18	64.26
2054T63	752	108.7	88.1	21.47	21.40	63.01
2054T64	932	86.7	81.6	27.42	-	75.57
2054T65	932	86.3	81.6	26.68	-	75.64
2054T66	932	86.4	81.4	27.42	-	75.46
2054T67	1112	57.9	57.4	36.53	-	85.65
2054T68	1112	58.4	57.7	44.47	-	86.32
2054T69	1112	60.7	60.3	40.77	-	86.24

Table 11. 2.25-Hour Tempering Time Specimen Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U31	RT	886.0	746.7	21.07	20.94	61.46
2054U32	RT	892.2	746.0	20.85	20.76	61.34
2054U51	RT	886.7	741.2	24.25	24.25	61.38
2054U22	100	836.3	699.1	19.77	20.04	62.14
2054U23	100	832.9	694.3	20.10	19.93	63.76
2054U24	100	836.3	704.0	19.47	19.95	63.81
2054U25	300	783.9	651.6	18.08	17.06	62.96
2054U26	300	785.3	641.9	18.32	18.19	63.03
2054U50	300	785.3	633.6	20.05	19.91	63.64
2054U28	400	739.8	598.5	19.25	18.90	63.98
2054U52	400	742.6	580.5	20.70	20.63	63.26
2054U53	400	737.7	602.6	20.87	20.90	63.90
2054U30	500	592.3	561.2	26.05	-	75.84
2054U54	500	588.8	555.0	27.40	-	75.69
2054U55	500	587.4	554.3	27.07	-	75.44
2054U56	600	395.8	393.0	35.42	-	86.24
2054U57	600	395.8	393.0	36.33	-	85.80
2054U58	600	390.9	388.2	35.80	-	85.18

Table 12. 2.25-Hour Tempering Time Specimen Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U31	RT	128.5	108.3	21.07	20.94	61.46
2054U32	RT	129.4	108.2	20.85	20.76	61.34
2054U51	RT	128.6	107.5	24.25	24.25	61.38
2054U22	212	121.3	101.4	19.77	20.04	62.14
2054U23	212	120.8	100.7	20.10	19.93	63.76
2054U24	212	121.3	102.1	19.47	19.95	63.81
2054U25	572	113.7	94.5	18.08	17.06	62.96
2054U26	572	113.9	93.1	18.32	18.19	63.03
2054U50	572	113.9	91.9	20.05	19.91	63.64
2054U28	752	107.3	86.8	19.25	18.90	63.98
2054U52	752	107.7	84.2	20.70	20.63	63.26
2054U53	752	107.0	87.4	20.87	20.90	63.90
2054U30	932	85.9	81.4	26.05	-	75.84
2054U54	932	85.4	80.5	27.40	-	75.69
2054U55	932	85.2	80.4	27.07	-	75.44
2054U56	1112	57.4	57.0	35.42	-	86.24
2054U57	1112	57.4	57.0	36.33	-	85.80
2054U58	1112	56.7	56.3	35.80	-	85.18

4.2. Stress-Strain Curve Composite Plots

Each of the three material tempering times had six test temperatures, creating eighteen test variable combinations. Three tensile tests were performed for each combination. For each scenario

the three resulting engineering stress-strain curves are presented in composite graphs in the following sections, broken down by the different material tempering times.

- Section 4.2.1 presents graphical results for specimens tempered for 1.25 hours.
- Section 4.2.2 presents graphical results for specimens tempered for 1.75 hours.
- Section 4.2.3 presents graphical results for specimens tempered for 2.25 hours.

4.2.1. Composite Graph Results for 1.25-Hour Tempering Time

This section provides the stress-strain plots for tensile specimens tempered for 1.25 hours. The results for the three specimens tested at each temperature are placed onto one graph. See Figure 39 through Figure 44.

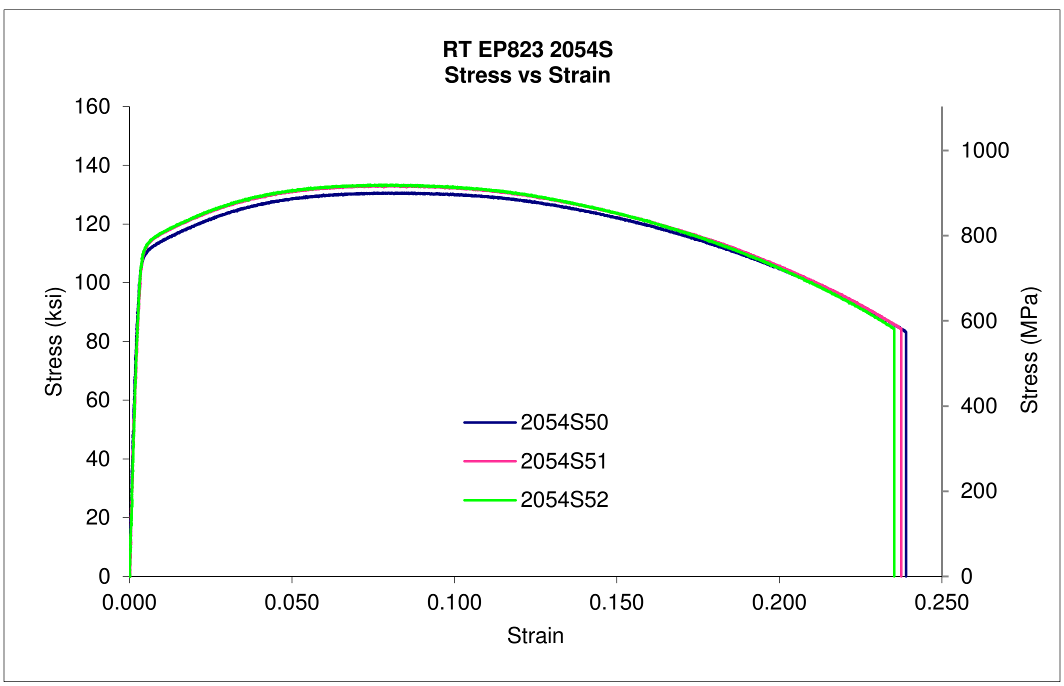


Figure 39. 1.25-Hour Tempering Time Composite Plot, Room Temperature

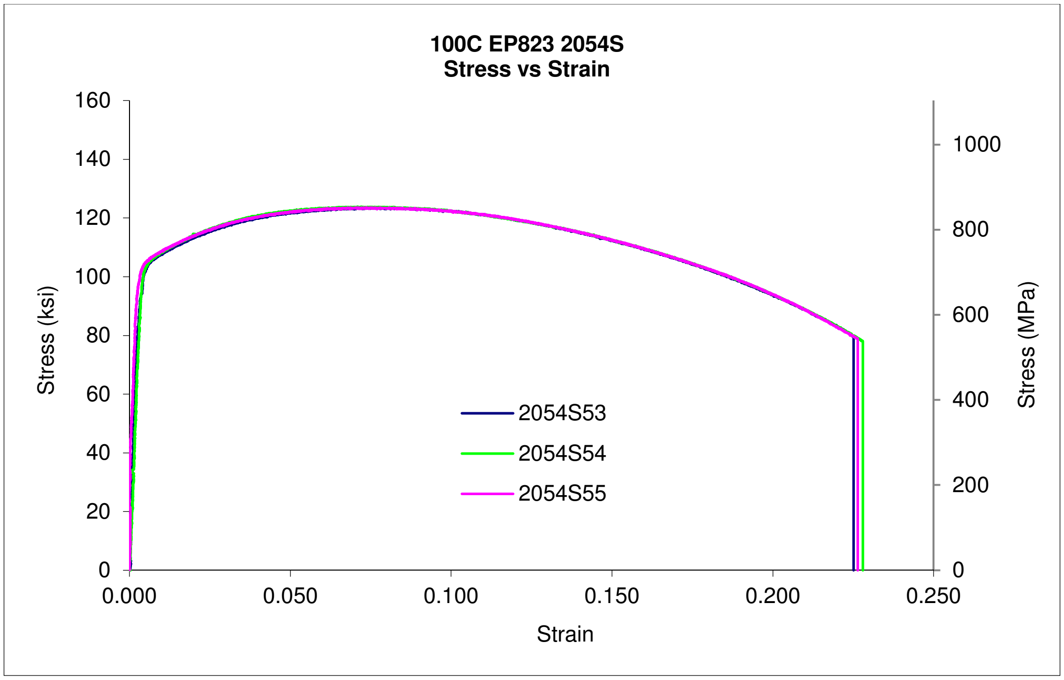


Figure 40. 1.25-Hour Tempering Time Composite Plot, 100°C (212°F)

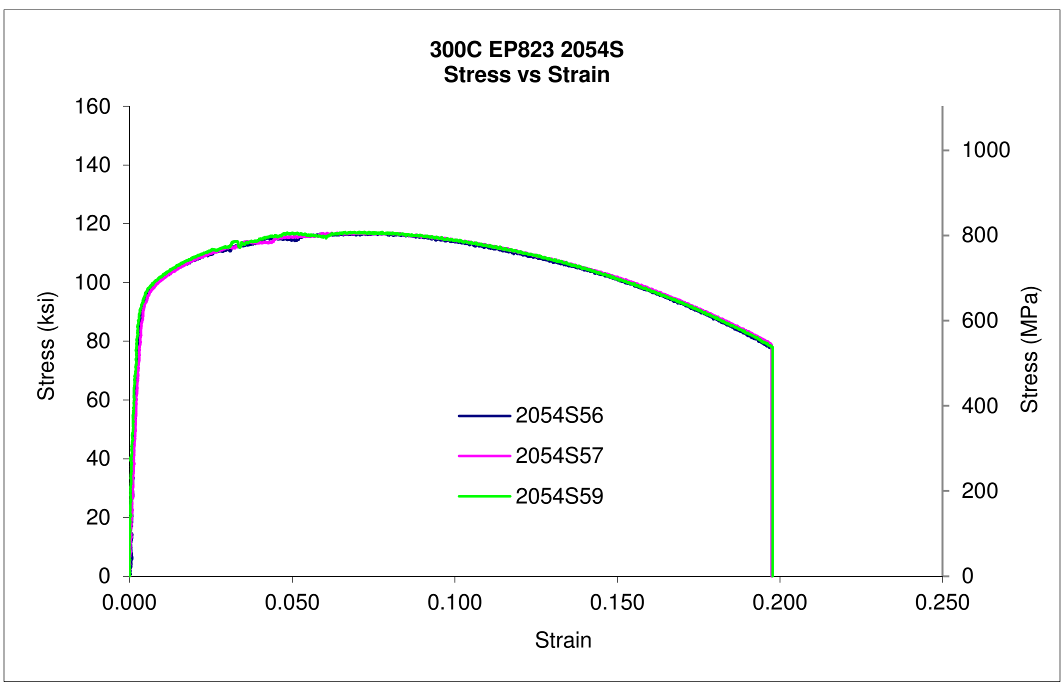


Figure 41. 1.25-Hour Tempering Time Composite Plot, 300°C (572°F)

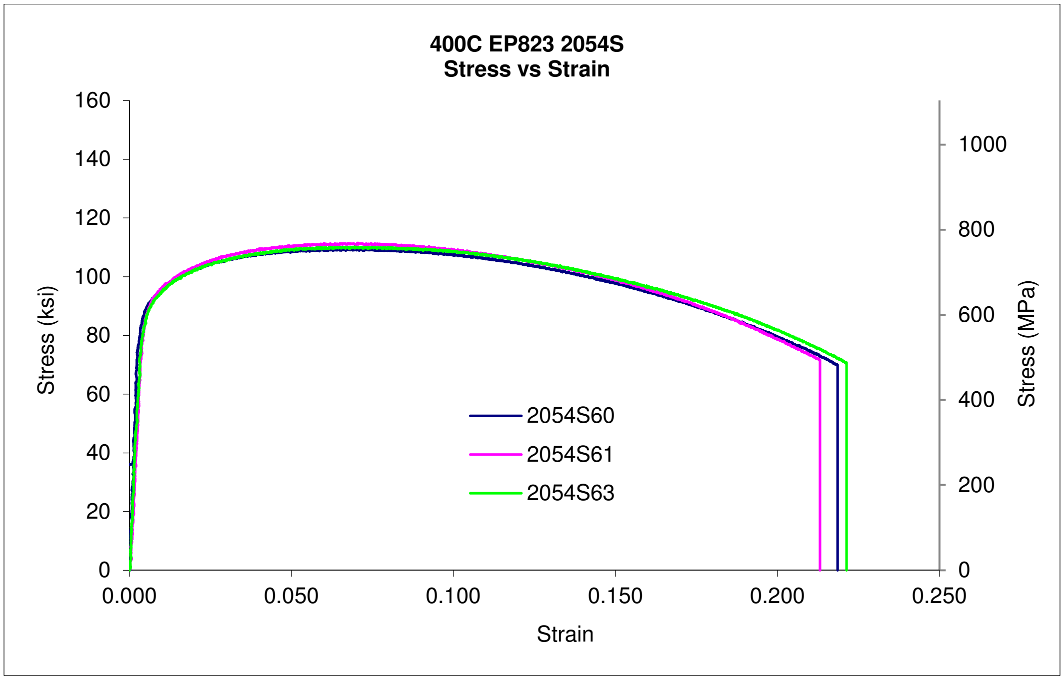


Figure 42. 1.25-Hour Tempering Time Composite Plot, 400°C (752°F)

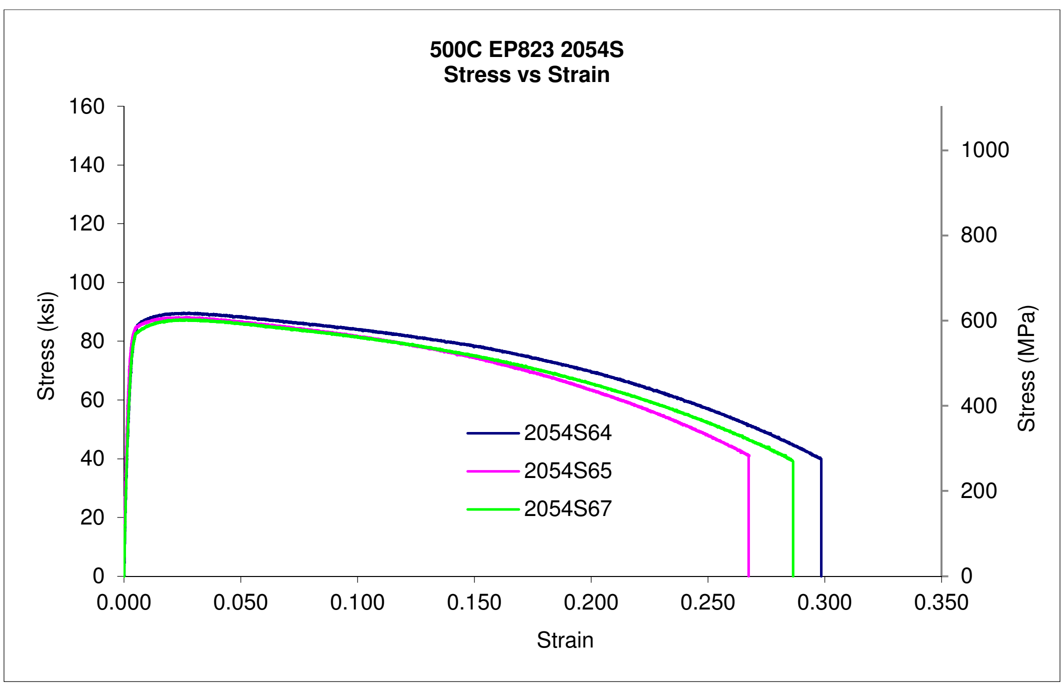


Figure 43. 1.25-Hour Tempering Time Composite Plot, 500°C (932°F)

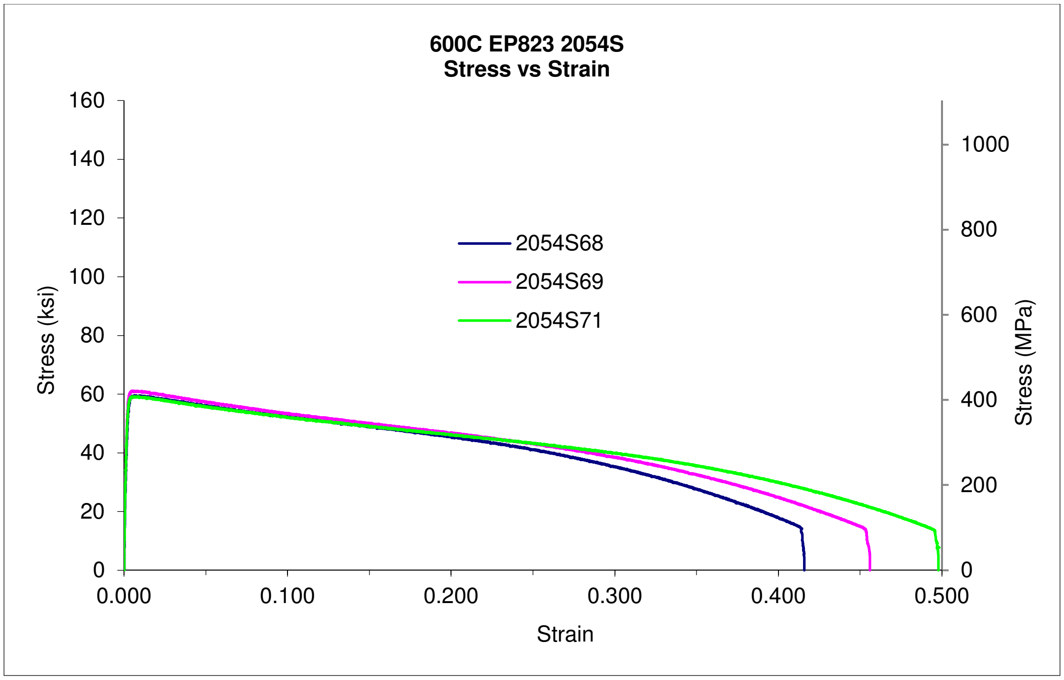


Figure 44. 1.25-Hour Tempering Time Composite Plot, 600°C (1112°F)

4.2.2. Composite Graph Results for 1.75-Hour Tempering Time

This section provides the stress-strain plots for tensile specimens tempered for 1.75 hours. The results for the three specimens tested at each temperature are placed onto one graph. See Figure 45 through Figure 50.

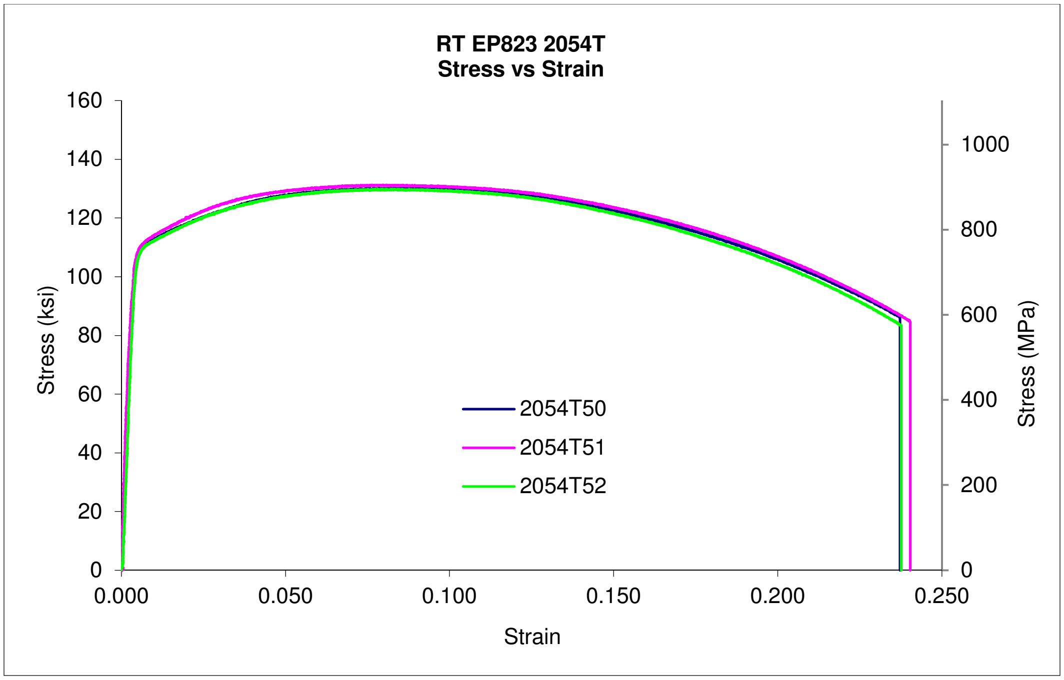


Figure 45. 1.75-Hour Tempering Time Composite Plot, Room Temperature

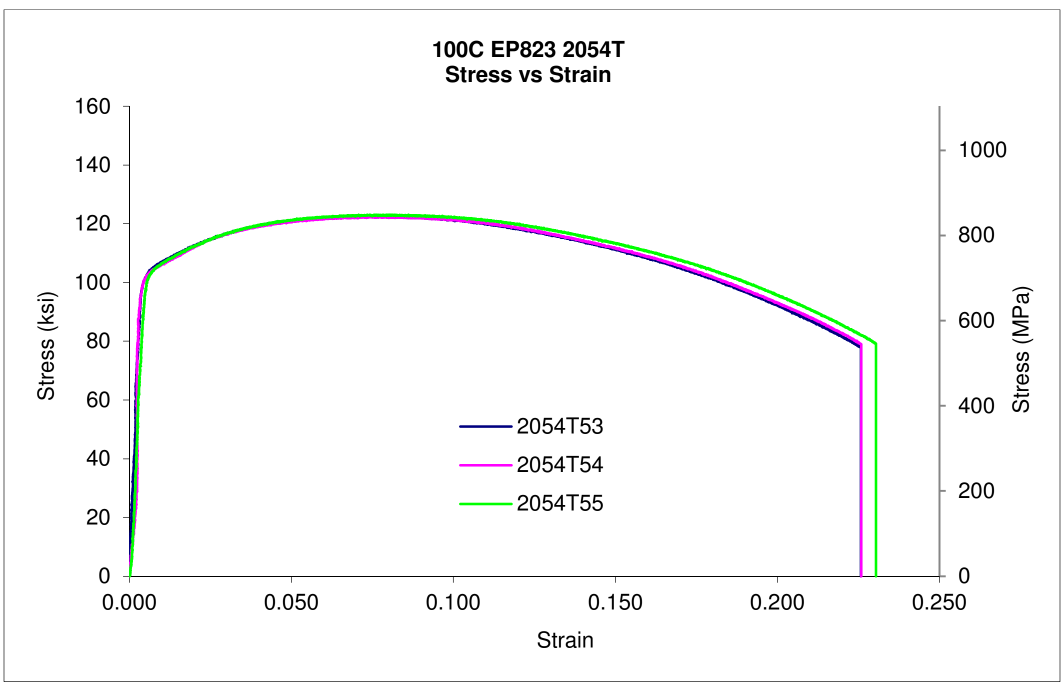


Figure 46. 1.75-Hour Tempering Time Composite Plot, 100°C (212°F)

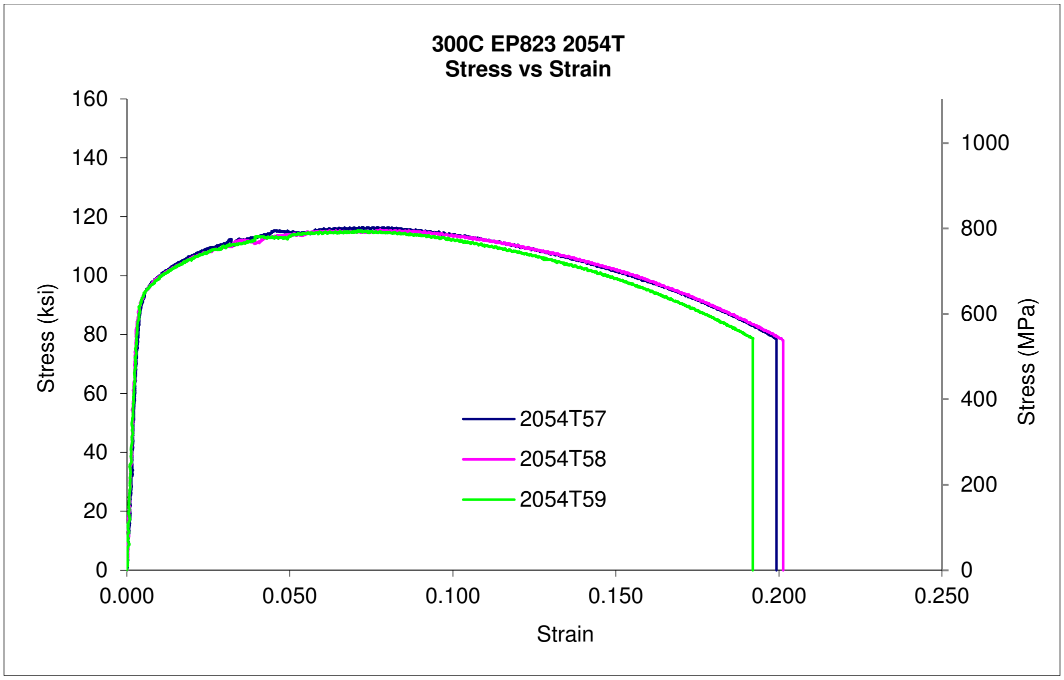


Figure 47. 1.75-Hour Tempering Time Composite Plot, 300°C (572°F)

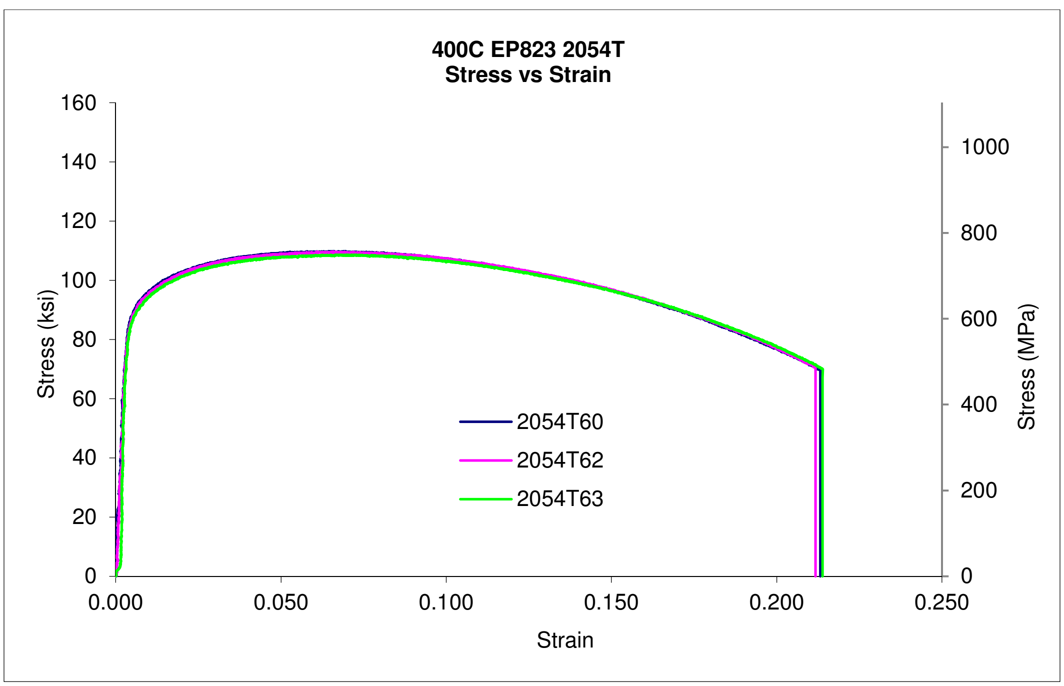


Figure 48. 1.75-Hour Tempering Time Composite Plot, 400°C (752°F)

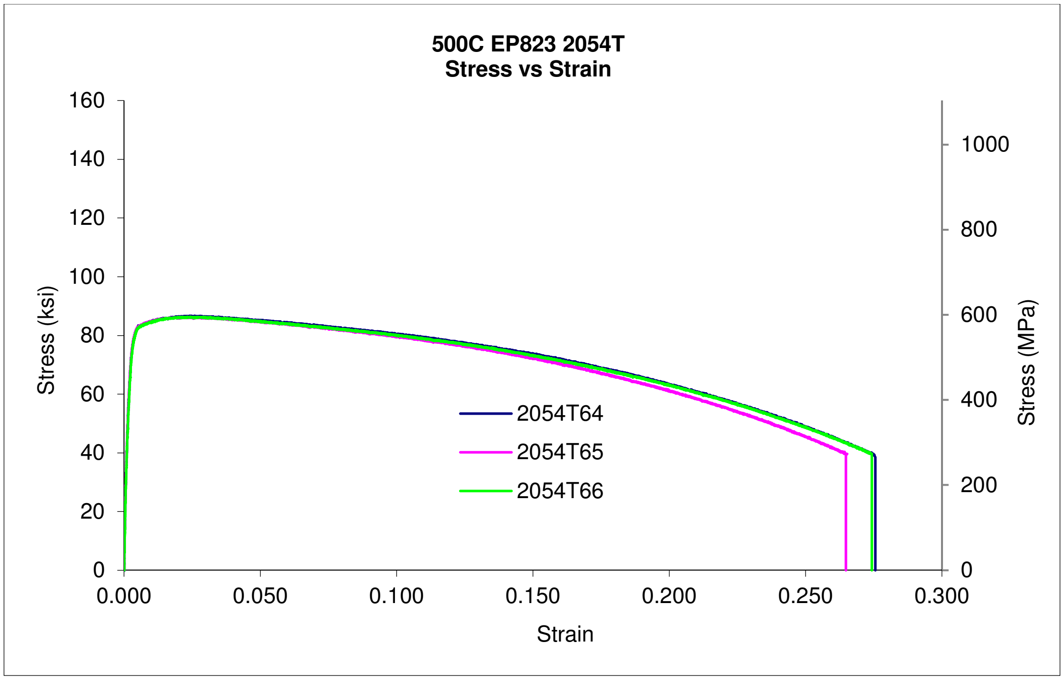


Figure 49. 1.75-Hour Tempering Time Composite Plot, 500°C (932°F)

One of the 600°C (1112°F) tests did not record data to the point of specimen rupture. The experiment ended prematurely for tensile sample 2054T68 when the tensile testing machine reached its 0.500-inch (12.7-mm) programmed displacement limit; however all material properties could be determined from the available data. Elongation was determined from overall length before and after tensile testing. The strain at failure is shown on the graph in Figure 50 and was calculated from caliper measurements.

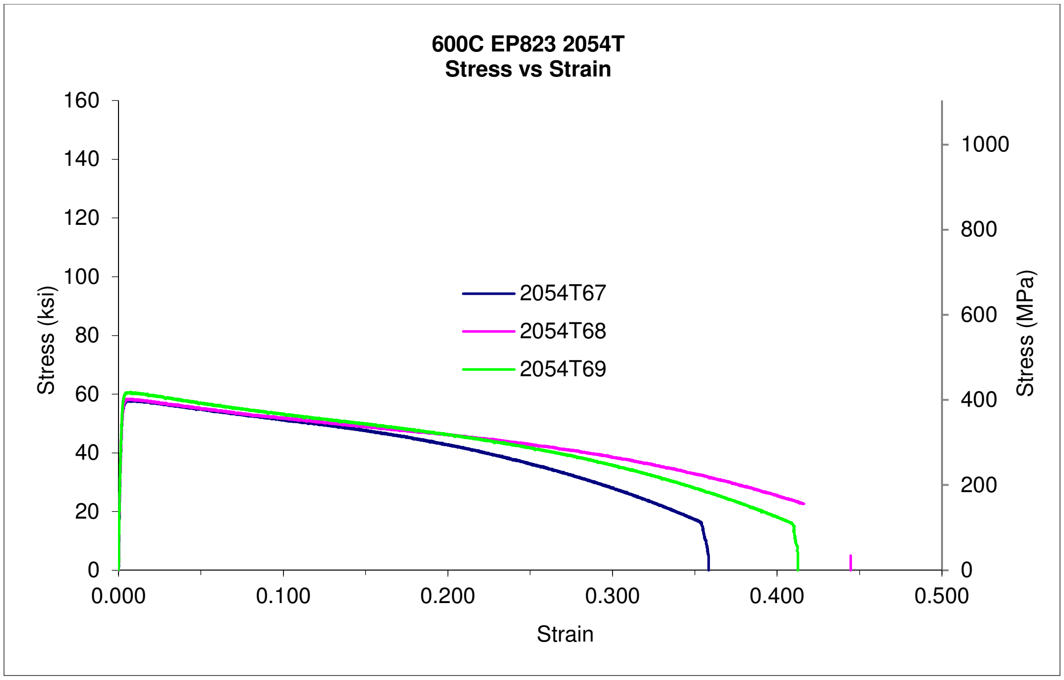


Figure 50. 1.75-Hour Tempering Time Composite Plot, 600°C (1112°F)

4.2.3. Composite Graph Results for 2.25-Hour Tempering Time

This section provides the stress-strain plots for tensile specimens tempered for 2.25 hours. The results for the three specimens tested at each temperature are placed onto one graph. See Figure 51 through Figure 56.

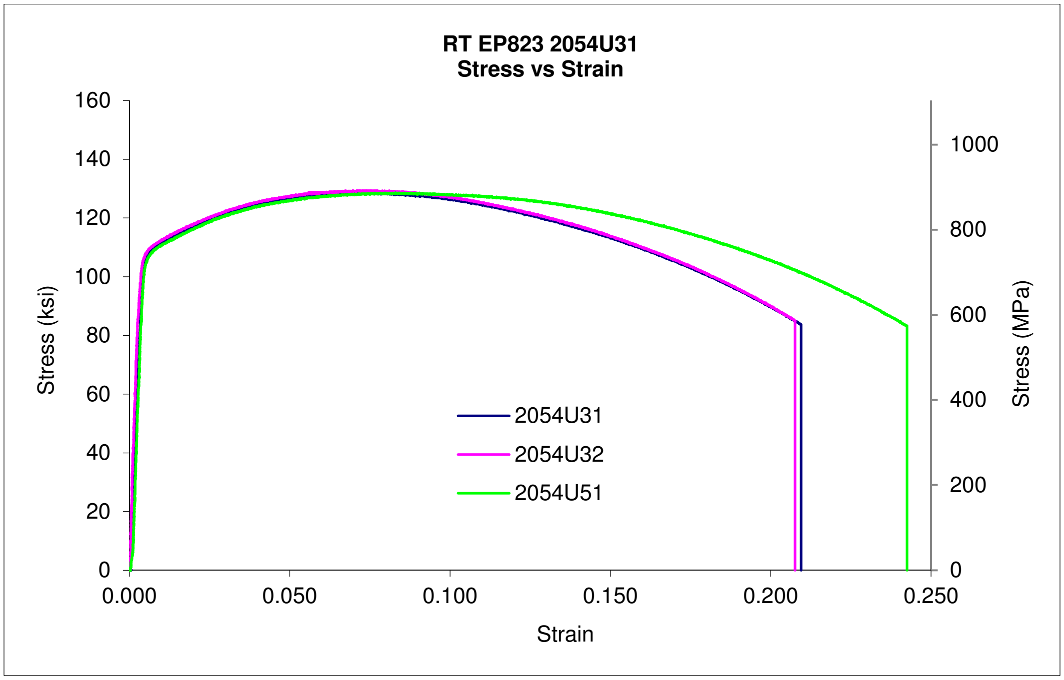


Figure 51. 2.25-Hour Tempering Time Composite Plot, Room Temperature

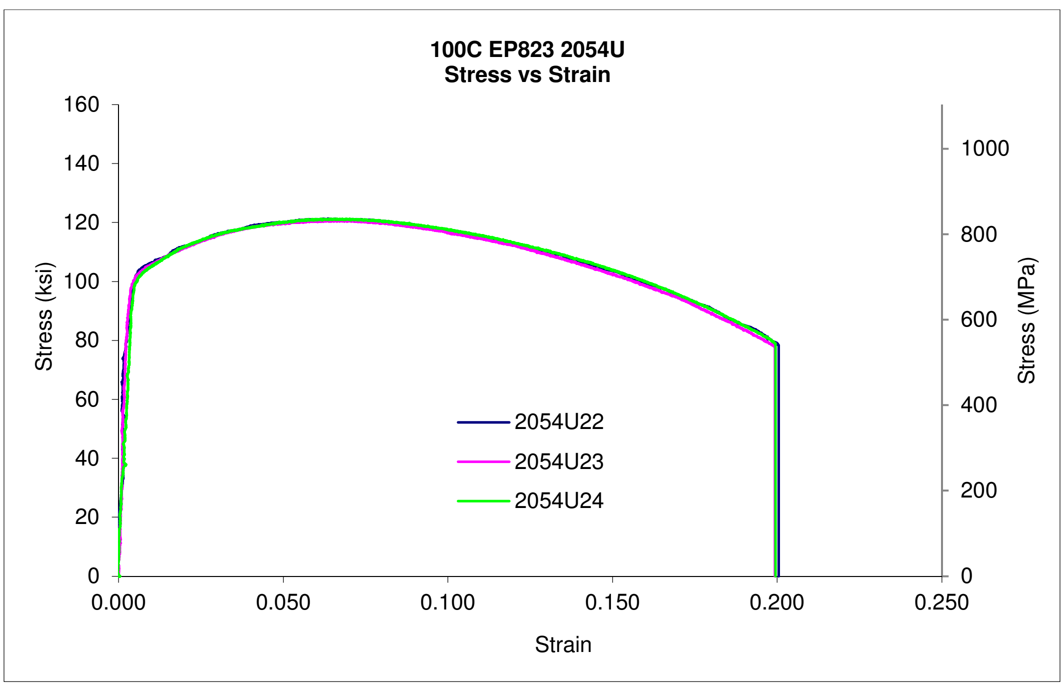


Figure 52. 2.25-Hour Tempering Time Composite Plot, 100°C (212°F)

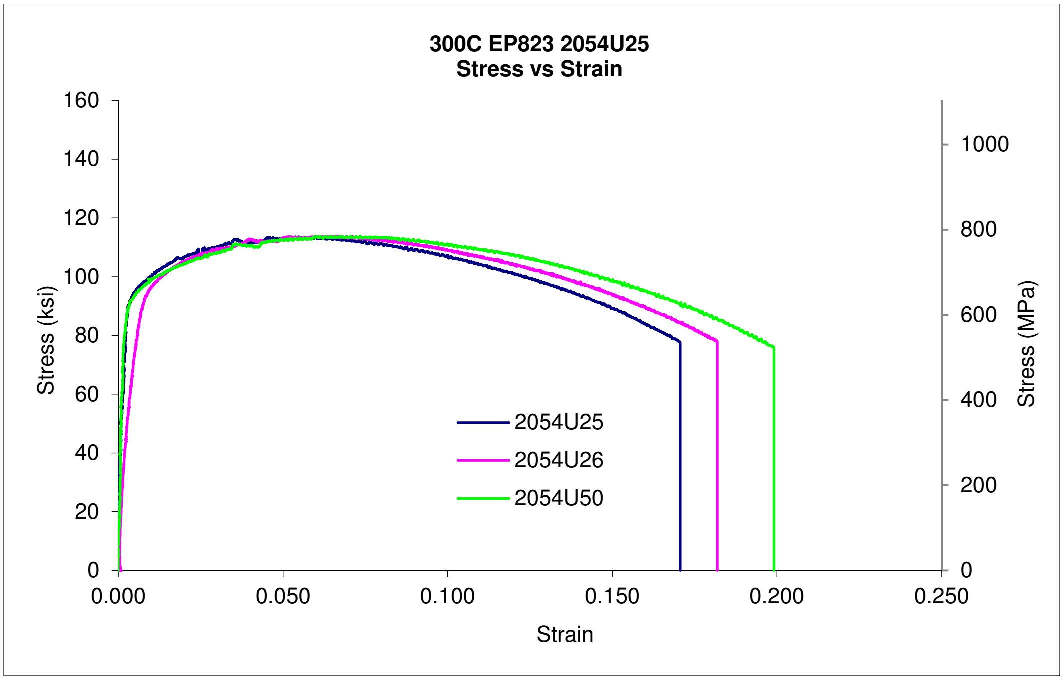


Figure 53. 2.25-Hour Tempering Time Composite Plot, 300°C (572°F)

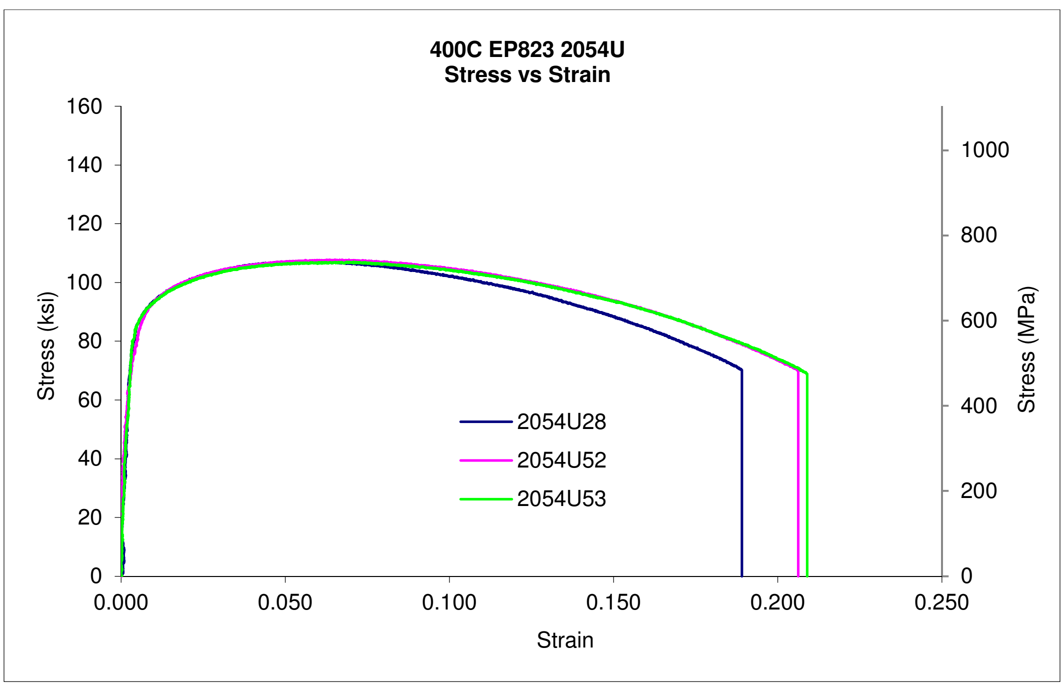


Figure 54. 2.25-Hour Tempering Time Composite Plot, 400°C (752°F)

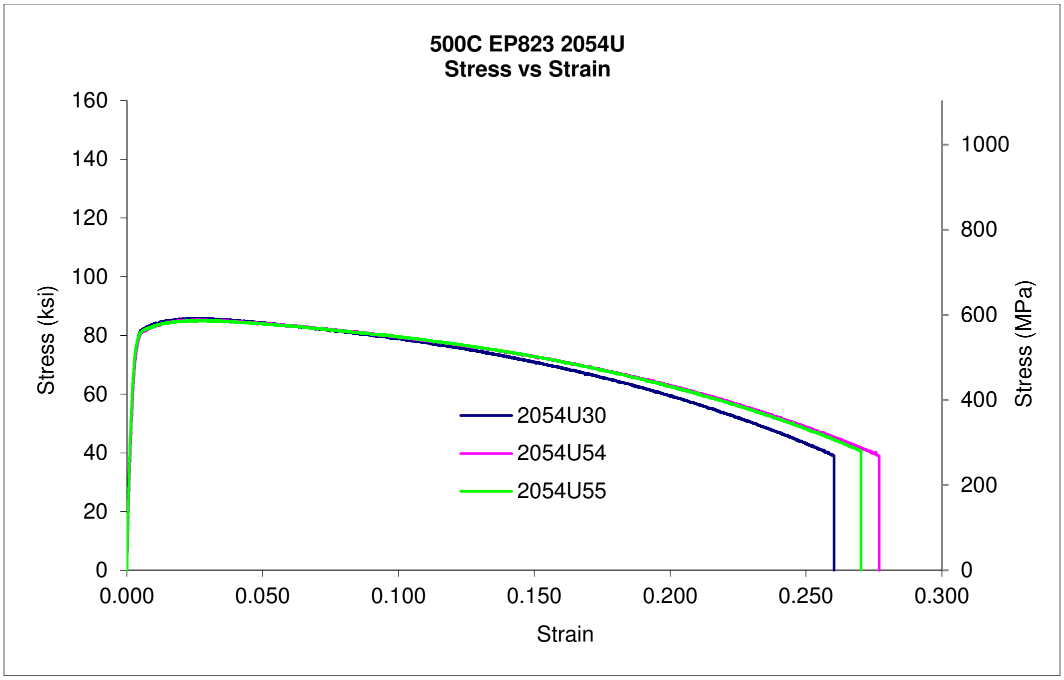


Figure 55. 2.25-Hour Tempering Time Composite Plot, 500°C (932°F)

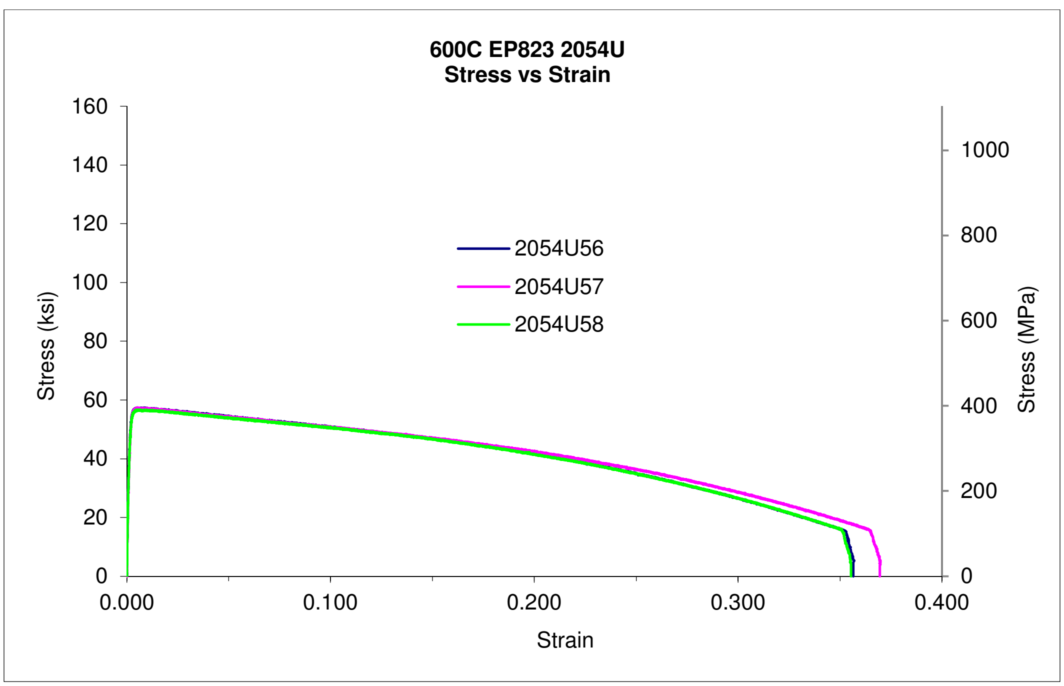


Figure 56. 2.25-Hour Tempering Time Composite Plot, 600°C (1112°F)

4.3. Individual Specimen Statistics, SI Units

The individual tensile specimen statistics are presented SI units in this section. For US customary units see Section 4.4. For each data set the average and standard deviation are calculated for each material performance parameter. Table 13 through Table 18 provide results for 1.25-hour tempered specimens. Similarly, Table 19 through Table 24 provide results for 1.75-hour tempered specimens. Finally, Table 25 through Table 30 provide results for 2.25-hour tempered specimens.

Table 13. Room Temp., 1.25-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S50	RT	901.1	758.4	23.55	23.89	62.59
2054S51	RT	918.4	777.7	23.47	23.75	63.40
2054S52	RT	919.8	777.7	24.38	23.54	65.02
Mean, μ		913.1	771.3	23.80	23.73	63.67
Standard Deviation, σ		8.5	9.1	0.41	0.14	1.01

Table 14. 100°C, 1.25-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S53	100	852.2	713.6	22.42	22.51	63.85
2054S54	100	853.6	720.5	22.48	22.80	63.57
2054S55	100	852.2	717.1	22.72	22.64	63.50
Mean, μ		852.7	717.1	22.54	22.65	63.64
Standard Deviation, σ		0.7	2.8	0.13	0.12	0.15

Table 15. 300°C, 1.25-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S56	300	805.3	661.2	20.22	19.75	61.26
2054S57	300	806.0	663.3	19.98	19.74	62.42
2054S59	300	808.1	663.3	19.75	19.78	62.93
Mean, μ		806.5	662.6	19.98	19.76	62.20
Standard Deviation, σ		1.2	1.0	0.19	0.02	0.70

Table 16. 400°C, 1.25-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S60	400	754.3	610.9	22.25	21.86	63.15
2054S61	400	768.8	620.5	21.30	21.31	63.74
2054S63	400	759.8	615.0	21.97	22.13	63.09
Mean, μ		761.0	615.5	21.84	21.77	63.33
Standard Deviation, σ		6.0	4.0	0.40	0.34	0.29

Table 17. 500°C, 1.25-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S64	500	618.5	583.3	29.08	-	76.46
2054S65	500	607.4	577.1	26.92	-	75.15
2054S67	500	602.6	569.5	28.05	-	74.86
Mean, μ		609.5	576.6	28.02	-	75.49
Standard Deviation, σ		6.6	5.6	0.88	-	0.70

Table 18. 600°C, 1.25-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S68	600	410.2	406.8	42.22	-	87.40
2054S69	600	421.3	420.6	45.37	-	87.98
2054S71	600	408.2	406.8	48.63	-	88.14
Mean, µ		413.2	411.4	45.41	-	87.84
Standard Deviation, σ		5.8	6.5	2.62	-	0.32

Table 19. Room Temp., 1.75-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T50	RT	897.7	750.8	23.85	23.72	61.79
2054T51	RT	905.3	756.4	23.35	24.03	62.88
2054T52	RT	895.6	750.1	23.62	23.76	62.47
Mean, µ		899.5	752.4	23.61	23.84	62.38
Standard Deviation, σ		4.1	2.8	0.20	0.14	0.45

Table 20. 100°C, 1.75-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T53	100	846.0	707.4	22.48	22.58	64.20
2054T54	100	844.6	697.7	22.35	22.59	63.66
2054T55	100	848.7	706.0	22.63	23.05	63.33
Mean, µ		846.4	703.7	22.49	22.74	63.73
Standard Deviation, σ		1.7	4.3	0.11	0.22	0.36

Table 21. 300°C, 1.75-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T57	300	803.2	646.0	19.90	19.93	62.40
2054T58	300	797.0	646.0	20.42	20.13	62.99
2054T59	300	795.0	649.5	19.78	19.20	61.88
Mean, μ		798.4	647.2	20.03	19.75	62.42
Standard Deviation, σ		3.5	1.6	0.28	0.40	0.45

Table 22. 400°C, 1.75-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T60	400	757.7	619.8	21.32	21.32	64.26
2054T62	400	756.4	615.7	21.38	21.18	64.26
2054T63	400	749.5	607.4	21.47	21.40	63.01
Mean, μ		754.5	614.3	21.39	21.30	63.84
Standard Deviation, σ		3.6	5.2	0.06	0.09	0.59

Table 23. 500°C, 1.75-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T64	500	597.8	562.6	27.42	-	75.57
2054T65	500	595.0	562.6	26.68	-	75.64
2054T66	500	595.7	561.2	27.42	-	75.46
Mean, μ		596.2	562.2	27.17	-	75.56
Standard Deviation, σ		1.2	0.7	0.35	-	0.07

Table 24. 600°C, 1.75-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T67	600	399.2	395.8	36.53	-	85.65
2054T68	600	402.7	397.8	44.47	-	86.32
2054T69	600	418.5	415.8	40.77	-	86.24
Mean, μ		406.8	403.1	40.59	-	86.07
Standard Deviation, σ		8.4	9.0	3.24	-	0.30

Table 25. Room Temp., 2.25-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U31	RT	886.0	746.7	21.07	20.94	61.46
2054U32	RT	892.2	746.0	20.85	20.76	61.34
2054U51	RT	886.7	741.2	24.25	24.25	61.38
Mean, μ		888.3	744.6	22.06	21.98	61.39
Standard Deviation, σ		2.8	2.5	1.55	1.60	0.05

Table 26. 100°C, 2.25-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U22	100	836.3	699.1	19.77	20.04	62.14
2054U23	100	832.9	694.3	20.10	19.93	63.76
2054U24	100	836.3	704.0	19.47	19.95	63.81
Mean, μ		835.2	699.1	19.78	19.97	63.24
Standard Deviation, σ		1.6	3.9	0.26	0.05	0.78

Table 27. 300°C, 2.25-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U25	300	783.9	651.6	18.08	17.06	62.96
2054U26	300	785.3	641.9	18.32	18.19	63.03
2054U50	300	785.3	633.6	20.05	19.91	63.64
Mean, μ		784.9	642.4	18.82	18.39	63.21
Standard Deviation, σ		0.7	7.3	0.88	1.17	0.31

Table 28. 400°C, 2.25-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U28	400	739.8	598.5	19.25	18.90	63.98
2054U52	400	742.6	580.5	20.70	20.63	63.26
2054U53	400	737.7	602.6	20.87	20.90	63.90
Mean, μ		740.0	593.9	20.27	20.14	63.71
Standard Deviation, σ		2.0	9.6	0.73	0.89	0.32

Table 29. 500°C, 2.25-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U30	500	592.3	561.2	26.05	-	75.84
2054U54	500	588.8	555.0	27.40	-	75.69
2054U55	500	587.4	554.3	27.07	-	75.44
Mean, μ		589.5	556.9	26.84	-	75.66
Standard Deviation, σ		2.0	3.1	0.57	-	0.16

Table 30. 600°C, 2.25-Hour Tempering Time Results, SI Units

Tensile Specimen Number	Temp. (°C)	UTS (MPa)	YS (MPa)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U56	600	395.8	393.0	35.42	-	86.24
2054U57	600	395.8	393.0	36.33	-	85.80
2054U58	600	390.9	388.2	35.80	-	85.18
Mean, µ		394.2	391.4	35.85	-	85.74
Standard Deviation, σ		2.3	2.3	0.37	-	0.43

4.4. Individual Specimen Statistics, US Customary Units

The individual tensile specimen results are presented in US customary units in this section. For SI units see Section 4.3. For each data set the average and standard deviation are calculated for each material performance parameter. Table 31 through Table 36 provide results for 1.25-hour tempered specimens. Similarly, Table 37 through Table 42 provide results for 1.75-hour tempered specimens. Finally, Table 43 through Table 48 provide results for 2.25-hour tempered specimens.

Table 31. Room Temp., 1.25-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S50	RT	130.7	110.0	23.55	23.89	62.59
2054S51	RT	133.2	112.8	23.47	23.75	63.40
2054S52	RT	133.4	112.8	24.38	23.54	65.02
Mean, µ		132.4	111.9	23.80	23.73	63.67
Standard Deviation, σ		1.2	1.3	0.41	0.14	1.01

Table 32. 212°F, 1.25-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S53	212	123.6	103.5	22.42	22.51	63.85
2054S54	212	123.8	104.5	22.48	22.80	63.57
2054S55	212	123.6	104.0	22.72	22.64	63.50
Mean, µ		123.7	104.0	22.54	22.65	63.64
Standard Deviation, σ		0.1	0.4	0.13	0.12	0.15

Table 33. 572°F, 1.25-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S56	572	116.8	95.9	20.22	19.75	61.26
2054S57	572	116.9	96.2	19.98	19.74	62.42
2054S59	572	117.2	96.2	19.75	19.78	62.93
Mean, µ		117.0	96.1	19.98	19.76	62.20
Standard Deviation, σ		0.2	0.1	0.19	0.02	0.70

Table 34. 752°F, 1.25-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S60	752	109.4	88.6	22.25	21.86	63.15
2054S61	752	111.5	90.0	21.30	21.31	63.74
2054S63	752	110.2	89.2	21.97	22.13	63.09
Mean, µ		110.4	89.3	21.84	21.77	63.33
Standard Deviation, σ		0.9	0.6	0.40	0.34	0.29

Table 35. 932°F, 1.25-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S64	932	89.7	84.6	29.08	-	76.46
2054S65	932	88.1	83.7	26.92	-	75.15
2054S67	932	87.4	82.6	28.05	-	74.86
Mean, μ		88.4	83.6	28.02	-	75.49
Standard Deviation, σ		1.0	0.8	0.88	-	0.70

Table 36. 1112°F, 1.25-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054S68	1112	59.5	59.0	42.22	-	87.40
2054S69	1112	61.1	61.0	45.37	-	87.98
2054S71	1112	59.2	59.0	48.63	-	88.14
Mean, μ		59.9	59.7	45.41	-	87.84
Standard Deviation, σ		0.8	0.9	2.62	-	0.32

Table 37. Room Temp., 1.75-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T50	RT	130.2	108.9	23.85	23.72	61.79
2054T51	RT	131.3	109.7	23.35	24.03	62.88
2054T52	RT	129.9	108.8	23.62	23.76	62.47
Mean, μ		130.5	109.1	23.61	23.84	62.38
Standard Deviation, σ		0.6	0.4	0.20	0.14	0.45

Table 38. 212°F, 1.75-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T53	212	122.7	102.6	22.48	22.58	64.20
2054T54	212	122.5	101.2	22.35	22.59	63.66
2054T55	212	123.1	102.4	22.63	23.05	63.33
Mean, µ		122.8	102.1	22.49	22.74	63.73
Standard Deviation, σ		0.2	0.6	0.11	0.22	0.36

Table 39. 572°F, 1.75-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T57	572	116.5	93.7	19.90	19.93	62.40
2054T58	572	115.6	93.7	20.42	20.13	62.99
2054T59	572	115.3	94.2	19.78	19.20	61.88
Mean, µ		115.8	93.9	20.03	19.75	62.42
Standard Deviation, σ		0.5	0.2	0.28	0.40	0.45

Table 40. 572°F, 1.75-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T60	752	109.9	89.9	21.32	21.32	64.26
2054T62	752	109.7	89.3	21.38	21.18	64.26
2054T63	752	108.7	88.1	21.47	21.40	63.01
Mean, µ		109.4	89.1	21.39	21.30	63.84
Standard Deviation, σ		0.5	0.7	0.06	0.09	0.59

Table 41. 932°F, 1.75-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T64	932	86.7	81.6	27.42	-	75.57
2054T65	932	86.3	81.6	26.68	-	75.64
2054T66	932	86.4	81.4	27.42	-	75.46
Mean, µ		86.5	81.5	27.17	-	75.56
Standard Deviation, σ		0.2	0.1	0.35	-	0.07

Table 42. 1112°F, 1.75-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054T67	1112	57.9	57.4	36.53	-	85.65
2054T68	1112	58.4	57.7	44.47	-	86.32
2054T69	1112	60.7	60.3	40.77	-	86.24
Mean, µ		59.0	58.5	40.59	-	86.07
Standard Deviation, σ		1.2	1.3	3.24	-	0.30

Table 43. Room Temp., 2.25-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U31	RT	128.5	108.3	21.07	20.94	61.46
2054U32	RT	129.4	108.2	20.85	20.76	61.34
2054U51	RT	128.6	107.5	24.25	24.25	61.38
Mean, µ		128.8	108.0	22.06	21.98	61.39
Standard Deviation, σ		0.4	0.4	1.55	1.60	0.05

Table 44. 212°F, 2.25-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U22	212	121.3	101.4	19.77	20.04	62.14
2054U23	212	120.8	100.7	20.10	19.93	63.76
2054U24	212	121.3	102.1	19.47	19.95	63.81
Mean, μ		121.1	101.4	19.78	19.97	63.24
Standard Deviation, σ		0.2	0.6	0.26	0.05	0.78

Table 45. 572°F, 2.25-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U25	572	113.7	94.5	18.08	17.06	62.96
2054U26	572	113.9	93.1	18.32	18.19	63.03
2054U50	572	113.9	91.9	20.05	19.91	63.64
Mean, μ		113.8	93.2	18.82	18.39	63.21
Standard Deviation, σ		0.1	1.1	0.88	1.17	0.31

Table 46. 752°F, 2.25-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U28	752	107.3	86.8	19.25	18.90	63.98
2054U52	752	107.7	84.2	20.70	20.63	63.26
2054U53	752	107.0	87.4	20.87	20.90	63.90
Mean, μ		107.3	86.1	20.27	20.14	63.71
Standard Deviation, σ		0.3	1.4	0.73	0.89	0.32

Table 47. 932°F, 2.25-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U30	932	85.9	81.4	26.05	-	75.84
2054U54	932	85.4	80.5	27.40	-	75.69
2054U55	932	85.2	80.4	27.07	-	75.44
Mean, μ		85.5	80.8	26.84	-	75.66
Standard Deviation, σ		0.3	0.4	0.57	-	0.16

Table 48. 1112°F, 2.25-Hour Tempering Time Results, US Customary Units

Tensile Specimen Number	Temp. (°F)	UTS (ksi)	YS (ksi)	Elongation, Calipers (%)	Elongation, Laser (%)	Reduction of Area (%)
2054U56	1112	57.4	57.0	35.42	-	86.24
2054U57	1112	57.4	57.0	36.33	-	85.80
2054U58	1112	56.7	56.3	35.80	-	85.18
Mean, μ		57.2	56.8	35.85	-	85.74
Standard Deviation, σ		0.3	0.3	0.37	-	0.43

4.5. Mean Ultimate Tensile Strength (UTS)

Table 49 and Figure 57 present the mean ultimate tensile strength (UTS) as a function of test temperature and tempering time in both tabulated and graphical format. For each experimental condition the standard error of the mean $\sigma_{\bar{x}}$ is also provided in the table and on the graph as error bars. For a more detailed inspection of the UTS graph, Figure 58 through Figure 63 offer closer perspectives of UTS values at each test temperature, detailing the relationship among material tempering time. Values in US customary units are provided in Table 50 and Figure 64.

Table 49. Mean Ultimate Tensile Strength (SI Units)

Temperature (℃)	Mean Ultimate Tensile Strength (MPa)					
	Tempered 1.25 h	$\sigma_{\bar{x}}$	Tempered 1.75 h	$\sigma_{\bar{x}}$	Tempered 2.25 h	$\sigma_{\bar{x}}$
Room Temp.	913.1	4.9	899.5	2.4	888.3	1.6
100	852.7	0.4	846.4	1.0	835.2	0.9
300	806.5	0.7	798.4	2.0	784.9	0.4
400	761.0	3.4	754.5	2.1	740.0	1.1
500	609.5	3.8	596.2	0.7	589.5	1.2
600	413.2	3.3	406.8	4.9	394.2	1.3

$\sigma_{\bar{x}}$ is the standard error of the mean.

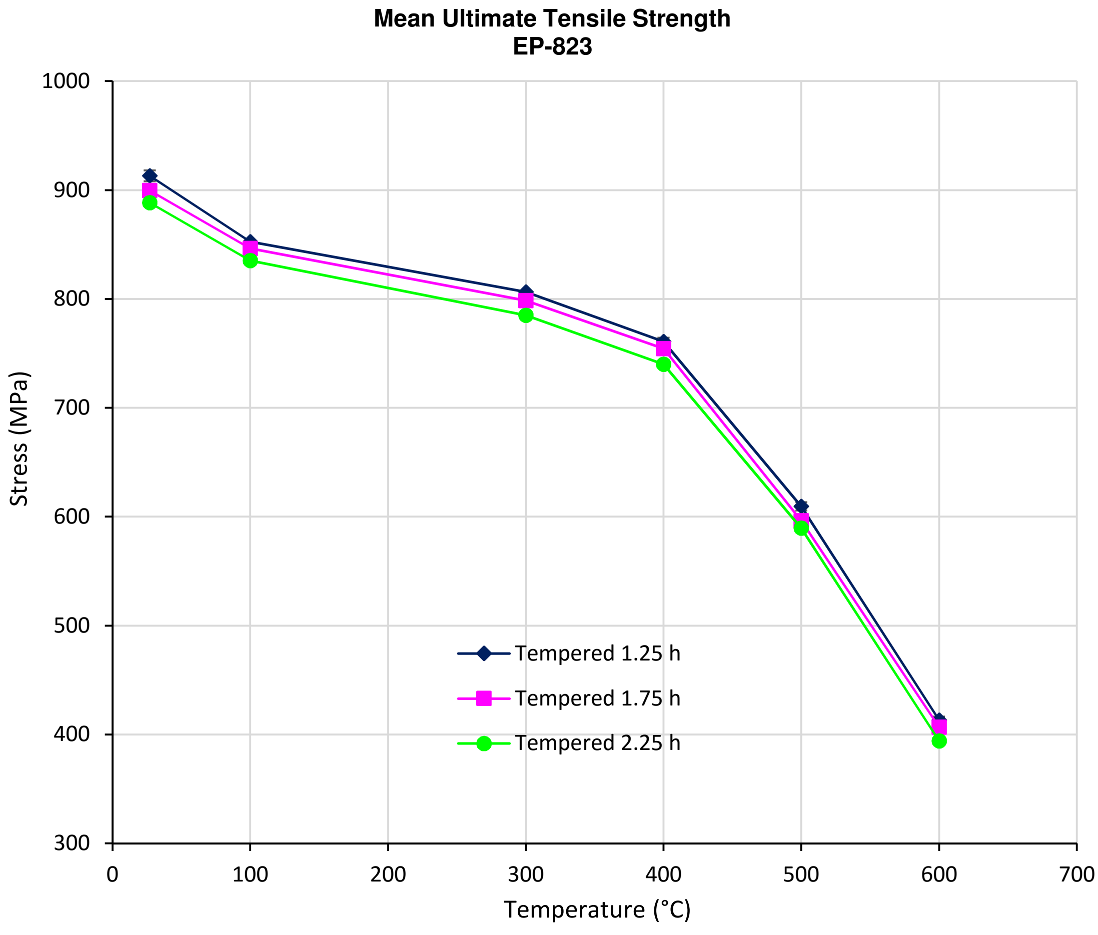


Figure 57. Mean Ultimate Tensile Strength (SI Units)

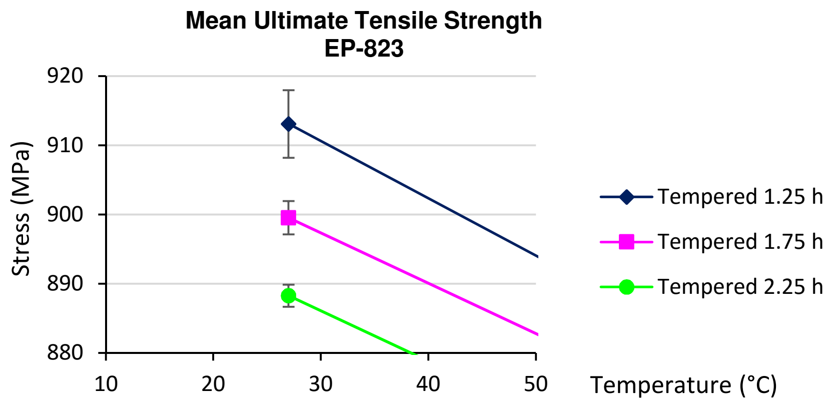


Figure 58. Mean Ultimate Tensile Strength, Room Temp. (SI Units)

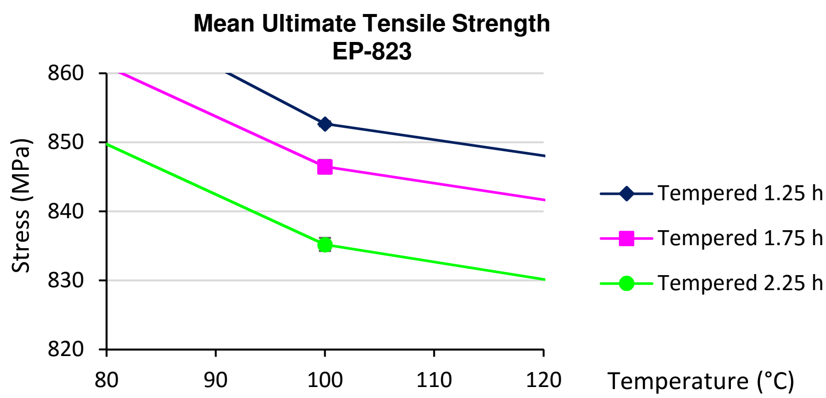


Figure 59. Mean Ultimate Tensile Strength, 100°C (SI Units)

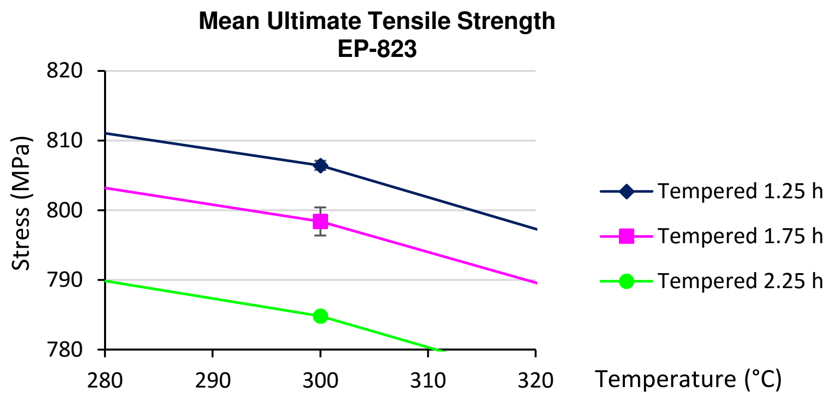


Figure 60. Mean Ultimate Tensile Strength, 300°C (SI Units)

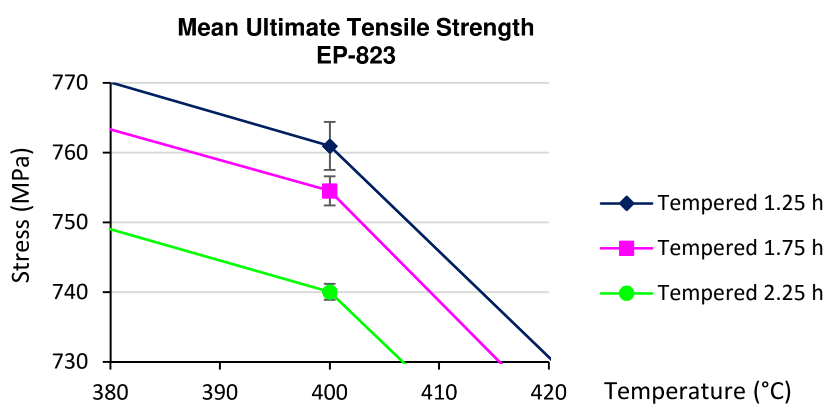


Figure 61. Mean Ultimate Tensile Strength, 400°C (SI Units)

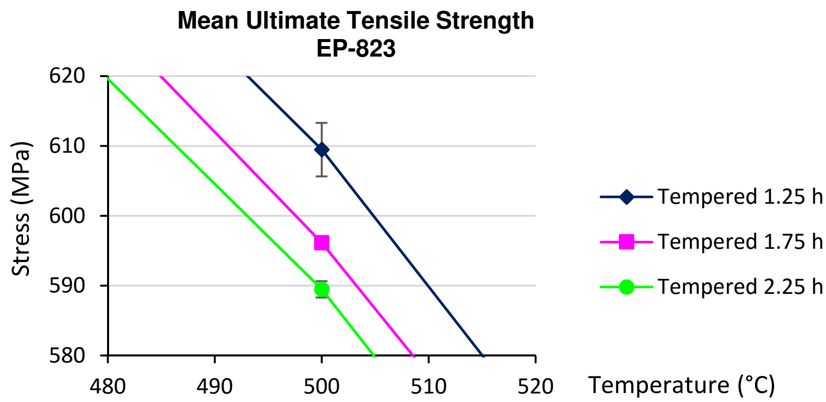


Figure 62. Mean Ultimate Tensile Strength, 500°C (SI Units)

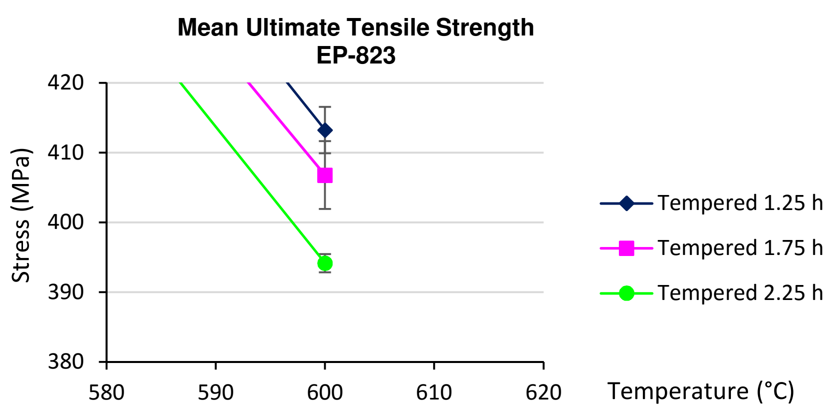


Figure 63. Mean Ultimate Tensile Strength, 600°C (SI Units)

Table 50 and Figure 64 present the mean ultimate tensile strength (UTS) according to test temperature and tempering time in both tabulated and graphical format in US customary units. As previously done, for each experimental condition the standard error of the mean $\sigma_{\bar{x}}$ is provided in the table and on the graph as error bars. Figure 65 through Figure 70 offer closer perspectives of

UTS values at each test temperature, detailing the relationship among material tempering time. Values in SI units are provided in Table 49 and Figure 57.

Table 50. Mean Ultimate Tensile Strength (US Customary Units)

Temperature (°F)	Mean Ultimate Tensile Strength (ksi)					
	Tempered 1.25 h	$\sigma_{\bar{x}}$	Tempered 1.75 h	$\sigma_{\bar{x}}$	Tempered 2.25 h	$\sigma_{\bar{x}}$
Room Temp.	132.4	0.7	130.5	0.3	128.8	0.2
212	123.7	0.1	122.8	0.1	121.1	0.1
572	117.0	0.1	115.8	0.3	113.8	0.1
752	110.4	0.5	109.4	0.3	107.3	0.2
932	88.4	0.6	86.5	0.1	85.5	0.2
1112	59.9	0.5	59.0	0.7	57.2	0.2

$\sigma_{\bar{x}}$ is the standard error of the mean.

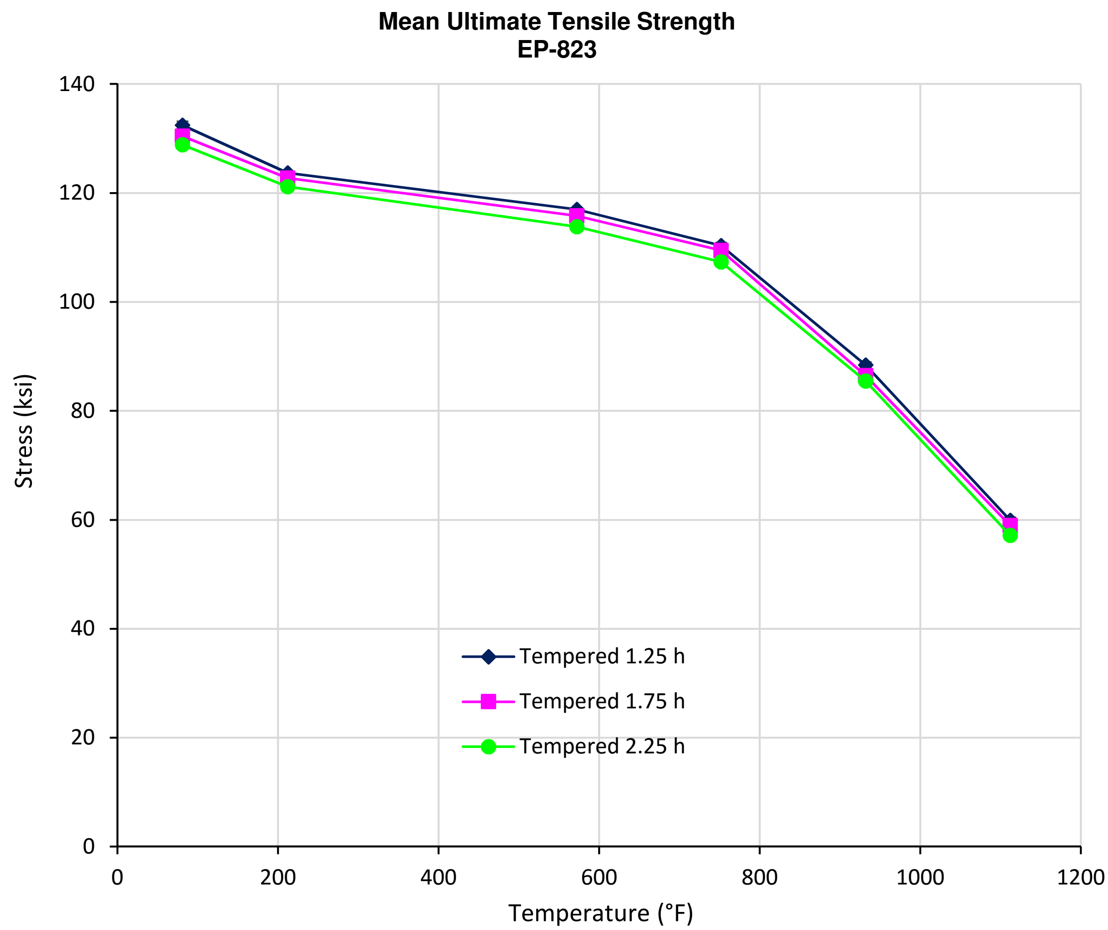


Figure 64. Mean Ultimate Tensile Strength (US Customary Units)

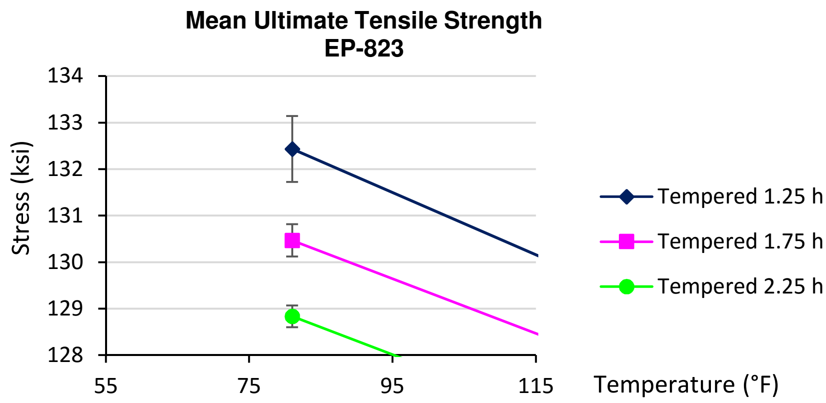


Figure 65. Mean Ultimate Tensile Strength, Room Temp. (US Customary Units)

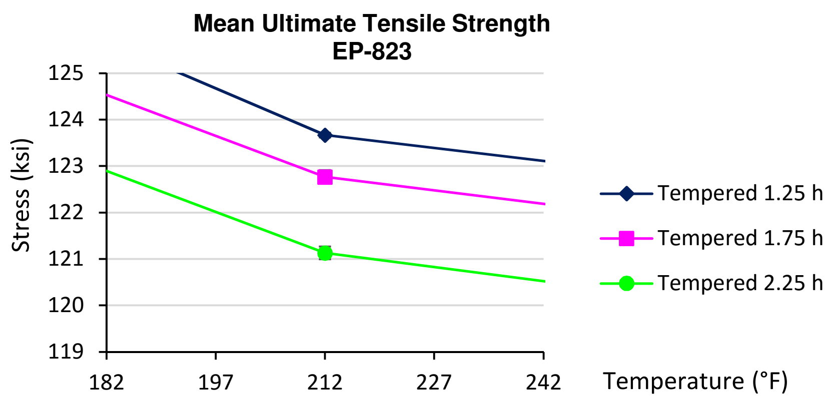


Figure 66. Mean Ultimate Tensile Strength, 212°F (US Customary Units)

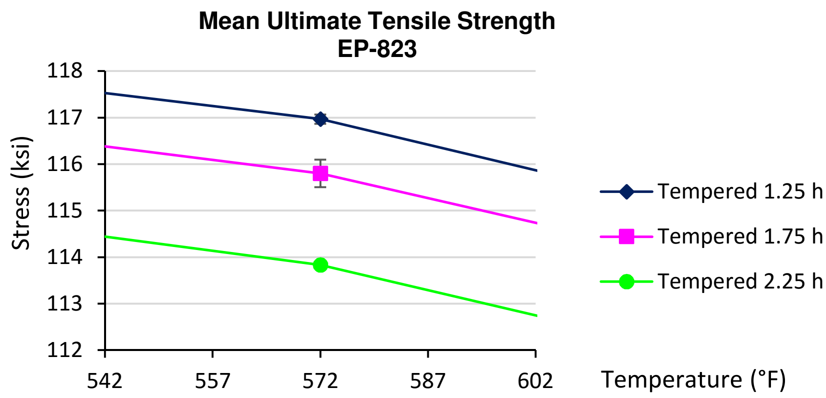


Figure 67. Mean Ultimate Tensile Strength, 572°F (US Customary Units)

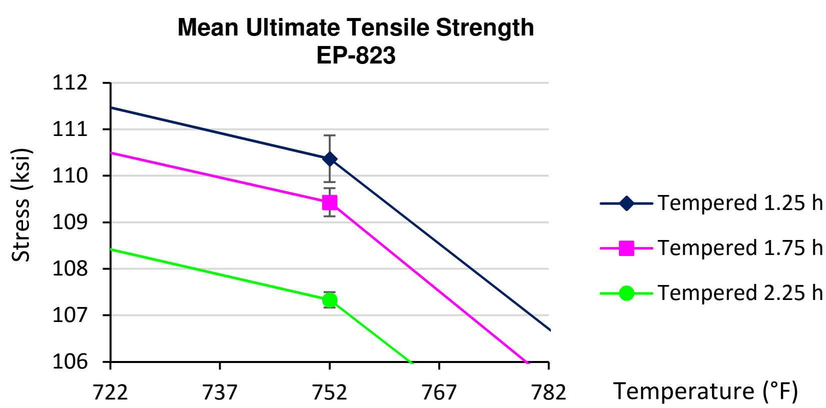


Figure 68. Mean Ultimate Tensile Strength, 752°F (US Customary Units)

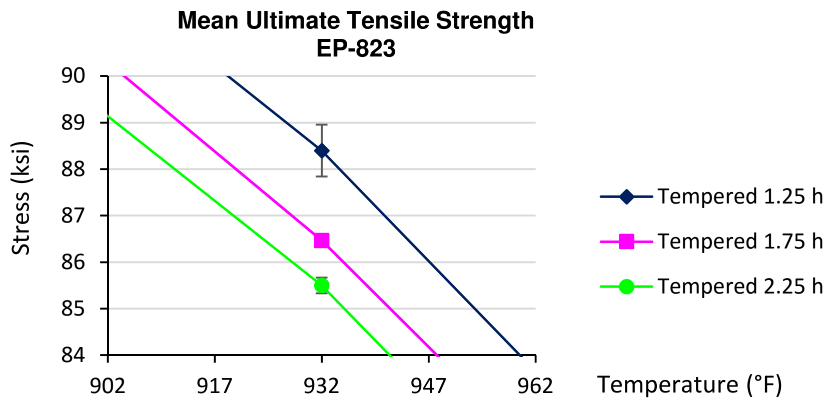


Figure 69. Mean Ultimate Tensile Strength, 932°F (US Customary Units)

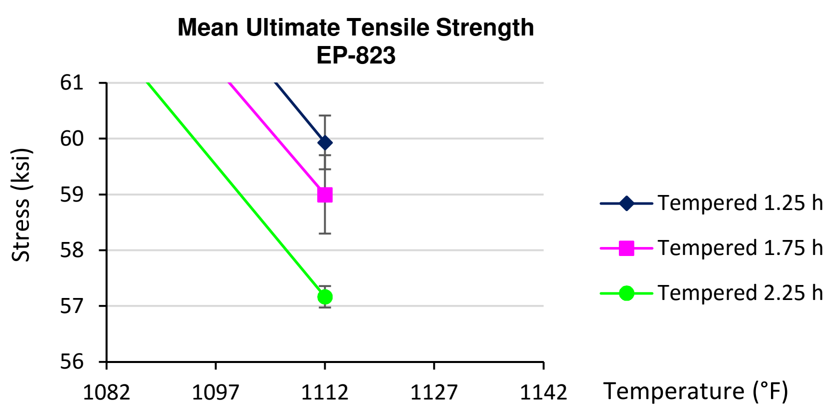


Figure 70. Mean Ultimate Tensile Strength, 1112°F (US Customary Units)

4.6. Mean Yield Strength (YS)

Table 51 and Figure 71 provide the mean yield strength (YS) with respect to test temperature and tempering time in both tabulated and graphical format. The standard error of the mean $\sigma_{\bar{x}}$ is also provided in the table and on the graph as error bars for each experimental condition. For a more detailed inspection of the YS graph, Figure 72 through Figure 77 offer closer perspectives of

YS values at each test temperature, detailing the relationship among material tempering time. Values in US customary units are provided in Table 52 and Figure 78.

Table 51. Mean Yield Strength (SI Units)

Temperature (°C)	Mean Yield Strength (MPa)					
	Tempered 1.25 h	$\sigma_{\bar{x}}$	Tempered 1.75 h	$\sigma_{\bar{x}}$	Tempered 2.25 h	$\sigma_{\bar{x}}$
Room Temp.	771.3	5.3	752.4	1.6	744.6	1.4
100	717.1	1.6	703.7	2.5	699.1	2.3
300	662.6	0.6	647.2	0.9	642.4	4.2
400	615.5	2.3	614.3	3.0	593.9	5.5
500	576.6	3.3	562.2	0.4	556.9	1.8
600	411.4	3.8	403.1	5.2	391.4	1.3

$\sigma_{\bar{x}}$ is the standard error of the mean.

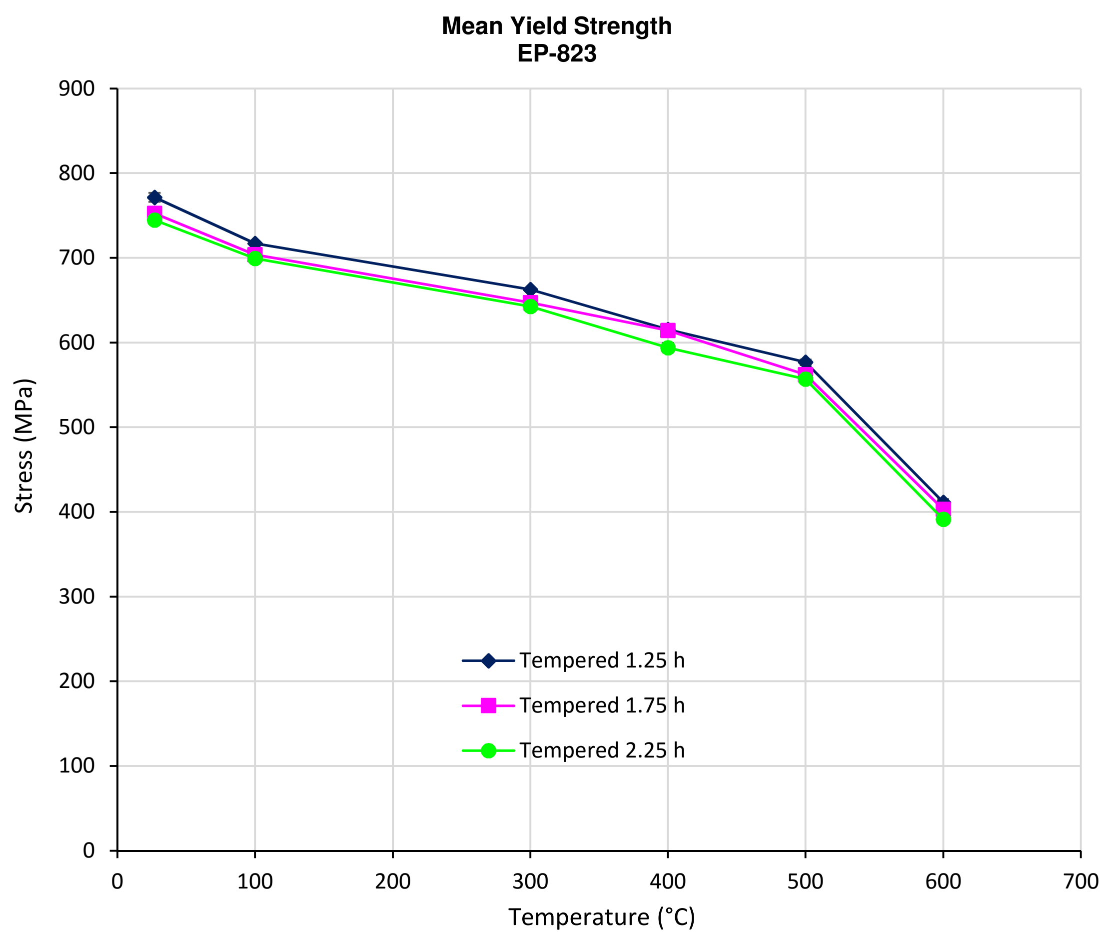


Figure 71. Mean Yield Strength (SI Units)

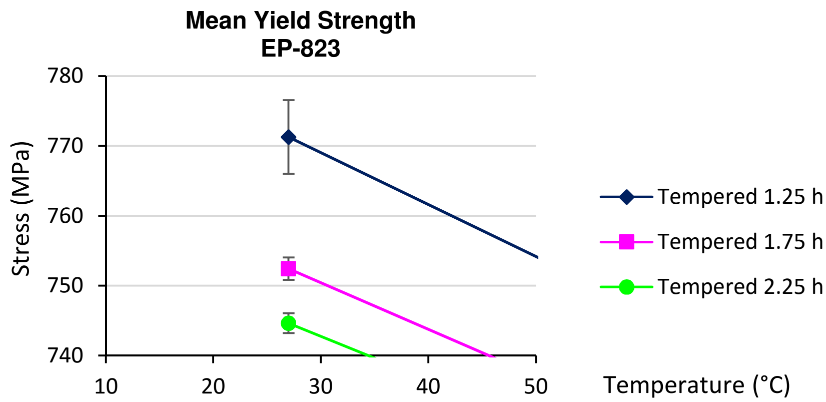


Figure 72. Mean Yield Strength, Room Temp. (SI Units)

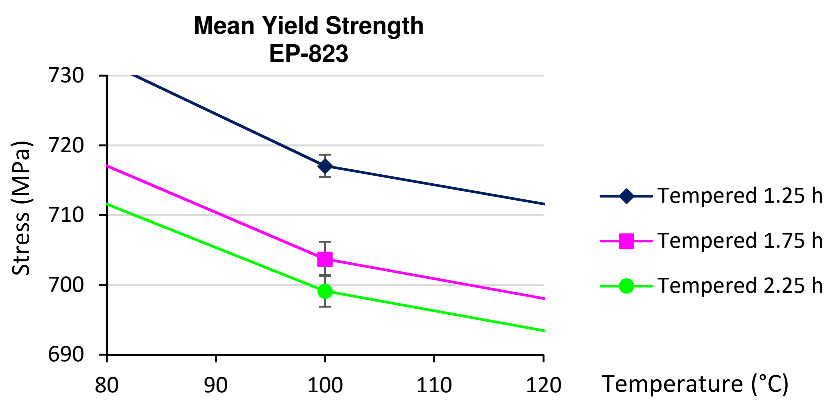


Figure 73. Mean Yield Strength, 100°C (SI Units)

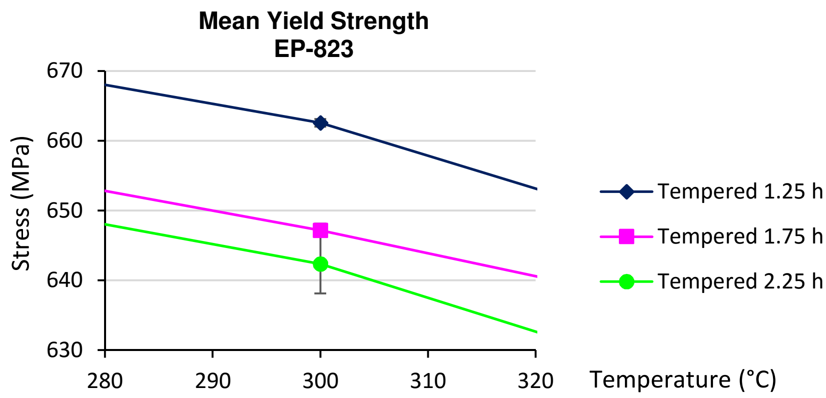


Figure 74. Mean Yield Strength, 300°C (SI Units)

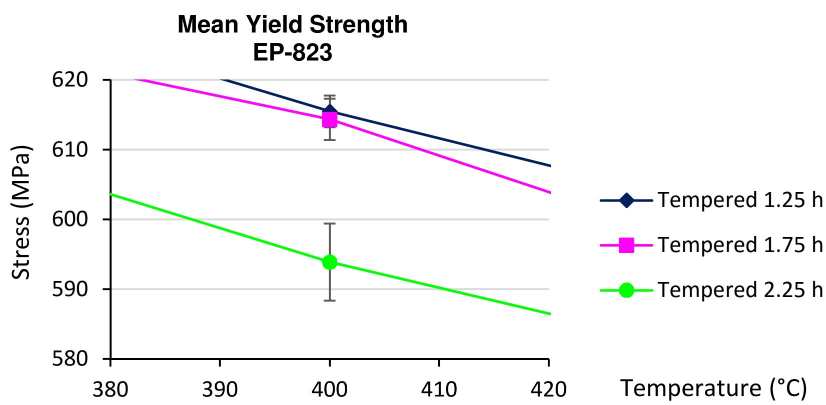


Figure 75. Mean Yield Strength, 400°C (SI Units)

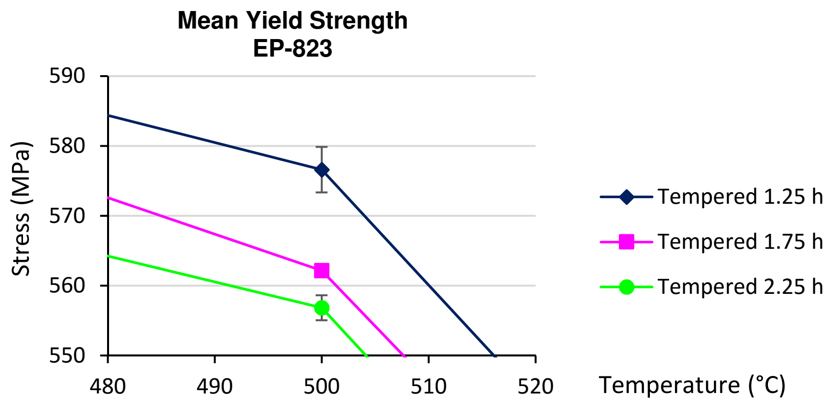


Figure 76. Mean Yield Strength, 500°C (SI Units)

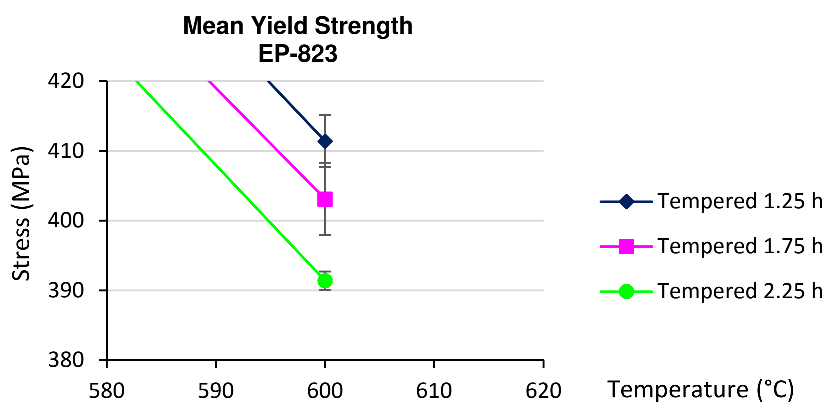


Figure 77. Mean Yield Strength, 600°C (SI Units)

Table 52 and Figure 78 present in US customary units the mean yield strength (YS) as a function of test temperature and tempering time in both tabulated and graphical format. As previously performed, for each experimental condition the standard error of the mean $\sigma_{\bar{x}}$ is provided in the table and on the graph as error bars. Figure 79 through Figure 84 offer closer

perspectives of UTS values at each test temperature, detailing the relationship among material tempering time. Values in SI units are provided in Table 51 and Figure 57.

Table 52. Mean Yield Strength (US Customary Units)

Temperature (°F)	Mean Yield Strength (ksi)					
	Tempered 1.25 h	$\sigma_{\bar{x}}$	Tempered 1.75 h	$\sigma_{\bar{x}}$	Tempered 2.25 h	$\sigma_{\bar{x}}$
Room Temp.	111.9	0.8	109.1	0.2	108.0	0.2
212	104.0	0.2	102.1	0.4	101.4	0.3
572	96.1	0.1	93.9	0.1	93.2	0.6
752	89.3	0.3	89.1	0.4	86.1	0.8
932	83.6	0.5	81.5	0.1	80.8	0.3
1112	59.7	0.5	58.5	0.8	56.8	0.2

$\sigma_{\bar{x}}$ is the standard error of the mean.

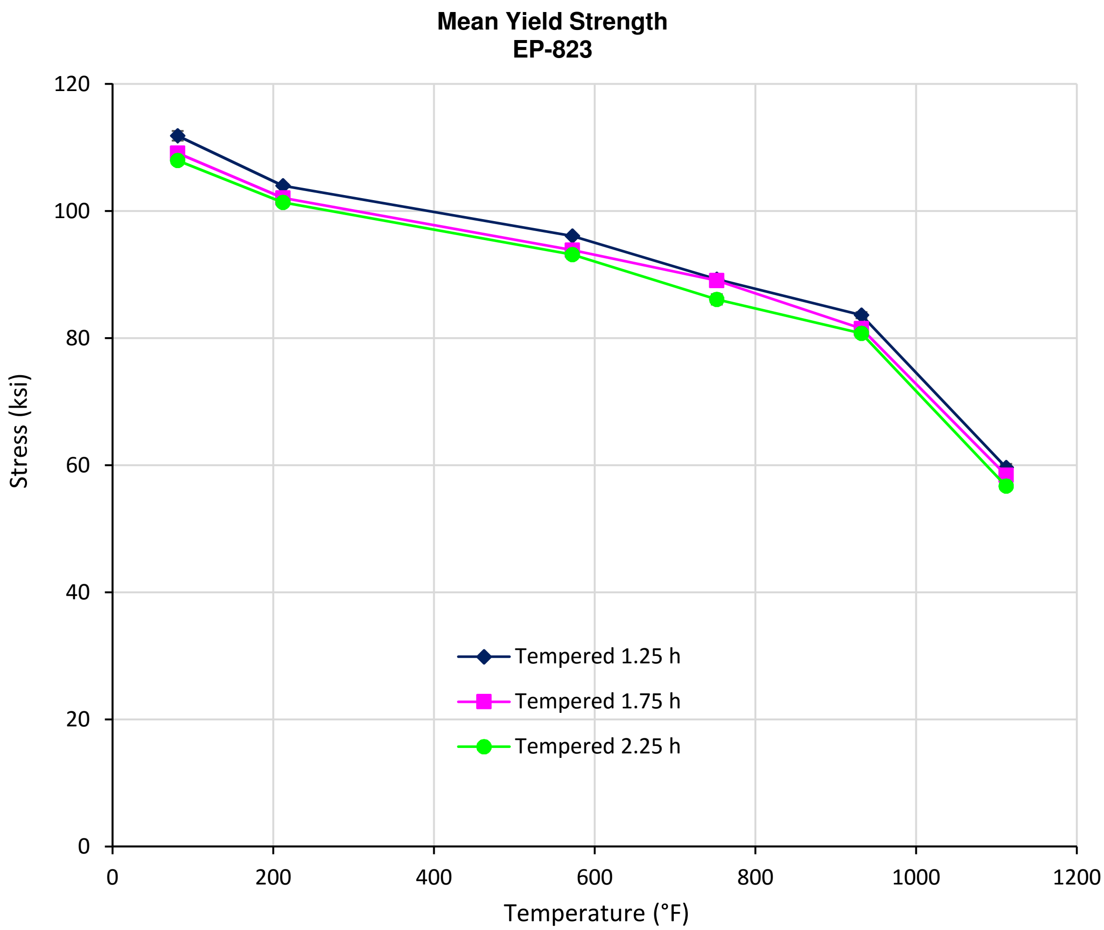


Figure 78. Mean Yield Strength (US Customary Units)

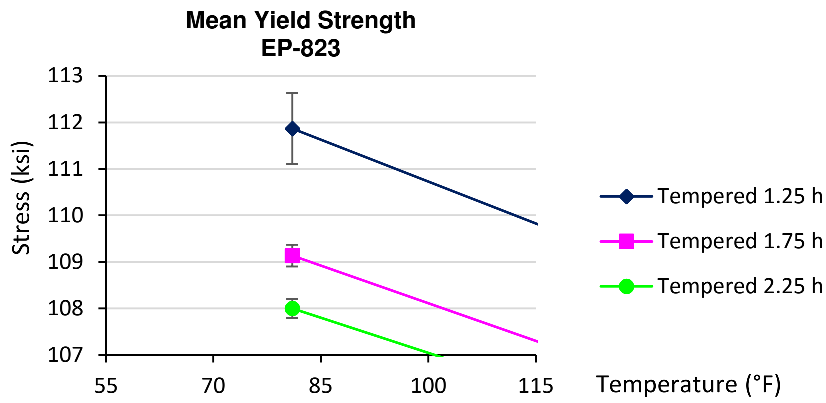


Figure 79. Mean Yield Strength, Room Temp. (US Customary Units)

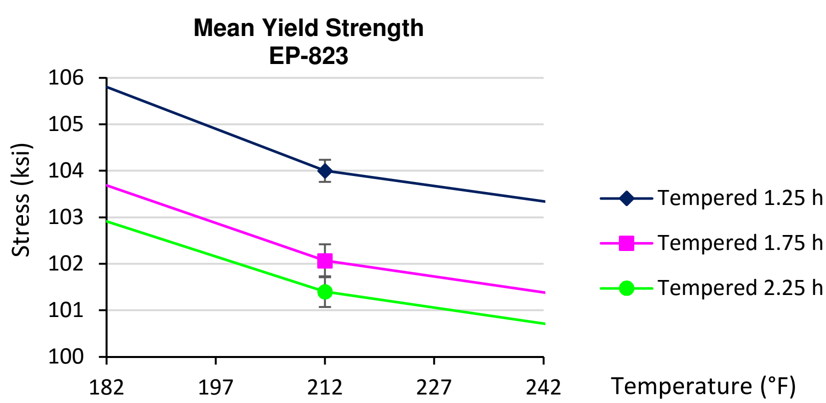


Figure 80. Mean Yield Strength, 212°F (US Customary Units)

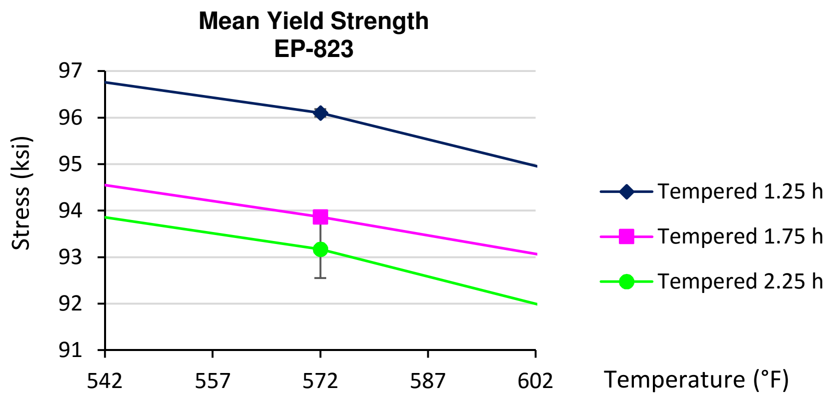


Figure 81. Mean Yield Strength, 572°F (US Customary Units)

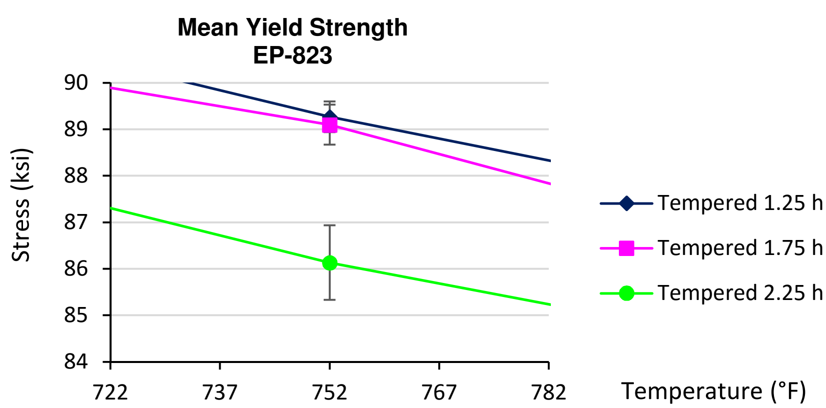


Figure 82. Mean Yield Strength, 752°F (US Customary Units)

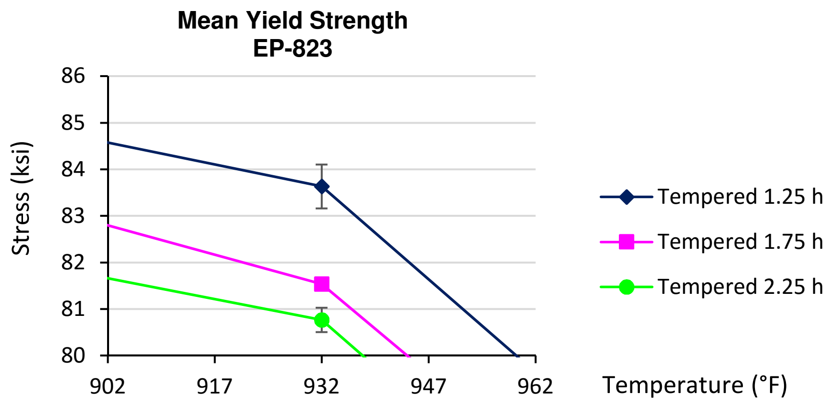


Figure 83. Mean Yield Strength, 932°F (US Customary Units)

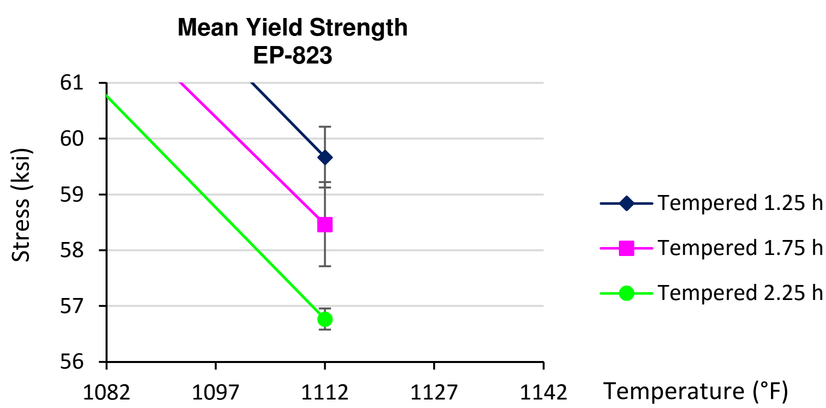


Figure 84. Mean Yield Strength, 1112°F (US Customary Units)

4.7. Mean Elongation

Average elongation values for each experimental condition are provided in Table 53 and Figure 85, according to test temperature and tempering time. Standard error of the means are provided in the table and in the graph shown as error bars. To illustrate the relationship of the mean

elongation values and the sensitivity to material tempering time, Figure 86 through Figure 91 show a detailed view for each test temperature.

Table 53. Mean Elongation

Temperature (°C / °F)	Mean Elongation (%)					
	Tempered 1.25 h	$\sigma_{\bar{x}}$	Tempered 1.75 h	$\sigma_{\bar{x}}$	Tempered 2.25 h	$\sigma_{\bar{x}}$
Room Temp.	23.80	0.24	23.61	0.12	22.06	0.90
100 / 212	22.54	0.07	22.49	0.07	19.78	0.15
300 / 572	19.98	0.11	20.03	0.16	18.82	0.51
400 / 752	21.84	0.23	21.39	0.04	20.27	0.42
500 / 932	28.02	0.51	27.17	0.20	26.84	0.33
600 / 1112	45.41	1.51	40.59	1.87	35.85	0.22

$\sigma_{\bar{x}}$ is the standard error of the mean.

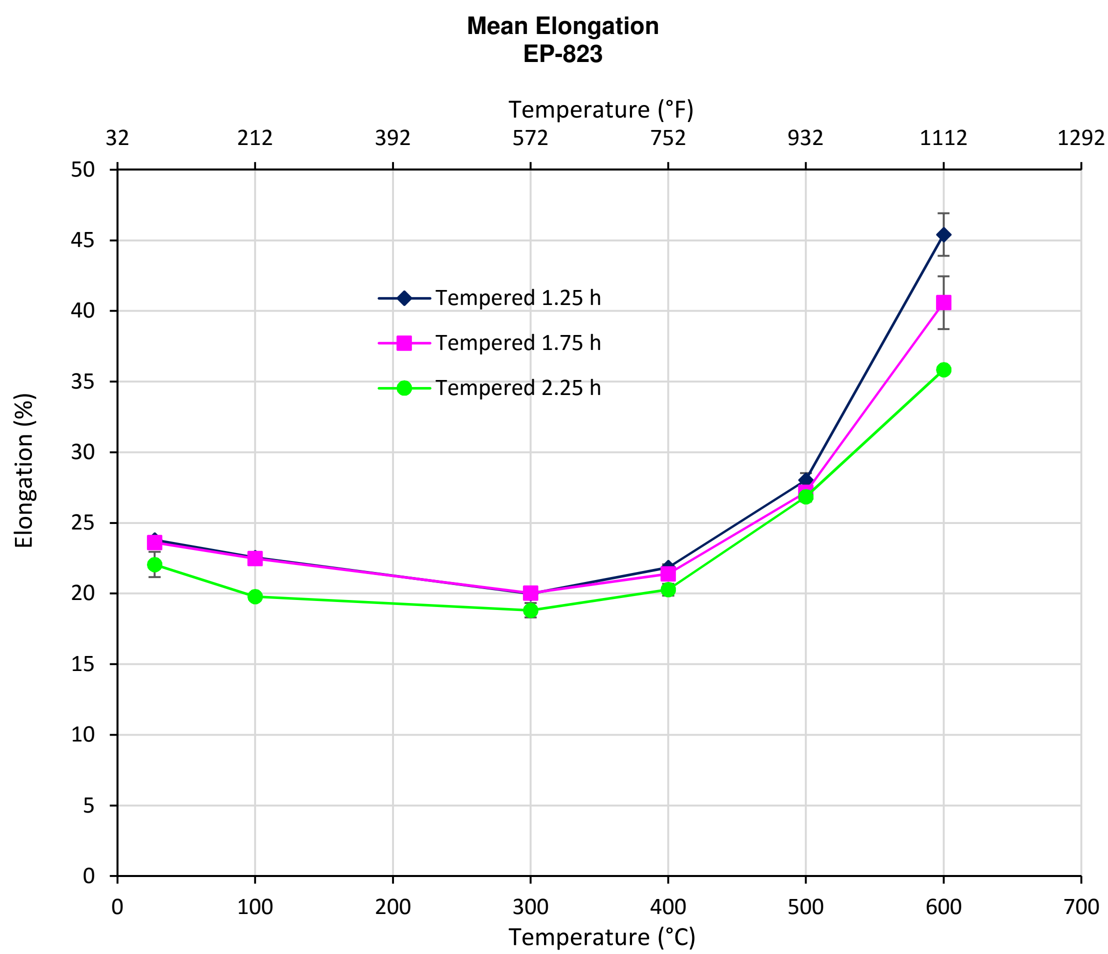


Figure 85. Mean Elongation of Alloy EP-823

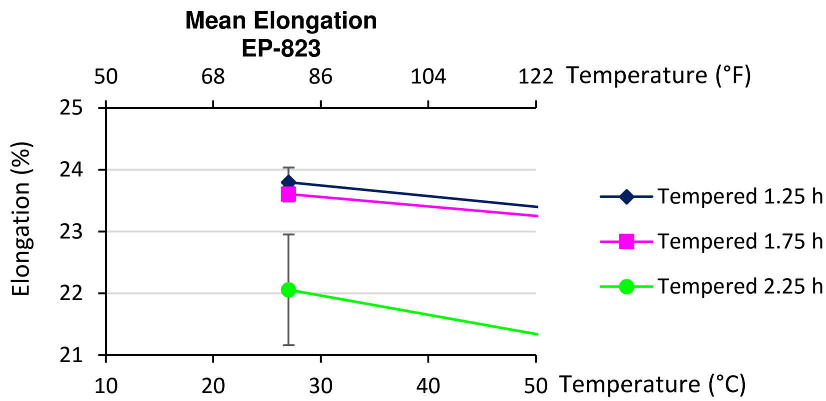


Figure 86. Mean Elongation, Room Temperature

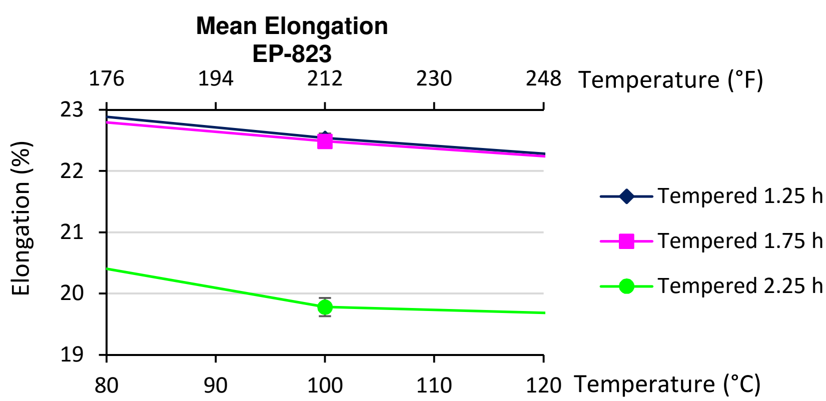


Figure 87. Mean Elongation, 100°C (212°F)

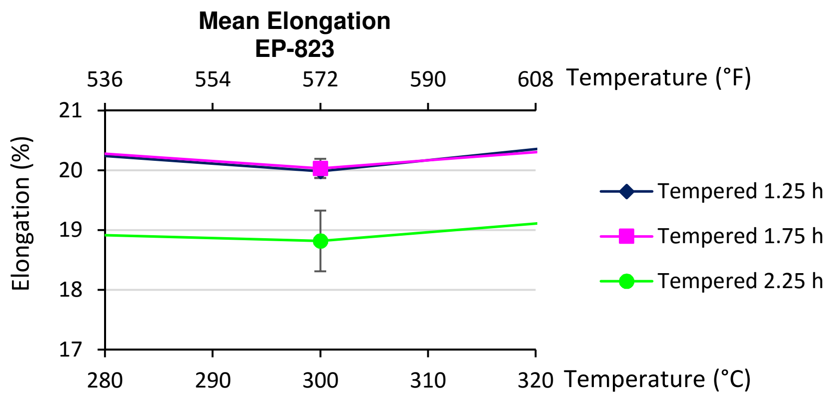


Figure 88. Mean Elongation, 300°C (572°F)

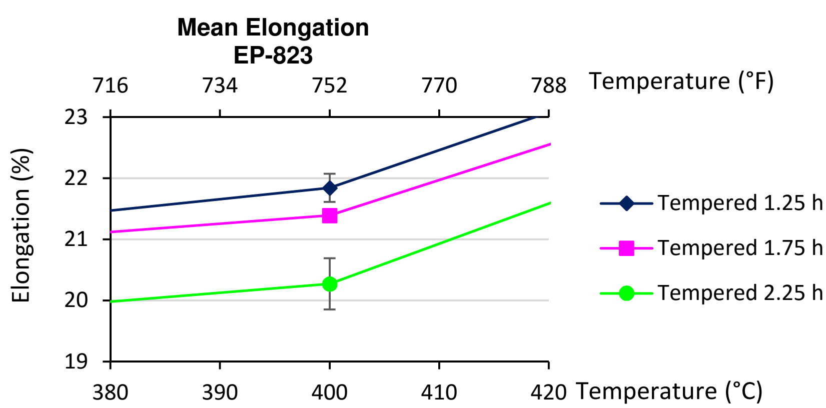


Figure 89. Mean Elongation, 400°C (752°F)

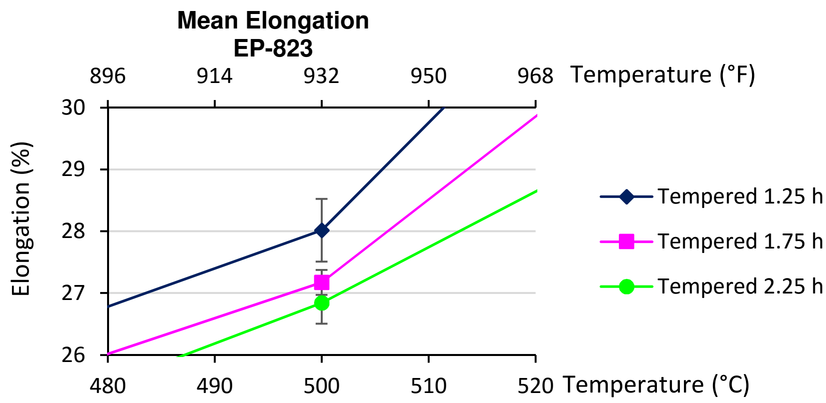


Figure 90. Mean Elongation, 500°C (932°F)

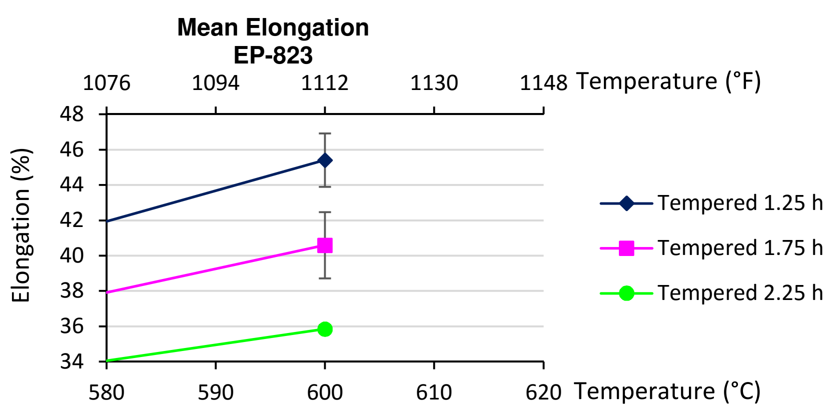


Figure 91. Mean Elongation, 600°C (1112°F)

4.8. Mean Reduction of Area

Table 54 and Figure 92 provide the mean reduction of area values at each temperature and heat treatment tempering time. Each mean value has the associated standard error of the mean tabulated and illustrated as error bars. More detailed views of Figure 92 are depicted in Figure 93 and Figure 98.

Table 54. Mean Reduction of Area

Temperature (°C / °F)	Mean Reduction of Area (%)					
	Tempered 1.25 h	$\sigma_{\bar{x}}$	Tempered 1.75 h	$\sigma_{\bar{x}}$	Tempered 2.25 h	$\sigma_{\bar{x}}$
Room Temp.	63.67	0.58	62.38	0.26	61.39	0.03
100 / 212	63.64	0.09	63.73	0.21	63.24	0.45
300 / 572	62.20	0.40	62.42	0.26	63.21	0.18
400 / 752	63.33	0.17	63.84	0.34	63.71	0.19
500 / 932	75.49	0.40	75.56	0.04	75.66	0.10
600 / 1112	87.84	0.18	86.07	0.17	85.74	0.25

$\sigma_{\bar{x}}$ is the standard error of the mean.

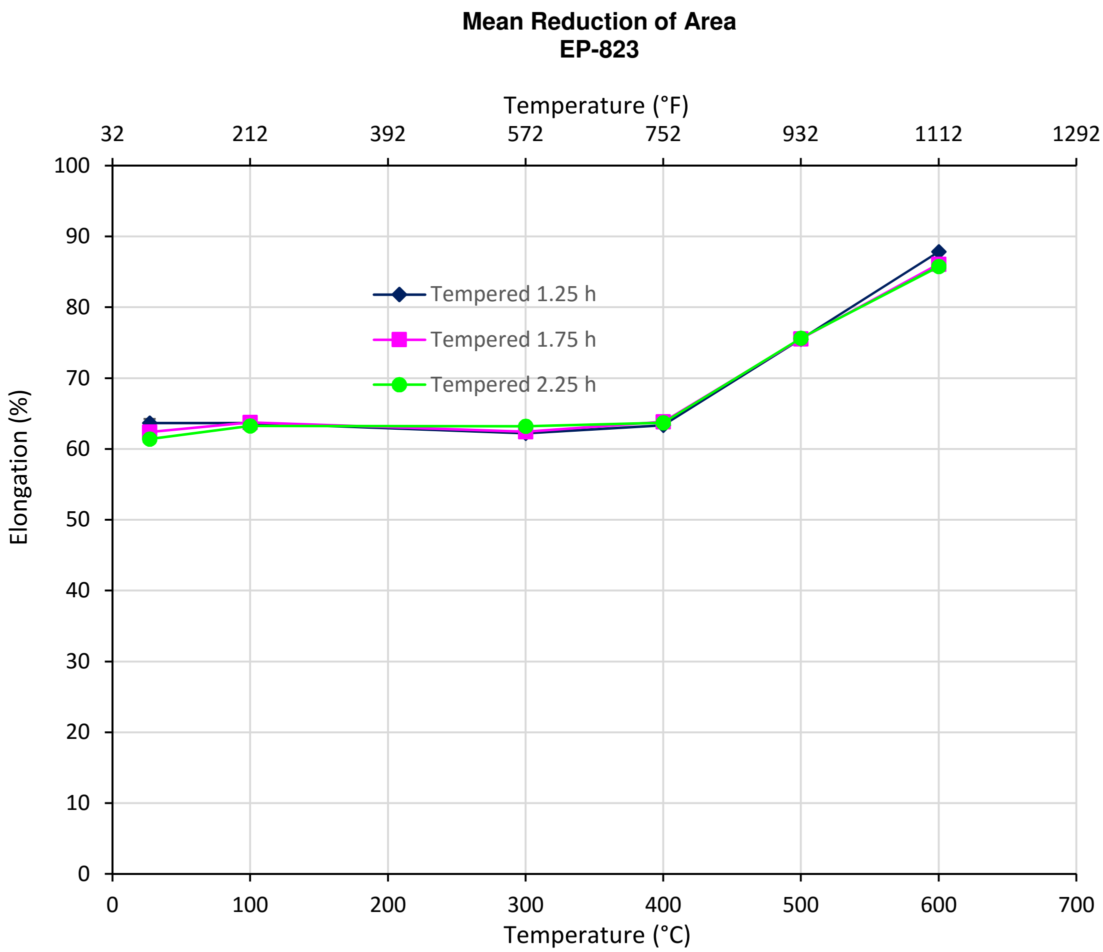


Figure 92. Mean Reduction of Area of Alloy EP-823

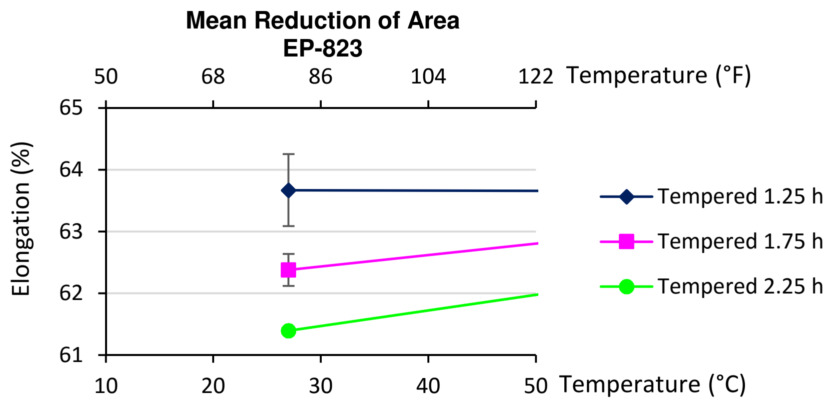


Figure 93. Mean Reduction of Area, Room Temperature

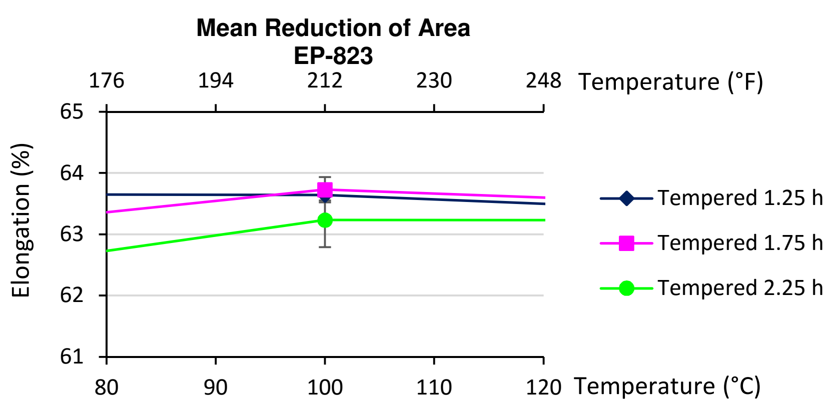


Figure 94. Mean Reduction of Area, 100°C (212°F)

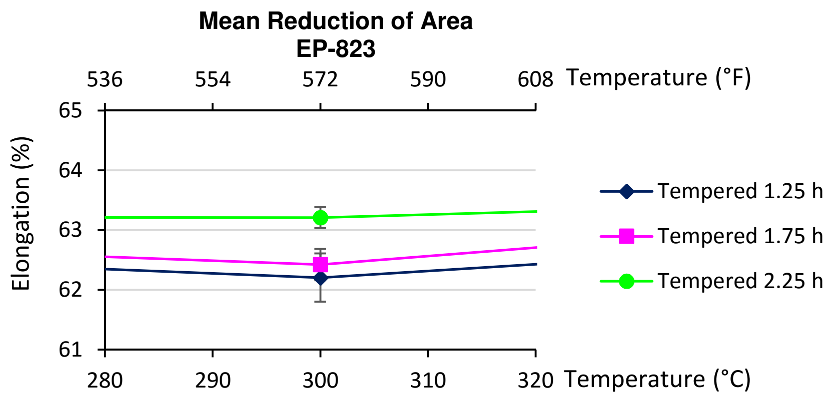


Figure 95. Mean Reduction of Area, 300°C (572°F)

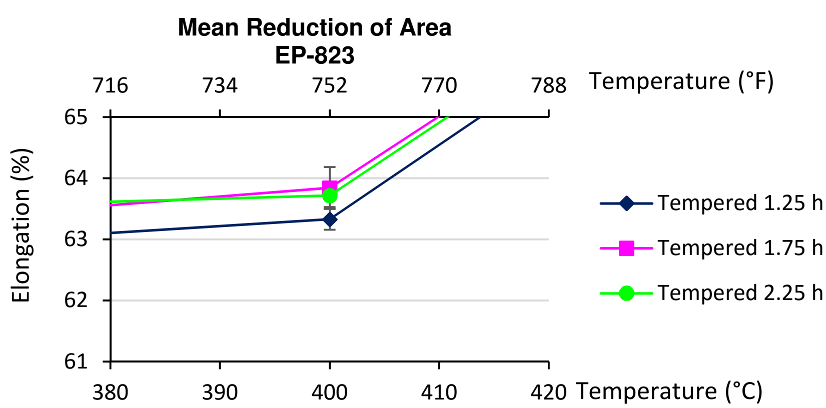


Figure 96. Mean Reduction of Area, 400°C (752°F)

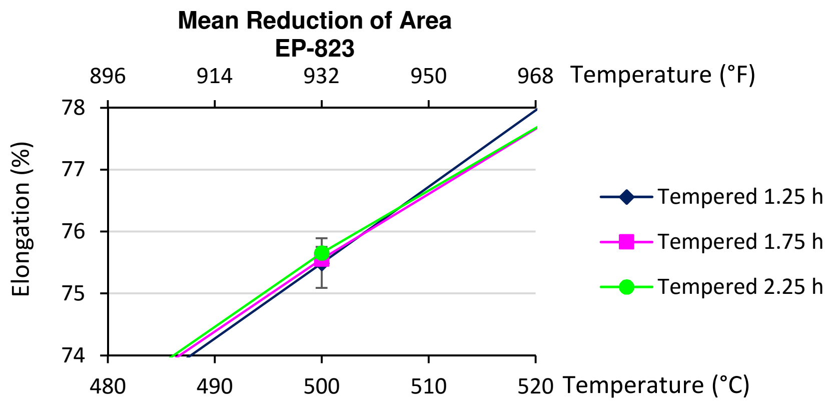


Figure 97. Mean Reduction of Area, 500°C (932°F)

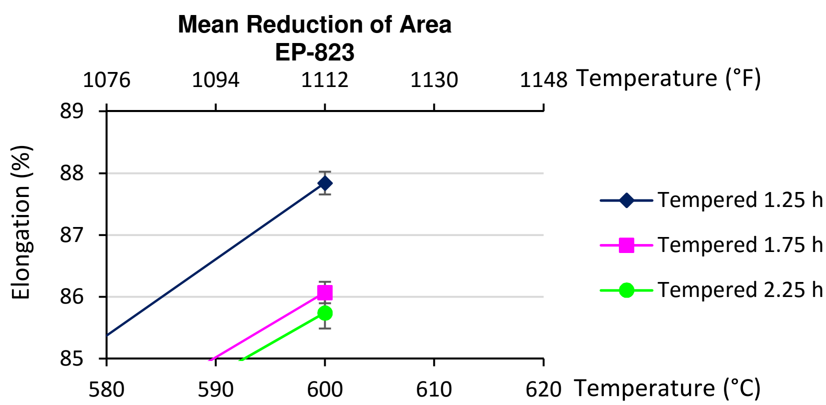


Figure 98. Mean Reduction of Area, 600°C (1112°F)

4.9. Temperature Effects on Mechanical Performance

For a visual understanding of temperature sensitivity on mechanical performance stress-strain curves from each test temperature are plotted on a composite graph. Of the three stress-strain curves at each temperature the curve data with the median ultimate tensile strength is shown. This

is performed for each material tempering time. See Figure 99 through Figure 101 for the temperature comparison plots.

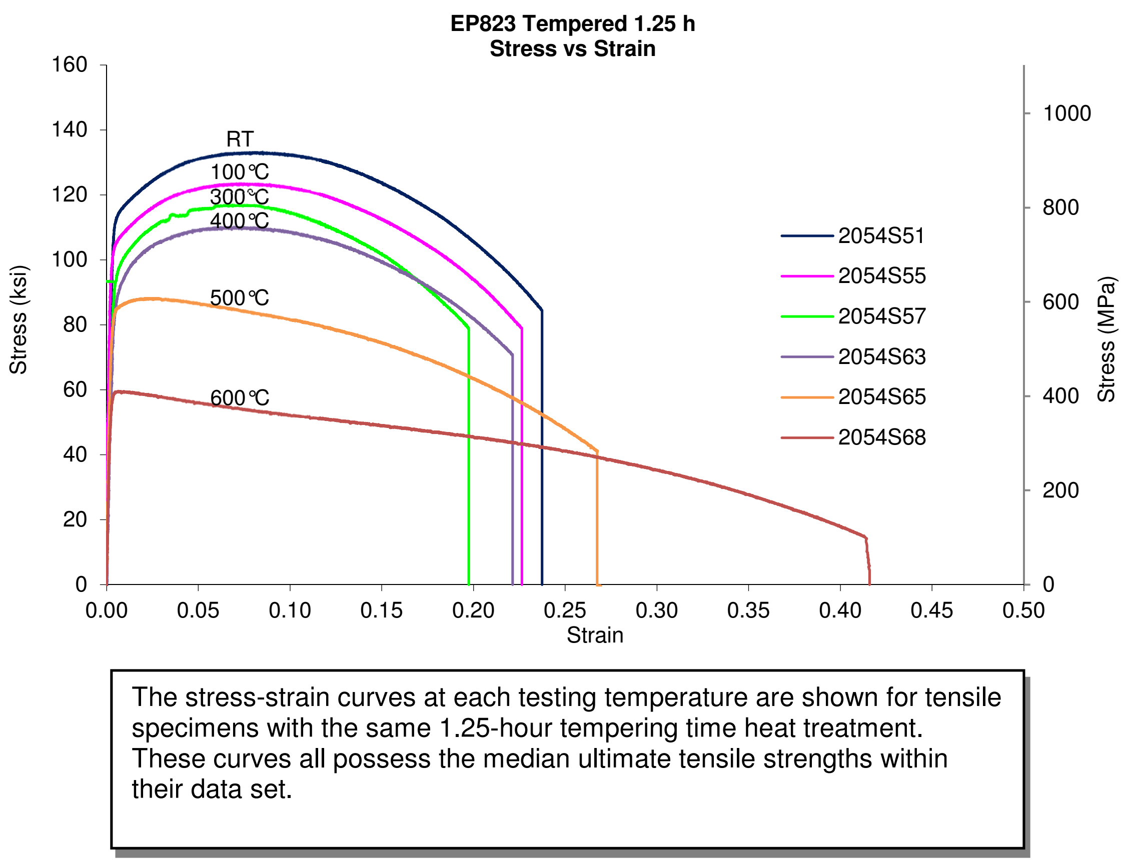
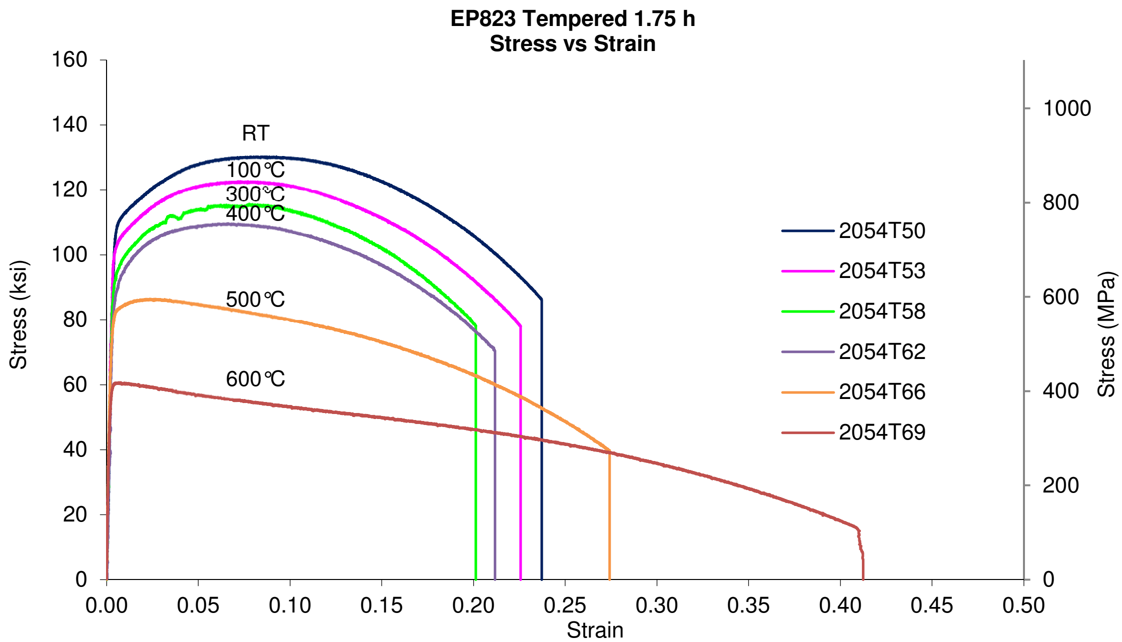


Figure 99. Temperature Comparison Plots for Alloy EP-823, Tempered 1.25 h

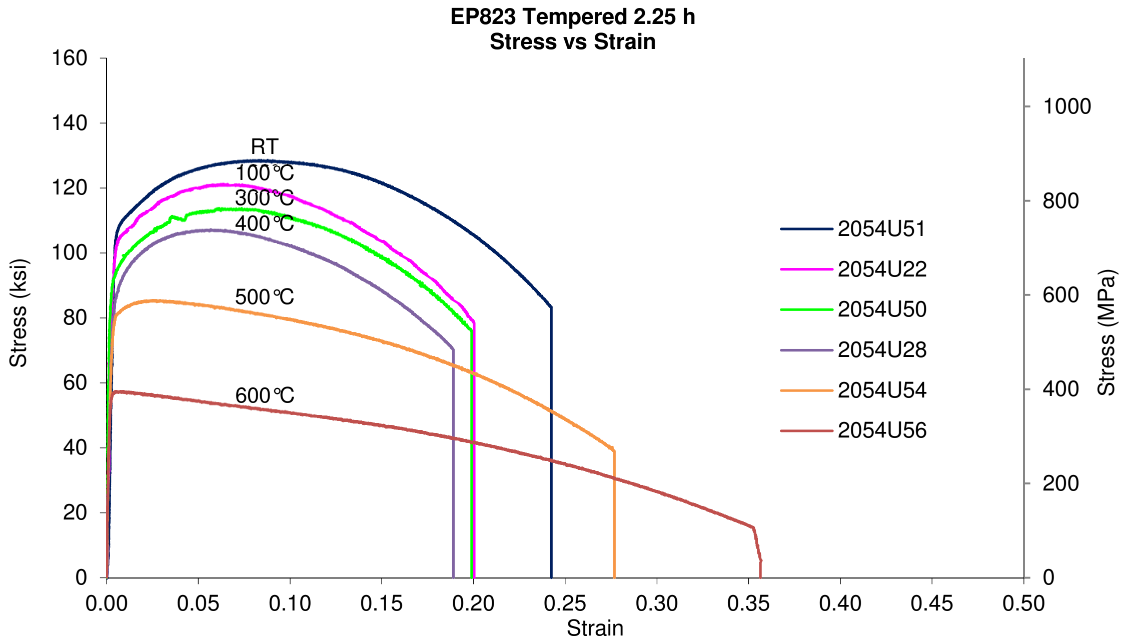
For Figure 100 the curves shown all possess the median ultimate tensile strengths except for the 600°C (1112°F) test. Tensile specimen 2054T68 had the median ultimate tensile strength value, but its tensile test ended prematurely. Consequently, it has a stress-strain curve that was truncated

before specimen failure. This was explained in further detail in Section 4.2.2. In its place the stress-strain curve for tensile specimen 2054T69 is shown.



The stress-strain curves at each testing temperature are shown for tensile specimens with the same 1.75-hour tempering time heat treatment. These curves all possess the median ultimate tensile strengths among their data set with exception to the 600℃ (1112℉) test. Tensile specimen 2054T68 had the median ultimate tensile strength value, but its tensile test ended prematurely. Consequently, its stress-strain curve was truncated before specimen failure. 2054T69 is shown in its place.

Figure 100. Temperature Comparison Plots for Alloy EP-823, Tempered 1.75 h

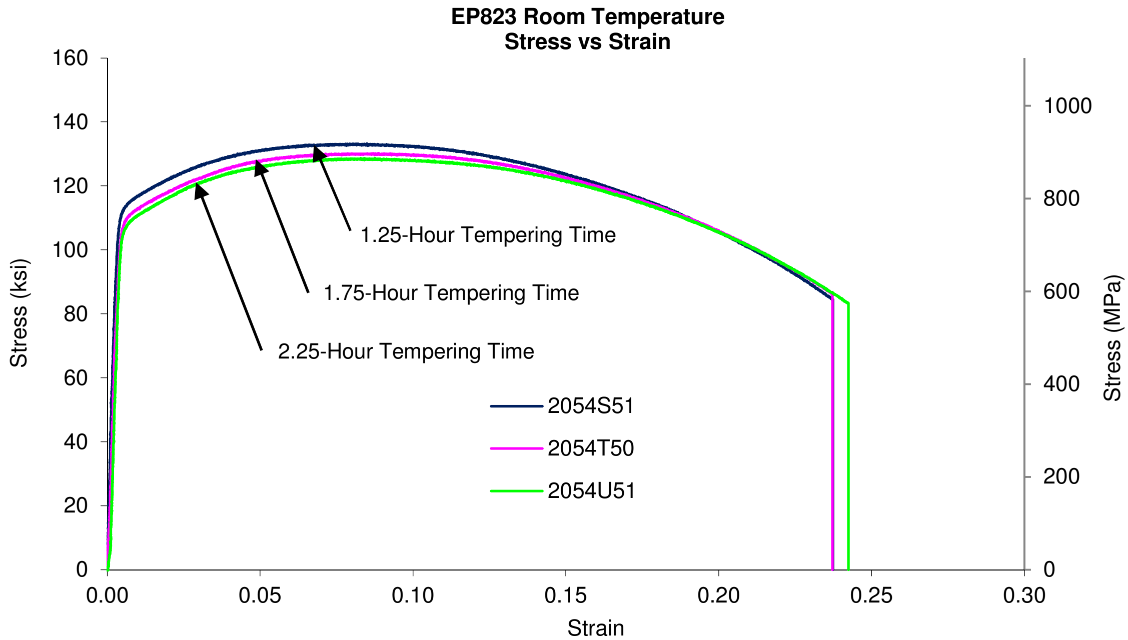


The stress-strain curves at each testing temperature are shown for tensile specimens with the same 2.25-hour tempering time heat treatment. These curves all possess the median ultimate tensile strengths within their data set.

Figure 101. Temperature Comparison Plots for Alloy EP-823, Tempered 2.25 h

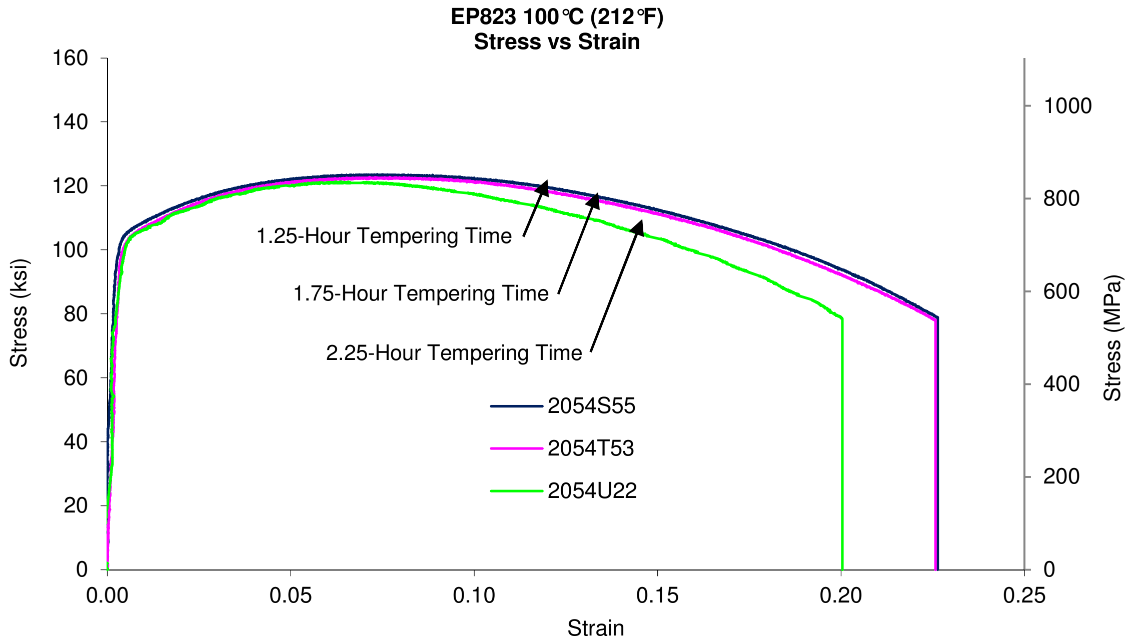
4.10. Tempering Time Effects on Mechanical Performance

This section illustrates the effect of heat treatment tempering time on the stress-strain curves for each testing temperature. For a given temperature three curves represent the three material tempering times. The stress-strain plots chosen for the graphs possessed the median ultimate tensile strengths within a data set. See Figure 102 through Figure 107.



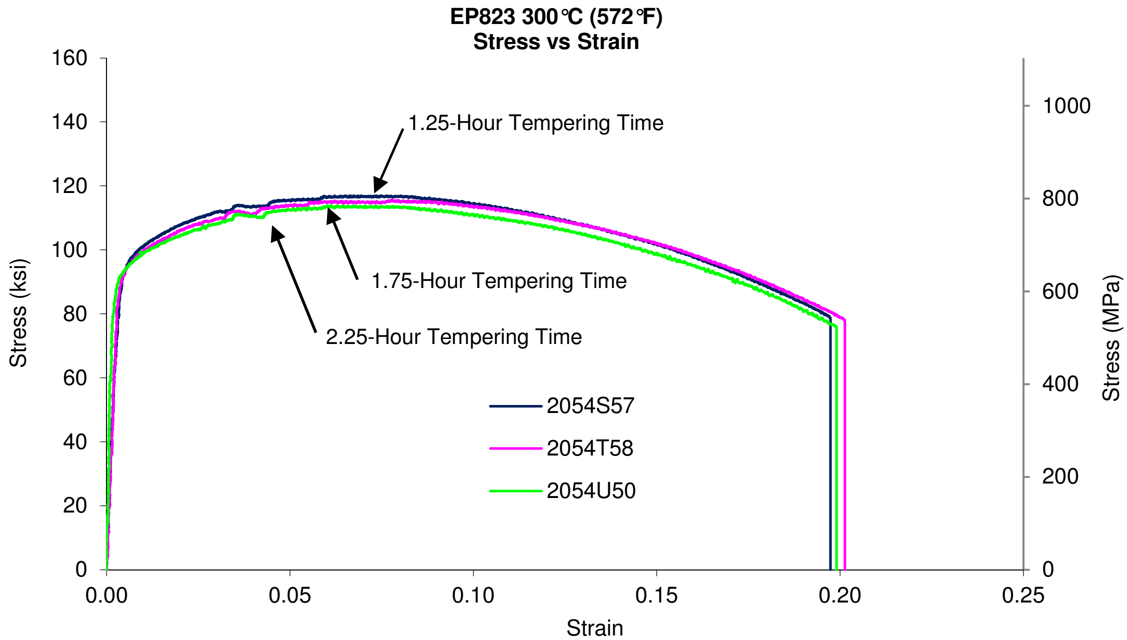
The stress-strain curves shown represent the three tempering times for heat treatment for room temperature tensile tests. These curves all possess the median ultimate tensile strengths within their data set.

Figure 102. Tempering Time Comparison Plots for Alloy EP-823, Room Temp.



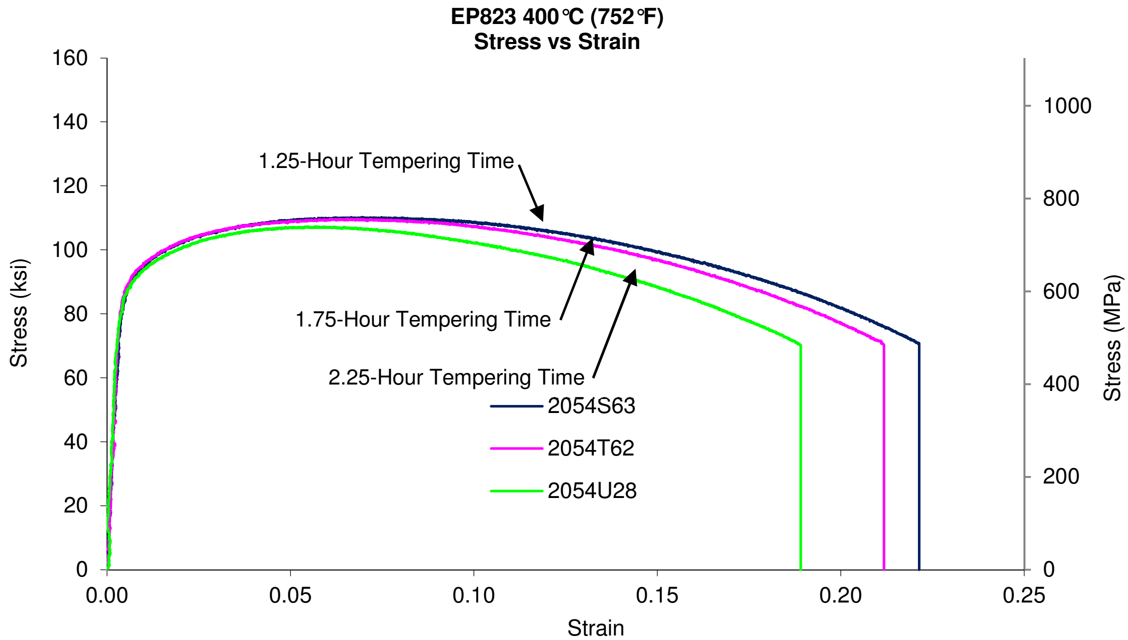
The stress-strain curves shown represent the three tempering times for heat treatment for 100°C (212°F) tensile tests. These curves all possess the median ultimate tensile strengths within their data set.

Figure 103. Tempering Time Comparison Plots for Alloy EP-823, 100°C (212°F)



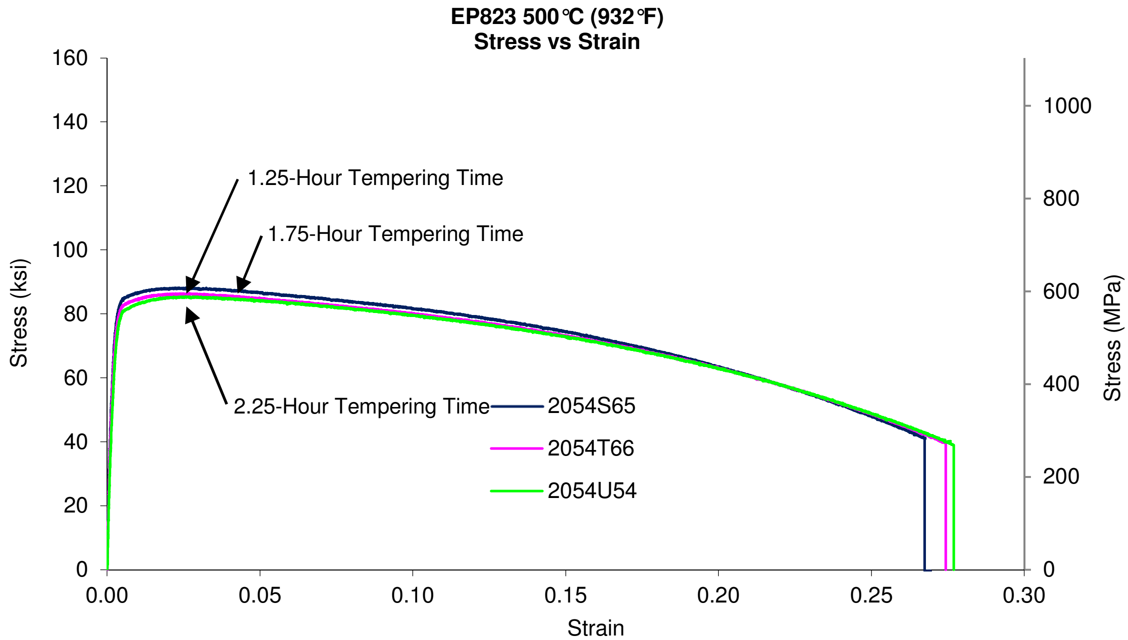
The stress-strain curves shown represent the three tempering times for heat treatment for 300°C (572°F) tensile tests. These curves all possess the median ultimate tensile strengths within their data set.

Figure 104. Tempering Time Comparison Plots for Alloy EP-823, 300°C (572°F)



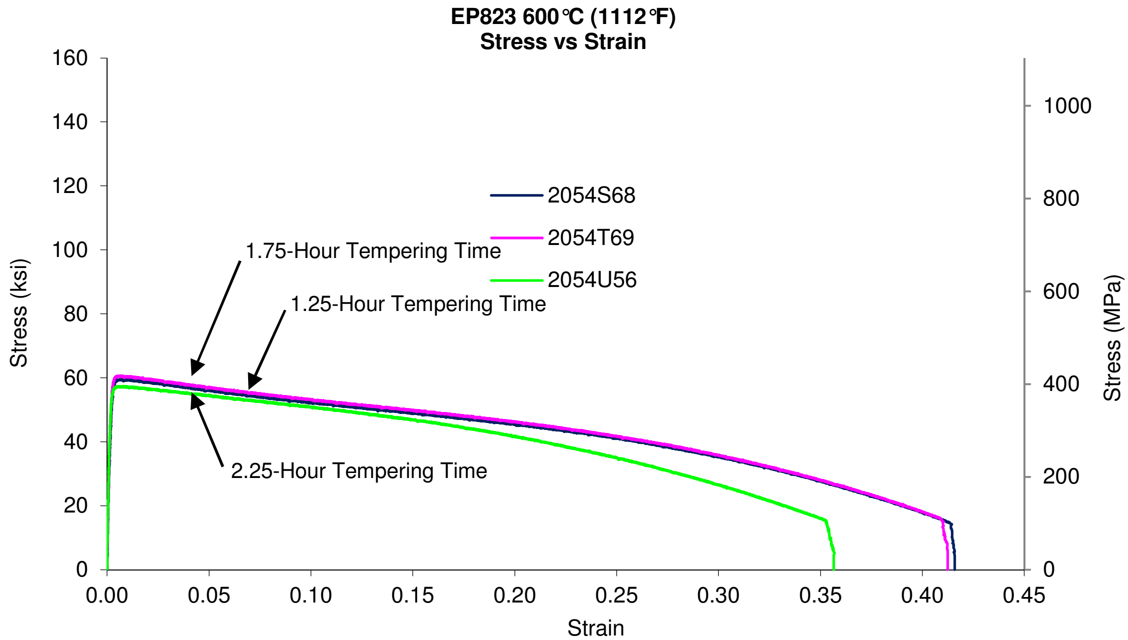
The stress-strain curves shown represent the three tempering times for heat treatment for 400°C (752°F) tensile tests. These curves all possess the median ultimate tensile strengths within their data set.

Figure 105. Tempering Time Comparison Plots for Alloy EP-823, 400°C (752°F)



The stress-strain curves shown represent the three tempering times for heat treatment for 500°C (932°F) tensile tests. These curves all possess the median ultimate tensile strengths within their data set.

Figure 106. Tempering Time Comparison Plots for Alloy EP-823, 500°C (932°F)



The stress-strain curves shown represent the three tempering times for heat treatment for 600°C (1112°F) tensile tests. These curves all possess the median ultimate tensile strengths within their data set.

Figure 107. Tempering Time Comparison Plots for Alloy EP-823, 600°C (1112°F)

CHAPTER 5:

DISCUSSION OF RESULTS

This section discusses the effect on mechanical properties of Alloy EP-823, driven by the two independent variables, specifically test temperature and tempering time. Discussion first addresses the statistical significance of the effects of tempering time on mechanical performance. It then turns to address the sensitivity of the material to both test temperature and tempering time.

5.1. Statistical Significance of Data

A t-test is performed to test for statistical significance of changes in mechanical performance results caused by increasing tempering time. A t-test examines the null hypothesis H_0 that two population means μ_1 and μ_2 are equal and that an observed difference is due to random sampling, not reflecting an actual difference between the two population means (Equation (5.1)). This suggests that the two sample sets come from the same population.

$$H_0 : \mu_1 = \mu_2 \tag{5.1}$$

$$H_a : \mu_1 \neq \mu_2 \tag{5.2}$$

Where:
H_0 = Null Hypothesis
H_a = Alternative Hypothesis
μ_1 = Mean, Sample Set 1
μ_2 = Mean, Sample Set 2

The t-test calculates the probability p that the null hypothesis H_0 is true. If the probability p, also known as the *p-value*, is below a certain threshold then the null hypothesis H_0 is rejected and the alternative hypothesis H_a is deemed to be true. This threshold is called the level of significance α and is generally accepted as 0.05. A level of significance α equal to 0.05 was used for this report.

The alternative hypothesis H_a states that the two population means μ_1 and μ_2 are not equal to each other (Equation (5.2)), suggesting that the two sample sets come from two different populations. If this is the case then the difference between the two population means, influenced by the independent variables, is statistically significant. Rejection of the null hypothesis H_0 further suggests that the risk of observing a sample mean difference due to random sampling is low.

In short for p greater than α there is no statistical significance and the observed changes in the results can be attributed to random sampling (null hypothesis H_0). See Equation (5.3). Conversely, for p less than or equal to α the results are statistically significant (alternative hypothesis H_a). See Equation (5.4).

$$\text{For } p > \alpha \text{ results are attributed to random sampling.} \tag{5.3}$$

$$\text{For } p \leq \alpha \text{ results are statistically significant.} \tag{5.4}$$

Where:
p = Probability (P-Value)
α = Level of Significance

Before performing the t-test it must be determined if the variances of the two populations are equal or unequal. An f-test is used to help make this determination.

The F-Test examines the null hypothesis H_0 that the two population variances σ_1^2 and σ_1^2 are equal. In other words the F-Test provides the probability p that the observed difference in the variances is based on random sampling and that the two population variances are indeed equal. If the probability p is less than or equal to the significance level α then the null hypothesis H_0 should be rejected and the alternative hypothesis H_a is assumed to be true. See Equations (5.5) and (5.6).

$$\text{If } p > \alpha \text{ then assume } H_0\text{: } {\sigma_1}^2 = {\sigma_2}^2\text{, variances are equal} \quad (5.5)$$

$$\text{If } p \leq \alpha \text{ then assume } H_a\text{: } {\sigma_1}^2 \neq {\sigma_2}^2\text{, variances are unequal} \quad (5.6)$$

Where:
p = Probability (P-Value)
α = Level of Significance
H_0 = Null Hypothesis
H_a = Alternative Hypothesis
σ_1^2 = Variance, Sample Set 1
σ_2^2 = Variance, Sample Set 2
σ_1 = Std. Deviation, Sample Set 1
σ_2 = Std. Deviation, Sample Set

The effects of increased temperature were so pronounced that they negated the requirement for statistical significance determination. Figure 99 through Figure 101 clearly illustrate this. On the other hand the effects of increased tempering time were not as obvious. The tempering time comparison plots in Figure 102 and Figure 107 indicate marginal effects due to an incremental increase in tempering time. Therefore, only tempering time effects on mechanical properties were tested for statistical significance.

This section provides the t-test results for calculating the probability *p* or *p-value* to determine the statistical significance of the effects from increasing tempering time on mechanical properties of Alloy EP-823. The f-test was performed prior to each t-test to determine if the two sample variances in question were equal or unequal. Then the appropriate t-test was performed to accommodate the variance results. The resulting probability *p* or *p-value* was used to deem the effect on results significant or attributed to random sampling.

Evaluating the significance of the effect on results due to increasing tempering time is performed by comparing the results three ways. These comparisons are listed below.

- *Change A* – Increasing Tempering Time from 1.25 h to 1.75 h.
- *Change B* – Increasing Tempering Time from 1.75 h to 2.25 h.
- *Change C* – Increasing Tempering Time from 1.25 h to 2.25 h.

The above comparisons were made for the results of each mechanical property listed below.

- Ultimate Tensile Strength
- Yield Strength
- Elongation
- Reduction of Area

The t-test results and significance findings are provided in Table 55 through

Table 66. Refer to APPENDIX G for more detailed results, statistics, and the statistical significance determinations.

5.1.1. Significance of Tempering Time on Ultimate Tensile Strength

The t-test results found in Table 55 and Table 56 show some *p-values* that do not lie below the level of significance α, which is equal to 0.05. These *p-values* indicate both statistical significance and random sampling characterizations of the observed effect caused by increased tempering time. *Change A* and *Change B* for these two tables are representative of half-hour increases in tempering time. Therefore, this indicates that there is little evidence that an increase in tempering time from 1.25 hours to 1.75 hours or from 1.75 hours to 2.25 hours will produce a statistically significant decrease in ultimate tensile strength.

Figure 57 (or Figure 64) corroborates this finding. By inspecting this figure, it can be seen that the mean ultimate tensile strength values found on the *Tempered 1.25 h* and *Tempered 1.75 h* curves are very close to one another. Checking the supporting figures of Figure 57, specifically Figure 61 and Figure 63, it can be seen that the UTS averages on these two curves at 400°C (752°F) and 600°C (1112°F) are extremely close. In fact the standard error of the mean values overlap at 600°C. This supports the relatively high *p-values* found in Table 55 at these two test temperatures.

Change C in

Table 57 is representative of a one-hour increase. An increase in tempering time from 1.25 hours to 2.25 hours resulted in all *p-values* to be below 0.01. That is, there is a less than one-percent risk that this decrease in UTS is caused by random sampling. There is strong evidence that the effect of *Change C* on UTS values is statistically significant. Therefore, there is a very significant negative relationship between a one-hour increase in tempering time from 1.25 hours and a decrease in UTS values in environmental temperatures ranging from room temperature up to 600°C (1112°F).

Table 55. Significance of Tempering Time on Ultimate Tensile Strength, *Change A*

Temperature (°C / °F)	**Significance of *Change A* on UTS: 1.25-Hour to 1.75-Hour Tempering Time**			
	F-Test Result	**F-Test Finding**	**P-Value**	**P-Value Finding**
Room Temp.	0.3872	Equal Var.	0.0559	Random
100 / 212	0.2500	Equal Var.	0.0044	Significant
300 / 572	0.2000	Equal Var.	0.0187	Significant
400 / 752	0.5380	Equal Var.	0.1311	Random
500 / 932	0.0605	Equal Var.	0.0245	Significant
600 / 1112	0.6375	Equal Var.	0.2110	Random

Condition 1: 1.25 Hours
Condition 2: 1.75 Hours

Table 56. Significance of Tempering Time on Ultimate Tensile Strength, *Change B*

Temperature (°C / °F)	Significance of *Change B* on UTS: 1.75-Hour to 2.25-Hour Tempering Time			
	F-Test Result	F-Test Finding	P-Value	P-Value Finding
Room Temp.	0.6186	Equal Var.	0.0166	Significant
100 / 212	0.9434	Equal Var.	0.0013	Significant
300 / 572	0.0661	Equal Var.	0.0029	Significant
400 / 752	0.4596	Equal Var.	0.0038	Significant
500 / 932	0.5000	Equal Var.	0.0079	Significant
600 / 1112	0.1365	Equal Var.	0.0547	Random

Condition 1: 1.75 Hours
Condition 2: 2.25 Hours

Table 57. Significance of Tempering Time on Ultimate Tensile Strength, *Change C*

Temperature (°C / °F)	Significance of *Change C* on UTS: 1.25-Hour to 2.25-Hour Tempering Time			
	F-Test Result	F-Test Finding	P-Value	P-Value Finding
Room Temp.	0.1941	Equal Var.	0.0085	Significant
100 / 212	0.2759	Equal Var.	0.0001	Significant
300 / 572	0.4706	Equal Var.	0.0000	Significant
400 / 752	0.1979	Equal Var.	0.0046	Significant
500 / 932	0.1711	Equal Var.	0.0076	Significant
600 / 1112	0.2707	Equal Var.	0.0060	Significant

Condition 1: 1.25 Hours
Condition 2: 2.25 Hours

5.1.2. Significance of Tempering Time on Yield Strength

The *p-values* in Table 58 and Table 59 suggest that there is no significant effect on yield strength with an increase of half-hour increments of tempering time. Figure 71 and Figure 75 support the high *p-value* result for the yield strength at 400°C. At this temperature the *Tempered 1.25 h* and *Tempered 1.75 h* curves practically overlap. The *p-values* above 0.05 indicate a random sampling characterization of the effects caused by *Change A* and *Change B*.

Table 60 shows the t-tests results for *Change C*, which is an increase in tempering time from 1.25 hours to 2.25 hours. All *p-values* lying below the 0.05 level of significance provides strong evidence that the increase in tempering time from 1.25 hours to 2.25 hours has a statistically significant negative relationship with yield strength for environmental temperatures ranging from room temperature up to 600°C (1112°F).

Table 58. Significance of Tempering Time on Yield Strength, *Change A*

Temperature (°C / °F)	Significance of *Change A* on YS: 1.25-Hour to 1.75-Hour Tempering Time			
	F-Test Result	F-Test Finding	P-Value	P-Value Finding
Room Temp.	0.1704	Equal Var.	0.0244	Significant
100 / 212	0.6073	Equal Var.	0.0105	Significant
300 / 572	0.5294	Equal Var.	0.0002	Significant
400 / 752	0.7400	Equal Var.	0.4075	Random
500 / 932	0.0262	Unequal Var.	0.0332	Significant
600 / 1112	0.6879	Equal Var.	0.1753	Random

Condition 1: 1.25 Hours
Condition 2: 1.75 Hours

Table 59. Significance of Tempering Time on Yield Strength, *Change B*

Temperature (°C / °F)	Significance of *Change B* on YS: 1.75-Hour to 2.25-Hour Tempering Time			
	F-Test Result	F-Test Finding	P-Value	P-Value Finding
Room Temp.	0.8769	Equal Var.	0.0203	Significant
100 / 212	0.9216	Equal Var.	0.1627	Random
300 / 572	0.0938	Equal Var.	0.2072	Random
400 / 752	0.4500	Equal Var.	0.0282	Significant
500 / 932	0.0842	Equal Var.	0.0388	Significant
600 / 1112	0.1207	Equal Var.	0.0740	Random

Condition 1: 1.75 Hours
Condition 2: 2.25 Hours

Table 60. Significance of Tempering Time on Yield Strength, *Change C*

Temperature (℃ / ℉)	Significance of *Change C* on YS: 1.25-Hour to 2.25-Hour Tempering Time			
	F-Test Result	F-Test Finding	P-Value	P-Value Finding
Room Temp.	0.1356	Equal Var.	0.0081	Significant
100 / 212	0.6757	Equal Var.	0.0032	Significant
300 / 572	0.0348	Unequal Var.	0.0287	Significant
400 / 752	0.2913	Equal Var.	0.0210	Significant
500 / 932	0.4643	Equal Var.	0.0061	Significant
600 / 1112	0.2183	Equal Var.	0.0074	Significant

Condition 1: 1.25 Hours
Condition 2: 2.25 Hours

5.1.3. Significance of Tempering Time on Elongation

Table 61 through Table 63 confirm the null hypothesis H_0 that there is no change between the mean elongation values caused by Change A, Change B, and Change C. Any observed differences in mean elongation values between tempering time curves can attributed to random sampling. This becomes evident when looking closely at Figure 85 and its supporting graphs found in Figure 86 through Figure 91.

Table 61. Significance of Tempering Time on Elongation, *Change A*

Temperature (℃ / ℉)	Significance of *Change A* on Elongation: 1.25-Hour to 1.75-Hour Tempering Time			
	F-Test Result	F-Test Finding	P-Value	P-Value Finding
Room Temp.	0.3957	Equal Var.	0.2919	Random
100 / 212	0.8758	Equal Var.	0.3426	Random
300 / 572	0.6461	Equal Var.	0.4222	Random
400 / 752	0.0467	Unequal Var.	0.1249	Random
500 / 932	0.2705	Equal Var.	0.1385	Random
600 / 1112	0.7885	Equal Var.	0.0888	Random

Condition 1: 1.25 Hours
Condition 2: 1.75 Hours

Table 62. Significance of Tempering Time on Elongation, *Change B*

Temperature (°C / °F)	Significance of *Change B* on Elongation: 1.75-Hour to 2.25-Hour Tempering Time			
	F-Test Result	F-Test Finding	P-Value	P-Value Finding
Room Temp.	0.0340	Unequal Var.	0.1464	Random
100 / 212	0.3302	Equal Var.	0.0001	Significant
300 / 572	0.1821	Equal Var.	0.0675	Random
400 / 752	0.0143	Unequal Var.	0.0805	Random
500 / 932	0.5386	Equal Var.	0.2609	Random
600 / 1112	0.0261	Unequal Var.	0.0866	Random

Condition 1: 1.75 Hours
Condition 2: 2.25 Hours

Table 63. Significance of Tempering Time on Elongation, *Change C*

Temperature (°C / °F)	Significance of *Change C* on Elongation: 1.25-Hour to 2.25-Hour Tempering Time			
	F-Test Result	F-Test Finding	P-Value	P-Value Finding
Room Temp.	0.1311	Equal Var.	0.0999	Random
100 / 212	0.4048	Equal Var.	0.0001	Significant
300 / 572	0.0913	Equal Var.	0.0701	Random
400 / 752	0.4623	Equal Var.	0.0278	Significant
500 / 932	0.5958	Equal Var.	0.0946	Random
600 / 1112	0.0399	Unequal Var.	0.0166	Significant

Condition 1: 1.25 Hours
Condition 2: 2.25 Hours

5.1.4. Significance of Tempering Time on Reduction of Area

T-tests for the increased tempering time effect on reduction of area resulted in *p-values* above the level of significance as shown in Table 64 through Table 66 . This suggest that there is little evidence that there is a significant effect of increased tempering time on reduction of area mean values. Refer to Figure 92 through Figure 98 for a visual understanding of why there is no

statistical significance of tempering time change on reduction of area. In these figures the three tempering time curves overlap tightly throughout the test temperature range.

Table 64. Significance of Tempering Time on Reduction of Area, *Change A*

Temperature (°C / °F)	Significance of *Change A* on Reduction of Area: 1.25-Hour to 1.75-Hour Tempering Time			
	F-Test Result	F-Test Finding	P-Value	P-Value Finding
Room Temp.	0.3305	Equal Var.	0.0872	Random
100 / 212	0.3019	Equal Var.	0.3800	Random
300 / 572	0.5926	Equal Var.	0.3639	Random
400 / 752	0.3971	Equal Var.	0.1646	Random
500 / 932	0.0224	Unequal Var.	0.4525	Random
600 / 1112	0.9380	Equal Var.	0.0023	Significant

Condition 1: 1.25 Hours
Condition 2: 1.75 Hours

Table 65. Significance of Tempering Time on Reduction of Area, *Change B*

Temperature (°C / °F)	Significance of *Change B* on Reduction of Area: 1.75-Hour to 2.25-Hour Tempering Time			
	F-Test Result	F-Test Finding	P-Value	P-Value Finding
Room Temp.	0.0243	Unequal Var.	0.0441	Significant
100 / 212	0.3522	Equal Var.	0.2301	Random
300 / 572	0.6241	Equal Var.	0.0558	Random
400 / 752	0.4604	Equal Var.	0.3989	Random
500 / 932	0.3356	Equal Var.	0.2390	Random
600 / 1112	0.6414	Equal Var.	0.2132	Random

Condition 1: 1.75 Hours
Condition 2: 2.25 Hours

Table 66. Significance of Tempering Time on Reduction of Area, *Change C*

Temperature (°C / °F)	Significance of *Change C* on Reduction of Area: 1.25-Hour to 2.25-Hour Tempering Time			
	F-Test Result	F-Test Finding	P-Value	P-Value Finding
Room Temp.	0.0049	Unequal Var.	0.0428	Significant
100 / 212	0.0732	Equal Var.	0.2552	Random
300 / 572	0.3207	Equal Var.	0.0677	Random
400 / 752	0.9062	Equal Var.	0.1389	Random
500 / 932	0.1064	Equal Var.	0.3792	Random
600 / 1112	0.6967	Equal Var.	0.0026	Significant

Condition 1: 1.25 Hours
Condition 2: 2.25 Hours

5.2. Sensitivity to Temperature and Tempering Time

The following sections discuss the effects of test temperature and heat treatment tempering time on mechanical properties, specifically, ultimate tensile strength, yield strength, elongation, and reduction of area.

5.2.1. Effects on Ultimate Tensile Strength

Intuitively, ultimate tensile strength of Alloy EP-823 varied inversely with test temperature. Examining Table 49 (or Table 50) and Figure 57 (Figure 64) indicated that with an increase in test temperature there was a steady decline in ultimate tensile strength up to 400°C (752°F). Beyond that temperature the UTS decreased drastically. This was common across all tempering time conditions.

Although not producing a drastic effect, there was a statistically significant negative relationship between a one-hour increase in tempering time from 1.25 hours to 2.25 hours and a decrease in UTS values in environmental temperatures ranging from room temperature up to

600°C (1112°F). Visually a clear trend was observed in Figure 57 (Figure 64), indicating that UTS decreased with longer tempering times.

5.2.2. Effects on Yield Strength

Similar to the effect on ultimate tensile strength, yield strength had an inverse relationship with temperature as expected. Table 51 (or Table 52) and Figure 71 (or Figure 78) show a steady decrease in YS as temperature increased up to 500°C (932°F). At 600°C (1112°F) the material YS decreased sharply. This was common across all tempering time conditions.

An increase in tempering time from 1.25 hours to 2.25 hours had a statistically significant negative relationship with yield strength for environmental temperatures ranging from room temperature up to 600°C (1112°F). Figure 71 (or Figure 78) showed a general decrease in YS according to increased tempering time.

5.2.3. Effects on Elongation

The stress-strain diagrams of Figure 99 through Figure 101 indicate a slight reduction in elongation values as temperatures increased up to 300°C (572°F). Elongations values were lowest at this temperature across all tempering times. At 400°C (752°) the elongation values were observed to increase with temperature and increase radically at 500°C (932°F) and even more so at 600°C (1112°F) as graphed in Figure 108. All tempering times were affected in this way. This behavior of decreasing and then increasing elongation values with temperature was observed in other ferritic-martensitic [30]-[32] and martensitic steels [33].

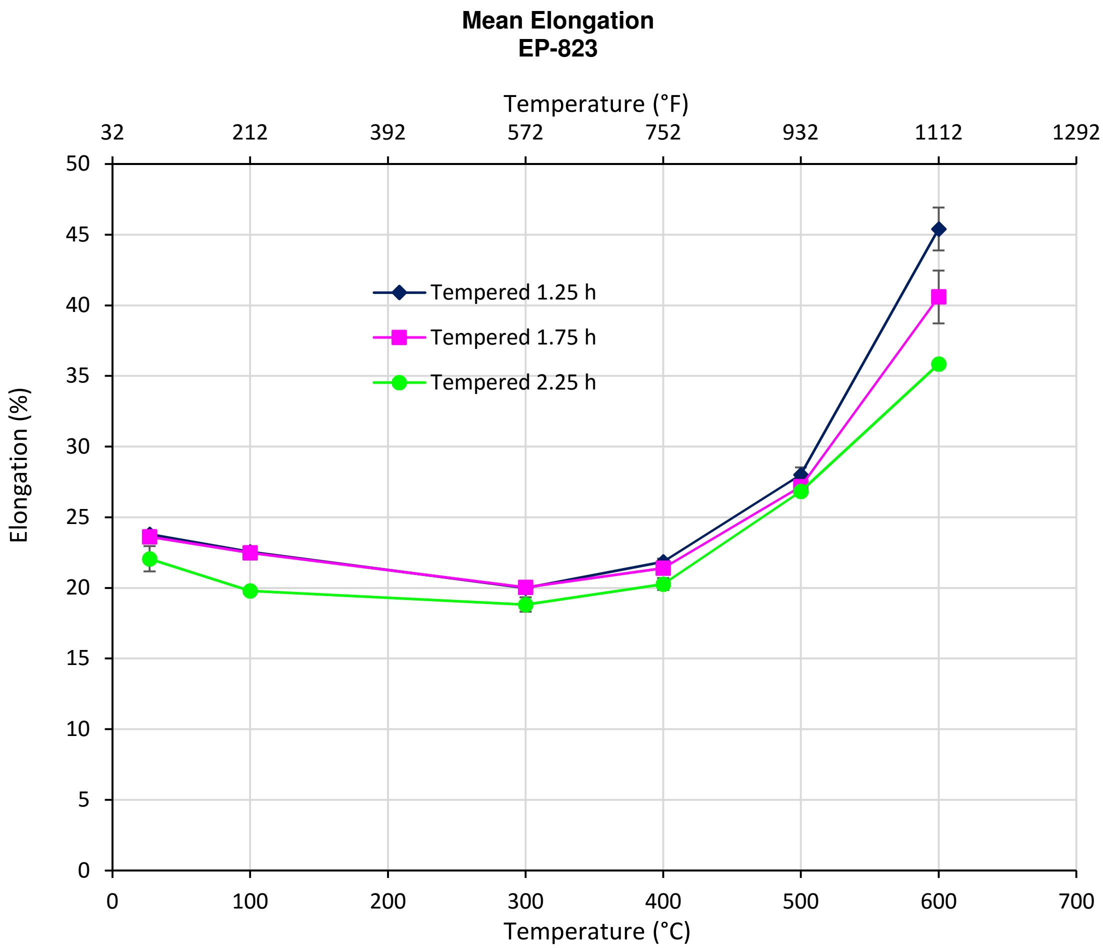


Figure 108. Mean Elongation of Alloy EP-823

Incidentally, all 300°C (572°F) tests exhibited erratic material flow in the uniform strain region of the stress-strain curve. Figure 109 provides an example of this phenomenon, which can be attributed to the Portevin-Le Chatelier (PLC) effect [34]. PLC is associated with dynamic strain aging, where dislocations are blocked by diffusing solutes and pile up until sufficient strain occurs to unlock this piling. At 300°C (572°F) the solutes in the material tend to migrate more readily towards the dislocations, resulting in a lowered energy state, inhibiting dislocation movement and

consequently, inhibiting material flow. This is commonly referred to as dislocation pinning by solutes.

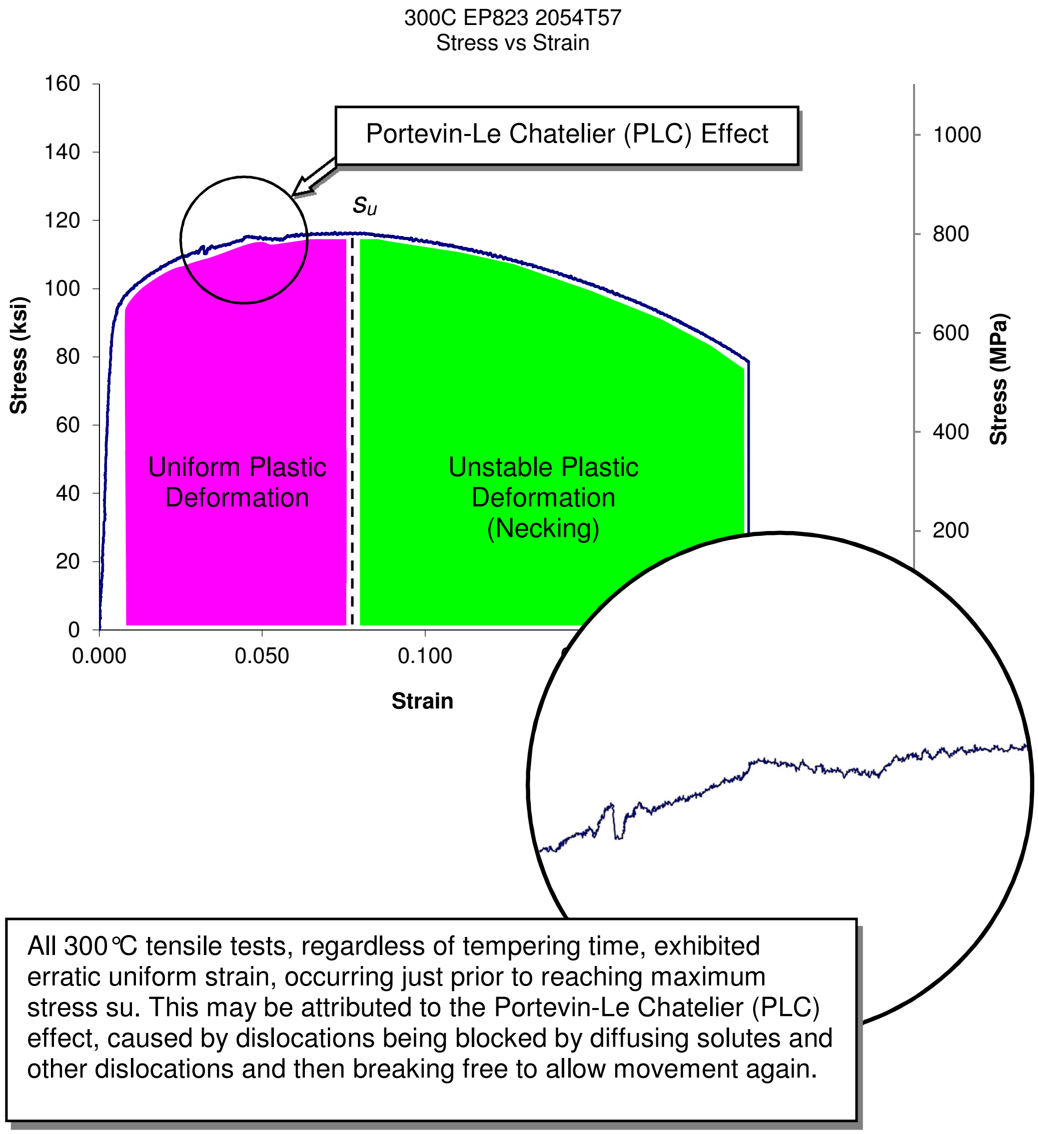
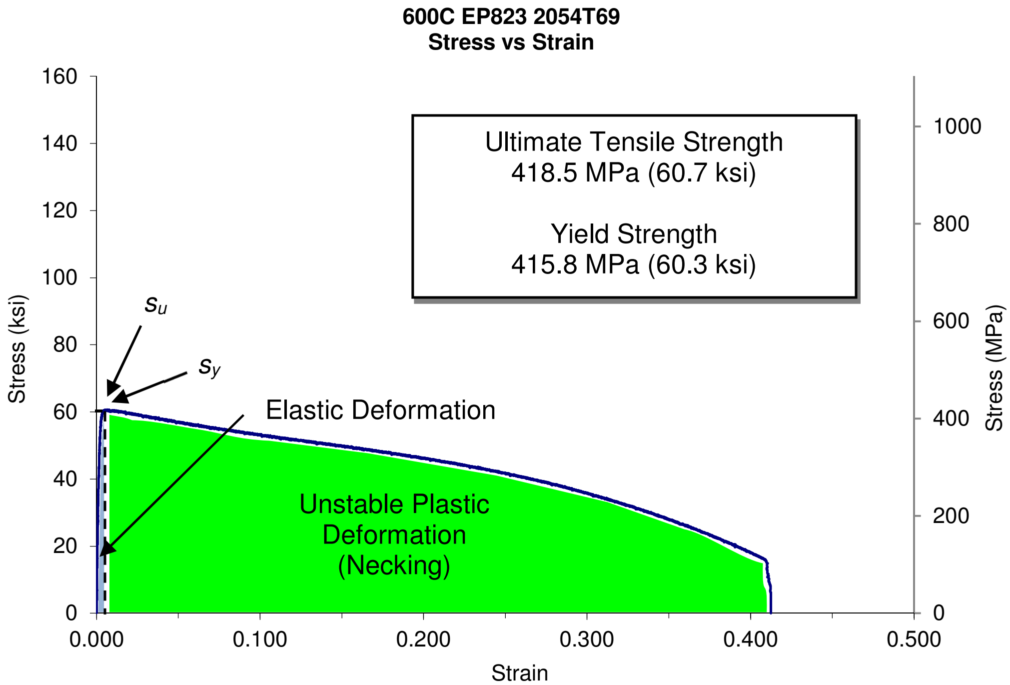


Figure 109. Portevin-Le Chatelier (PLC) Effect for 300°C

The strain hardening effects were diminished with an increase in temperature, and at 600°C (1112°F) were almost nonexistent, allowing for increased free movement of dislocations, characterized by enhanced strain. This effect can be attributed to thermally activated dislocation motion [31]. Consequently, as shown in Figure 108, beyond 400°C (752°F) elongation values increased significantly, revealing a radical increase in ductility.

Another interesting observation came from inspecting Figure 99 through Figure 101. After reaching 500°C (932°F) the strain associated with the maximum stress at s_u decreased significantly, signifying that uniform strain is greatly truncated with temperatures at 500°C and above as compared to those at lower temperatures. At 600°C (1112°F) the strain at maximum stress s_u is almost equal to the strain at yielding stress s_y. Almost the entire stress-strain curve is characterized by necking or unstable plastic deformation. Uniform plastic deformation is practically nonexistent as shown in Figure 110. This differs from a typical stress-strain curve at lower test temperatures that has a uniform plastic deformation region as depicted in Figure 109 for example.



After reaching 500°C (932°F) the strain associated with the maximum stress s_u decreased significantly. For 600°C (1112°F) the strain at maximum stress s_u is almost equal to the strain at yielding stress s_y. Almost the entire stress-strain curve is characterized by necking or unstable plastic deformation. Uniform plastic deformation is practically nonexistent.

Figure 110. Unstable Plastic Deformation at 600°C (1112°F)

For test temperatures above 400°C (752°F) it appeared that deformation instability or necking occurred shortly after reaching the yield strength and the uniform plastic deformation was severely attenuated. Plotting the ultimate tensile strength and yield strength values together as a function of temperature offers another perspective of this change. As shown in Figure 111 the UTS values appear to have converged on the YS values as temperatures increased beyond 400°C (752°F). Perhaps this implies that a critical temperature lies between 400°C and 500°C (752°F and 932°F). This information may be important for design use.

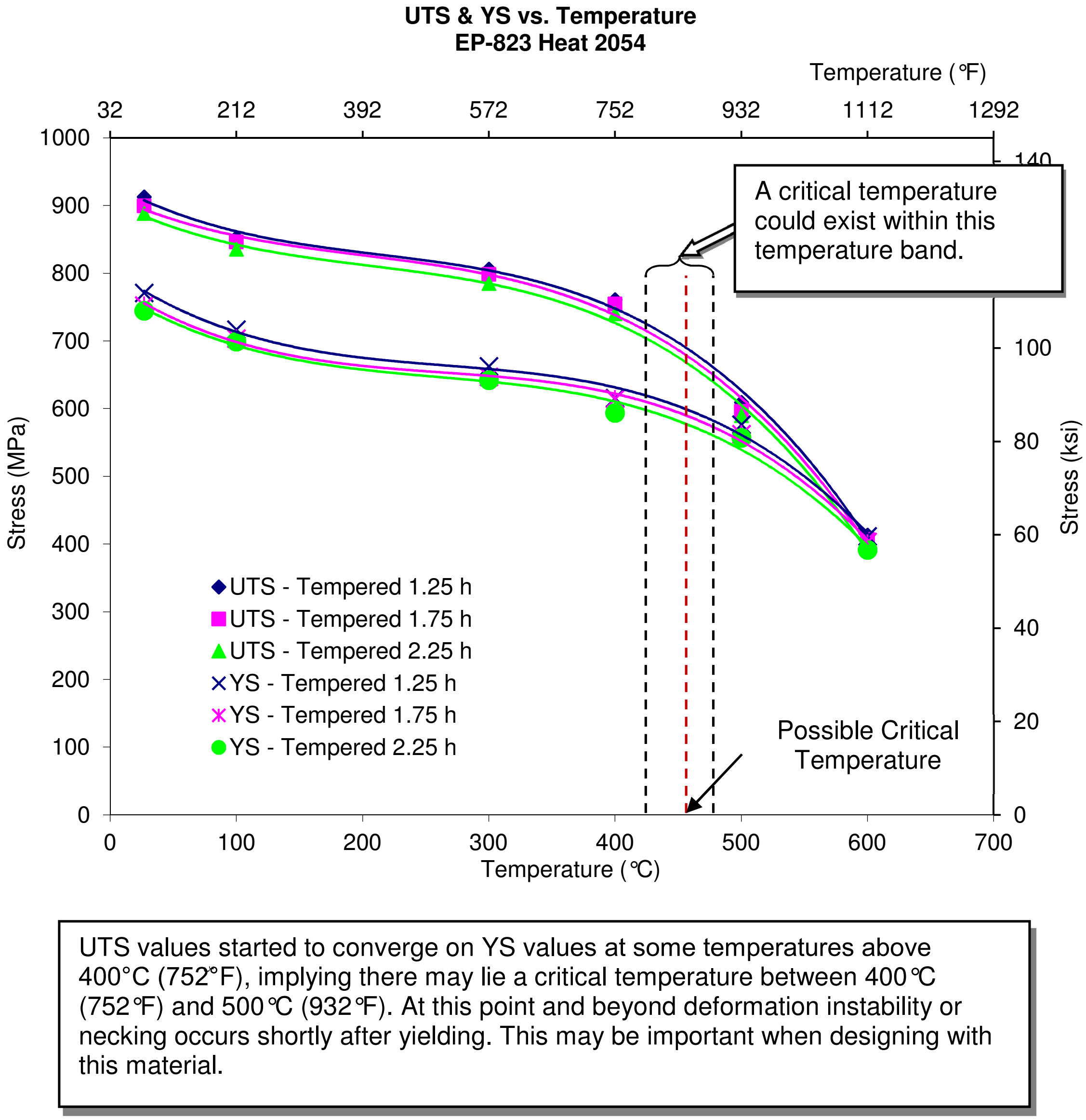


Figure 111. UTS and YS Convergence

With regard to tempering time effects on elongation, an increase in tempering time consistently resulted in slightly diminished elongation performance. The effect was not noteworthy until reaching 600°C (1112°F), where elongation values reported in Table 53 and Figure 85 dropped from about 45% to 36%, yielding a 20% reduction in ductility with increased tempering time. In

general there did not appear to be a statistically significant relationship between an increase in tempering time and elongation values. Section 5.1.3 explains this determination.

5.2.4. Effects on Reduction of Area

Referring to Table 54 and Figure 92, an increase in temperature up to 400°C (752°F) did not have any apparent effect on reduction of area. Values essentially remained unchanged at 63% up to 400°C (752°F) and then ramped upwards beyond this temperature, supporting the idea of a critical temperature. An approximate 27% increase in reduction of area was observed from 400°C to 600°C (752°F to 1112°F).

There is no evidence that an increase in tempering time has any effect on reduction of area. All reduction of area values were tightly grouped throughout the temperature range, regardless of tempering time. Section 5.1.4 strongly supports the lack of statistical significance of this relationship.

CHAPTER 6:

SUMMARY AND CONCLUSIONS

6.1. Summary

The primary objective for this thesis was to develop a mechanistic understanding of Alloy EP-823, determining the effect of temperature and tempering time on mechanical properties. To accomplish this meant developing a test system apparatus to provide tensile testing at elevated temperatures. This required developing both hardware and software for successful data acquisition. Fulfilling this objective required a systematic means for data processing and data reduction.

6.1.1. Elevated Temperature Tensile Testing System

For this study, an MTS machine was outfitted with elevated temperature test equipment, including a furnace, laser extensometer, custom high temperature grips, and automated nitrogen and cooling systems. In addition to the researchers of this project the intended use of this system was designed for other independent researchers outside of this project. The system hardware and software and a data reduction tool were developed with user instructions for use by other graduate and faculty research. The complete system was capable of acquiring and processing accurate and repeatable results to help discern a clear trend from system independent variables, specifically temperature and tempering time.

6.1.2. Determine Mechanical Properties

The data reduction tool provided a systematic means to process data, featuring a numerical algorithm to determine yield strength to mitigate the potential human error associated with visual

inspection. In addition to yield strength, ultimate tensile strength, elongation, and reduction of area were determined at room temperature up to 600°C across three tempering times. The data reduction tool also provided a means for strain correction when the LVDT was used, correcting for system compliance. This correction algorithm was necessary to create more realistic stress-strain curves at elevated temperatures.

6.2. Conclusions

The data generated was repeatable and reliable and was capable of providing a definitive mechanistic understanding of Alloy EP-823 [33]. Having performed this study and looking back on it in retrospect has given rise to some improvements for future work.

6.2.1. Mechanistic Understanding

Overall, the tensile test results of Alloy EP-823 indicate a general trend of decreasing mechanical performance with an increase in tempering time. A half-hour incremental change in tempering time provided marginally noticeable changes in mechanical properties. Evaluating a larger one-hour increase in tempering time produced more measurable changes in both yield strength and ultimate tensile strength. Conclusively, there is a statistically significant inverse relationship between a one-hour increase in tempering time from 1.25 hours and a decrease in both UTS and YS values in environmental temperatures ranging from room temperature up to 600°C (1112°F).

Effects from changes in temperature were more noticeable, trending UTS and YS values downward with increasing temperature. Elongation values experienced a slight reduction up to 300°C (572°F) then ramped upwards for increasing temperatures. Reduction of area values had no

effect from temperature or tempering time up to 400°C (752°F) but did experience an increase with greater temperatures.

With increasing temperature the mechanical properties changed gradually and predictably up to 400°C (752°F). Starting with 500°C (932°F) they changed drastically. This became evident studying the resulting data and the stress-strain plots, implying that a critical temperature may be found between 400°C and 500°C (752°F and 932°F). This critical temperature could be important to structural design integrity. At temperatures beyond this critical temperature the material experienced unstable deformation shortly after reaching yield stress, exhibiting severely truncated uniform plastic deformation characteristics.

6.2.2. Future Work

If future work is conducted to determine Alloy EP-823's sensitivity to tempering time a larger incremental increase is suggested. While half-hour increments produced marginally noticeable changes, a one-hour increase in tempering time produced significant mechanical property results.

Another suggestion for future work is to determine the critical temperature at which this material exhibits a lack of uniform plastic deformation. At this temperature the strain values for UTS and YS converge, severely attenuating the strain hardening region, which occurs before reaching the maximum engineering stress. In other words once the yield stress is reached the material almost immediately starts to neck or experience unstable plastic deformation. This information could be useful for structural design using this material.

Regarding equipment, the laser extensometer had proven itself extremely useful for generating accurate extension data. Unfortunately, its major weakness was faulted by the aluminum-backed reflective adhesives having a maximum operating temperature of 482°C (900°F). Perhaps more robust reflectors could be developed to withstand much greater temperatures, using different

materials or cooling methods. Perhaps water-cooled reflectors could be developed so that high temperature tests can be monitored by the laser extensometer. This would eliminate the necessity for stress-strain curve correction due to system compliance.

APPENDIX A:

HIGH TEMPERATURE TENSION GRIPS

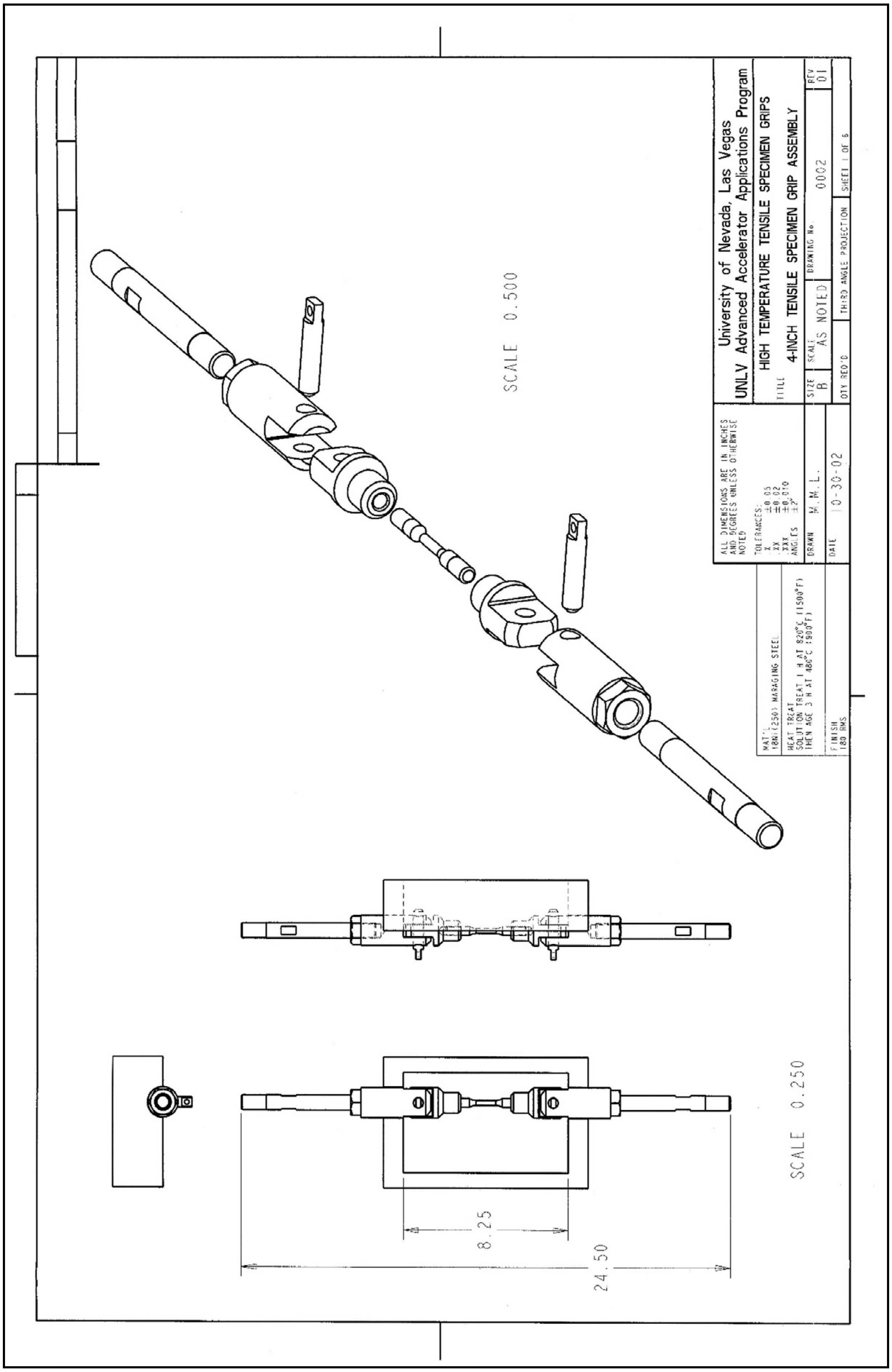
The high temperature tension grips were designed by Martin Lewis. The machining and fabrication was performed by Mark Jones.

Material:	18Ni (250) Maraging Steel
As-Received Heat Treatment:	Solution-annealed 1 hour at 820°C (1500° F), followed by air cooling. Aged 3 hours at 480°C (900° F).

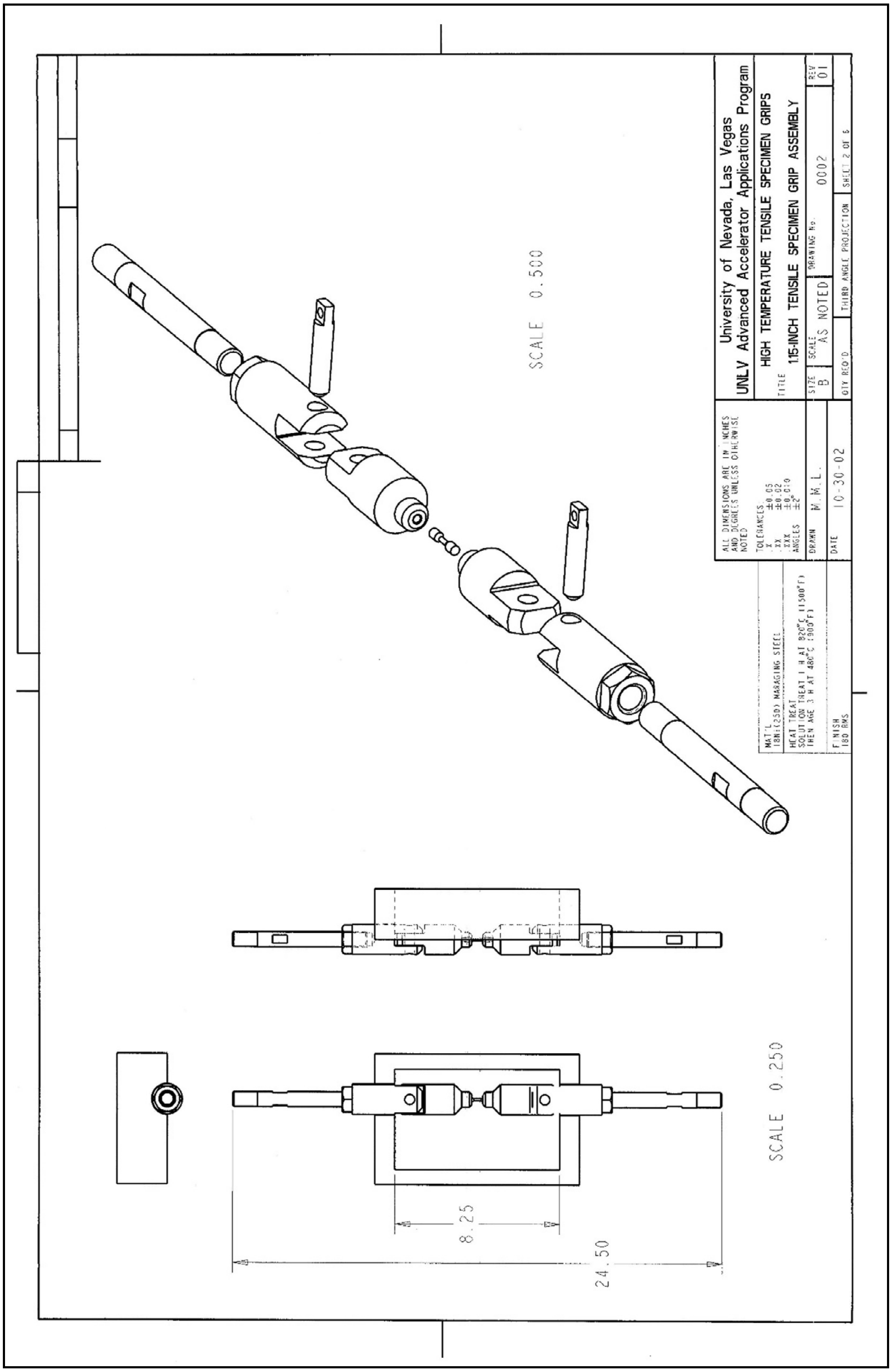
Table 67. 18Ni (250) Maraging Steel Chemical Composition

Element	Weight Percent (%)
Aluminum (Al)	0.10
Boron (B)	0.003
Carbon (C)	≤ 0.03
Cobalt (Co)	7.50
Manganese (Mn)	≤ 0.10
Molybdenum (Mo)	4.80
Nickel (Ni)	18.5
Phosphorous (P)	≤ 0.01
Silicon (Si)	≤ 0.10
Sulfur (S)	≤ 0.01
Titanium (Ti)	0.40
Zirconium (Zr)	0.01
Iron (Fe)	Balance

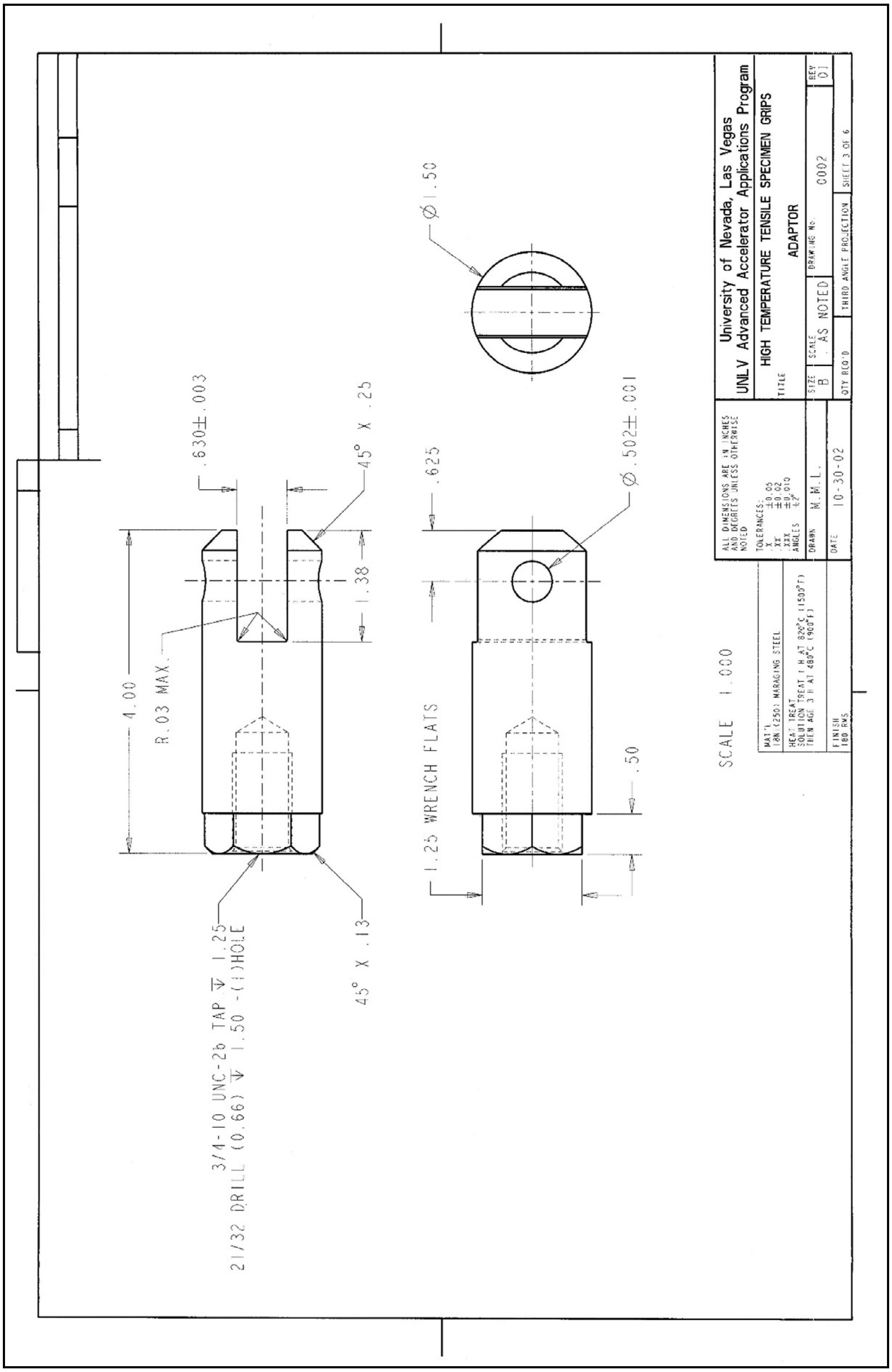
A.1. Grip Assembly Drawing for 4-Inch Long Tensile Specimens



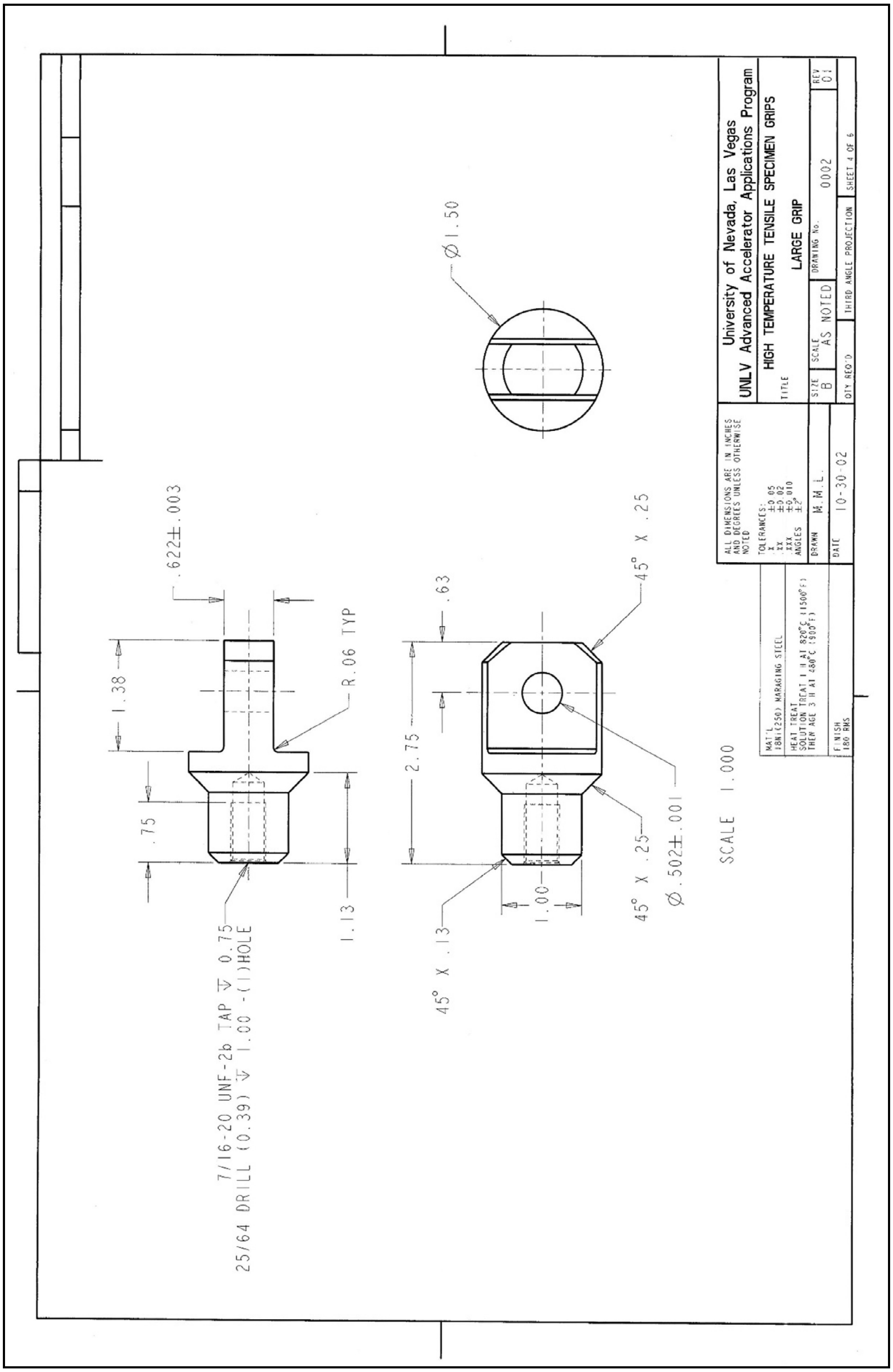
A.2. Grip Assembly Drawing for 1.15-Inch Long Tensile Specimens



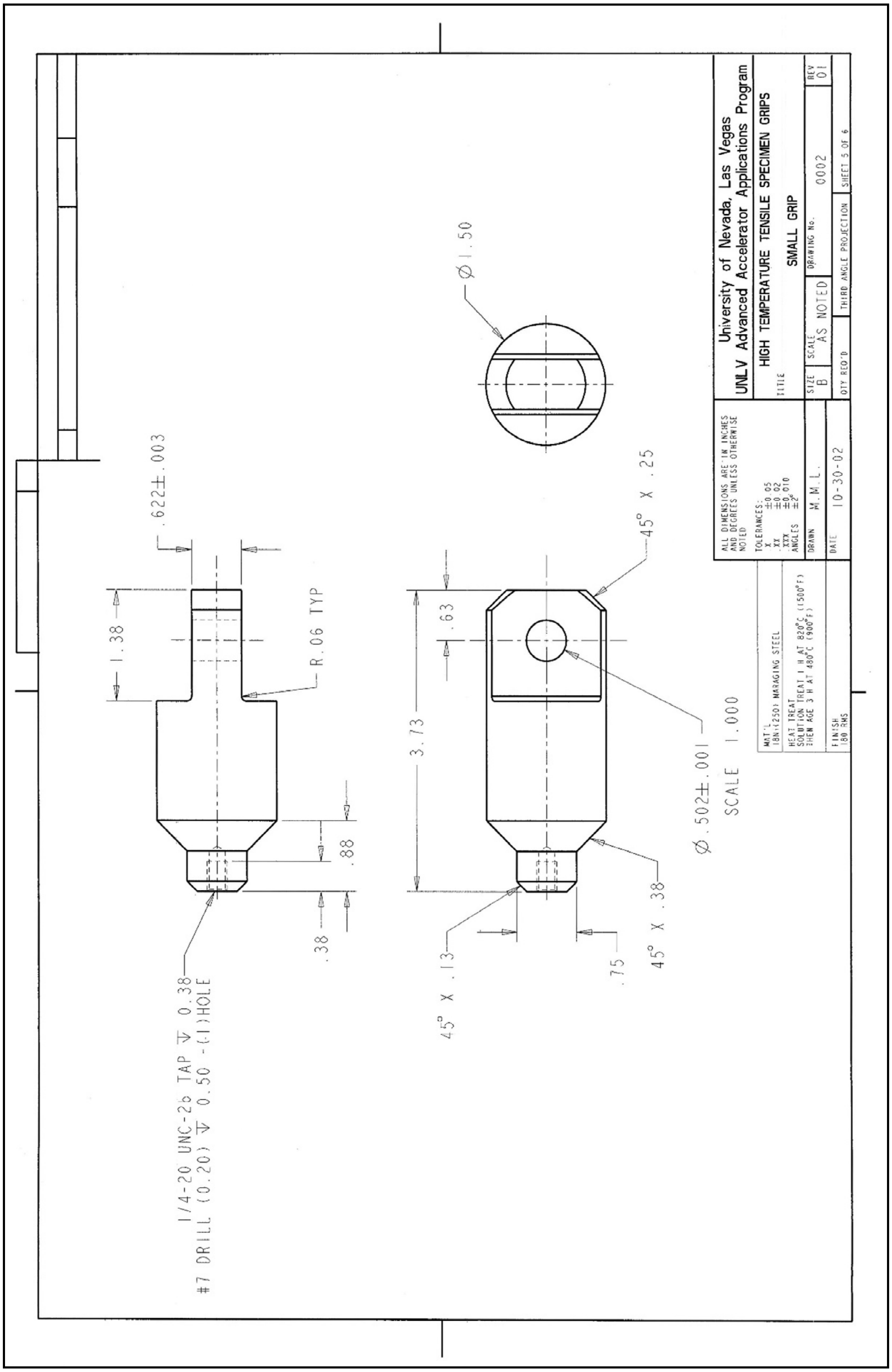
A.3. Adaptor Drawing



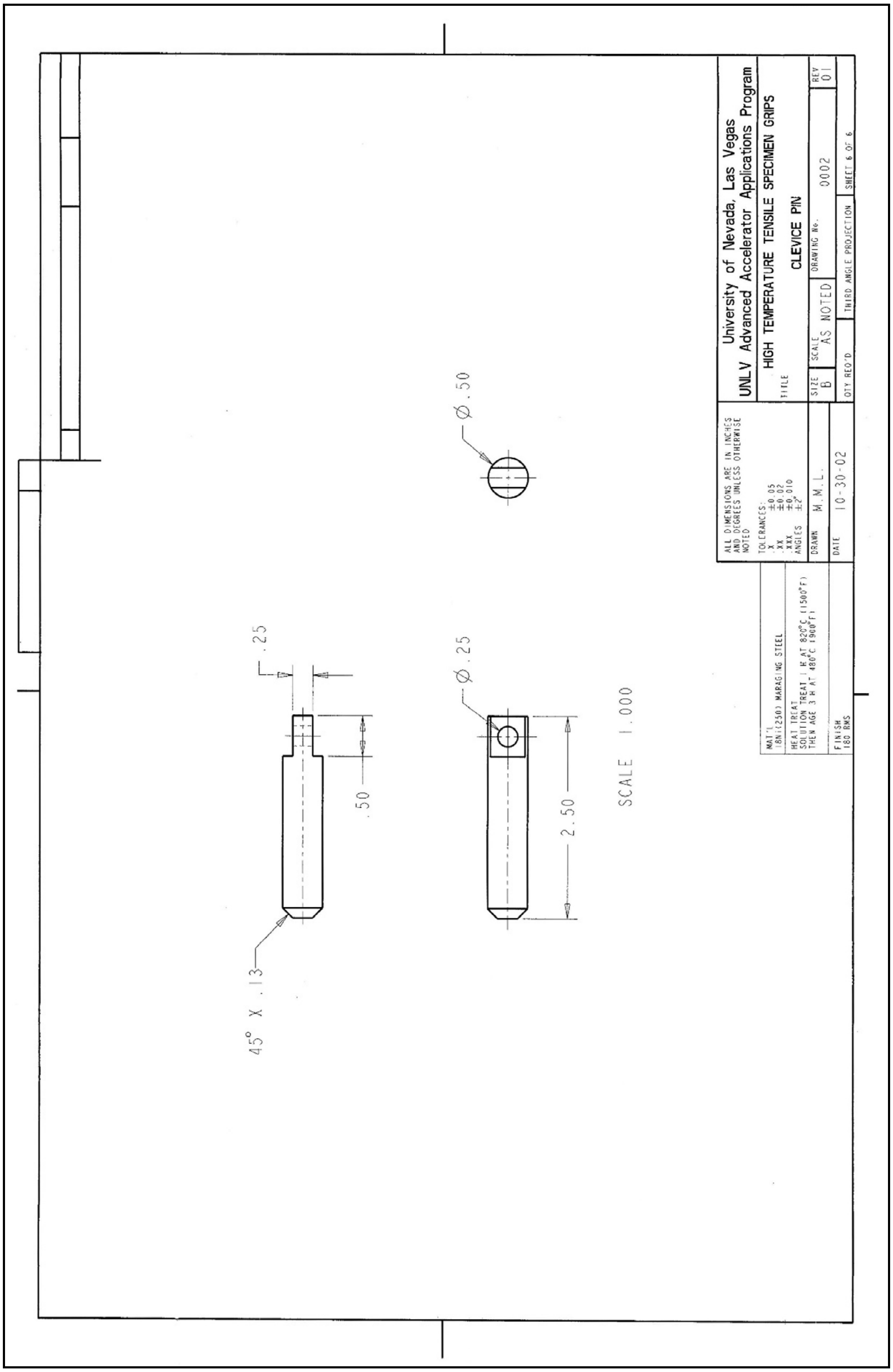
A.4. Grip Drawing for the 4-Inch Long Tensile Specimen



A.5. Grip Drawing for the 1.15-Inch Long Tensile Specimen



A.6. Clevis Pin Drawing



APPENDIX B :

MTS TESTING TEMPLATE

TestWare-SX Version 4.0D software was used to create the testing template for controlling the loads and displacements and recording test data. The template was programmed to first zero the load on the specimen, hold for five seconds, and then apply a displacement rate of .0005 in/sec. (0.0127 mm/sec.) for load application. It recorded cross-head displacement, load, temperature, and specimen extension as a function of time and output the data to a data file. The data was tab-delimited and could be opened with standard commercially-available spreadsheet software.

The following information comes from a tensile test data file created for this thesis, detailing the set-up of the TestWare-SX testing template. It is provided as an information header printed above the all data output files. The testing template was written by Raymond Kozak.

```
TWSX|.|/|:|1|0|0|E|2|A
Procedure Detail                                Time:  6935.8496
       TestWare-SX

       Procedure Name             = EP823 Specimen test 3 Default Procedure
       File Specification         = H:\EP823\EP823 Specimen test 3.000
       Software Version           = 4.0D
       Printout Date              = 9/9/2003 7:38:01 PM

       Data File Options
         File Format                     = Excel Text File
         Log Events                      = Yes
         Include Procedure Description   = Yes

       Recovery Options
         Autosave disabled.

       Ramp Up : Step
         Step Done Trigger 1             = Apply Load

         Zero Load : Monotonic Command
          Start Trigger    = Step Start
          End Trigger      = Hold
          Segment Shape    = Ramp
          Rate      = 10 ( lbf/Sec )
          Axial
          Control Mode     = force control
          End level        = 0 ( lbf )

         Hold : Hold Command
          Start Trigger    = Zero Load
          End Trigger      = Apply Load
          Hold Time        = 5 ( Sec )
          Axial
          Control Mode     = force control

         collect Data : Data Acquisition
          Start Trigger    = Hold
          End Trigger      = <none>
          Mode             = Timed
          Buffer Type      = Single
          Master Channel   = Time
          Slave Channel 1  = Displacement
          Slave Channel 2  = Load Cell
          Slave Channel 3  = tempsensor
          Slave Channel 4  = Laser Extens
          Data Header      = Collect Data
          Time Increment   = 0.1 ( Sec )
          Buffer Size      = 16000

         Apply Load : Monotonic Command
          Start Trigger    = Hold
          End Trigger      = <none>
          Segment Shape    = Ramp
          Rate      = 0.0005 ( in/Sec )
          Axial
          Control Mode     = Length
          End level        = 0.5 ( in )

Test Control                Started                Time:  0.027399998
       Calendar Time:       9/9/2003 7:38:11 PM
       File Name:           H:\EP823\EP823 Specimen test 3.000
       Procedure Name:      EP823 Specimen test 3 Default Procedure
       Operator:            LEWISM
       Teststar Config:     deflect with temp1.tcc

DRP Process Data            Collect Data        Time:  442.30377
Time         Displacement   Load Cell    tempsensor    Laser Extens
Sec          in             lbf          deg_C         in
<Data>       <Data>         <Data>       <Data>        <Data>
```

APPENDIX C:

DATA REDUCTION TOOL

The following spreadsheet template was developed to standardize recording and processing test data, calculate ductility parameters, and output pertinent graphs. The spreadsheet was developed with the end user in mind and was provided with instructions for entering the data and for extracting key properties. Based on the MTS data output file and the initial and final specimen dimensions, the spreadsheet generated the mechanical properties and stress-strain plot. The spreadsheet template was developed in Microsoft Excel and information in each spreadsheet tab is provided in the following sections.

C.1. Time, M&TE Tab

This first tab titled "Time, M&TE" provided a location to enter test conditions, date/time, and measuring equipment calibration dates. This tab was used as a cover sheet for the entire test spreadsheet file. Generally throughout the template, yellow cells were for user input, while non-yellow cells were calculations performed by the spreadsheet. It also provided a test summary of the mechanical properties calculated by the other tabs. The following example comes from an actual test performed for this thesis. Portions of the spreadsheet have been moved to fit the physical page constraints of this document.

User instructions were provided for data entry.

Instructions: Enter data in all yellow fields.

Specimen ID	2054S60
Testing Temperature (deg. C)	400
Set Point (deg. F)	873
Set Point (deg. C)	467

Date	9/20/2003
Time	2:56 PM

Testing Equipment	Equipment	**MTS Machine**
	Brand	TestStar Test System
	Model	University of Nevada
		Bechtel Nevada
	Cal Sticker	Calibration
	ID number	7868
	Date	2/20/2003
	Due	2/20/2005
	By	MB

Equipment	**Calipers**
Brand	Mitutoyo
Model	CD-6" CS
Cal Sticker	Bechtel Nevada Calibration
ID number	8787
Date	9/17/2003
Due	9/17/2004
By	MB

Equipment	**Micrometer**
Brand	Mitutoyo
Model	Digital
Cal Sticker	Bechtel Nevada Calibration
ID number	8790
Date	9/18/2003
Due	9/18/2004
By	MB

An at-a-glance summary of results was provided.

Test Summary		
UTS	111.5	ksi
YS	90.0	ksi
Elongation (Extensometer)	21.31	%
Elongation (LVDT)	N/A	%
Elongation (Calipers)	21.30	%
Reduction in Area	63.74	%

C.2. Data Sheet Tab

This tab titled "Data Sheet" provided a location to enter initial and final dimensional characteristics. It averaged the triple measurements and calculated elongation and reduction in area ductility parameters. The user simply entered the requested information in the yellow cells, and the spreadsheet performed the calculations. The ductility parameters were output to the Test Summary table on the "Time, M&TE" tab.

User instructions were provided for data entry.

Instructions: Enter data in all yellow fields.

Specimen ID	2054S61	
Testing Temperature (deg. C)	400	
Extensometer (Laser or Ceramic)	Type	Laser
Initial Diameter (in.) (3 measurements in middle 25%)	D_1	0.2510
	D_2	0.2511
	D_3	0.2510
	$\mathbf{D_0}$	**0.2510**
	$\mathbf{Area_0}$	**0.04949**
Initial Specimen Length (in.) (3 measurements, end to end)	L_1	4.0035
	L_2	4.0045
	L_3	4.0040
	$\mathbf{L_0}$	**4.0040**
Initial Extensometer Length (Cold) (in.) (must be between 0.930" and 0.970"	Lext_cold	0.9627
At Temperature	**Lext_hot**	**0.9660**

Final Diameter (in.) (3 measurements at broken end)	D_{f1}	0.1510
	D_{f2}	0.1510
	D_{f3}	0.1515
	$\mathbf{D_f}$	**0.1512**
	$\mathbf{Area_f}$	**0.0179**
Final Specimen Length (in.) (3 measurements, end to end)	L_{f1}	4.2170
	L_{f2}	4.2170
	L_{f3}	4.2170
	$\mathbf{L_f}$	**4.2170**
Final Extensometer Length (in.)	$\mathbf{L_{extf}}$	**1.1719**
Elongation (Extensometer)		**0.2131**
Elongation (Calipers)		**0.2130**
Reduction in Area		**0.6374**

C.3. UTS & YS Tab

This tab, titled "UTS & YS," provided a location to input the MTS output files. It provided a stress-strain curve and is used to extract the ultimate tensile strength (UTS) and yield strength (YS). Generally on a stress-strain curve, the yield point is found on a gradual sweep, making it difficult to distinguish the exact location along the curve for yielding. For this a 0.2% offset is used to define the yield point. This is usually performed by visual inspection, subjecting this mechanical property to human error. To mitigate human error effects, this spreadsheet template incorporated an algorithm to systematically extract the yield point, providing repeatable results. Instructions were provided to the user to aid with data reduction.

The yield strength was determined by a 0.2% offset. To do this, the spreadsheet tab performed a linear curve fit of the elastic region of the data with a 0.2% positive shift along the x-axis. To represent the elastic-plastic transition, a second-order curve fit was performed. The curve fit polynomial equations were provided on a second graph. The user was then able to enter the polynomial coefficients, and an algorithm determined the yield strength, based on the numerical intersection of these two polynomial equations. Portions of the spreadsheet have been moved to fit the physical page constraints of this document.

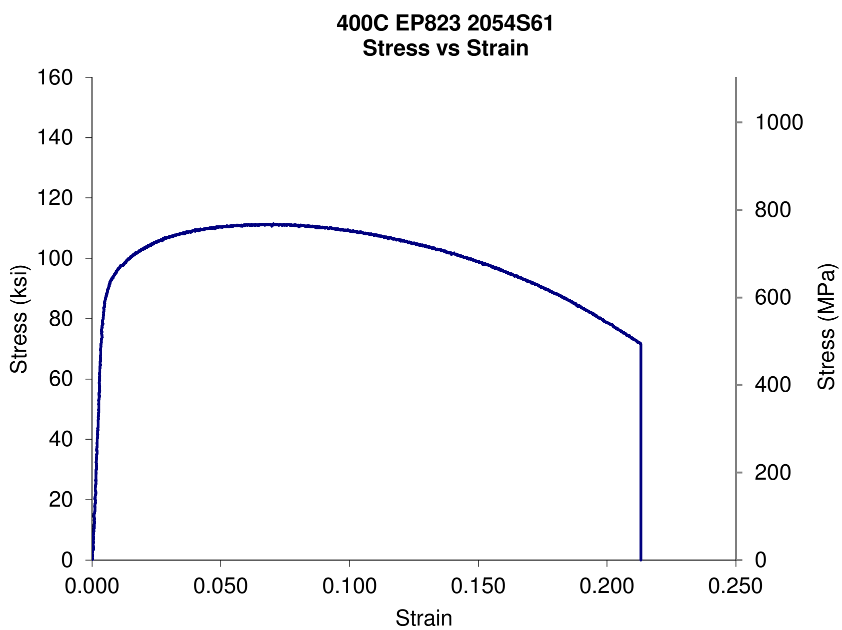
User instructions were provided for data entry.

Instructions		
	1	Copy data and start at row 110
	2	Find beginning of test and enter initial displacement
	3	Enter diameter
	4	Adjust plot series and UTS range
	5	Create trend lines.
	6	Enter coefficients

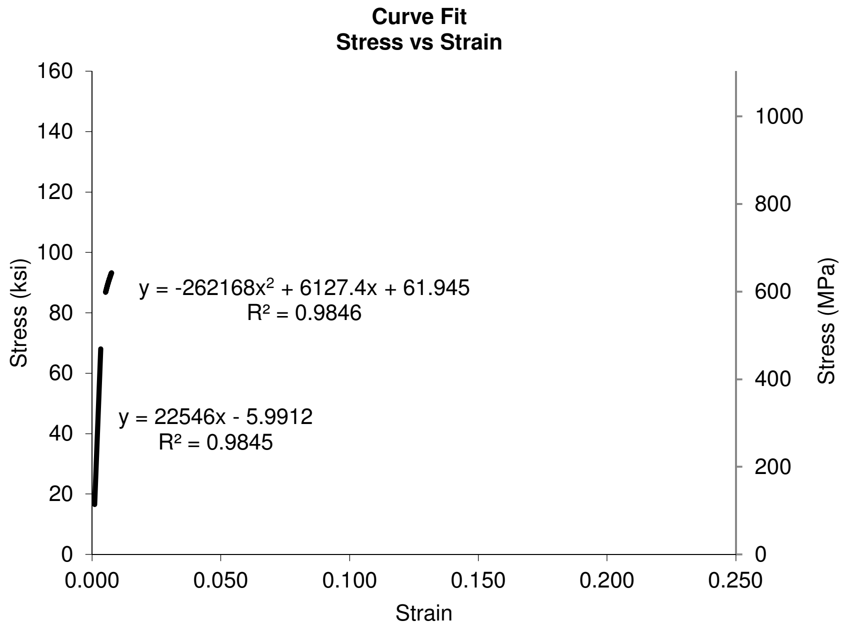
The data file was pasted into the spreadsheet. For this example most data was removed for brevity. Strain and stress data was calculated for each data point.

Time	Displacement	Load Cell	Laser Extens	tempsensor	Strain	Stress
Sec	in	lbf	in	deg_C		psi
7.817400	0.157041	6.779543	0.965992	407.5472	0.00E+00	0.136977
7.9176	0.157041	10.56985	0.966129	407.5127	1.43E-04	0.213558
8.017599	0.157386	10.91442	0.966129	407.5127	1.43E-04	0.22052
8.1176	0.157386	13.67101	0.96606	407.5472	7.13E-05	0.276216
8.217599	0.157558	16.4276	0.965992	407.5472	0.00E+00	0.331911
8.317599	0.157558	16.4276	0.965992	407.5472	0.00E+00	0.331911
8.4176	0.157386	19.52876	0.96606	407.5816	7.13E-05	0.394568
8.517599	0.157558	19.52876	0.96606	407.5472	7.13E-05	0.394568
8.6176	0.157558	22.28535	0.965992	407.5127	0.00E+00	0.450264
8.717599	0.157731	24.69736	0.965992	407.4782	0.00E+00	0.498997
8.817599	0.157903	31.58883	0.96606	407.4438	7.13E-05	0.638236
8.9176	0.157731	31.93341	0.96606	407.4093	7.13E-05	0.645198
<Data>	<Data>	<Data>	<Data>	<Data>	<Data>	<Data>

An engineering stress-strain curve was generated, based on the output data, factored with the initial gage length and initial diameter.

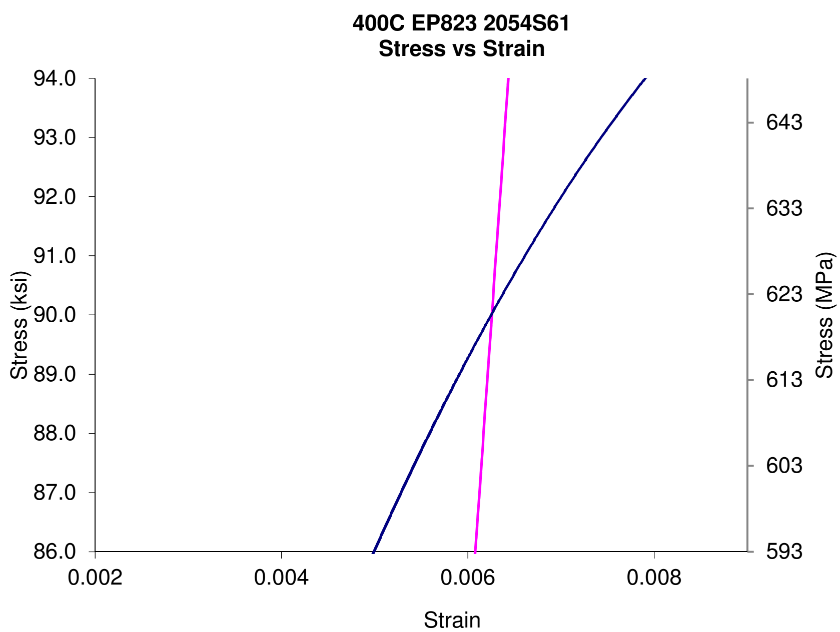


A linear regression of the elastic region of the data was generated. To represent the elastic-plastic transition, a second-order curve fit was performed. The polynomial coefficients were presented on the graph.

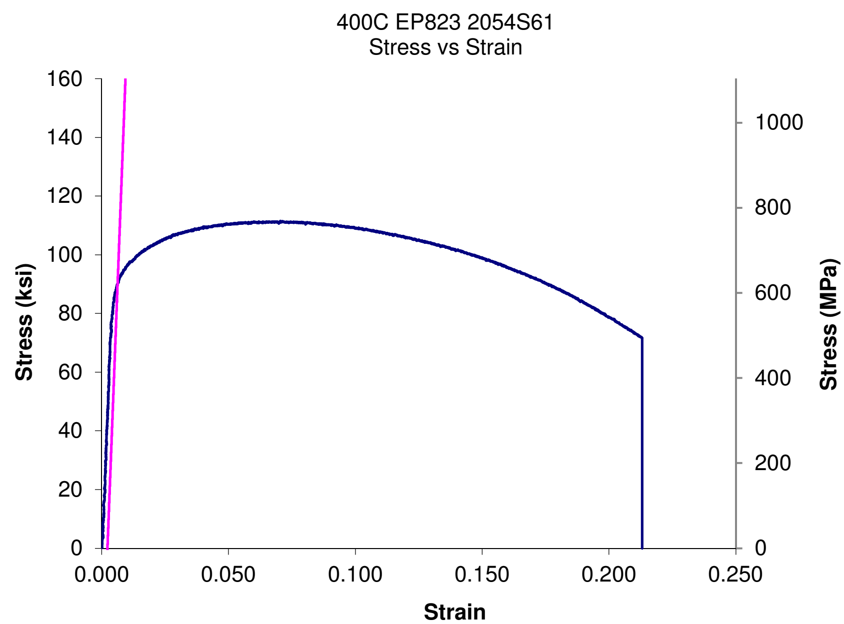


The coefficients of the polynomial equations were entered and used by the spreadsheet to determine the numerical intersection of the offset line and the elastic-plastic transition. Although the yield strength was calculated, a graphical representation of the polynomial equations was generated as a feasibility check for the user.

Coefficients			
m	22546	Ca	-262168
b	-5.9912	Cb	6127.4
offset	0.20%	Cc	61.945



For a final output, an engineering stress-strain curve with 0.2% offset line was generated, based on the output MTS machine data, factored with the initial gage length and diameter. The offset line was generated by the polynomial equation determined earlier, with a positive 0.2% shift along the x-axis. UTS and YS are presented and then output to the Test Summary table on the "Time, M&TE" tab.



Initial Disp	0.965992	in
Final Disp	1.171884	in
Dia	0.2510	in
Area	0.0495	in^2
UTS	111.5	ksi
YS	90.0	ksi

C.4. LVDT Correction Tab

This final tab, titled "LVDT Correction," provided an algorithm to condition the LVDT strain to remove the effect of system compliance. The spreadsheet used two second-order polynomials that represent the relationship between LVDT strain data and laser extensometer strain data. The method for this determination is provided in Section 3.4.8. The LVDT data was processed through these equations to output the corrected LVDT data set. Section 3.4.8 also provides a demonstration and details.

User instructions were provided for data entry.

Instructions

1 Drag the "Strain, LVDT" formula to the end of the data set.
2 Find the yield point through inspection and the corresponding "Strain, LVDT" data point.
3 Drag the "Strain, Corrected LVDT" Elastic Region formula (green) to the yield point.
4 Drag the "Strain, Corrected LVDT" Plastic Region formula (red) from the yield point to the end of the data set

The correction polynomial equation coefficients were listed and used for data conditioning.

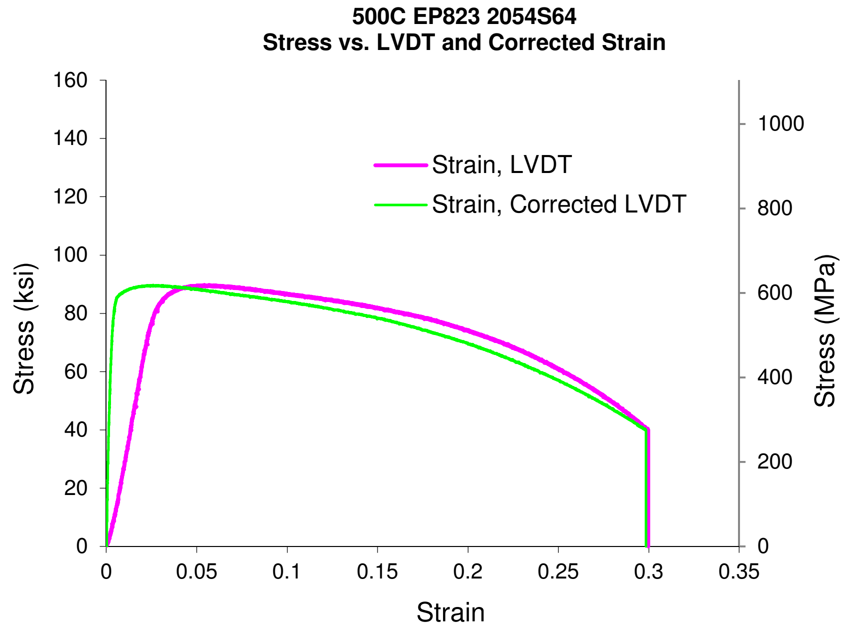
Elastic Range	
Correction Factor (2)	4.65637
Correction Factor (m)	0.02327
Correction Factor (b)	0.00018
Plastic Range	
Correction Factor (2)	0.73387
Correction Factor (m)	0.85160
Correction Factor (b)	-0.02270

The uncorrected LVDT strain data is copied from the "UTS & YS" tab. The spreadsheet plotted this data to aid with visually determining a yield point estimate. The elastic response correction equation is embedded in the cells with green font. This cell was dragged or copied to the strain value associated with yielding. The plastic response correction equation is embedded in the cells

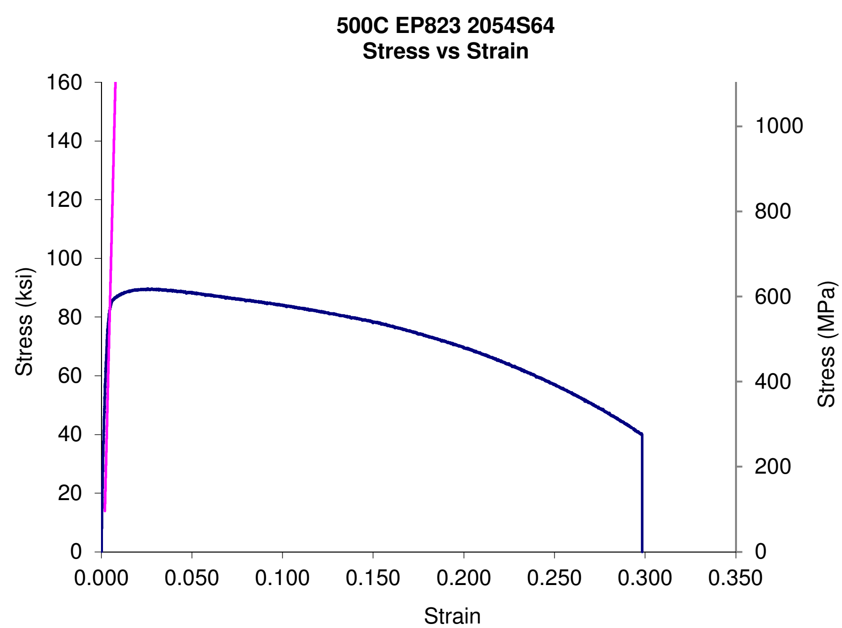
with red font. This cell was dragged or copied from the strain value associated with yielding to the data end. For brevity most data was removed.

Strain, LVDT	Strain, Corrected LVDT	
0	0.000183333	Elastic Region
0	0.000183333	
-0.000172347	0.000179462	
0.000172339	0.000187481	
0	0.000183333	
0	0.000183333	
0	0.000183333	
0	0.000183333	
0.000517033	0.000196608	
0.000517033	0.000196608	
<Data>	<Data>	
…	…	
<Data>	<Data>	
0.032573472	0.005881759	
0.032573472	0.005881759	
0.032573472	0.005818224	Plastic Region
0.032918172	0.006128338	
0.032918172	0.006128338	
0.032918172	0.006128338	
0.032745822	0.005973259	
0.032918172	0.006128338	
0.032918172	0.006128338	
0.032918172	0.006128338	
<Data>	<Data>	

The corrected LVDT plot was then displayed with the unprocessed data to show the data shift.



This data was automatically plotted on the “UTS & YS” tab to execute the yield strength determination algorithm (appendix Section C.3). The following is the final plot.



An at-a-glance summary of results was provided on the summary tab "Time, M&TE."

Test Summary		
UTS	89.7	ksi
YS	84.6	ksi
Elongation (Extensometer)	N/A	%
Elongation (LVDT)	29.85	%
Elongation (Calipers)	29.08	%
Reduction in Area	76.46	%

APPENDIX D:

TEMPERING TIME: 1.25 HOURS

This section provides mechanical properties and test data for “2054S” series EP-823 specimens that are tempered for 1.25 hours at 621°C (1150°F).

D.1. Room Temperature Tests (2054S)

Material:	EP-823
Heat Number:	2054S

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 1.25 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature:	Room Temperature
Extensometer Type:	Laser Extensometer

Abbreviations used below:

- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

Testing Temperature:	Room Temperature
Specimen ID:	2054S50

Diameter

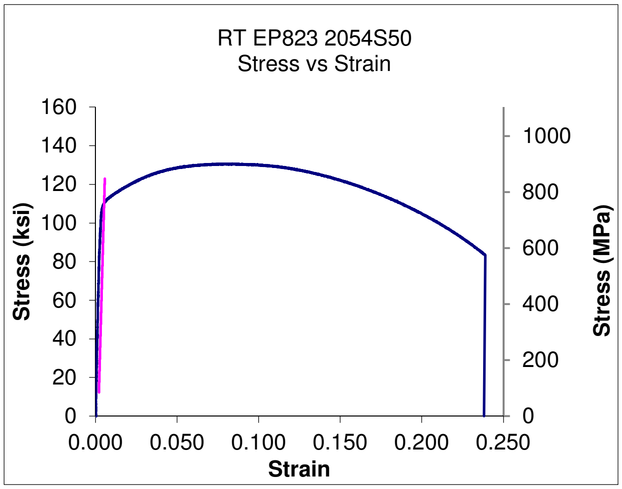
- D_o: 0.2512 in. (6.38 mm)
- D_f : 0.1537 in. (3.90 mm)

Overall Length (Calipers)

- OAL_o: 4.0055 in. (101.74 mm)
- OAL_f: 4.2410 in. (107.72 mm)

Length (Laser Extensometer)

- L_o: 0.9526 in. (24.20 mm)
- L_f: 1.1802 in. (29.98 mm)



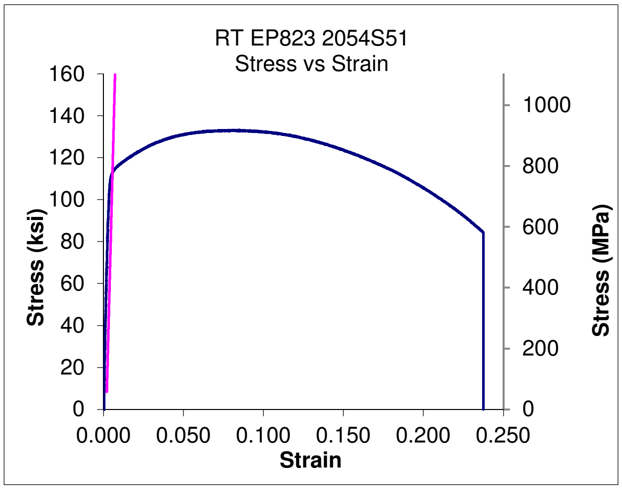
Elongation (Laser Ext.):	23.89 %
Elongation (Calipers):	23.55 %
Reduction in Area:	62.59 %
Ultimate Tensile Strength:	130.7 ksi (901.1 MPa)
Yield Strength:	110.0 ksi (758.4 MPa)

Testing Temperature: Room Temperature
Specimen ID: 2054S51

Diameter
- D_o: 0.2507 in. (6.37 mm)
- D_f : 0.1517 in. (3.85 mm)

Overall Length (Calipers)
- OAL_o: 4.0043 in. (101.71 mm)
- OAL_f: 4.2390 in. (107.67 mm)

Length (Laser Extensometer)
- L_o: 0.9515 in. (24.17 mm)
- L_f: 1.1775 in. (29.91 mm)



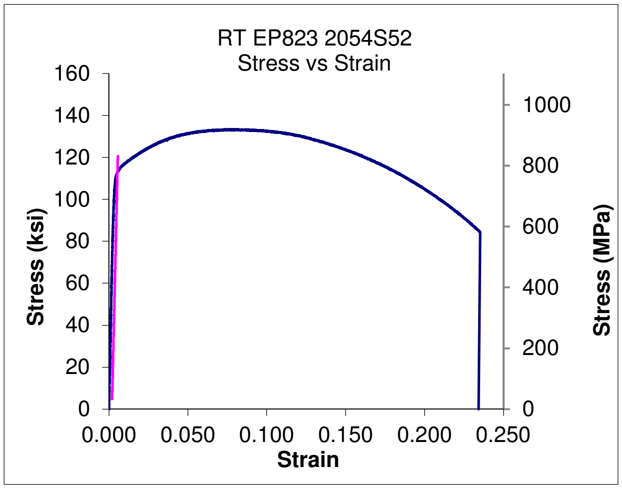
Elongation (Laser Ext.): 23.75 %
Elongation (Calipers): 23.47 %
Reduction in Area: 63.40 %
Ultimate Tensile Strength: 133.2 ksi (918.4 MPa)
Yield Strength: 112.8 ksi (777.7 MPa)

Testing Temperature: Room Temperature
Specimen ID: 2054S52

Diameter
- D_o: 0.2511 in. (6.38 mm)
- D_f : 0.1485 in. (3.77 mm)

Overall Length (Calipers)
- OAL_o: 4.0038 in. (101.70 mm)
- OAL_f: 4.2477 in. (107.89 mm)

Length (Laser Extensometer)
- L_o: 0.9688 in. (24.61 mm)
- L_f: 1.1968 in. (30.40 mm)



Elongation (Laser Ext.): 23.54 %
Elongation (Calipers): 24.38 %
Reduction in Area: 65.02 %
Ultimate Tensile Strength: 133.4 ksi (919.8 MPa)
Yield Strength: 112.8 ksi (777.7 MPa)

D.2. 100°C Tests (2054S)

Material: EP-823
Heat Number: 2054S

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 1.25 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: 100°C
Extensometer Type: Laser Extensometer

Abbreviations used below:

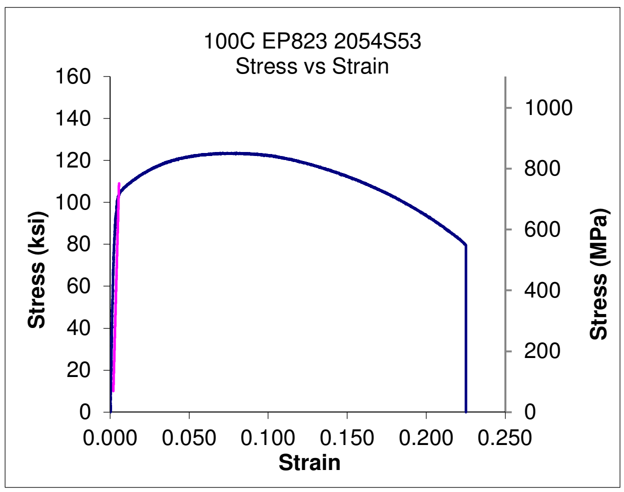
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

<u>Testing Temperature: 100°C</u>
Specimen ID: 2054S53

Diameter
- D_o: 0.2509 in. (6.37 mm)
- D_f : 0.1508 in. (3.83 mm)

Overall Length (Calipers)
- OAL_o: 4.0063 in. (101.76 mm)
- OAL_f: 4.2305 in. (107.45 mm)

Length (Laser Extensometer)
- L_o: 0.9626 in. (24.45 mm)
- L_f: 1.1793 in. (29.95 mm)



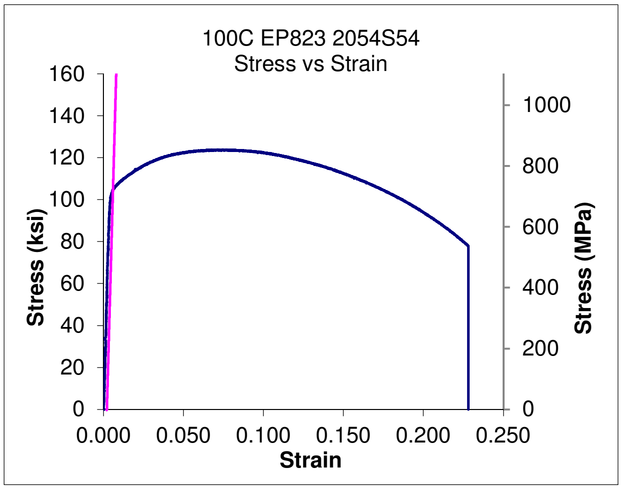
Elongation (Laser Ext.): 22.51 %
Elongation (Calipers): 22.42 %
Reduction in Area: 63.85 %
Ultimate Tensile Strength: 123.6 ksi (852.2 MPa)
Yield Strength: 103.5 ksi (713.6 MPa)

Testing Temperature: 100°C
Specimen ID: 2054S54

Diameter
D_o: 0.2513 in. (6.38 mm)
D_f : 0.1517 in. (3.85 mm)

Overall Length (Calipers)
OAL_o: 4.0065 in. (101.77 mm)
OAL_f: 4.2313 in. (107.47 mm)

Length (Laser Extensometer)
L_o: 0.9501 in. (24.13 mm)
L_f: 1.1668 in. (29.64 mm)



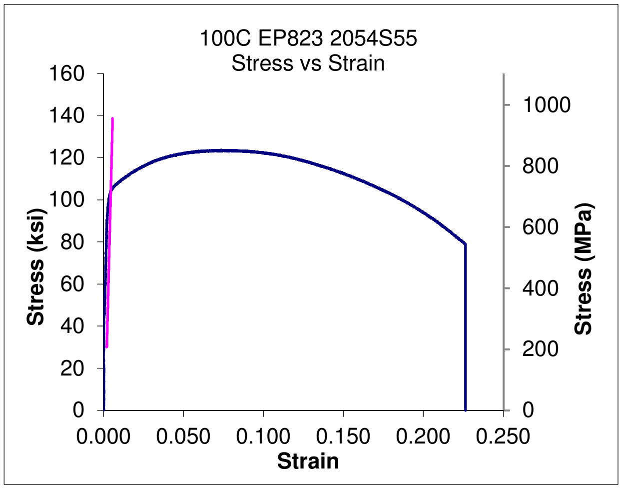
Elongation (Laser Ext.): 22.80 %
Elongation (Calipers): 22.48 %
Reduction in Area: 63.57 %
Ultimate Tensile Strength: 123.8 ksi (853.6 MPa)
Yield Strength: 104.5 ksi (720.5 MPa)

Testing Temperature: 100°C
Specimen ID: 2054S55

Diameter
D_o: 0.2508 in. (6.37 mm)
D_f : 0.1515 in. (3.85 mm)

Overall Length (Calipers)
OAL_o: 4.0037 in. (101.69 mm)
OAL_f: 4.2308 in. (107.46 mm)

Length (Laser Extensometer)
L_o: 0.9600 in. (24.38 mm)
L_f: 1.1773 in. (29.90 mm)



Elongation (Laser Ext.): 22.64 %
Elongation (Calipers): 22.72 %
Reduction in Area: 63.50 %
Ultimate Tensile Strength: 123.6 ksi (852.2 MPa)
Yield Strength: 104.0 ksi (717.1 MPa)

D.3. 300°C Tests (2054S)

Material: EP-823
Heat Number: 2054S

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 1.25 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: 300°C
Extensometer Type: Laser Extensometer

Abbreviations used below:

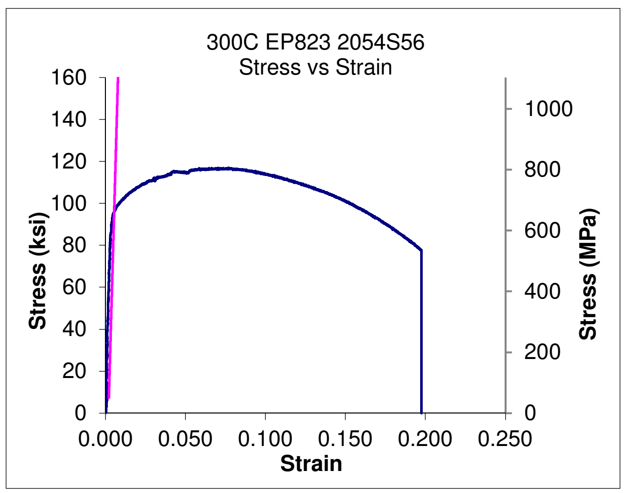
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

Testing Temperature: 300°C
Specimen ID: 2054S56

Diameter
- D_o: 0.2512 in. (6.38 mm)
- D_f : 0.1563 in. (3.97 mm)

Overall Length (Calipers)
- OAL_o: 4.0042 in. (101.71 mm)
- OAL_f: 4.2063 in. (106.84 mm)

Length (Laser Extensometer)
- L_o: 0.9645 in. (24.50 mm)
- L_f: 1.1549 in. (29.33 mm)



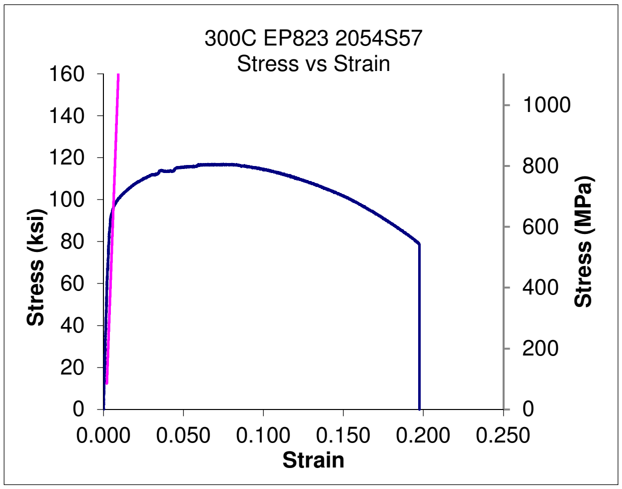
Elongation (Laser Ext.): 19.75 %
Elongation (Calipers): 20.22 %
Reduction in Area: 61.26 %
Ultimate Tensile Strength: 116.8 ksi (805.3 MPa)
Yield Strength: 95.9 ksi (661.2 MPa)

Testing Temperature: 300°C
Specimen ID: 2054S57

Diameter
D_o: 0.2512 in. (6.38 mm)
D_f : 0.1540 in. (3.91 mm)

Overall Length (Calipers)
OAL_o: 4.0037 in. (101.69 mm)
OAL_f: 4.2035 in. (106.77 mm)

Length (Laser Extensometer)
L_o: 0.9700 in. (24.64 mm)
L_f: 1.1615 in. (29.50 mm)



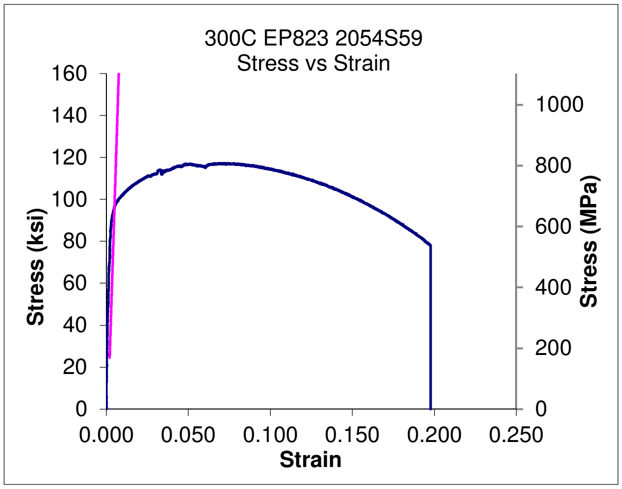
Elongation (Laser Ext.): 19.74 %
Elongation (Calipers): 19.98 %
Reduction in Area: 62.42 %
Ultimate Tensile Strength: 116.9 ksi (806.0 MPa)
Yield Strength: 96.2 ksi (663.3 MPa)

Testing Temperature: 300°C
Specimen ID: 2054S59

Diameter
D_o: 0.2510 in. (6.38 mm)
D_f : 0.1528 in. (3.88 mm)

Overall Length (Calipers)
OAL_o: 4.0060 in. (101.75 mm)
OAL_f: 4.2035 in. (106.77 mm)

Length (Laser Extensometer)
L_o: 0.9572 in. (24.31 mm)
L_f: 1.1465 in. (29.12 mm)



Elongation (Laser Ext.): 19.78 %
Elongation (Calipers): 19.75 %
Reduction in Area: 62.93 %
Ultimate Tensile Strength: 117.2 ksi (808.1 MPa)
Yield Strength: 96.2 ksi (663.3 MPa)

D.4. 400°C Tests (2054S)

Material: EP-823
Heat Number: 2054S

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 1.25 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: 400°C
Extensometer Type: Laser Extensometer

Abbreviations used below:

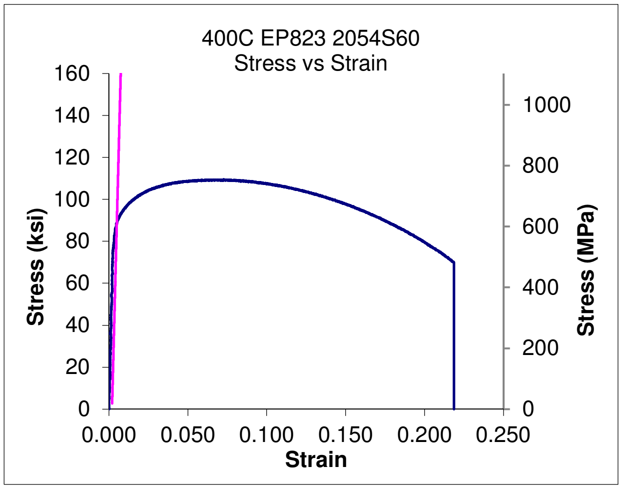
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

Testing Temperature: 400°C
Specimen ID: 2054S60

Diameter
- D_o: 0.2515 in. (6.39 mm)
- D_f : 0.1527 in. (3.88 mm)

Overall Length (Calipers)
- OAL_o: 4.0035 in. (101.69 mm)
- OAL_f: 4.2260 in. (107.34 mm)

Length (Laser Extensometer)
- L_o: 0.9680 in. (24.59 mm)
- L_f: 1.1796 in. (29.96 mm)



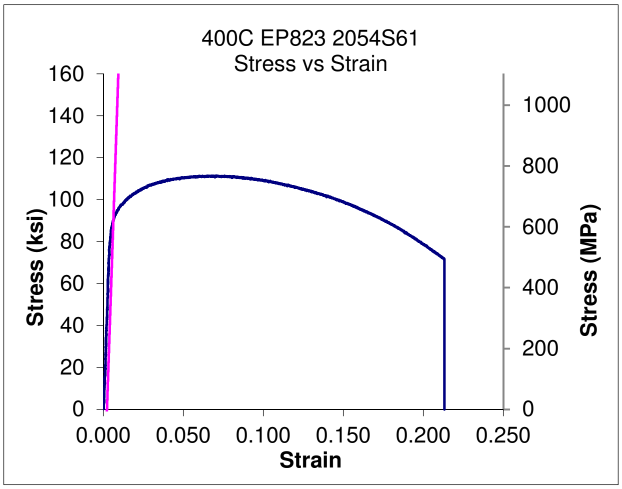
Elongation (Laser Ext.): 21.86 %
Elongation (Calipers): 22.25 %
Reduction in Area: 63.15 %
Ultimate Tensile Strength: 109.4 ksi (754.3 MPa)
Yield Strength: 88.6 ksi (610.9 MPa)

Testing Temperature: 400°C
Specimen ID: 2054S61

Diameter
D_o: 0.2510 in. (6.38 mm)
D_f : 0.1512 in. (3.84 mm)

Overall Length (Calipers)
OAL_o: 4.0040 in. (101.70 mm)
OAL_f: 4.2170 in. (107.11 mm)

Length (Laser Extensometer)
L_o: 0.9660 in. (24.54 mm)
L_f: 1.1719 in. (29.77 mm)



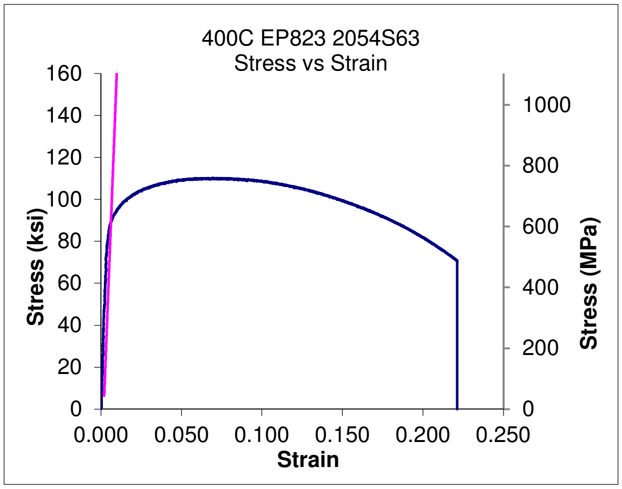
Elongation (Laser Ext.): 21.31 %
Elongation (Calipers): 21.30 %
Reduction in Area: 63.74 %
Ultimate Tensile Strength: 111.5 ksi (768.8 MPa)
Yield Strength: 90.0 ksi (620.5 MPa)

Testing Temperature: 400°C
Specimen ID: 2054S63

Diameter
D_o: 0.2513 in. (6.38 mm)
D_f : 0.1527 in. (3.88 mm)

Overall Length (Calipers)
OAL_o: 4.0043 in. (101.71 mm)
OAL_f: 4.2240 in. (107.29 mm)

Length (Laser Extensometer)
L_o: 0.9679 in. (24.58 mm)
L_f: 1.1821 in. (30.03 mm)



Elongation (Laser Ext.): 22.13 %
Elongation (Calipers): 21.97 %
Reduction in Area: 63.09 %
Ultimate Tensile Strength: 110.2 ksi (759.8 MPa)
Yield Strength: 89.2 ksi (615.0 MPa)

D.5. 500°C Tests (2054S)

Material: EP-823
Heat Number: 2054S

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 1.25 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: 500°C
Displacement Measuring Device: LVDT (Linear Variable Differential Transducer)

Abbreviations used below:

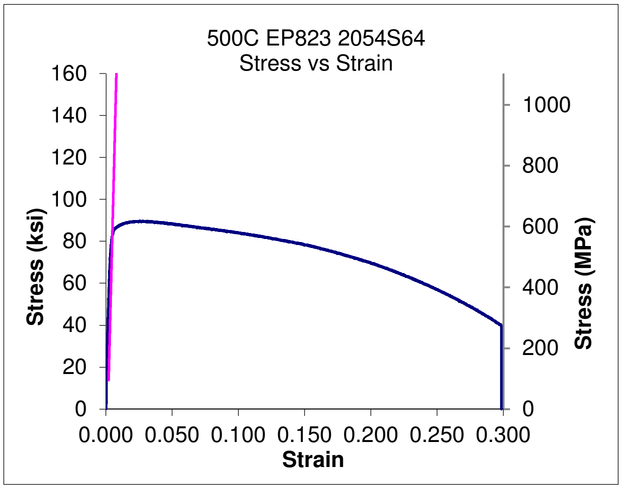
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

Testing Temperature: 500°C
Specimen ID: 2054S64

Diameter
- D_o: 0.2511 in. (6.38 mm)
- D_f: 0.1218 in. (3.09 mm)

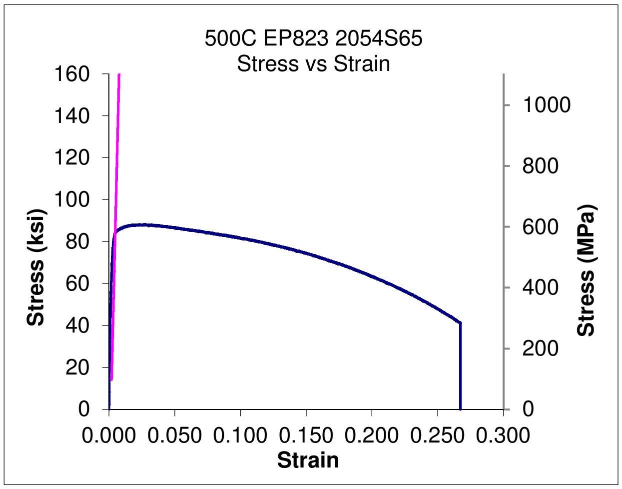
Overall Length (Calipers)
- OAL_o: 4.0032 in. (101.68 mm)
- OAL_f: 4.2940 in. (109.07 mm)

Length (Laser Extensometer)
- L_o: N/A
- L_f: N/A



Elongation (Laser Ext.): N/A
Elongation (Calipers): 29.08 %
Reduction in Area: 76.46 %
Ultimate Tensile Strength: 89.7 ksi (618.5 MPa)
Yield Strength: 84.6 ksi (583.3 MPa)

Testing Temperature: 500°C
Specimen ID: 2054S65



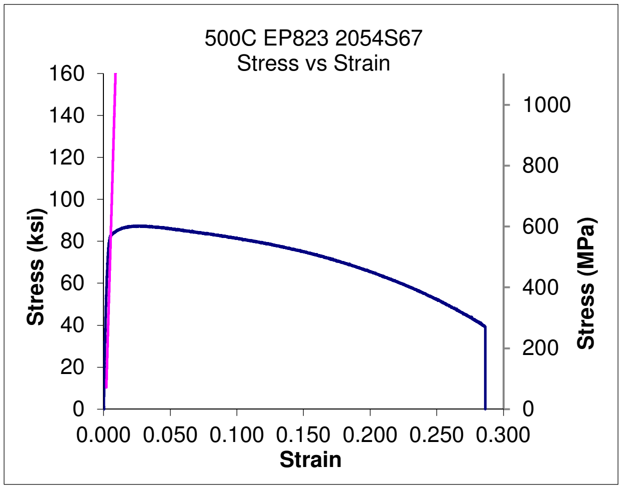
Diameter
- D_o: 0.2507 in. (6.37 mm)
- D_f : 0.1250 in. (3.18 mm)

Overall Length (Calipers)
- OAL_o: 4.0037 in. (101.69 mm)
- OAL_f: 4.2728 in. (108.53 mm)

Length (Laser Extensometer)
- L_o: N/A
- L_f: N/A

Elongation (Laser Ext.): N/A
Elongation (Calipers): 26.92 %
Reduction in Area: 75.15 %
Ultimate Tensile Strength: 88.1 ksi (617.4 MPa)
Yield Strength: 83.7 ksi (577.1 MPa)

Testing Temperature: 500°C
Specimen ID: 2054S67



Diameter
- D_o: 0.2513 in. (6.38 mm)
- D_f : 0.1260 in. (3.20 mm)

Overall Length (Calipers)
- OAL_o: 4.0045 in. (101.71 mm)
- OAL_f: 4.2850 in. (108.84 mm)

Length (Laser Extensometer)
- L_o: N/A
- L_f: N/A

Elongation (Laser Ext.): N/A
Elongation (Calipers): 28.05 %
Reduction in Area: 74.86 %
Ultimate Tensile Strength: 87.4 ksi (602.6 MPa)
Yield Strength: 82.6 ksi (569.5 MPa)

D.6. 600°C Tests (2054S)

Material: EP-823
Heat Number: 2054S

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 1.25 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: 600°C
Displacement Measuring Device: LVDT (Linear Variable Differential Transducer)

Abbreviations used below:

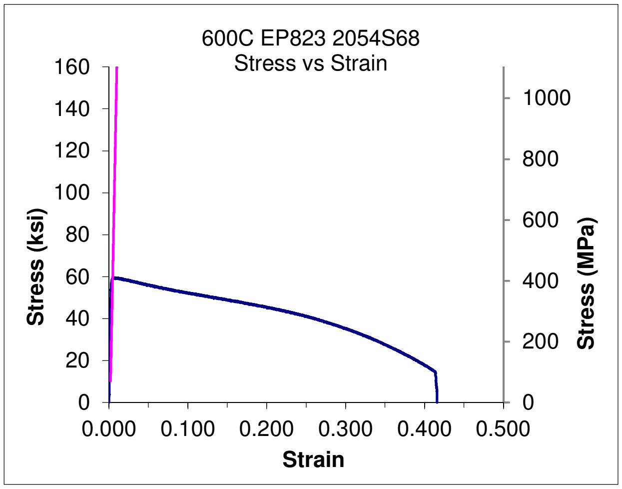
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

Testing Temperature: 600°C
Specimen ID: 2054S68

Diameter
- D_o: 0.2521 in. (6.40 mm)
- D_f : 0.0895 in. (2.27 mm)

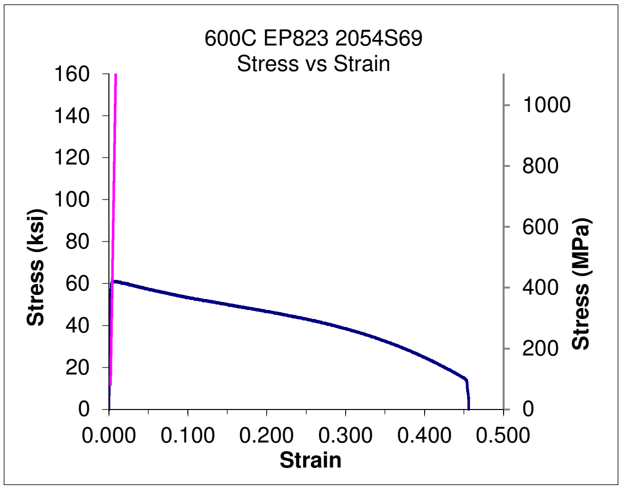
Overall Length (Calipers)
- OAL_o: 4.0028 in. (101.67 mm)
- OAL_f: 4.4250 in. (112.40 mm)

Length (Laser Extensometer)
- L_o: N/A
- L_f: N/A



Elongation (Laser Ext.): N/A
Elongation (Calipers): 42.22 %
Reduction in Area: 87.40 %
Ultimate Tensile Strength: 59.5 ksi (410.2 MPa)
Yield Strength: 59.0 ksi (406.8 MPa)

Testing Temperature: 600°C
Specimen ID: 2054S69



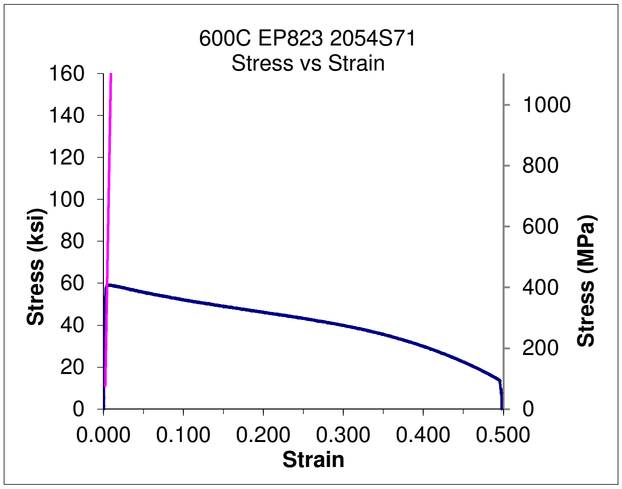
Diameter
- D_o: 0.2519 in. (6.40 mm)
- D_f : 0.0873 in. (2.22 mm)

Overall Length (Calipers)
- OAL_o: 4.0013 in. (101.63 mm)
- OAL_f: 4.4550 in. (113.16 mm)

Length (Laser Extensometer)
- L_o: N/A
- L_f: N/A

Elongation (Laser Ext.): N/A
Elongation (Calipers): 45.37 %
Reduction in Area: 87.98 %
Ultimate Tensile Strength: 61.1 ksi (421.3 MPa)
Yield Strength: 61.0 ksi (420.6 MPa)

Testing Temperature: 600°C
Specimen ID: 2054S71



Diameter
- D_o: 0.2507 in. (6.37 mm)
- D_f : 0.0863 in. (2.19 mm)

Overall Length (Calipers)
- OAL_o: 4.0027 in. (101.67 mm)
- OAL_f: 4.4890 in. (114.02 mm)

Length (Laser Extensometer)
- L_o: N/A
- L_f: N/A

Elongation (Laser Ext.): N/A
Elongation (Calipers): 48.63 %
Reduction in Area: 88.14 %
Ultimate Tensile Strength: 59.2 ksi (408.2 MPa)
Yield Strength: 59.0 ksi (406.8 MPa)

APPENDIX E :

TEMPERING TIME: 1.75 HOURS

This section provides mechanical properties and test data for “2054T” series EP-823 specimens that are tempered for 1.75 hours at 621°C (1150°F).

E.1. Room Temperature Tests (2054T)

Material: EP-823
Heat Number: 2054T

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 1.75 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: Room Temperature
Extensometer Type: Laser Extensometer

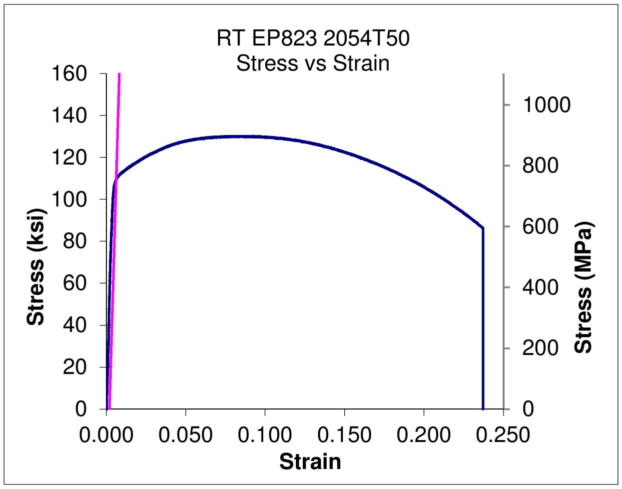
Abbreviations used below:
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

<u>Testing Temperature: Room Temperature</u>
Specimen ID: 2054T50

Diameter
- D_o: 0.2513 in. (6.38 mm)
- D_f : 0.1553 in. (3.94 mm)

Overall Length (Calipers)
- OAL_o: 4.0045 in. (101.71 mm)
- OAL_f: 4.2630 in. (108.28 mm)

Length (Laser Extensometer)
- L_o: 0.9583 in. (24.34 mm)
- L_f: 1.1856 in. (30.11 mm)



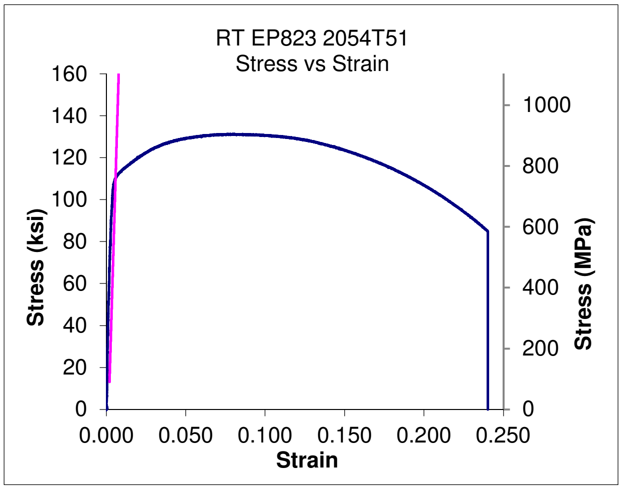
Elongation (Laser Ext.): 23.72 %
Elongation (Calipers): 23.85 %
Reduction in Area: 61.79 %
Ultimate Tensile Strength: 130.2 ksi (897.7 MPa)
Yield Strength: 108.9 ksi (750.8 MPa)

Testing Temperature: Room Temperature
pecimen ID: 2054T51

Diameter
D_o: 0.2506 in. (6.37 mm)
D_f : 0.1527 in. (3.88 mm)

Overall Length (Calipers)
OAL_o: 4.0047 in. (101.72 mm)
OAL_f: 4.2582 in. (108.16 mm)

Length (Laser Extensometer)
L_o: 0.9636 in. (24.48 mm)
L_f: 1.1952 in. (30.36 mm)



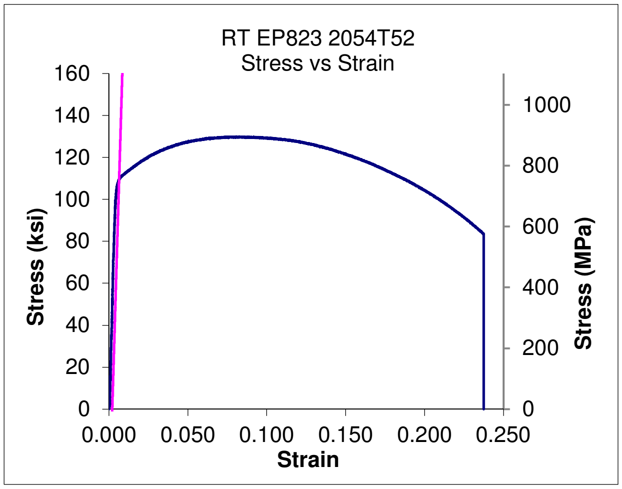
Elongation (Laser Ext.): 24.03 %
Elongation (Calipers): 23.35 %
Reduction in Area: 62.88 %
Ultimate Tensile Strength: 131.3 ksi (905.3 MPa)
Yield Strength: 109.7 ksi (756.4 MPa)

Testing Temperature: Room Temperature
Specimen ID: 2054T52

Diameter
D_o: 0.2506 in. (6.37 mm)
D_f : 0.1535 in. (3.90 mm)

Overall Length (Calipers)
OAL_o: 4.0047 in. (101.72 mm)
OAL_f: 4.2408 in. (107.72 mm)

Length (Laser Extensometer)
L_o: 0.9666 in. (24.55 mm)
L_f: 1.1963 in. (30.39 mm)



Elongation (Laser Ext.): 23.76 %
Elongation (Calipers): 23.62 %
Reduction in Area: 62.47 %
Ultimate Tensile Strength: 129.9 ksi (985.6 MPa)
Yield Strength: 108.8 ksi (750.1 MPa)

E.2. 100°C Tests (2054T)

Material: EP-823
Heat Number: 2054T

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 1.75 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: 100°C Tests
Extensometer Type: Laser Extensometer

Abbreviations used below:

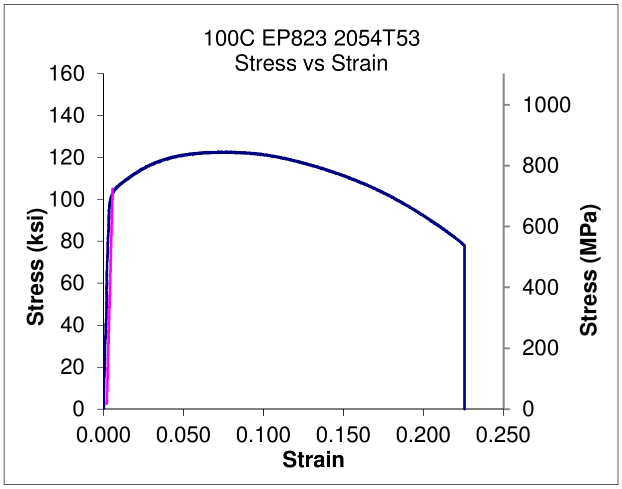
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

<u>Testing Temperature: 100°C</u>
Specimen ID: 2054T53

Diameter
- D_o: 0.2510 in. (6.38 mm)
- D_f : 0.1502 in. (3.82 mm)

Overall Length (Calipers)
- OAL_o: 4.0043 in. (101.71 mm)
- OAL_f: 4.2292 in. (107.42 mm)

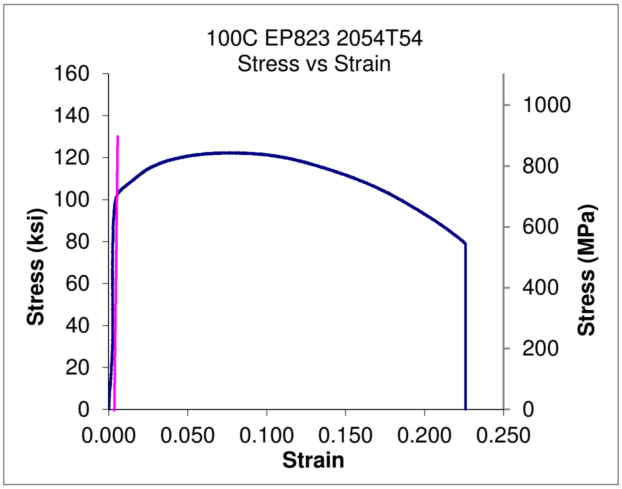
Length (Laser Extensometer)
- L_o: 0.9558 in. (24.28 mm)
- L_f: 1.1716 in. (29.76 mm)



Elongation (Laser Ext.): 22.58 %
Elongation (Calipers): 22.48 %
Reduction in Area: 64.20 %
Ultimate Tensile Strength: 122.7 ksi (846.0 MPa)
Yield Strength: 102.6 ksi (707.4 MPa)

Testing Temperature: 100°C
Specimen ID: 2054T54

Diameter
- D_o: 0.2513 in. (6.38 mm)
- D_f : 0.1515 in. (3.85 mm)



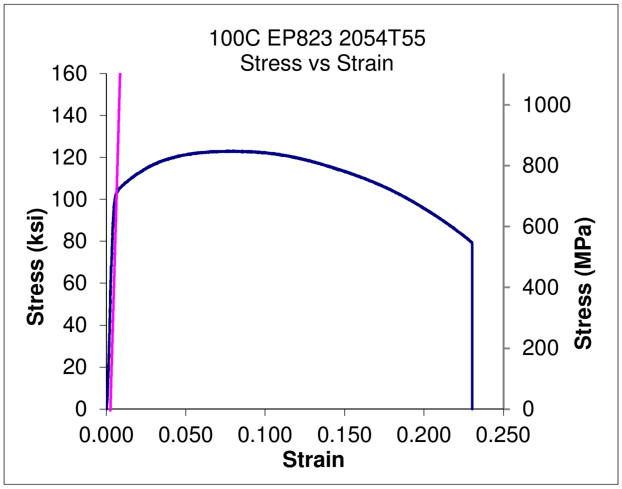
Overall Length (Calipers)
- OAL_o: 4.0050 in. (101.73 mm)
- OAL_f: 4.2285 in. (107.40 mm)

Length (Laser Extensometer)
- L_o: 0.9555 in. (24.27 mm)
- L_f: 1.1714 in. (29.75 mm)

Elongation (Laser Ext.): 22.59 %
Elongation (Calipers): 22.35 %
Reduction in Area: 63.66 %
Ultimate Tensile Strength: 122.5 ksi (844.6 MPa)
Yield Strength: 101.2 ksi (697.7 MPa)

Testing Temperature: 100°C
Specimen ID: 2054T55

Diameter
- D_o: 0.2510 in. (6.38 mm)
- D_f : 0.1520 in. (3.86 mm)



Overall Length (Calipers)
- OAL_o: 4.0045 in. (101.71 mm)
- OAL_f: 4.2308 in. (107.46 mm)

Length (Laser Extensometer)
- L_o: 0.9532 in. (24.21 mm)
- L_f: 1.1728 in. (29.79 mm)

Elongation (Laser Ext.): 23.05 %
Elongation (Calipers): 22.63 %
Reduction in Area: 63.33 %
Ultimate Tensile Strength: 123.1 ksi (848.7 MPa)
Yield Strength: 102.4 ksi (706.0 MPa)

E.3. 300°C Tests (2054T)

Material:	EP-823
Heat Number:	2054T

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 1.75 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature:	300°C Tests
Extensometer Type:	Laser Extensometer

Abbreviations used below:

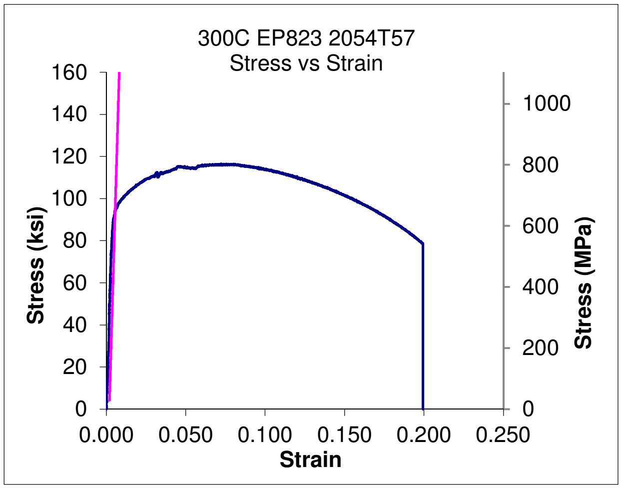
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

<u>Testing Temperature: 300°C</u>
Specimen ID: 2054T57

Diameter
- D_o: 0.2511 in. (6.38 mm)
- D_f : 0.1540 in. (3.91 mm)

Overall Length (Calipers)
- OAL_o: 4.0057 in. (101.74 mm)
- OAL_f: 4.2047 in. (106.80 mm)

Length (Laser Extensometer)
- L_o: 0.9529 in. (24.20 mm)
- L_f: 1.1428 in. (29.03 mm)



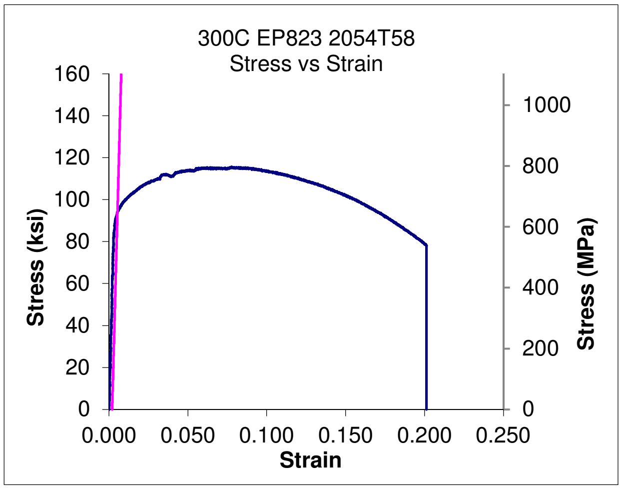
Elongation (Laser Ext.):	19.93 %
Elongation (Calipers):	19.90 %
Reduction in Area:	62.40 %
Ultimate Tensile Strength:	116.5 ksi (803.2 MPa)
Yield Strength:	93.7 ksi (646.0 MPa)

Testing Temperature: 300°C
Specimen ID: 2054T58

Diameter
- D_o: 0.2515 in. (6.39 mm)
- D_f: 0.1530 in. (3.89 mm)

Overall Length (Calipers)
- OAL_o: 4.0035 in. (101.69 mm)
- OAL_f: 4.2077 in. (106.88 mm)

Length (Laser Extensometer)
- L_o: 0.9665 in. (24.55 mm)
- L_f: 1.1611 in. (29.49 mm)



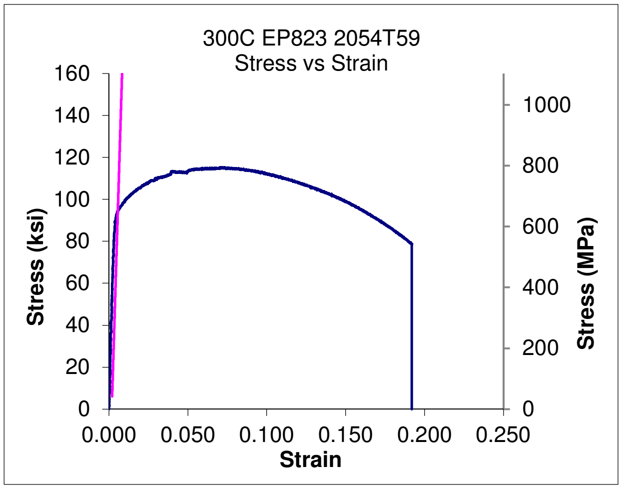
Elongation (Laser Ext.): 20.13 %
Elongation (Calipers): 20.42 %
Reduction in Area: 62.99 %
Ultimate Tensile Strength: 115.6 ksi (797.0 MPa)
Yield Strength: 93.7 ksi (646.0 MPa)

Testing Temperature: 300°C
Specimen ID: 2054T59

Diameter
- D_o: 0.2508 in. (6.37 mm)
- D_f: 0.1548 in. (3.93 mm)

Overall Length (Calipers)
- OAL_o: 4.0028 in. (101.67 mm)
- OAL_f: 4.2007 in. (106.70 mm)

Length (Laser Extensometer)
- L_o: 0.9610 in. (24.41 mm)
- L_f: 1.1455 in. (29.10 mm)



Elongation (Laser Ext.): 19.20 %
Elongation (Calipers): 19.78 %
Reduction in Area: 61.88 %
Ultimate Tensile Strength: 115.3 ksi (795.0 MPa)
Yield Strength: 94.2 ksi (649.5 MPa)

E.4. 400°C Tests (2054T)

Material: EP-823
Heat Number: 2054T

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 1.75 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: 400°C Tests
Extensometer Type: Laser Extensometer

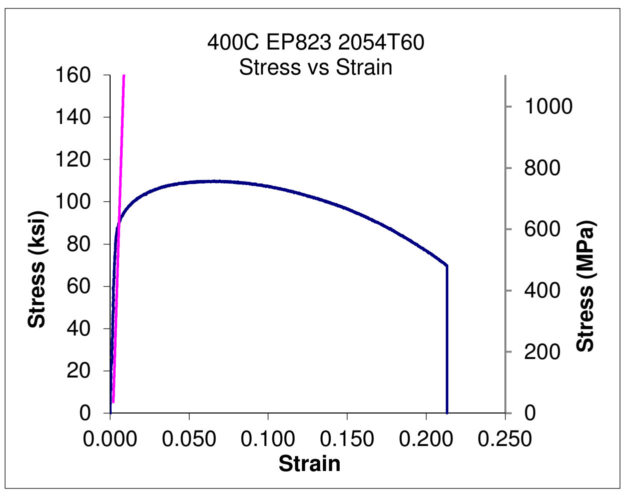
Abbreviations used below:
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

Testing Temperature: 400°C
Specimen ID: 2054T60

Diameter
- D_o: 0.2512 in. (6.38 mm)
- D_f : 0.1502 in. (3.82 mm)

Overall Length (Calipers)
- OAL_o: 4.0018 in. (101.65 mm)
- OAL_f: 4.2150 in. (107.06 mm)

Length (Laser Extensometer)
- L_o: 0.9566 in. (24.30 mm)
- L_f: 1.1604 in. (29.47 mm)



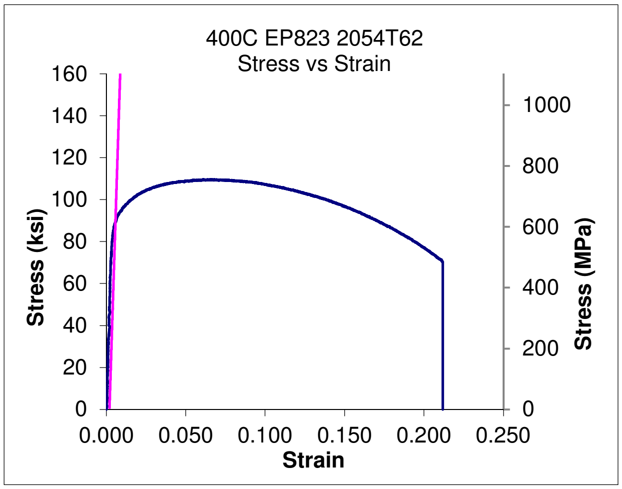
Elongation (Laser Ext.): 21.32 %
Elongation (Calipers): 21.32 %
Reduction in Area: 64.26 %
Ultimate Tensile Strength: 109.9 ksi (757.7 MPa)
Yield Strength: 89.9 ksi (619.8 MPa)

Testing Temperature: 400°C
Specimen ID: 2054T62

Diameter
D_o: 0.2509 in. (6.37 mm)
D_f : 0.1500 in. (3.81 mm)

Overall Length (Calipers)
OAL_o: 4.0035 in. (101.69 mm)
OAL_f: 4.2173 in. (107.12 mm)

Length (Laser Extensometer)
L_o: 0.9771 in. (24.82 mm)
L_f: 1.1840 in. (30.07 mm)



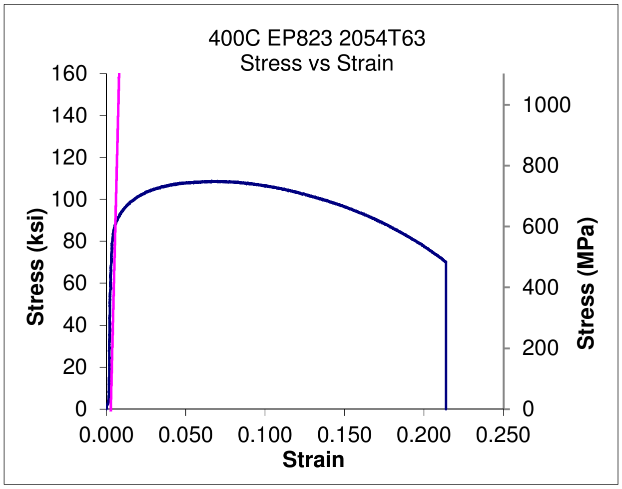
Elongation (Laser Ext.): 21.18 %
Elongation (Calipers): 21.38 %
Reduction in Area: 64.26 %
Ultimate Tensile Strength: 109.7 ksi (756.4 MPa)
Yield Strength: 89.3 ksi (615.7 MPa)

Testing Temperature: 400°C
Specimen ID: 2054T63

Diameter
D_o: 0.2516 in. (6.39 mm)
D_f : 0.1530 in. (3.82 mm)

Overall Length (Calipers)
OAL_o: 4.0065 in. (101.77 mm)
OAL_f: 4.2212 in. (107.22 mm)

Length (Laser Extensometer)
L_o: 0.9687 in. (24.60 mm)
L_f: 1.1760 in. (29.87 mm)



Elongation (Laser Ext.): 21.40 %
Elongation (Calipers): 21.47 %
Reduction in Area: 63.01 %
Ultimate Tensile Strength: 108.7 ksi (749.5 MPa)
Yield Strength: 88.1 ksi (607.4 MPa)

E.5. 500°C Tests (2054T)

Material: EP-823
Heat Number: 2054T

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 1.75 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: 500°C Tests
Displacement Measuring Device: LVDT (Linear Variable Differential Transducer)

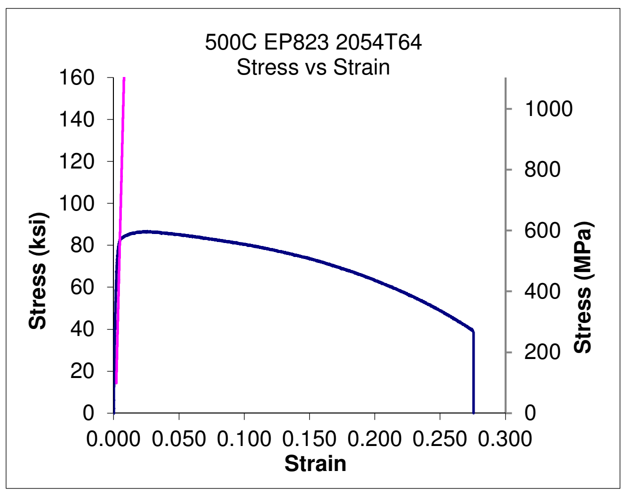
Abbreviations used below:
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

Testing Temperature: 500°C
Specimen ID: 2054T64

Diameter
- D_o: 0.2512 in. (6.38 mm)
- D_f : 0.1242 in. (3.15 mm)

Overall Length (Calipers)
- OAL_o: 4.0045 in. (101.71 mm)
- OAL_f: 4.2787 in. (108.68 mm)

Length (Laser Extensometer)
- L_o: N/A
- L_f: N/A



Elongation (Laser Ext.): N/A
Elongation (Calipers): 27.42 %
Reduction in Area: 75.57 %
Ultimate Tensile Strength: 86.7 ksi (597.8 MPa)
Yield Strength: 81.6 ksi (562.6 MPa)

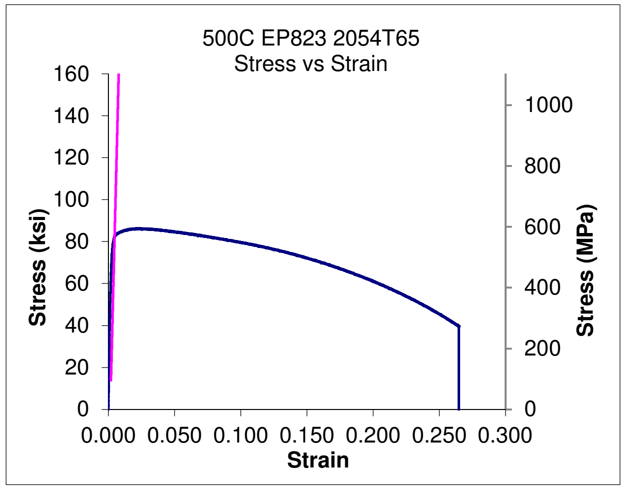
Testing Temperature: 500°C
Specimen ID: 2054T65

Diameter
D_o: 0.2509 in. (6.37 mm)
D_f : 0.1238 in. (3.14 mm)

Overall Length (Calipers)
OAL_o: 4.0032 in. (101.68 mm)
OAL_f: 4.2700 in. (108.46 mm)

Length (Laser Extensometer)
L_o: N/A
L_f: N/A

Elongation (Laser Ext.): N/A
Elongation (Calipers): 26.68 %
Reduction in Area: 75.64 %
Ultimate Tensile Strength: 86.3 ksi (595.0 MPa)
Yield Strength: 81.6 ksi (562.6 MPa)



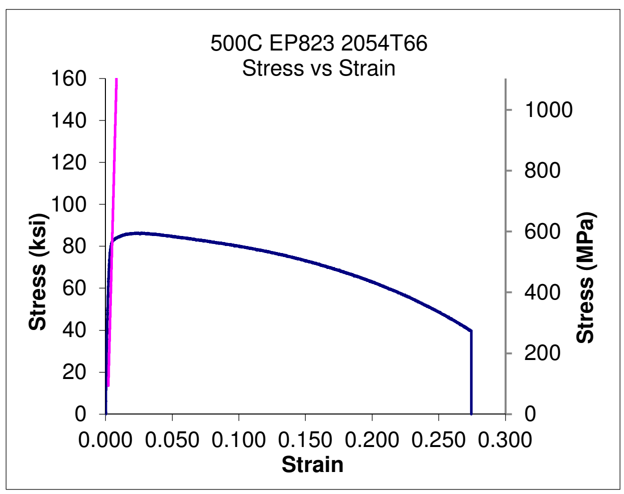
Testing Temperature: 500°C
Specimen ID: 2054T66

Diameter
D_o: 0.2503 in. (6.36 mm)
D_f : 0.1240 in. (3.15 mm)

Overall Length (Calipers)
OAL_o: 4.0013 in. (101.63 mm)
OAL_f: 4.2755 in. (108.60 mm)

Length (Laser Extensometer)
L_o: N/A
L_f: N/A

Elongation (Laser Ext.): N/A
Elongation (Calipers): 27.42 %
Reduction in Area: 75.46 %
Ultimate Tensile Strength: 86.4 ksi (595.7 MPa)
Yield Strength: 81.4 ksi (561.2 MPa)



E.6. 600°C Tests (2054T)

Material: EP-823
Heat Number: 2054T

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 1.75 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: 600°C Tests
Displacement Measuring Device: LVDT (Linear Variable Differential Transducer)

Abbreviations used below:

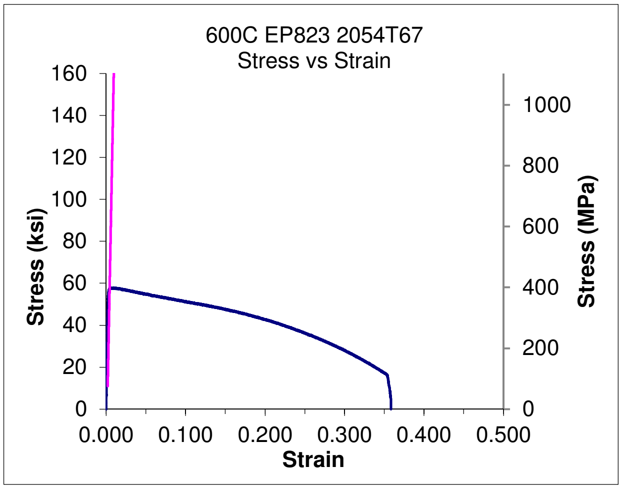
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

Testing Temperature: 600°C
Specimen ID: 2054T67

Diameter
- D_o: 0.2508 in. (6.37 mm)
- D_f : 0.0950 in. (2.41 mm)

Overall Length (Calipers)
- OAL_o: 4.0002 in. (101.61 mm)
- OAL_f: 4.3655 in. (110.88 mm)

Length (Laser Extensometer)
- L_o: N/A
- L_f: N/A



Elongation (Laser Ext.): N/A
Elongation (Calipers): 36.53 %
Reduction in Area: 85.65 %
Ultimate Tensile Strength: 57.9 ksi (399.2 MPa)
Yield Strength: 57.4 ksi (395.8 MPa)

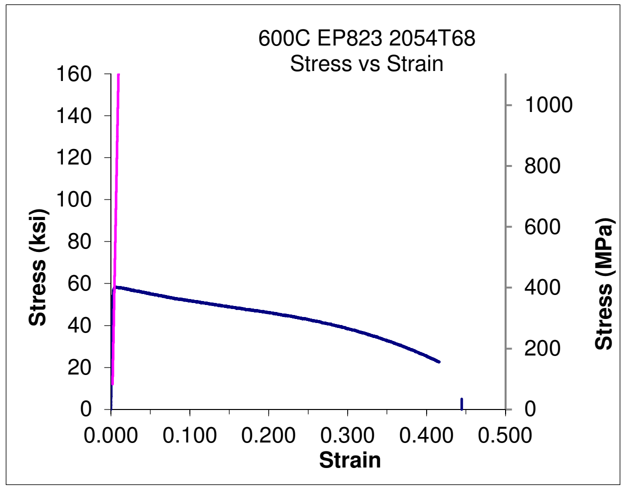
Testing Temperature: 600°C
Specimen ID: 2054T68

Diameter
- D_o: 0.2519 in. (6.40 mm)
- D_f : 0.0932 in. (2.37 mm)

Overall Length (Calipers)
- OAL_o: 4.0008 in. (101.62 mm)
- OAL_f: 4.4455 in. (112.92 mm)

Length (Laser Extensometer)
- L_o: N/A
- L_f: N/A

Elongation (Laser Ext.): N/A
Elongation (Calipers): 44.47 %
Reduction in Area: 86.32 %
Ultimate Tensile Strength: 58.4 ksi (402.7 MPa)
Yield Strength: 57.7 ksi (397.8 MPa)



This experiment ended prematurely when the tensile testing machine reached its 0.500-inch (12.7-mm) programmed displacement limit; however all material properties can be determined from the available data. Elongation is determined from overall length before and after tensile testing. The strain at failure is shown on the graph and is determined from caliper measurements.

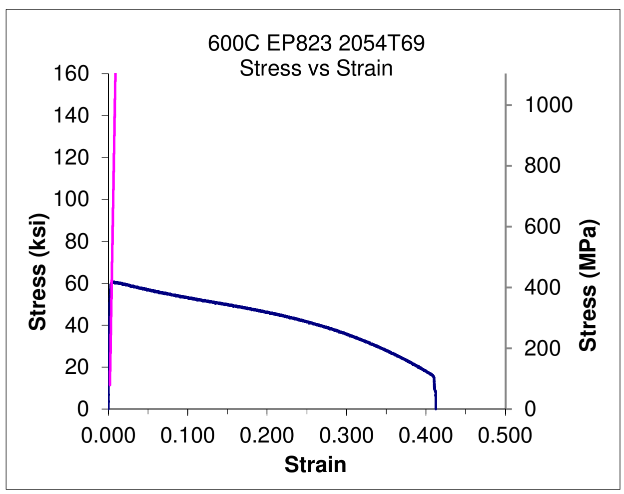
Testing Temperature: 600°C
Specimen ID: 2054T69

Diameter
- D_o: 0.2516 in. (6.39 mm)
- D_f : 0.0933 in. (2.37 mm)

Overall Length (Calipers)
- OAL_o: 4.0010 in. (101.63 mm)
- OAL_f: 4.4087 in. (111.98 mm)

Length (Laser Extensometer)
- L_o: N/A
- L_f: N/A

Elongation (Laser Ext.): N/A
Elongation (Calipers): 40.77 %
Reduction in Area: 86.24 %
Ultimate Tensile Strength: 60.7 ksi (418.5 MPa)
Yield Strength: 60.3 ksi (415.8 MPa)



APPENDIX F :

TEMPERING TIME: 2.25 HOURS

This section provides mechanical properties and test data for “2054U” series EP-823 specimens that are tempered for 2.25 hours at 621°C (1150°F).

F.1. Room Temperature Tests (2054U)

Material: EP-823
Heat Number: 2054U

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 2.25 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: Room Temperature
Extensometer Type: Laser Extensometer

Abbreviations used below:

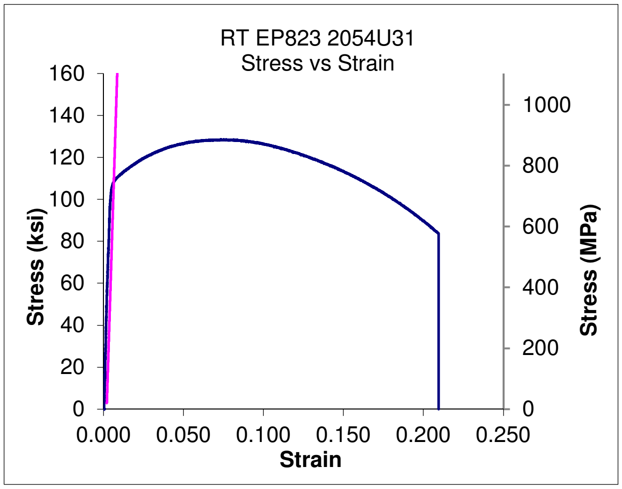
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

<u>Testing Temperature: Room Temperature</u>
Specimen ID: 2054U31

Diameter
- D_o: 0.2521 in. (6.40 mm)
- D_f : 0.1565 in. (3.98 mm)

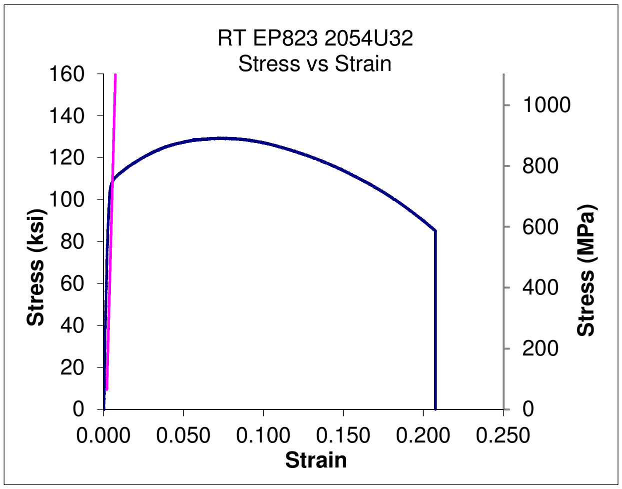
Overall Length (Calipers)
- OAL_o: 4.0050 in. (101.73 mm)
- OAL_f: 4.2157 in. (107.08 mm)

Length (Laser Extensometer)
- L_o: 0.9590 in. (24.36 mm)
- L_f: 1.1599 in. (29.46 mm)



Elongation (Laser Ext.): 20.94 %
Elongation (Calipers): 21.07 %
Reduction in Area: 61.46 %
Ultimate Tensile Strength: 128.5 ksi (886.0 MPa)
Yield Strength: 108.3 ksi (746.7 MPa)

Testing Temperature: Room Temperature
Specimen ID: 2054U32



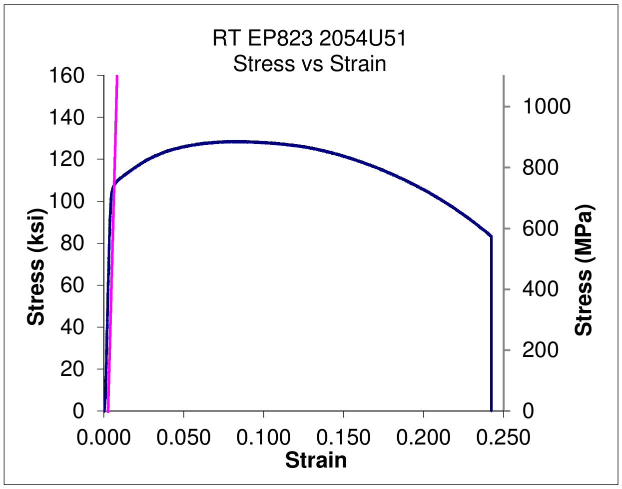
Diameter
- D_o: 0.2520 in. (6.40 mm)
- D_f : 0.1567 in. (3.98 mm)

Overall Length (Calipers)
- OAL_o: 4.0087 in. (101.82 mm)
- OAL_f: 4.2172 in. (107.12 mm)

Length (Laser Extensometer)
- L_o: 0.9649 in. (24.51 mm)
- L_f: 1.1652 in. (29.60 mm)

Elongation (Laser Ext.): 20.76 %
Elongation (Calipers): 20.85 %
Reduction in Area: 61.34 %
Ultimate Tensile Strength: 129.4 ksi (892.2 MPa)
Yield Strength: 108.2 ksi (746.0 MPa)

Testing Temperature: Room Temperature
Specimen ID: 2054U51



Diameter
- D_o: 0.2510 in. (6.38 mm)
- D_f : 0.1560 in. (3.96 mm)

Overall Length (Calipers)
- OAL_o: 4.0032 in. (101.68 mm)
- OAL_f: 4.2457 in. (107.84 mm)

Length (Laser Extensometer)
- L_o: 0.9659 in. (24.53 mm)
- L_f: 1.2001 in. (30.48 mm)

Elongation (Laser Ext.): 24.25 %
Elongation (Calipers): 24.25 %
Reduction in Area: 61.38 %
Ultimate Tensile Strength: 128.6 ksi (886.7 MPa)
Yield Strength: 107.5 ksi (741.2 MPa)

F.2. 100°C Tests (2054U)

Material: EP-823
Heat Number: 2054U

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 2.25 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: 100°C
Extensometer Type: Laser Extensometer

Abbreviations used below:

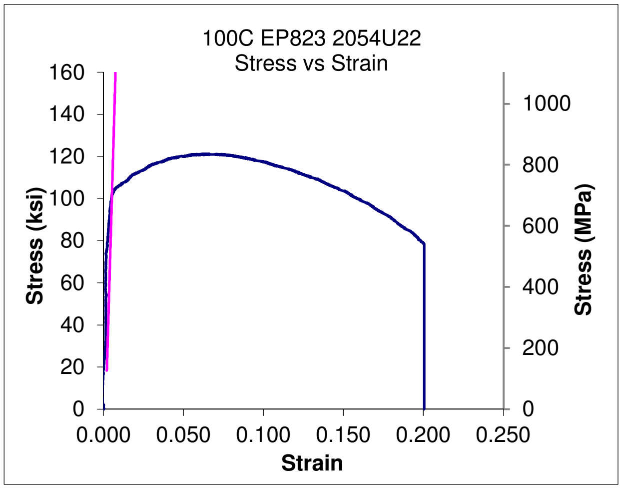
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

Testing Temperature: 100°C
Specimen ID: 2054U22

Diameter
- D_o: 0.2524 in. (6.41 mm)
- D_f: 0.1553 in. (3.94 mm)

Overall Length (Calipers)
- OAL_o: 3.9980 in. (101.55 mm)
- OAL_f: 4.1957 in. (106.57 mm)

Length (Laser Extensometer)
- L_o: 0.9472 in. (24.06 mm)
- L_f: 1.1370 in. (28.88 mm)



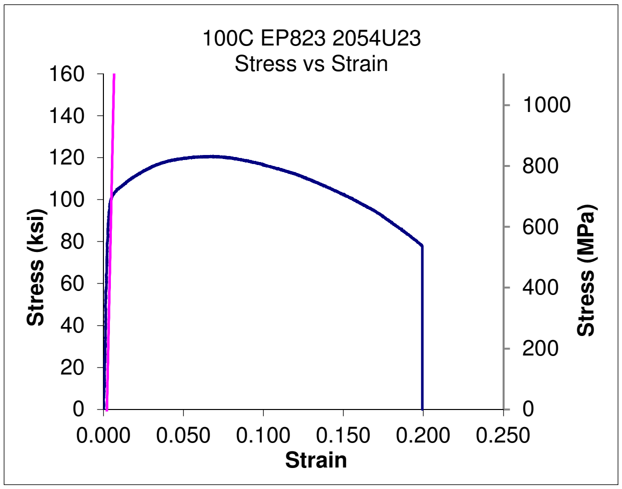
Elongation (Laser Ext.): 20.04 %
Elongation (Calipers): 19.77 %
Reduction in Area: 62.14 %
Ultimate Tensile Strength: 121.3 ksi (836.3 MPa)
Yield Strength: 101.4 ksi (699.1 MPa)

Testing Temperature: 100°C
Specimen ID: 2054U23

Diameter
D_o: 0.2528 in. (6.42 mm)
D_f: 0.1522 in. (3.87 mm)

Overall Length (Calipers)
OAL_o: 3.9993 in. (101.58 mm)
OAL_f: 4.2003 in. (106.69 mm)

Length (Laser Extensometer)
L_o: 0.9666 in. (24.55 mm)
L_f: 1.1592 in. (29.44 mm)



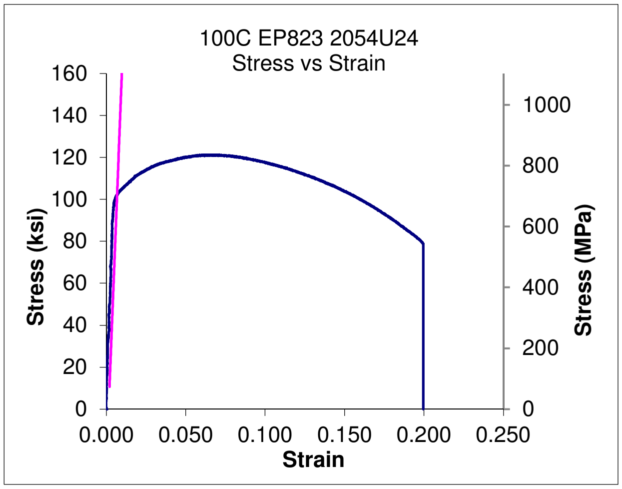
Elongation (Laser Ext.): 19.93 %
Elongation (Calipers): 20.10 %
Reduction in Area: 63.76 %
Ultimate Tensile Strength: 120.8 ksi (832.9 MPa)
Yield Strength: 100.7 ksi (694.3 MPa)

Testing Temperature: 100°C
Specimen ID: 2054U24

Diameter
D_o: 0.2527 in. (6.42 mm)
D_f: 0.1520 in. (3.86 mm)

Overall Length (Calipers)
OAL_o: 4.0050 in. (101.73 mm)
OAL_f: 4.1997 in. (106.67 mm)

Length (Laser Extensometer)
L_o: 0.9499 in. (24.13 mm)
L_f: 1.1394 in. (28.94 mm)



Elongation (Laser Ext.): 19.95 %
Elongation (Calipers): 19.47 %
Reduction in Area: 63.81 %
Ultimate Tensile Strength: 121.3 ksi (836.3 MPa)
Yield Strength: 102.1 ksi (704.0 MPa)

F.3. 300°C Tests (2054U)

Material: EP-823
Heat Number: 2054U

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 2.25 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: 300°C
Extensometer Type: Laser Extensometer

Abbreviations used below:

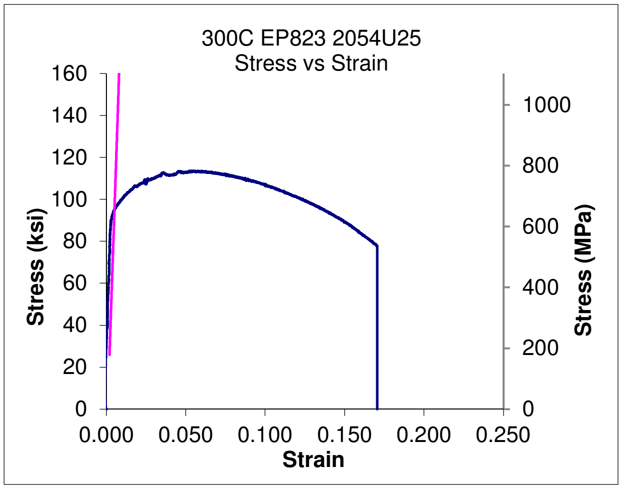
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

<u>Testing Temperature: 300°C</u>
Specimen ID: 2054U25

Diameter
- D_o: 0.2522 in. (6.41 mm)
- D_f: 0.1535 in. (3.90 mm)

Overall Length (Calipers)
- OAL_o: 4.0065 in. (101.77 mm)
- OAL_f: 4.1873 in. (106.36 mm)

Length (Laser Extensometer)
- L_o: 0.9725 in. (24.70 mm)
- L_f: 1.1384 in. (28.92 mm)



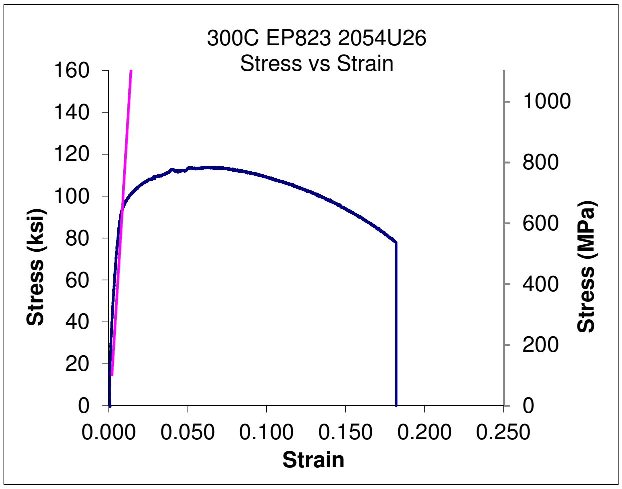
Elongation (Laser Ext.): 17.06 %
Elongation (Calipers): 18.08 %
Reduction in Area: 62.96 %
Ultimate Tensile Strength: 113.7 ksi (783.9 MPa)
Yield Strength: 94.5 ksi (651.6 MPa)

Testing Temperature: 300°C
Specimen ID: 2054U26

Diameter
- D_o: 0.2525 in. (6.41 mm)
- D_f : 0.1535 in. (3.90 mm)

Overall Length (Calipers)
- OAL_o: 3.9922 in. (101.40 mm)
- OAL_f: 4.1535 in. (105.50 mm)

Length (Laser Extensometer)
- L_o: 0.9406 in. (23.89 mm)
- L_f: 1.1117 in. (28.24 mm)



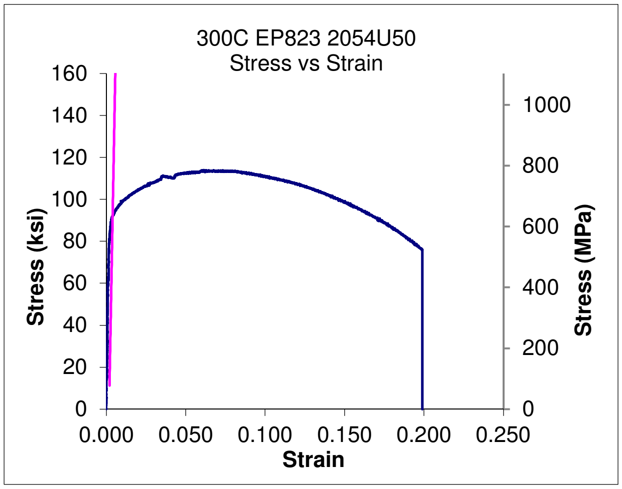
Elongation (Laser Ext.): 18.19 %
Elongation (Calipers): 18.32 %
Reduction in Area: 63.03 %
Ultimate Tensile Strength: 113.9 ksi (785.3 MPa)
Yield Strength: 93.1 ksi (641.9 MPa)

Testing Temperature: 300°C
Specimen ID: 2054U50

Diameter
- D_o: 0.2515 in. (6.39 mm)
- D_f : 0.1517 in. (3.85 mm)

Overall Length (Calipers)
- OAL_o: 4.0037 in. (101.69 mm)
- OAL_f: 4.2042 in. (106.79 mm)

Length (Laser Extensometer)
- L_o: 0.9610 in. (24.41 mm)
- L_f: 1.1522 in. (29.27 mm)



Elongation (Laser Ext.): 19.91 %
Elongation (Calipers): 20.05 %
Reduction in Area: 63.64 %
Ultimate Tensile Strength: 113.9 ksi (785.3 MPa)
Yield Strength: 91.9 ksi (633.6 MPa)

F.4. 400°C Tests (2054U)

Material:	EP-823
Heat Number:	2054U

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 2.25 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature:	400°C
Extensometer Type:	Laser Extensometer

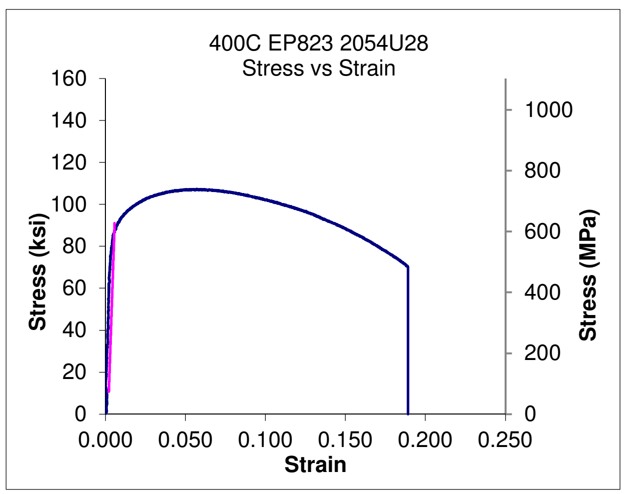
Abbreviations used below:
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

<u>Testing Temperature: 400°C</u>
Specimen ID: 2054U28

Diameter
- D_o: 0.2530 in. (6.43 mm)
- D_f : 0.1518 in. (3.86 mm)

Overall Length (Calipers)
- OAL_o: 3.9977 in. (101.54 mm)
- OAL_f: 4.1902 in. (106.43 mm)

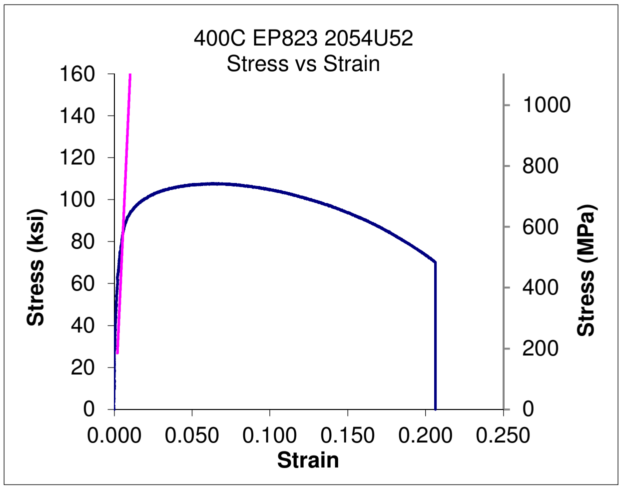
Length (Laser Extensometer)
- L_o: 0.9619 in. (24.43 mm)
- L_f: 1.1438 in. (29.05 mm)



Elongation (Laser Ext.):	18.90 %
Elongation (Calipers):	19.25 %
Reduction in Area:	63.98 %
Ultimate Tensile Strength:	107.3 ksi (739.8 MPa)
Yield Strength:	86.6 ksi (597.1 MPa)

Testing Temperature: 400°C
Specimen ID: 2054U52

Diameter
- D_o: 0.2508 in. (6.37 mm)
- D_f : 0.1520 in. (3.86 mm)



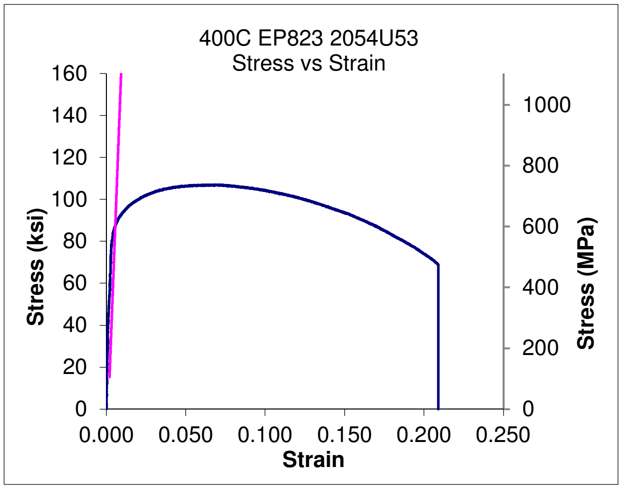
Overall Length (Calipers)
- OAL_o: 4.0035 in. (101.69 mm)
- OAL_f: 4.2105 in. (106.95 mm)

Length (Laser Extensometer)
- L_o: 0.9564 in. (24.29 mm)
- L_f: 1.1537 in. (29.30 mm)

Elongation (Laser Ext.): 20.63 %
Elongation (Calipers): 20.70 %
Reduction in Area: 63.26 %
Ultimate Tensile Strength: 107.7 ksi (742.6 MPa)
Yield Strength: 84.2 ksi (580.5 MPa)

Testing Temperature: 400°C
Specimen ID: 2054U53

Diameter
- D_o: 0.2501 in. (6.35 mm)
- D_f : 0.1515 in. (3.85 mm)



Overall Length (Calipers)
- OAL_o: 4.0032 in. (101.68 mm)
- OAL_f: 4.2118 in. (106.98 mm)

Length (Laser Extensometer)
- L_o: 0.9577 in. (24.33 mm)
- L_f: 1.1578 in. (29.41 mm)

Elongation (Laser Ext.): 20.90 %
Elongation (Calipers): 20.87 %
Reduction in Area: 63.30 %
Ultimate Tensile Strength: 107.0 ksi (737.7 MPa)
Yield Strength: 87.4 ksi (602.6 MPa)

F.5. 500°C Tests (2054U)

Material: EP-823
Heat Number: 2054U

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 2.25 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: 500°C Tests
Displacement Measuring Device: LVDT (Linear Variable Differential Transducer)

Abbreviations used below:

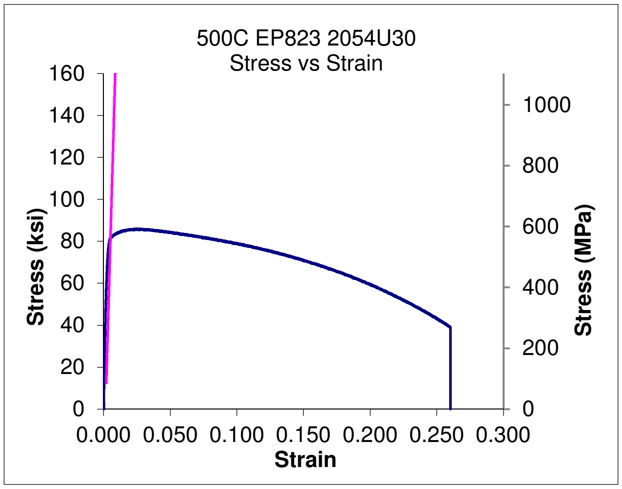
- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

Testing Temperature: 500°C
Specimen ID: 2054U30

Diameter
- D_o: 0.2526 in. (6.42 mm)
- D_f : 0.1242 in. (3.15 mm)

Overall Length (Calipers)
- OAL_o: 4.0113 in. (101.89 mm)
- OAL_f: 4.2718 in. (108.50 mm)

Length (Laser Extensometer)
- L_o: N/A
- L_f: N/A



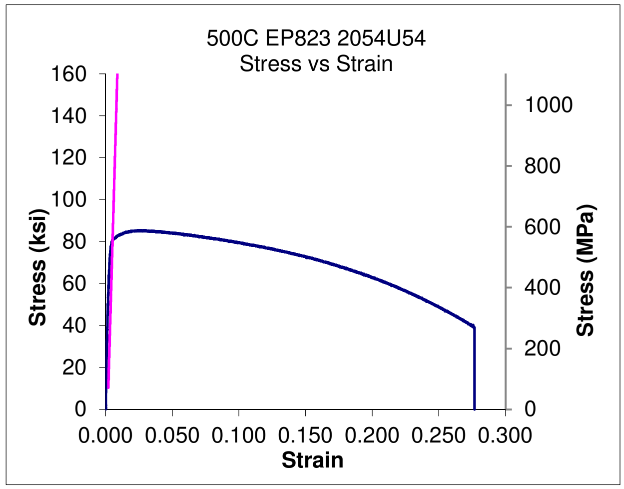
Elongation (Laser Ext.): N/A
Elongation (Calipers): 26.05 %
Reduction in Area: 75.84 %
Ultimate Tensile Strength: 85.9 ksi (592.3 MPa)
Yield Strength: 81.4 ksi (561.2 MPa)

Testing Temperature: 500°C
Specimen ID: 2054U54

Diameter
- D_o: 0.2512 in. (6.38 mm)
- D_f : 0.1238 in. (3.14 mm)

Overall Length (Calipers)
- OAL_o: 4.0038 in. (101.70 mm)
- OAL_f: 4.2778 in. (108.66 mm)

Length (Laser Extensometer)
- L_o: N/A
- L_f: N/A



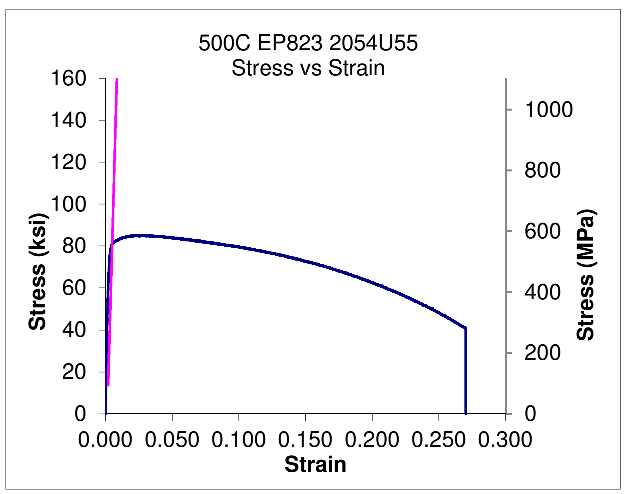
Elongation (Laser Ext.): N/A
Elongation (Calipers): 27.40 %
Reduction in Area: 75.69 %
Ultimate Tensile Strength: 85.4 ksi (588.8 MPa)
Yield Strength: 80.5 ksi (555.0 MPa)

Testing Temperature: 500°C
Specimen ID: 2054U55

Diameter
- D_o: 0.2515 in. (6.39 mm)
- D_f : 0.1247 in. (3.17 mm)

Overall Length (Calipers)
- OAL_o: 4.0037 in. (101.69 mm)
- OAL_f: 4.2743 in. (108.57 mm)

Length (Laser Extensometer)
- L_o: N/A
- L_f: N/A



Elongation (Laser Ext.): N/A
Elongation (Calipers): 27.07 %
Reduction in Area: 75.44 %
Ultimate Tensile Strength: 85.2 ksi (587.4 MPa)
Yield Strength: 80.4 ksi (554.3 MPa)

F.6. 600°C Tests (2054U)

Material: EP-823
Heat Number: 2054U

Austenitized 1 Hour at 1010°C (1850°F) followed by Oil Quench
Tempered 2.25 Hours at 621°C (1150°F) followed by Air Cool

Testing Temperature: 600°C Tests
Displacement Measuring Device: LVDT (Linear Variable Differential Transducer)

Abbreviations used below:

- D_o = initial gage diameter
- D_f = final gage diameter (at necked region)
- OAL_o = initial overall length of specimen
- OAL_f = final overall length of specimen
- L_o = initial gage length
- L_f = final gage length

Testing Temperature: 600°C
Specimen ID: 2054U56

Diameter

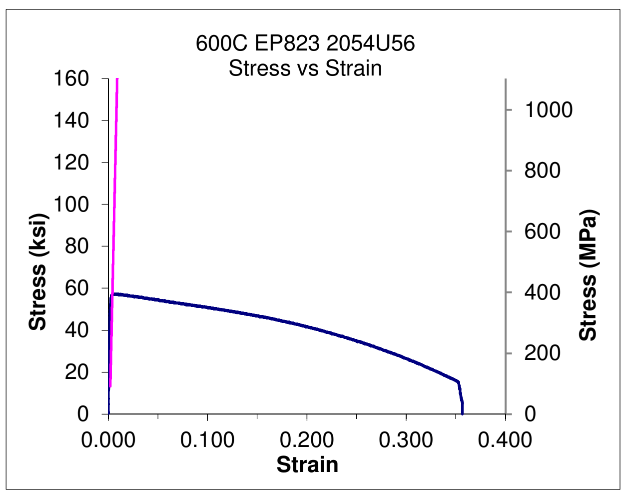
- D_o: 0.2512 in. (6.38 mm)
- D_f : 0.0932 in. (2.37 mm)

Overall Length (Calipers)

- OAL_o: 4.0023 in. (101.66 mm)
- OAL_f: 4.3565 in. (110.66 mm)

Length (Laser Extensometer)

- L_o: N/A
- L_f: N/A



Elongation (Laser Ext.): N/A
Elongation (Calipers): 35.42 %
Reduction in Area: 86.24 %
Ultimate Tensile Strength: 57.4 ksi (395.8 MPa)
Yield Strength: 57.0 ksi (393.0 MPa)

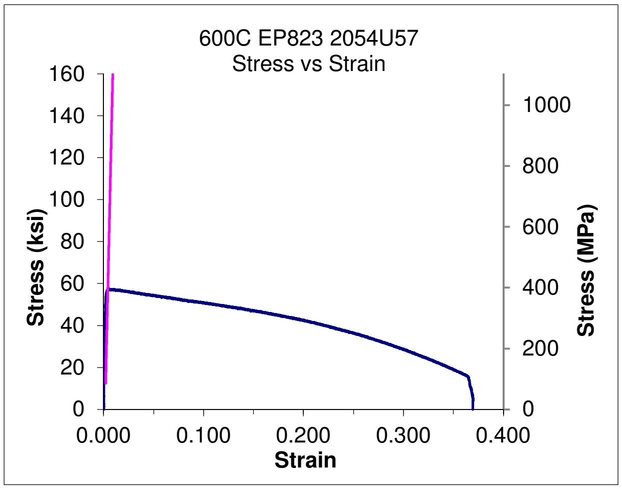
Testing Temperature: 600°C
Specimen ID: 2054U57

Diameter
D_o: 0.2517 in. (6.39 mm)
D_f : 0.0948 in. (2.41 mm)

Overall Length (Calipers)
OAL_o: 4.0030 in. (101.68 mm)
OAL_f: 4.3663 in. (110.90 mm)

Length (Laser Extensometer)
L_o: N/A
L_f: N/A

Elongation (Laser Ext.): N/A
Elongation (Calipers): 36.33 %
Reduction in Area: 85.80 %
Ultimate Tensile Strength: 57.4 ksi (395.8 MPa)
Yield Strength: 57.0 ksi (393.0 MPa)



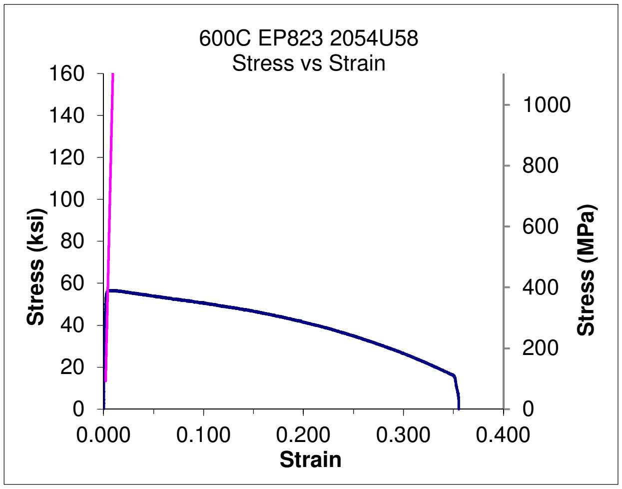
Testing Temperature: 600°C
Specimen ID: 2054U58

Diameter
D_o: 0.2511 in. (6.38 mm)
D_f : 0.0967 in. (2.46 mm)

Overall Length (Calipers)
OAL_o: 4.0012 in. (101.63 mm)
OAL_f: 4.3592 in. (110.72 mm)

Length (Laser Extensometer)
L_o: N/A
L_f: N/A

Elongation (Laser Ext.): N/A
Elongation (Calipers): 35.80 %
Reduction in Area: 85.18 %
Ultimate Tensile Strength: 56.7 ksi (390.9 MPa)
Yield Strength: 56.3 ksi (388.2 MPa)



APPENDIX G:

STATISTICAL SIGNIFICANCE DETERMINATION

This section provides the t-test results for calculating the probability *p* or *p-value* to determine the statistical significance of the effects from increasing tempering time on mechanical properties of Alloy EP-823. The f-test is performed prior to each t-test to determine if the two sample variances in question are equal or unequal. Then the appropriate t-test is performed to accommodate the variance results. The resulting probability *p* or *p-value* is used to deem the effect on results significant or attributed to random sampling. For a more detailed explanation for determining statistical significance refer to Section 5.1.

Evaluating the significance of the effect on results due to increasing tempering time is performed by comparing the results three ways. These comparisons are listed below.

- Change A – Increasing Tempering Time from 1.25 h to 1.75 h.
- Change B – Increasing Tempering Time from 1.75 h to 2.25 h.
- Change C – Increasing Tempering Time from 1.25 h to 2.25 h.

The above comparisons are made for the results of each mechanical property listed below.

- Ultimate Tensile Strength
- Yield Strength
- Elongation
- Reduction of Area

The t-test results and significance findings are provided in Table 68 through Table 79 of this appendix.

G.1. Tempering Time Effect on Ultimate Tensile Strength

Table 68. Tempering Significance on UTS, 1.25 h to 1.75 h, *Change A*

1.25 Hours			1.75 Hours				
Specimen	Temp. (℃)	UTS (MPa)	Specimen	Temp. (℃)	UTS (MPa)		
2054S50	RT	901.1	2054T50	RT	897.7	F-Test	P-Value
2054S51	RT	918.4	2054T51	RT	905.3	0.3872	0.0559
2054S52	RT	919.8	2054T52	RT	895.6	Equal Var.	Random
	Mean	913.1		Mean	899.5		
	Std Dev	8.5		Std Dev	4.1		
	Std Error	4.9		Std Error	2.4		
2054S53	100	852.2	2054T53	100	846.0	F-Test	P-Value
2054S54	100	853.6	2054T54	100	844.6	0.2500	0.0044
2054S55	100	852.2	2054T55	100	848.7	Equal Var.	Significant
	Mean	852.7		Mean	846.4		
	Std Dev	0.7		Std Dev	1.7		
	Std Error	0.4		Std Error	1.0		
2054S56	300	805.3	2054T57	300	803.2	F-Test	P-Value
2054S57	300	806.0	2054T58	300	797.0	0.2000	0.0187
2054S59	300	808.1	2054T59	300	795.0	Equal Var.	Significant
	Mean	806.5		Mean	798.4		
	Std Dev	1.2		Std Dev	3.5		
	Std Error	0.7		Std Error	2.0		
2054S60	400	754.3	2054T60	400	757.7	F-Test	P-Value
2054S61	400	768.8	2054T62	400	756.4	0.5380	0.1311
2054S63	400	759.8	2054T63	400	749.5	Equal Var.	Random
	Mean	761.0		Mean	754.5		
	Std Dev	6.0		Std Dev	3.6		
	Std Error	3.4		Std Error	2.1		
2054S64	500	618.5	2054T64	500	597.8	F-Test	P-Value
2054S65	500	607.4	2054T65	500	595.0	0.0605	0.0245
2054S67	500	602.6	2054T66	500	595.7	Equal Var.	Significant
	Mean	609.5		Mean	596.2		
	Std Dev	6.6		Std Dev	1.2		
	Std Error	3.8		Std Error	0.7		
2054S68	600	410.2	2054T67	600	399.2	F-Test	P-Value
2054S69	600	421.3	2054T68	600	402.7	0.6375	0.2110
2054S71	600	408.2	2054T69	600	418.5	Equal Var.	Random
	Mean	413.2		Mean	406.8		
	Std Dev	5.8		Std Dev	8.4		
	Std Error	3.3		Std Error	4.9		

Table 69. Tempering Significance on UTS, 1.75 h to 2.25 h, *Change B*

1.75 Hours			2.25 Hours				
Specimen	Temp. (°C)	UTS (MPa)	Specimen	Temp. (°C)	UTS (MPa)		
2054T50	RT	897.7	2054U31	RT	886.0	F-Test	P-Value
2054T51	RT	905.3	2054U32	RT	892.2	0.6186	0.0166
2054T52	RT	895.6	2054U51	RT	886.7	Equal Var.	Significant
	Mean	899.5		Mean	888.3		
	Std Dev	4.1		Std Dev	2.8		
	Std Error	2.4		Std Error	1.6		
2054T53	100	846.0	2054U22	100	836.3	F-Test	P-Value
2054T54	100	844.6	2054U23	100	832.9	0.9434	0.0013
2054T55	100	848.7	2054U24	100	836.3	Equal Var.	Significant
	Mean	846.4		Mean	835.2		
	Std Dev	1.7		Std Dev	1.6		
	Std Error	1.0		Std Error	0.9		
2054T57	300	803.2	2054U25	300	783.9	F-Test	P-Value
2054T58	300	797.0	2054U26	300	785.3	0.0661	0.0029
2054T59	300	795.0	2054U50	300	785.3	Equal Var.	Significant
	Mean	798.4		Mean	784.9		
	Std Dev	3.5		Std Dev	0.7		
	Std Error	2.0		Std Error	0.4		
2054T60	400	757.7	2054U28	400	739.8	F-Test	P-Value
2054T62	400	756.4	2054U52	400	742.6	0.4596	0.0038
2054T63	400	749.5	2054U53	400	737.7	Equal Var.	Significant
	Mean	754.5		Mean	740.0		
	Std Dev	3.6		Std Dev	2.0		
	Std Error	2.1		Std Error	1.1		
2054T64	500	597.8	2054U30	500	592.3	F-Test	P-Value
2054T65	500	595.0	2054U54	500	588.8	0.5000	0.0079
2054T66	500	595.7	2054U55	500	587.4	Equal Var.	Significant
	Mean	596.2		Mean	589.5		
	Std Dev	1.2		Std Dev	2.0		
	Std Error	0.7		Std Error	1.2		
2054T67	600	399.2	2054U56	600	395.8	F-Test	P-Value
2054T68	600	402.7	2054U57	600	395.8	0.1365	0.0547
2054T69	600	418.5	2054U58	600	390.9	Equal Var.	Random
	Mean	406.8		Mean	394.2		
	Std Dev	8.4		Std Dev	2.3		
	Std Error	4.9		Std Error	1.3		

Table 70. Tempering Significance on UTS, 1.25 h to 2.25 h, *Change C*

1.25 Hours			2.25 Hours				
Specimen	Temp. (°C)	UTS (MPa)	Specimen	Temp. (°C)	UTS (MPa)		
2054S50	RT	901.1	2054U31	RT	886.0	F-Test	P-Value
2054S51	RT	918.4	2054U32	RT	892.2	0.1941	0.0085
2054S52	RT	919.8	2054U51	RT	886.7	Equal Var.	Significant
	Mean	913.1		Mean	888.3		
	Std Dev	8.5		Std Dev	2.8		
	Std Error	4.9		Std Error	1.6		
2054S53	100	852.2	2054U22	100	836.3	F-Test	P-Value
2054S54	100	853.6	2054U23	100	832.9	0.2759	0.0001
2054S55	100	852.2	2054U24	100	836.3	Equal Var.	Significant
	Mean	852.7		Mean	835.2		
	Std Dev	0.7		Std Dev	1.6		
	Std Error	0.4		Std Error	0.9		
2054S56	300	805.3	2054U25	300	783.9	F-Test	P-Value
2054S57	300	806.0	2054U26	300	785.3	0.4706	0.0000
2054S59	300	808.1	2054U50	300	785.3	Equal Var.	Significant
	Mean	806.5		Mean	784.9		
	Std Dev	1.2		Std Dev	0.7		
	Std Error	0.7		Std Error	0.4		
2054S60	400	754.3	2054U28	400	739.8	F-Test	P-Value
2054S61	400	768.8	2054U52	400	742.6	0.1979	0.0046
2054S63	400	759.8	2054U53	400	737.7	Equal Var.	Significant
	Mean	761.0		Mean	740.0		
	Std Dev	6.0		Std Dev	2.0		
	Std Error	3.4		Std Error	1.1		
2054S64	500	618.5	2054U30	500	592.3	F-Test	P-Value
2054S65	500	607.4	2054U54	500	588.8	0.1711	0.0076
2054S67	500	602.6	2054U55	500	587.4	Equal Var.	Significant
	Mean	609.5		Mean	589.5		
	Std Dev	6.6		Std Dev	2.0		
	Std Error	3.8		Std Error	1.2		
2054S68	600	410.2	2054U56	600	395.8	F-Test	P-Value
2054S69	600	421.3	2054U57	600	395.8	0.2707	0.0060
2054S71	600	408.2	2054U58	600	390.9	Equal Var.	Significant
	Mean	413.2		Mean	394.2		
	Std Dev	5.8		Std Dev	2.3		
	Std Error	3.3		Std Error	1.3		

G.2. Tempering Time Effect on Yield Strength

Table 71. Tempering Significance on YS, 1.25 h to 1.75 h, Change A

1.25 Hours			1.75 Hours				
Specimen	Temp. (℃)	YS (MPa)	Specimen	Temp. (℃)	YS (MPa)		
2054S50	RT	758.4	2054T50	RT	750.8	F-Test	P-Value
2054S51	RT	777.7	2054T51	RT	756.4	0.1704	0.0244
2054S52	RT	777.7	2054T52	RT	750.1	Equal Var.	Significant
	Mean	771.3		Mean	752.4		
	Std Dev	9.1		Std Dev	2.8		
	Std Error	5.3		Std Error	1.6		
2054S53	100	713.6	2054T53	100	707.4	F-Test	P-Value
2054S54	100	720.5	2054T54	100	697.7	0.6073	0.0105
2054S55	100	717.1	2054T55	100	706.0	Equal Var.	Significant
	Mean	717.1		Mean	703.7		
	Std Dev	2.8		Std Dev	4.3		
	Std Error	1.6		Std Error	2.5		
2054S56	300	661.2	2054T57	300	646.0	F-Test	P-Value
2054S57	300	663.3	2054T58	300	646.0	0.5294	0.0002
2054S59	300	663.3	2054T59	300	649.5	Equal Var.	Significant
	Mean	662.6		Mean	647.2		
	Std Dev	1.0		Std Dev	1.6		
	Std Error	0.6		Std Error	0.9		
2054S60	400	610.9	2054T60	400	619.8	F-Test	P-Value
2054S61	400	620.5	2054T62	400	615.7	0.7400	0.4075
2054S63	400	615.0	2054T63	400	607.4	Equal Var.	Random
	Mean	615.5		Mean	614.3		
	Std Dev	4.0		Std Dev	5.2		
	Std Error	2.3		Std Error	3.0		
2054S64	500	583.3	2054T64	500	562.6	F-Test	P-Value
2054S65	500	577.1	2054T65	500	562.6	0.0262	0.0332
2054S67	500	569.5	2054T66	500	561.2	Unequal Var.	Significant
	Mean	576.6		Mean	562.2		
	Std Dev	5.6		Std Dev	0.7		
	Std Error	3.3		Std Error	0.4		
2054S68	600	406.8	2054T67	600	395.8	F-Test	P-Value
2054S69	600	420.6	2054T68	600	397.8	0.6879	0.1753
2054S71	600	406.8	2054T69	600	415.8	Equal Var.	Random
	Mean	411.4		Mean	403.1		
	Std Dev	6.5		Std Dev	9.0		
	Std Error	3.8		Std Error	5.2		

Table 72. Tempering Significance on YS, 1.25 h to 2.25 h, *Change B*

1.75 Hours			2.25 Hours				
Specimen	Temp. (°C)	YS (MPa)	Specimen	Temp. (°C)	YS (MPa)		
2054T50	RT	750.8	2054U31	RT	746.7	F-Test	P-Value
2054T51	RT	756.4	2054U32	RT	746.0	0.8769	0.0203
2054T52	RT	750.1	2054U51	RT	741.2	Equal Var.	Significant
	Mean	752.4		Mean	744.6		
	Std Dev	2.8		Std Dev	2.5		
	Std Error	1.6		Std Error	1.4		
2054T53	100	707.4	2054U22	100	699.1	F-Test	P-Value
2054T54	100	697.7	2054U23	100	694.3	0.9216	0.1627
2054T55	100	706.0	2054U24	100	704.0	Equal Var.	Random
	Mean	703.7		Mean	699.1		
	Std Dev	4.3		Std Dev	3.9		
	Std Error	2.5		Std Error	2.3		
2054T57	300	646.0	2054U25	300	651.6	F-Test	P-Value
2054T58	300	646.0	2054U26	300	641.9	0.0938	0.2072
2054T59	300	649.5	2054U50	300	633.6	Equal Var.	Random
	Mean	647.2		Mean	642.4		
	Std Dev	1.6		Std Dev	7.3		
	Std Error	0.9		Std Error	4.2		
2054T60	400	619.8	2054U28	400	598.5	F-Test	P-Value
2054T62	400	615.7	2054U52	400	580.5	0.4500	0.0282
2054T63	400	607.4	2054U53	400	602.6	Equal Var.	Significant
	Mean	614.3		Mean	593.9		
	Std Dev	5.2		Std Dev	9.6		
	Std Error	3.0		Std Error	5.5		
2054T64	500	562.6	2054U30	500	561.2	F-Test	P-Value
2054T65	500	562.6	2054U54	500	555.0	0.0842	0.0388
2054T66	500	561.2	2054U55	500	554.3	Equal Var.	Significant
	Mean	562.2		Mean	556.9		
	Std Dev	0.7		Std Dev	3.1		
	Std Error	0.4		Std Error	1.8		
2054T67	600	395.8	2054U56	600	393.0	F-Test	P-Value
2054T68	600	397.8	2054U57	600	393.0	0.1207	0.0740
2054T69	600	415.8	2054U58	600	388.2	Equal Var.	Random
	Mean	403.1		Mean	391.4		
	Std Dev	9.0		Std Dev	2.3		
	Std Error	5.2		Std Error	1.3		

Table 73. Tempering Significance on YS, 1.25 h to 2.25 h, *Change C*

1.25 Hours			**2.25 Hours**				
Specimen	Temp. (°C)	YS (MPa)	Specimen	Temp. (°C)	YS (MPa)		
2054S50	RT	758.4	2054U31	RT	746.7	F-Test	P-Value
2054S51	RT	777.7	2054U32	RT	746.0	0.1356	0.0081
2054S52	RT	777.7	2054U51	RT	741.2	Equal Var.	Significant
	Mean	771.3		Mean	744.6		
	Std Dev	9.1		Std Dev	2.5		
	Std Error	5.3		Std Error	1.4		
2054S53	100	713.6	2054U22	100	699.1	F-Test	P-Value
2054S54	100	720.5	2054U23	100	694.3	0.6757	0.0032
2054S55	100	717.1	2054U24	100	704.0	Equal Var.	Significant
	Mean	717.1		Mean	699.1		
	Std Dev	2.8		Std Dev	3.9		
	Std Error	1.6		Std Error	2.3		
2054S56	300	661.2	2054U25	300	651.6	F-Test	P-Value
2054S57	300	663.3	2054U26	300	641.9	0.0348	0.0287
2054S59	300	663.3	2054U50	300	633.6	Unequal Var.	Significant
	Mean	662.6		Mean	642.4		
	Std Dev	1.0		Std Dev	7.3		
	Std Error	0.6		Std Error	4.2		
2054S60	400	610.9	2054U28	400	598.5	F-Test	P-Value
2054S61	400	620.5	2054U52	400	580.5	0.2913	0.0210
2054S63	400	615.0	2054U53	400	602.6	Equal Var.	Significant
	Mean	615.5		Mean	593.9		
	Std Dev	4.0		Std Dev	9.6		
	Std Error	2.3		Std Error	5.5		
2054S64	500	583.3	2054U30	500	561.2	F-Test	P-Value
2054S65	500	577.1	2054U54	500	555.0	0.4643	0.0061
2054S67	500	569.5	2054U55	500	554.3	Equal Var.	Significant
	Mean	576.6		Mean	556.9		
	Std Dev	5.6		Std Dev	3.1		
	Std Error	3.3		Std Error	1.8		
2054S68	600	406.8	2054U56	600	393.0	F-Test	P-Value
2054S69	600	420.6	2054U57	600	393.0	0.2183	0.0074
2054S71	600	406.8	2054U58	600	388.2	Equal Var.	Significant
	Mean	411.4		Mean	391.4		
	Std Dev	6.5		Std Dev	2.3		
	Std Error	3.8		Std Error	1.3		

G.3. Tempering Time Effect on Elongation Results

Table 74. Tempering Significance on Elongation, 1.25 h to 1.75 h, Change A

1.25 Hours			1.75 Hours				
Specimen	Temp. (°C)	Elongation (%)	Specimen	Temp. (°C)	Elongation (%)		
2054S50	RT	23.55	2054T50	RT	23.85	F-Test	P-Value
2054S51	RT	23.47	2054T51	RT	23.35	0.3957	0.2919
2054S52	RT	24.38	2054T52	RT	23.62	Equal Var.	Random
	Mean	23.80		Mean	23.61		
	Std Dev	0.41		Std Dev	0.20		
	Std Error	0.24		Std Error	0.12		
2054S53	100	22.42	2054T53	100	22.48	F-Test	P-Value
2054S54	100	22.48	2054T54	100	22.35	0.8758	0.3426
2054S55	100	22.72	2054T55	100	22.63	Equal Var.	Random
	Mean	22.54		Mean	22.49		
	Std Dev	0.13		Std Dev	0.11		
	Std Error	0.07		Std Error	0.07		
2054S56	300	20.22	2054T57	300	19.90	F-Test	P-Value
2054S57	300	19.98	2054T58	300	20.42	0.6461	0.4222
2054S59	300	19.75	2054T59	300	19.78	Equal Var.	Random
	Mean	19.98		Mean	20.03		
	Std Dev	0.19		Std Dev	0.28		
	Std Error	0.11		Std Error	0.16		
2054S60	400	22.25	2054T60	400	21.32	F-Test	P-Value
2054S61	400	21.30	2054T62	400	21.38	0.0467	0.1249
2054S63	400	21.97	2054T63	400	21.47	Unequal Var.	Random
	Mean	21.84		Mean	21.39		
	Std Dev	0.40		Std Dev	0.06		
	Std Error	0.23		Std Error	0.04		
2054S64	500	29.08	2054T64	500	27.42	F-Test	P-Value
2054S65	500	26.92	2054T65	500	26.68	0.2705	0.1385
2054S67	500	28.05	2054T66	500	27.42	Equal Var.	Random
	Mean	28.02		Mean	27.17		
	Std Dev	0.88		Std Dev	0.35		
	Std Error	0.51		Std Error	0.20		
2054S68	600	42.22	2054T67	600	36.53	F-Test	P-Value
2054S69	600	45.37	2054T68	600	44.47	0.7885	0.0888
2054S71	600	48.63	2054T69	600	40.77	Equal Var.	Random
	Mean	45.41		Mean	40.59		
	Std Dev	2.62		Std Dev	3.24		
	Std Error	1.51		Std Error	1.87		

Table 75. Tempering Significance on Elongation, 1.75 h to 2.25 h, *Change B*

1.75 Hours			2.25 Hours				
Specimen	Temp. (°C)	Elongation (%)	Specimen	Temp. (°C)	Elongation (%)		
2054T50	RT	23.85	2054U31	RT	21.07	F-Test	P-Value
2054T51	RT	23.35	2054U32	RT	20.85	0.0340	0.1464
2054T52	RT	23.62	2054U51	RT	24.25	Unequal Var.	Random
	Mean	23.61		Mean	22.06		
	Std Dev	0.20		Std Dev	1.55		
	Std Error	0.12		Std Error	0.90		
2054T53	100	22.48	2054U22	100	19.77	F-Test	P-Value
2054T54	100	22.35	2054U23	100	20.10	0.3302	0.0001
2054T55	100	22.63	2054U24	100	19.47	Equal Var.	Significant
	Mean	22.49		Mean	19.78		
	Std Dev	0.11		Std Dev	0.26		
	Std Error	0.07		Std Error	0.15		
2054T57	300	19.90	2054U25	300	18.08	F-Test	P-Value
2054T58	300	20.42	2054U26	300	18.32	0.1821	0.0675
2054T59	300	19.78	2054U50	300	20.05	Equal Var.	Random
	Mean	20.03		Mean	18.82		
	Std Dev	0.28		Std Dev	0.88		
	Std Error	0.16		Std Error	0.51		
2054T60	400	21.32	2054U28	400	19.25	F-Test	P-Value
2054T62	400	21.38	2054U52	400	20.70	0.0143	0.0805
2054T63	400	21.47	2054U53	400	20.87	Unequal Var.	Random
	Mean	21.39		Mean	20.27		
	Std Dev	0.06		Std Dev	0.73		
	Std Error	0.04		Std Error	0.42		
2054T64	500	27.42	2054U30	500	26.05	F-Test	P-Value
2054T65	500	26.68	2054U54	500	27.40	0.5386	0.2609
2054T66	500	27.42	2054U55	500	27.07	Equal Var.	Random
	Mean	27.17		Mean	26.84		
	Std Dev	0.35		Std Dev	0.57		
	Std Error	0.20		Std Error	0.33		
2054T67	600	36.53	2054U56	600	35.42	F-Test	P-Value
2054T68	600	44.47	2054U57	600	36.33	0.0261	0.0866
2054T69	600	40.77	2054U58	600	35.80	Unequal Var.	Random
	Mean	40.59		Mean	35.85		
	Std Dev	3.24		Std Dev	0.37		
	Std Error	1.87		Std Error	0.22		

Table 76. Tempering Significance on Elongation, 1.25 h to 2.25 h, *Change C*

1.25 Hours			2.25 Hours				
Specimen	Temp. (°C)	Elongation (%)	Specimen	Temp. (°C)	Elongation (%)		
2054S50	RT	23.55	2054U31	RT	21.07	F-Test	P-Value
2054S51	RT	23.47	2054U32	RT	20.85	0.1311	0.0999
2054S52	RT	24.38	2054U51	RT	24.25	Equal Var.	Random
	Mean	23.80		Mean	22.06		
	Std Dev	0.41		Std Dev	1.55		
	Std Error	0.24		Std Error	0.90		
2054S53	100	22.42	2054U22	100	19.77	F-Test	P-Value
2054S54	100	22.48	2054U23	100	20.10	0.4048	0.0001
2054S55	100	22.72	2054U24	100	19.47	Equal Var.	Significant
	Mean	22.54		Mean	19.78		
	Std Dev	0.13		Std Dev	0.26		
	Std Error	0.07		Std Error	0.15		
2054S56	300	20.22	2054U25	300	18.08	F-Test	P-Value
2054S57	300	19.98	2054U26	300	18.32	0.0913	0.0701
2054S59	300	19.75	2054U50	300	20.05	Equal Var.	Random
	Mean	19.98		Mean	18.82		
	Std Dev	0.19		Std Dev	0.88		
	Std Error	0.11		Std Error	0.51		
2054S60	400	22.25	2054U28	400	19.25	F-Test	P-Value
2054S61	400	21.30	2054U52	400	20.70	0.4623	0.0278
2054S63	400	21.97	2054U53	400	20.87	Equal Var.	Significant
	Mean	21.84		Mean	20.27		
	Std Dev	0.40		Std Dev	0.73		
	Std Error	0.23		Std Error	0.42		
2054S64	500	29.08	2054U30	500	26.05	F-Test	P-Value
2054S65	500	26.92	2054U54	500	27.40	0.5958	0.0946
2054S67	500	28.05	2054U55	500	27.07	Equal Var.	Random
	Mean	28.02		Mean	26.84		
	Std Dev	0.88		Std Dev	0.57		
	Std Error	0.51		Std Error	0.33		
2054S68	600	42.22	2054U56	600	35.42	F-Test	P-Value
2054S69	600	45.37	2054U57	600	36.33	0.0399	0.0166
2054S71	600	48.63	2054U58	600	35.80	Unequal Var.	Significant
	Mean	45.41		Mean	35.85		
	Std Dev	2.62		Std Dev	0.37		
	Std Error	1.51		Std Error	0.22		

G.4. Tempering Time Effect on Reduction of Area

Table 77. Tempering Significance on Reduction of Area, 1.25 h to 1.75 h, Change A

1.25 Hours			1.75 Hours				
Specimen	Temp. (°C)	Reduction of Area (%)	Specimen	Temp. (°C)	Reduction of Area (%)		
2054S50	RT	62.59	2054T50	RT	61.79	F-Test	P-Value
2054S51	RT	63.40	2054T51	RT	62.88	0.3305	0.0872
2054S52	RT	65.02	2054T52	RT	62.47	Equal Var.	Random
	Mean	63.67		Mean	62.38		
	Std Dev	1.01		Std Dev	0.45		
	Std Error	0.58		Std Error	0.26		
2054S53	100	63.85	2054T53	100	64.20	F-Test	P-Value
2054S54	100	63.57	2054T54	100	63.66	0.3019	0.3800
2054S55	100	63.50	2054T55	100	63.33	Equal Var.	Random
	Mean	63.64		Mean	63.73		
	Std Dev	0.15		Std Dev	0.36		
	Std Error	0.09		Std Error	0.21		
2054S56	300	61.26	2054T57	300	62.40	F-Test	P-Value
2054S57	300	62.42	2054T58	300	62.99	0.5926	0.3639
2054S59	300	62.93	2054T59	300	61.88	Equal Var.	Random
	Mean	62.20		Mean	62.42		
	Std Dev	0.70		Std Dev	0.45		
	Std Error	0.40		Std Error	0.26		
2054S60	400	63.15	2054T60	400	64.26	F-Test	P-Value
2054S61	400	63.74	2054T62	400	64.26	0.3971	0.1646
2054S63	400	63.09	2054T63	400	63.01	Equal Var.	Random
	Mean	63.33		Mean	63.84		
	Std Dev	0.29		Std Dev	0.59		
	Std Error	0.17		Std Error	0.34		
2054S64	500	76.46	2054T64	500	75.57	F-Test	P-Value
2054S65	500	75.15	2054T65	500	75.64	0.0224	0.4525
2054S67	500	74.86	2054T66	500	75.46	Unequal Var.	Random
	Mean	75.49		Mean	75.56		
	Std Dev	0.70		Std Dev	0.07		
	Std Error	0.40		Std Error	0.04		
2054S68	600	87.40	2054T67	600	85.65	F-Test	P-Value
2054S69	600	87.98	2054T68	600	86.32	0.9380	0.0023
2054S71	600	88.14	2054T69	600	86.24	Equal Var.	Significant
	Mean	87.84		Mean	86.07		
	Std Dev	0.32		Std Dev	0.30		
	Std Error	0.18		Std Error	0.17		

Table 78. Tempering Significance on Reduction of Area, 1.75 h to 2.25 h, *Change B*

1.75 Hours			2.25 Hours				
Specimen	Temp. (℃)	Reduction of Area (%)	Specimen	Temp. (℃)	Reduction of Area (%)		
2054T50	RT	61.79	2054U31	RT	61.46	F-Test	P-Value
2054T51	RT	62.88	2054U32	RT	61.34	0.0243	0.0441
2054T52	RT	62.47	2054U51	RT	61.38	Unequal Var.	Significant
	Mean	62.38		Mean	61.39		
	Std Dev	0.45		Std Dev	0.05		
	Std Error	0.26		Std Error	0.03		
2054T53	100	64.20	2054U22	100	62.14	F-Test	P-Value
2054T54	100	63.66	2054U23	100	63.76	0.3522	0.2301
2054T55	100	63.33	2054U24	100	63.81	Equal Var.	Random
	Mean	63.73		Mean	63.24		
	Std Dev	0.36		Std Dev	0.78		
	Std Error	0.21		Std Error	0.45		
2054T57	300	62.40	2054U25	300	62.96	F-Test	P-Value
2054T58	300	62.99	2054U26	300	63.03	0.6241	0.0558
2054T59	300	61.88	2054U50	300	63.64	Equal Var.	Random
	Mean	62.42		Mean	63.21		
	Std Dev	0.45		Std Dev	0.31		
	Std Error	0.26		Std Error	0.18		
2054T60	400	64.26	2054U28	400	63.98	F-Test	P-Value
2054T62	400	64.26	2054U52	400	63.26	0.4604	0.3989
2054T63	400	63.01	2054U53	400	63.90	Equal Var.	Random
	Mean	63.84		Mean	63.71		
	Std Dev	0.59		Std Dev	0.32		
	Std Error	0.34		Std Error	0.19		
2054T64	500	75.57	2054U30	500	75.84	F-Test	P-Value
2054T65	500	75.64	2054U54	500	75.69	0.3356	0.2390
2054T66	500	75.46	2054U55	500	75.44	Equal Var.	Random
	Mean	75.56		Mean	75.66		
	Std Dev	0.07		Std Dev	0.16		
	Std Error	0.04		Std Error	0.10		
2054T67	600	85.65	2054U56	600	86.24	F-Test	P-Value
2054T68	600	86.32	2054U57	600	85.80	0.6414	0.2132
2054T69	600	86.24	2054U58	600	85.18	Equal Var.	Random
	Mean	86.07		Mean	85.74		
	Std Dev	0.30		Std Dev	0.43		
	Std Error	0.17		Std Error	0.25		

Table 79. Tempering Significance on Reduction of Area, 1.25 h to 2.25 h, *Change C*

1.25 Hours			2.25 Hours				
Specimen	Temp. (°C)	Reduction of Area (%)	Specimen	Temp. (°C)	Reduction of Area (%)		
2054S50	RT	62.59	2054U31	RT	61.46	F-Test	P-Value
2054S51	RT	63.40	2054U32	RT	61.34	0.0049	0.0428
2054S52	RT	65.02	2054U51	RT	61.38	Unequal Var.	Significant
	Mean	63.67		Mean	61.39		
	Std Dev	1.01		Std Dev	0.05		
	Std Error	0.58		Std Error	0.03		
2054S53	100	63.85	2054U22	100	62.14	F-Test	P-Value
2054S54	100	63.57	2054U23	100	63.76	0.0732	0.2552
2054S55	100	63.50	2054U24	100	63.81	Equal Var.	Random
	Mean	63.64		Mean	63.24		
	Std Dev	0.15		Std Dev	0.78		
	Std Error	0.09		Std Error	0.45		
2054S56	300	61.26	2054U25	300	62.96	F-Test	P-Value
2054S57	300	62.42	2054U26	300	63.03	0.3207	0.0677
2054S59	300	62.93	2054U50	300	63.64	Equal Var.	Random
	Mean	62.20		Mean	63.21		
	Std Dev	0.70		Std Dev	0.31		
	Std Error	0.40		Std Error	0.18		
2054S60	400	63.15	2054U28	400	63.98	F-Test	P-Value
2054S61	400	63.74	2054U52	400	63.26	0.9062	0.1389
2054S63	400	63.09	2054U53	400	63.90	Equal Var.	Random
	Mean	63.33		Mean	63.71		
	Std Dev	0.29		Std Dev	0.32		
	Std Error	0.17		Std Error	0.19		
2054S64	500	76.46	2054U30	500	75.84	F-Test	P-Value
2054S65	500	75.15	2054U54	500	75.69	0.1064	0.3792
2054S67	500	74.86	2054U55	500	75.44	Equal Var.	Random
	Mean	75.49		Mean	75.66		
	Std Dev	0.70		Std Dev	0.16		
	Std Error	0.40		Std Error	0.10		
2054S68	600	87.40	2054U56	600	86.24	F-Test	P-Value
2054S69	600	87.98	2054U57	600	85.80	0.6967	0.0026
2054S71	600	88.14	2054U58	600	85.18	Equal Var.	Significant
	Mean	87.84		Mean	85.74		
	Std Dev	0.32		Std Dev	0.43		
	Std Error	0.18		Std Error	0.25		

REFERENCES

[1] Harries, D. R., 1987, "The Materials Requirements for NET," *Radiation Effects*, **161**, pp. 3.

[2] Klueh, R. L., Ehrlich, K., Abe, F., 1992, "Ferritic/Martensitic Steels: Promises and Problems", *J. Nuclear Materials.*, **191**, pp. 116-124.

[3] Rusanov, A. E., Troyanov, V. M., Belomytzev, Y. S., 1999, Proceedings of the Conference on Heavy Metal Liquid Coolants in Nuclear Technology Anonymous Obninsk, Kaluga Region, Russia, **2,** pp. 633.

[4] Yeliseyeva, O., and Tsisar, V., 2004, "Comparison of Oxidation of Ferritic-Martensitic Steel EP-823 and Armco-Fe in Pb Melt Saturated by Oxygen," Journal of Corrosion Science and Engineering, 7(37) pp. 1-13.

[5] Dvoriashin, A. M., Porollo, S. I., Konobeev, Y. V., 2007, "Mechanical Properties and Microstructure of Three Russian ferritic/martensitic Steels Irradiated in BN-350 Reactor to 50 dpa at 490 °C," Journal of Nuclear Materials, **367–370, Part A**(0) pp. 92-96.

[6] Maloy, S. A., Romero, T., James, M. R., 2006, "Tensile Testing of EP-823 and HT-9 After Irradiation in STIP II," Journal of Nuclear Materials, **356**(1–3) pp. 56-61

[7] ASTM Designation: E 8 - 01 Standard Test Methods for Tension Testing of Metallic Materials, pp. 60-81.

[8] Pothana, S., Aquino, H., Roy, A., O'Toole, B., 2003, "Effect of Stress Concentration on Cracking Behavior of Cladding Materials," *American Nuclear Society Accelerator Applications in a Nuclear Renaissance*, AccApp, San Diego.

[9] Roy, A.K., Hossain, M.K., O'Toole, B.J., 2003, "Stress Corrosion Cracking of Martensitic Stainless Steel for Transmutation Applications," *Proceedings of the 10th International High-Level Radioactive Waste Management Conference*, pp 838-843.

[10] Roy, A.K., Pothana, S., Aquino, H., O'Toole, B.J., Trabia, M.B., Wang, Z., 2003, "Environment-Assisted-Cracking of Cladding Materials under Different Loading Conditions," *Proceedings of the 10th International High-Level Radioactive Waste Management Conference*, pp. 1286-1292.

[11] Roy, A.K., Prabhakaran, R., and Hossain, M.K., 2003, "Environment-Induced Degradation of Spallation Target Materials," *Sixth International Meeting on Nuclear Applications of Accelerator Technology*, pp. 893-899.

[12] Roy, A.K., Prabhakaran, R., Hossain, M. K., Sama, S., O'Toole, B., 2003, "Environment-Induced Degradation of Spallation Target Materials," *American Nuclear Society Accelerator Applications in a Nuclear Renaissance*, San Diego.

[13] Roy, A. K., and Hossain, M. K., 2006, “Cracking of Martensitic Alloy EP-823 Under Controlled Potential,” Journal of Materials Engineering and Performance, **15**(3) pp. 336-344.

[14] Aquino, H.T., 2003, “Cracking of Zirconium Alloys at Constant Load With and Without Applied Potentials,” University of Nevada, Las Vegas.

[15] Dronavalli, S.B., and Roy, A.K., 2004, “Residual Stress Measurements and Analysis by Destructive and Non Destructive Techniques,” University of Nevada, Las Vegas.

[16] Gudipati, P.P., and Roy, A.K., 2004, “Stress Corrosion Cracking Resistance of Martensitic Stainless Steels for Transmutation Applications,” University of Nevada, Las Vegas.

[17] Jones, M., 2003, “Mechanistic Understanding of High-Temperature Deformation of Alloy EP-823, 2054-U Series,” University of Nevada, Las Vegas.

[18] Kukatla, S.R., 2004, “Corrosion and High-Temperature Deformation Characteristics of a Target Structural Material for Transmutation Applications,” University of Nevada, Las Vegas.

[19] Pothana, S., 2003, “Evaluation of Cracking and Localized Corrosion Behavior of Cladding Materials,” University of Nevada, Las Vegas.

[20] Potluri, V.N., 2004, “Effect of Heat Treatment on Deformation and Corrosion Behavior of Type 422 Stainless Steel,” University of Nevada, Las Vegas.

[21] Prabhakaran, R., 2004, “Environment-Induced Degradations in a Target Structural Material for Transmutation Applications,” University of Nevada, Las Vegas.

[22] Sama, S., and Roy, A.K., 2004, “Embrittlement and Localized Corrosion in Alloy HT-9,” University of Nevada, Las Vegas.

[23] Selvaraj, V., and Roy, A.K., 2004, “Environment Assisted Cracking of Target Structural Materials under Different Loading Conditions,” University of Nevada, Las Vegas.

[24] Yarlagadda, B., 2004, “Elevated Temperature Mechanical Properties and Corrosion Characteristics Evaluation of Alloy HT-9,” University of Nevada, Las Vegas.

[25] Hossain, M.K., and Roy, A.K., 2004, "Stress Corrosion Cracking and Hydrogen Embrittlement of Martensitic Alloy EP-823," University of Nevada, Las Vegas.

[26] INCO, 1976, "18 Percent Nickel Maraging Steels, Engineering Properties," Nickel Development Institute, (4419) pp. 20.

[27] Zabotkin, K.G., 2002, "Identification of Dynamic Properties of Materials for the Nuclear Waste Package," University of Nevada, Las Vegas.

[28] Dusi, S., 2003, "Identification of Dynamic Properties of Materials for the Spent Nuclear Fuel Package at Elevated Temperatures," University of Nevada, Las Vegas.

[29] O'Toole, B. J., 2003, "Elevated Temperature Tensile Testing with the MTS Axial/Torsional Material Test System," UCCSN, (IPLV-061) pp. 1-15.

[30] Maloy, S., James, M., and Toloczko, M., 2003, "The High Temperature Tensile Properties of Ferritic-Martensitic and Austenitic Steels after Irradiation in an 800 MeV Proton Beam," Seventh Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation 14-16 Oct 2002, NEA, Republic of Korea, Jeju, pp. 669-678.

[31] Marmy, P., Martin, J. L., Victoria, M., 1993, "Deformation Mechanisms of a Ferritic-Martensitic Steel between 290 and 870 K," *Materials Science and Engineering*, **A164**, pp. 159-163.

[32] Victoria, M., Gavillet, D., Spätig, P., 1996, "Microstructure and Mechanical Properties of Newly Developed Low Activation Martensitic Steels," Journal of Nuclear Materials, **233–237, Part 1,** pp. 326-330.

[33] Roy, A., Kukatla, S. R., Yarlagadda, B., Lewis, M., Jones, M., O'Toole, B.J., 2005, "Tensile Properties of Martensitic Stainless Steels at Elevated Temperatures," Journal of Materials Engineering and Performance, **14**(2) pp. 212-218.

[34] Yilmaz, A., 2011, "The Portevin-Le Chatelier Effect: A Review of Experimental Findings," Science and Technology of Advanced Materials, **12**(6), 063001, pp. 2-3.

CURRICULUM VITAE

Graduate College
University of Nevada, Las Vegas

Martin M. Lewis

Home Address:
5149 Villa Dante Avenue
Las Vegas, NV 89141

Degree:
Bachelor of Science, Mechanical Engineering, 2000
University of Nevada, Las Vegas

Publications:
A.K. Roy, S.R. Kukatla, B. Yarlagadda, V.N. Potluri, M. Lewis, M. Jones, B.J. O'Toole. "Tensile Properties of Martensitic Stainless Steels at Elevated Temperatures." *Journal of Materials Engineering and Performance* 14. 2 (2005): 212-218. Print.

Thesis Title:
Effect of Thermal Treatment on High Temperature Deformation of Alloy EP-823

Thesis Examination Committee:
Chairperson, Dr. Brendan O'Toole, Ph.D.
Committee Member, Dr. Mohamed Trabia, Ph.D.
Committee Member, Dr. Zhiyong Wang, Ph.D.
Graduate Faculty Representative, Dr. Robert Schill, Ph.D.