Example Long Laboratory Report

MECHANICAL PROPERTIES OF 1018 STEEL IN TENSION

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LIST OF SYMBOLS

SYMBOL	DEFINITION
A	Area over which force (F) acts (m^2)
E	Elastic modulus (GPa)
F	Force (N)
$(l_o)_i$	Initial dimension in direction i (mm)
t	Specimen thickness (m)
V_{chart}	Rate of chart displacement (mm/min)
$V_{displacement}$	Rate of sample displacement (mm/min)
w	Specimen width (m)
δ_{chart}	Displacement of chart (mm)
δ_{sample}	Displacement of sample (mm)
ε	Strain
$\varepsilon_{\sigma=0}$	Predicted strain at zero stress
ε_i	Normal strain in direction i
ΔE	Error in the predicted elastic modulus (GPa)
ΔF	Error in the force (N)
Δl_i	Change in dimension in direction i (mm)
Δt	Error in the specimen thickness (m)
Δw	Error in the width (m)
$\Delta \varepsilon_{\sigma=0}$	Error in the predicted strain at zero stress
$\Delta \phi$	Error in the predicted intercept of stress-stain data (MPa)
$\Delta \sigma$	Error in the stress (MPa)
ϕ	Predicted intercept of stress-strain data (MPa)
σ	Engineering stress (MPa)
σ_y	Yield point (MPa)
σ_{ult}	Ultimate strength (MPa)

ABSTRACT

The elastic modulus, yield point, and ultimate strength of 1018 steel were determined in uniaxial tension. The "dogbone" specimen geometry was used with the region of minimum cross section having the dimensions: thickness = 3.18 ± 0.05 mm, width = 6.35 ± 0.05 mm, and gage section = 38.1 ± 0.05 mm. The elastic modulus of the specimen was determined to be 196.7 GPa with a standard deviation of 2.0 GPa. The lower limit on the yield point was determined to be 357.1 MPa with a standard deviation of 6.3 MPa. The upper limit on the yield point was determined to be 385.7 MPa with a standard deviation of 6.8 MPa. The ultimate strength was determined to be 487.7 MPa with a standard deviation of 8.6 MPa.

INTRODUCTION

Mechanical properties are of interest to engineers utilizing materials in any application where forces are applied, dimensions are critical, or failure is undesirable. Three fundamental mechanical properties of metals are the elastic modulus (E), the yield point (σ_y), and the ultimate strength (σ_{ult}). This report contains the results of an experiment to determine the elastic modulus, yield point, and ultimate strength of 1018 steel.

THEORY

When forces are applied to materials, they deform in reaction to those forces. The magnitude of the deformation for a constant force depends on the geometry of the materials. Likewise, the magnitude of the force required to cause a given deformation, depends on the geometry of the material. For these reasons, engineers define stress and strain. Stress (engineering definition) is given by:

$$\sigma = \frac{F}{A} \tag{1}$$

Defined in this manner, the stress can be thought of as a normalized force. Strain (engineering definition) is given by:

$$\varepsilon_i = \frac{\Delta l_i}{(l_o)_i} \tag{2}$$

The strain can be thought of as a normalized deformation.

While the relationship between the force and deformation depends on the geometry of the material, the relationship between the stress and strain is geometry independent. The relationship between stress and strain is given by a simplified form of Hooke's Law [1]:

$$\sigma = E\varepsilon \tag{3}$$

Since E is independent of geometry, it is often thought of as a material constant. However, E is known to depend on both the chemistry, structure, and temperature of a material. Change in any of these characteristics must be known before using a "handbook value" for the elastic modulus.

Hooke's Law (Equation 3) predicts a linear relationship between the strain and the stress and describes the elastic response of a material. In materials where Hook's Law describes the stress-strain relationship, the elastic response is the dominant deformation mechanism. However, many materials exhibit nonlinear behavior at higher levels of stress. This nonlinear behavior occurs when plasticity becomes the dominant deformation mechanism. Metals are known to exhibit both elastic and plastic response regions [2]. The transition from an elastic response to a plastic response occurs at a critical point known as the yield point (σ_y). Since a plastic response is characterized by permanent deformation (bending), the yield point is an important characteristic to know. In practice, the yield point is the stress where the stress-strain behavior transforms from a linear relationship to a non-linear relationship. The most commonly used method to experimentally determine the yield point is the 0.2% offset method [3]. In this method, a line is drawn from the point (σ =0, ε =0.2%) parallel to the linear region of the stress-strain graph. The slope of this line is equal to the elastic modulus. The yield point is then determined as the intersection of this line with the experimental data.

In materials that exhibit a large plastic response, the deformation tends to localize. Continued deformation occurs only in this local region, and is known as necking [4]. Necking begins at a critical point known as the ultimate stress (σ_{ult}). Since failure occurs soon after necking begins, the ultimate stress is an important characteristic to know.

While many experimental tests exist to determine the mechanical properties, the simplest is the tension test. A convenient sample geometry for the tensile test is the "dogbone" geometry (Figure 1). In this test geometry, one end of

the test specimen is held fixed while the other end is pulled in uniaxial tension collinear with the long axis of the sample. The forces throughout the sample and test machine are constant, but the stress varies with cross sectional area. The stress reaches critical values first in the region of the sample of minimum cross section, and the minimum cross section is in the sample. Therefore, the properties of the material are determined in this region.
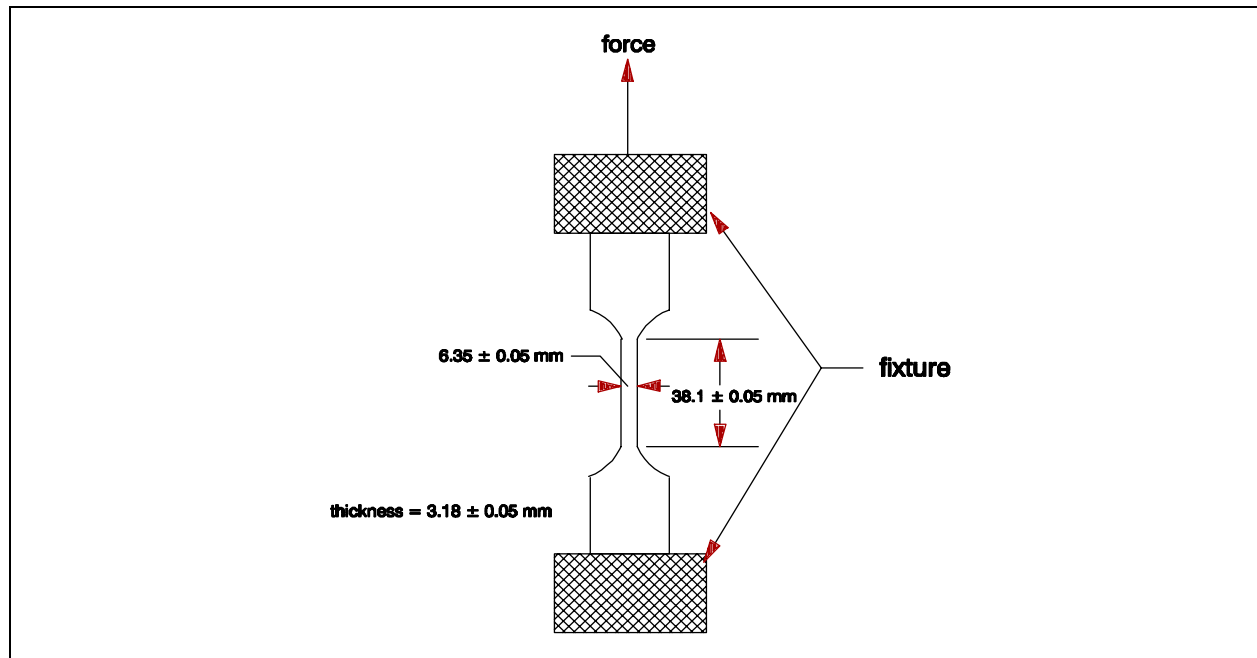
Figure 1. "Dogbone" specimen geometry used for tensile test.

EXPERIMENTAL PROCEDURE

     A tensile test sample was machined from 1018 steel stock (106.1 mm X 19.05 mm X 3.18 mm) to the geometry shown in Figure 1. The region of minimum cross section had dimensions 6.35 mm in width, 3.18 mm in thickness, and 38.1 mm in length. The error in these dimensions was ± 0.05 mm. This sample was clamped into an Instron Universal Test Machine (Model 1125). The Instron test machine is a displacement controlled machine. One end of the sample was held at a fixed position with the other end was displaced at a constant rate. A load cell (Instron model 2511-319) was used to determine the force required to maintain a constant displacement rate. The accuracy of the load cell was ± 1 N. Data was collected on a strip chart (Instron model A1030) that monitored the force as a function of chart displacement. The stress in the sample at any force level can be determined from Equation 1. The calculation of strain requires the conversion of chart displacement (δ_{chart}) to sample displacement (δ_{sample}). The sample displacement can be calculated from:

$$\delta_{sample} = \frac{\delta_{chart} V_{displacment}}{V_{chart}} \tag{4}$$

The rate of sample displacement was 1 ± 0.01 mm/min. The rate of chart displacement was 10 ± 0.1 mm/min. The elastic modulus, yield point, and ultimate stress were determined from the stress-strain plot.

RESULTS AND DISCUSSION

     The force-chart displacement graph for the 1018 steel examined is shown in Figure 2. The data shown in Figure 2 were converted to a corresponding stress-strain graph, Figure 3. Figure 3 clearly indicates two regions of linear behavior in the low strain region of the stress-strain graph. This behavior suggests that the sample was very compliant at low stress levels, and very stiff at high stress levels. Unfortunately, there is no structural or chemical reason why steel should exhibit an increasing modulus with increasing stress. Therefore, a more probable explanation is realignment and rotation of the test fixture in the low stress (low force) region. Remember, that the text fixture and the sample are under the same applied force. Under these experimental conditions, the most compliant member will dominate the stress-strain behavior. While the fixture appears very compliant during realignment and rotation, the fixture appears very stiff due to

its large cross section at higher force levels. In this second region, the stress-strain behavior is dominated by the sample.
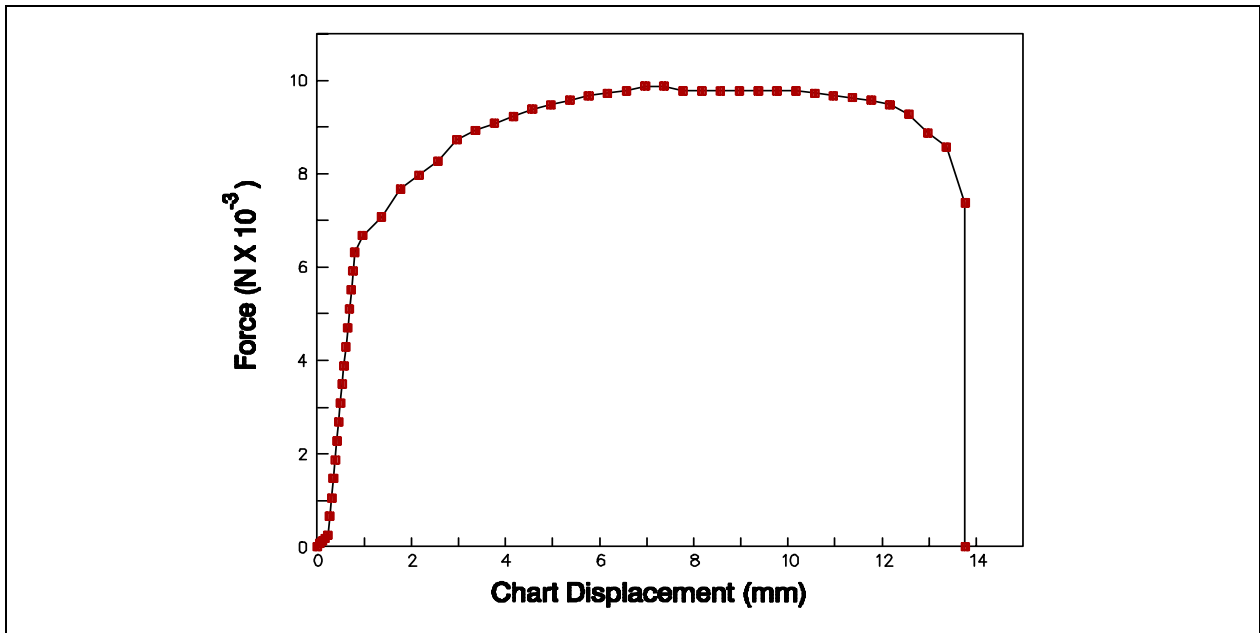
Figure 2. Force as a function of chart displacement for 1018 steel tested in tension.

The elastic modulus was determined from linear regression analysis of the experimental stress-strain data in the second linear region. This region is shown in Figure 4 along with the predicted regression line (σ_1=[196.7 GPa]ε_2-[103.2 MPa]). The elastic modulus of this steel sample was determined to be 196.7 GPa with a standard deviation of 2 GPa. This estimate is consistent with a typical textbook value for modulus of plain carbon steel (205 GPa) [3].

Figure 3. Stress-Strain plot for 1018 steel tested in tension.

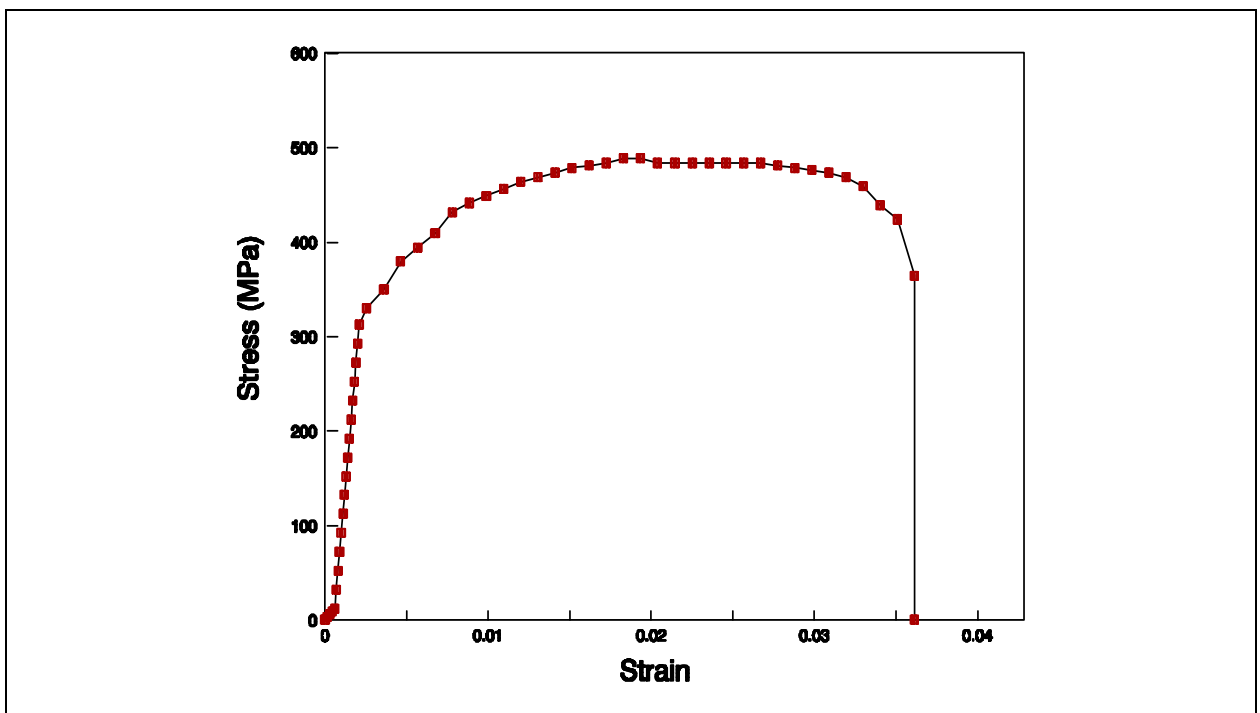The regression line shown in Figure 4 predicts an intercept value of -103.2 MPa. This non-zero intercept suggests that the sample must be compressed in order to obtain zero strain. It should be noted, that this non-zero intercept resulted from the shift in strain values due to realignment and rotation of the fixture, and not due to permanent deformation or violation of Hooke's Law. The region of fixture realignment and rotation creates some difficulties in determining the yield point by the 0.2% offset method. In the initial linear region, the majority of the deformation occurs in the fixture and not in the sample. At the same time, some small amount of deformation must occur in the sample since the force in the sample is greater than zero. The linear region used to estimate the elastic modulus of the sample, Figure 4, must be extrapolated to zero stress to determine the onset of deformation in the sample. A general regression line can be predicted:

$$\sigma = E\varepsilon + \phi \tag{5}$$

The strain at zero stress ($\varepsilon_{\sigma=0}$) can be predicted from:

$$\varepsilon_{\sigma=0} = \frac{-\phi}{E} \tag{6}$$

In the case of the relationship shown in Figure 4 (E=196.7 GPa and ϕ 3=-103.2 MPa), the strain at zero stress was calculated to be 5.2 x 10^{-4}. However, since both E and ϕ were predicted, and contain error associated with that prediction, there must also be error in calculated strain at zero stress. That error can be approximated according to:

$$\Delta\varepsilon_{\sigma=0} = \sqrt{\left(-\frac{\Delta\phi}{E}\right)^2 + \left(\frac{\phi}{E^2}\Delta E\right)^2} \tag{7}$$
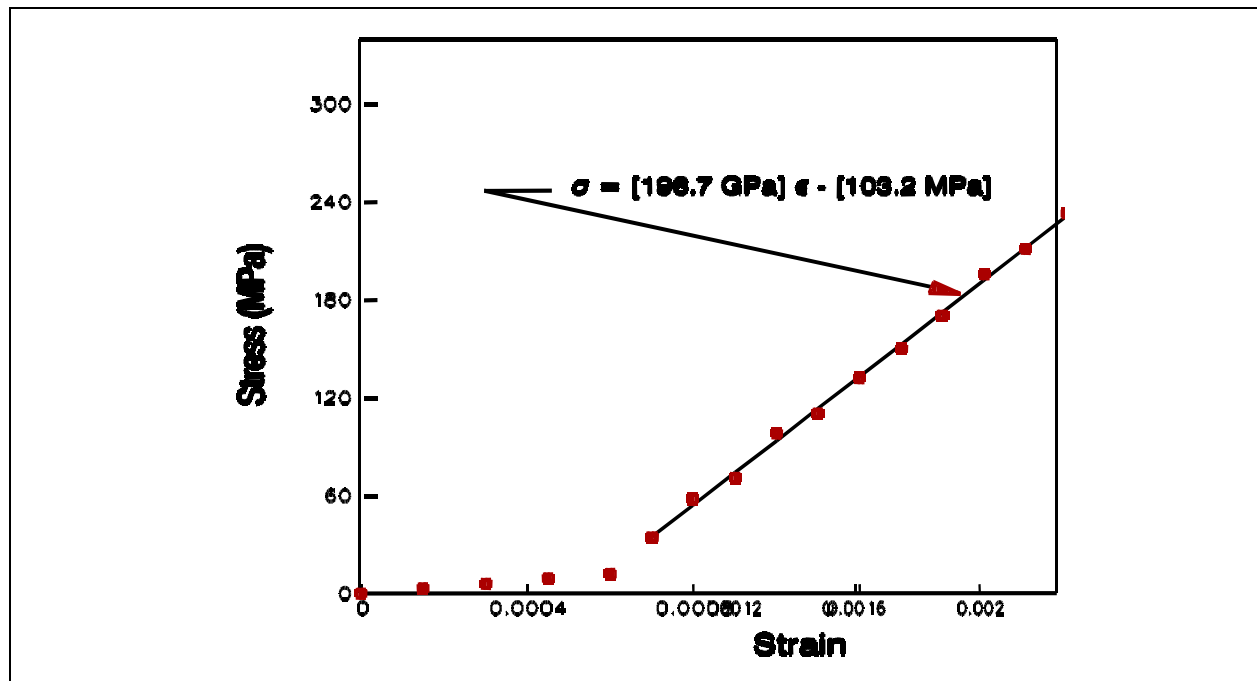
Figure 4. Low strain region of the stress-strain plot of 1018 steel showing two linear regions and predicted regression line.

where the standard deviation of the predicted intercept was 3.3 MPa, and the standard deviation of the predicted elastic modulus was 2 GPa. Solving Equation 7 yields:

$$\Delta \varepsilon_{\sigma=0} = 1.7 \ x \ 10^{-4} \tag{8}$$

Since the errors terms input into Equation were standard deviations, the resulting $\Delta\varepsilon_{\sigma=0}$ calculated (Equation 8) is also a standard deviation. It is appropriate to use the strain at zero stress ($\varepsilon_{\sigma=0}$ in Equation 6) minus some error term as the minimum limit for the starting point of the 0.2% offset line. Likewise, it is appropriate to use the strain at zero stress plus some error term as the maximum limit for the starting point of the 0.2% offset line. Two error terms can be used. The first is the standard deviation ($\Delta\varepsilon_{\sigma=0}$). However since the standard deviation is less than the corresponding distribution width, and alternate approach is to use three times the standard deviation as the appropriate error term [4]. While both approaches are common, the second approach produces the largest range of starting points for the 0.2% offset line, and would be considered the worst case scenario. This worst case scenario will be utilized in this instance. Therefore, the starting point for the line of 0.2% offset must be between 2.01 x 10^{-3} and 3 x 10^{-3} strain.

The range of 0.2% offset lines is shown in Figure 5. The yield point is between 357.1 MPa and 385.7 MPa based upon the intersection of these lines with the experimental data. Addition error in these stress resulted form errors in determining the force and errors in the dimensions. The force was determined to the nearest 25 N. The error in stress can be approximated from:

$$\Delta\sigma = \sqrt{\left(\frac{\Delta F}{wt}\right)^2 + \left(\frac{-F}{w^2 t}\Delta w\right)^2 + \left(\frac{-F}{wt^2}\Delta t\right)^2} \tag{9}$$
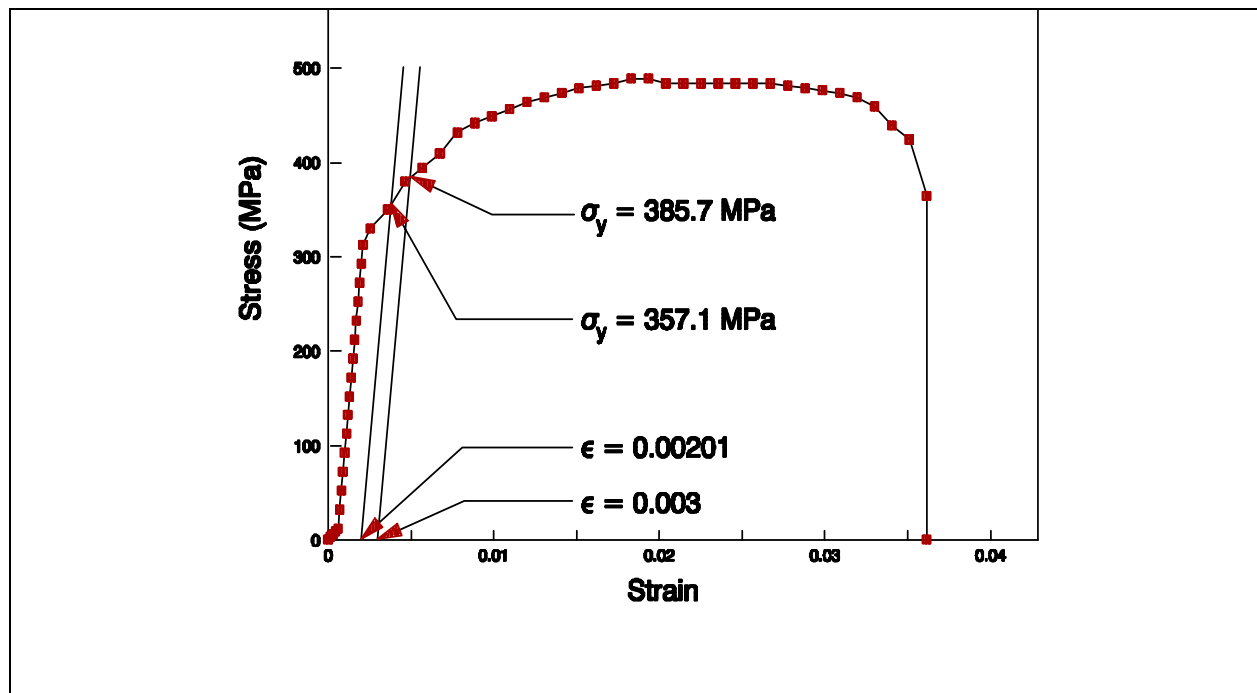
Figure 5. Determination of yield point by the 0.2% offset method.

The error in the force was 12.5 N; the error in both the width and thickness was 0.05 mm. It should be noted that Equation 9 predicts an error in stress that depends on the force. Forces of 7211 N and 7788 N correspond to stresses of 357.1 MPa and 385.7 MPa respectively. The error in stress for a stress of 357.1 MPa was calculated to be 6.3 MPa. The error in stress for a stress of 385.7 MPa was calculated to be 6.8 MPa.

The ultimate stress (maximum in the stress-strain graph) can be determined graphically as shown in Figure 6. The ultimate stress was determined to be 487.7 MPa. The error in the ultimate stress as calculated from Equation 9 at a force level of 9848 N was $\pm$ 8.6 MPa.
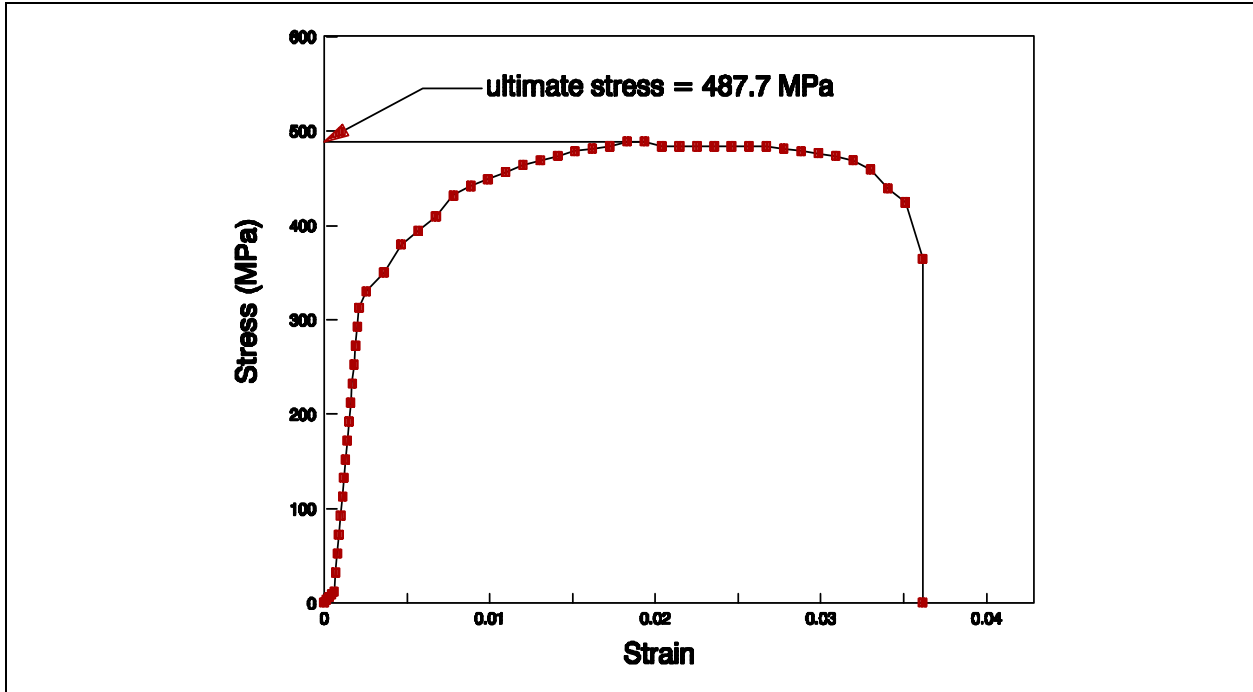
Figure 6. Determination of the ultimate strength of 1018 steel tested in tension.

CONCLUSIONS

    The elastic modulus, yield point, and ultimate stress of 1018 steel were determined in uniaxial tension. The "dogbone" specimen geometry was used. The dimension of the region of reduced cross section was: thickness = 3.18 ± 0.05 mm, width = 6.35 ± 0.05 mm, and gage length = 38.1 ± 0.05 mm. At low forces, the dominant response was realignment and rotation of the test fixture. At high forces, deformation of the sample was the dominant response. The elastic modulus, yield point, and ultimate strength values determined are shown in Table I. The mean and standard deviation of the yield point were not calculated due to problems associated with realignment and rotation of the fixture.

REFERENCES

1.   Van Vlack, L.H., *Introduction to Materials Science and Engineering - 6th Edition*, Addison Wesley, 1989, p 8.

2.   Smith,W.F., *Principles of Materials Science and Engineering - 2nd Edition*, McGraw Hill, 1990, p 255.

3.   Van Vlack, L.H., *Introduction to Materials Science and Engineering - 6th Edition*, Addison Wesley, 1989, p 556.

4.   Dewey, B. R., Introduction to Engineering Computing - 2nd Edition, McGraw-Hill, 1995, p 69.

Table 1. Summary of elastic modulus, yield point, and ultimate strength of 1018 steel tested in uniaxial tension.

Property	Mean	Standard Deviation
Elastic Modulus	196.7 GPa	2.0 GPa
Yield Point (F = 7211N)	357.1 MPa	3.6 MPa
(F = 7788N)	385.7 MPa	6.8 MPa
Ultimate Strength	487.7 MPa	8.6 MPa

TABLE 2. Sample Calculations - Results of linear regression analysis from Excel.

Stress range = 50 to 300 MPa
Strain range = 0.0007 to 0.0021

	Regression Output:
Constant	-103.2
Std Err of Y Est	3.330181
R Squared	0.998671
No. of Observations	15
Degrees of Freedom	13

X Coefficient(s) 196714.2
Std Err of Coef. 1990.164

APPENDIX 1. Chart of Experimental displacement - force data.

Displacement	Force
0 mm	0 N
0.06	60
0.11	121
0.17	181
0.23	242
0.27	687
0.30	1171
0.34	1434
0.38	1979
0.42	2222
0.46	2665
0.50	3029
0.53	3433
0.57	3958
0.61	4261
0.65	4705
0.69	5028
0.72	5351
0.76	5957
0.80	6280
0.97	6658
1.37	7058
1.77	7658
2.17	7958
2.57	8258
2.97	8708
3.37	8908
3.77	9058
4.17	9208
4.57	9358
4.97	9458
5.37	9558
5.77	9658
6.17	9708
6.57	9758
6.97	9858
7.37	9858
7.77	9758
8.17	9758
8.57	9758
8.97	9758
9.37	9758
9.77	9758
10.17	9758
10.57	9708
10.97	9658
11.37	9608
11.77	9558
12.17	9458
12.57	9258
12.97	8858
13.37	8558
13.77	7358
13.77	0

APPENDIX 2. Sample Calculations - Conversion of force to stress and conversion of chart displacement to strain.

Conversion of force to stress:

$$\sigma = \frac{F}{A} = \frac{F}{wt}$$

$$w = 6.35 \times 10^{-3} \, m$$
$$t = 6.35 \times 10^{-3} \, m$$

$$\sigma = F \left(4.95 \times 10^{4} \, m^{-2} \right)$$

if $\quad F = 100 \, N, \quad \sigma = 4.95 \, MPa$

if $\quad F = 1000 \, N, \quad \sigma = 49.5 \, MPa$

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Conversion of chart displacement to strain:

$$\varepsilon = \frac{\Delta l}{l_0}$$

$$\Delta l = \delta_{sample} = \frac{\delta_{chart} \, V_{displacement}}{V_{chart}}$$

combining yields:

$$\varepsilon = \frac{\delta_{chart} \, V_{displacement}}{l_0 \, V_{chart}}$$

$$V_{displacement} = 1 \, \frac{mm}{min}$$

$$V_{chart} = 10 \, \frac{mm}{min}$$

$$l_0 = 38.1 \, mm$$

$$\varepsilon = \delta_{chart} \left(2.62 \times 10^{-3} \, mm^{-1} \right)$$

if $\quad \delta_{chart} = 1 \, mm, \quad \varepsilon = 2.62 \times 10^{-3} = 0.0026$

if $\quad \delta_{chart} = 10 \, mm, \quad \varepsilon = 2.62 \times 10^{-2} = 0.0262$

APPENDIX 3. Experimental data converted to strain and stress.

Strain	Stress (MPa)
0	0
0.0002	3
0.0003	6
0.0005	9
0.0006	12
0.0007	34
0.0008	58
0.0009	71
0.001	98
0.0011	110
0.0012	132
0.0013	150
0.0014	170
0.0015	196
0.0016	211
0.0017	233
0.0018	249
0.0019	265
0.002	295
0.0021	311
0.0025	330
0.0036	350
0.0046	379
0.0057	394
0.0067	409
0.0078	431
0.008	441
0.0099	449
0.0109	456
0.0120	463
0.0130	468
0.0141	473
0.0151	478
0.0162	481
0.0172	483
0.0183	488
0.0193	488
0.0204	483
0.0214	483
0.0225	483
0.0235	483
0.0246	483
0.0256	483
0.0267	483
0.0277	481
0.0288	478
0.029	476
0.0309	473
0.0319	468
0.0330	458
0.0340	439
0.0351	424
0.0361	364
0.0361	0