Experiments of Part I

Mechanical Behavior of Materials

Prof. Dr. Mohammad D. AL-Tahat
Department of Industrial Engineering
The University of Jordan
Lab. of Manufacturing Processes
Course No: IE IE0906412

1. Objectives

The main purpose of this experiment is to study the fundamental aspects of the mechanical behavior of materials during deformation processing.

2. Background

For more information about the subject of the experiments, it is recommended for the student to review sections 2.1-2.10 of chapter two of the text.

3. Theory

There are three principal ways in which forces may be applied during deformation processing: namely, tension, compression, and shear (Figures 1a,b, c). In engineering practice many loads are torsional rather than pure shear; this type of loading is illustrated in figure 1.

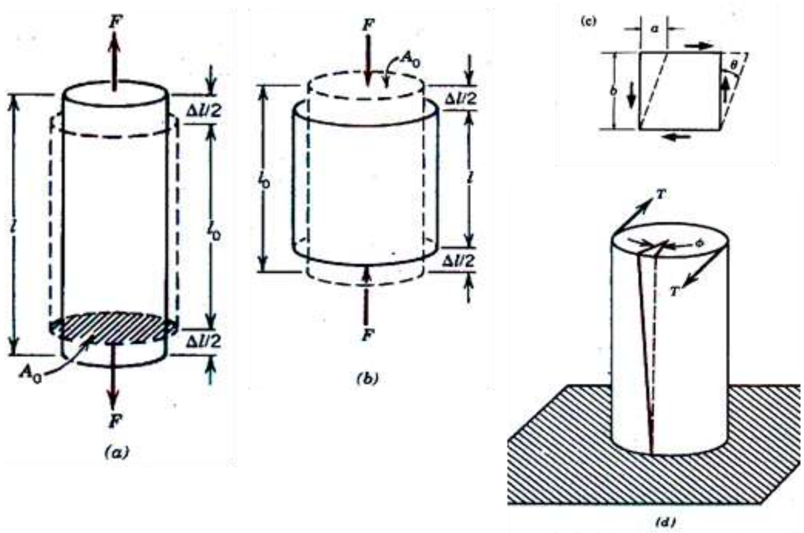


Figure 1: Some Types of Strains [1]

The degree of deformation to which the material is subjected is defined as strain. In order to change the geometry of an element, forces must be applied to them. The determination of these forces as function of the deformation (strain) is very important. We have to know the forces in order to: Design the proper machine; Select tools and die materials for proper strength; and determine whether metalworking operation can be accomplished on certain equipment. Thus the relation between a force and the deformation it produces is an essential parameter in manufacturing.

4. Tension Test.

One of the most common mechanical tests is performed in tension. The tension test is used to ascertain several mechanical properties of materials that are important in design. A specimen is deformed, usually to fracture, with a gradually increasing tensile load that is applied uniaxial along the long axis of a specimen. A standard tensile specimen is shown in Figure.2. Normally, the cross section is circular, but rectangular specimens are also used. Tables 1, and 2 give examples of test specimen dimensions and tolerances per standard ASTM E8.

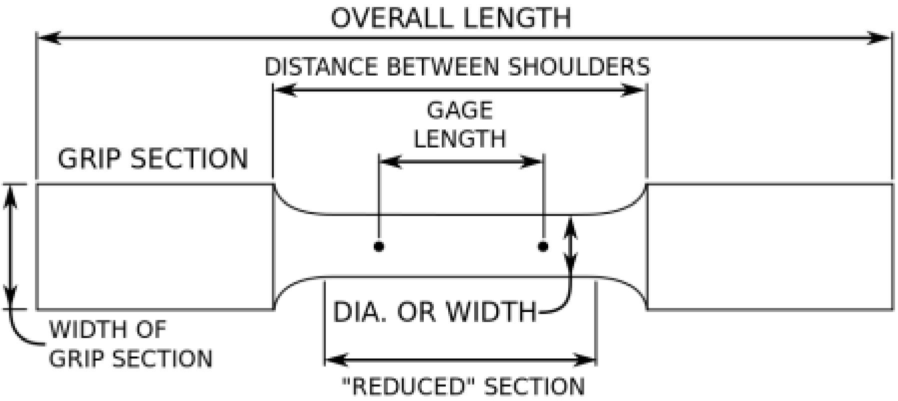


Figure 2. Standard Tensile-test Specimen.

Table 1: Flat test specimen

All values in inches	**Plate type (1.5 in. wide)**	**Sheet type (0.5 in. wide)**	**Sub-size specimen (0.25 in. wide)**
Gauge length	8.00±0.01	2.00±0.005	1.000±0.003
Width	1.5 +0.125–0.25	0.500±0.010	0.250±0.005
Thickness	0.188 ≤ T	0.005 ≤ T ≤ 0.75	0.005 ≤ T ≤ 0.25
Fillet radius (min.)	1	0.25	0.25
Overall length (min.)	18	8	4
Length of reduced section (min.)	9	2.25	1.25
Length of grip section (min.)	3	2	1.25
Width of grip section (approx.)	2	0.75	3/8

Table 2: Round test specimen

All values in inches		**Standard specimen at nominal diameter:**		**Small specimen at nominal diameter:**		
		0.500 inch 12.7 mm	**0.350 8.9**	**0.25 6.4**	**0.160 4.1**	**0.113 2.9**
Gauge length	Inch.	2.00 ±0.005	1.400±0.005	1.000±0.005	0.640±0.005	0.450±0.005
	mm	50.8 ±0.127	35.56±0.127	25.4±0.127	16.256±0.127	11.43±0.127
Diameter tolerance (in.)		± 0.010	± 0.007	± 0.005	± 0.003	± 0.002
Fillet radius (in.)		3/8	0.25	5/16	5/32	3/32
Length of reduced section (in.)		2.5	1.75	1.25	0.75	5/8

The specimen is mounted by its ends into the holding grips of the testing apparatus (Figure.3). The tensile testing machine is designed to elongate the specimen at a constant rate, and to continuously and simultaneously measure the instantaneous applied load (with a load cell) and the resulting elongations (using an extensometer).

A stress-strain test typically takes several minutes to perform and is destructive; that is, the test specimen that has an original length l_o and an original cross-sectional area A_o (figure 3) is permanently deformed and usually fractured.

Typical results from a tension test are shown in figure 4. The figure outline the relation between engineering stress and engineering strain (nominal stress-strain), also the figure presents an outline of a tensile-test sequence showing different stages in the elongation of the specimen. The output of such a tensile test is recorded on a strip chart as load or force versus elongation. Engineering stress σ is defined by the relationship

$$\sigma = \frac{F}{A_0} \tag{1}$$

In which F is the instantaneous load applied perpendicular to the specimen cross section, in units of pounds force (lbf) or Newtons (N), and Ao is the original cross-sectional area before any load is applied (in.2 or m2). Engineering strain e is defined according to

$$e = \frac{l - l_0}{l_0} = \frac{\Delta l}{l_0} \tag{2}$$

Where, l_o is the original length before any load is applied, and l is the instantaneous length.

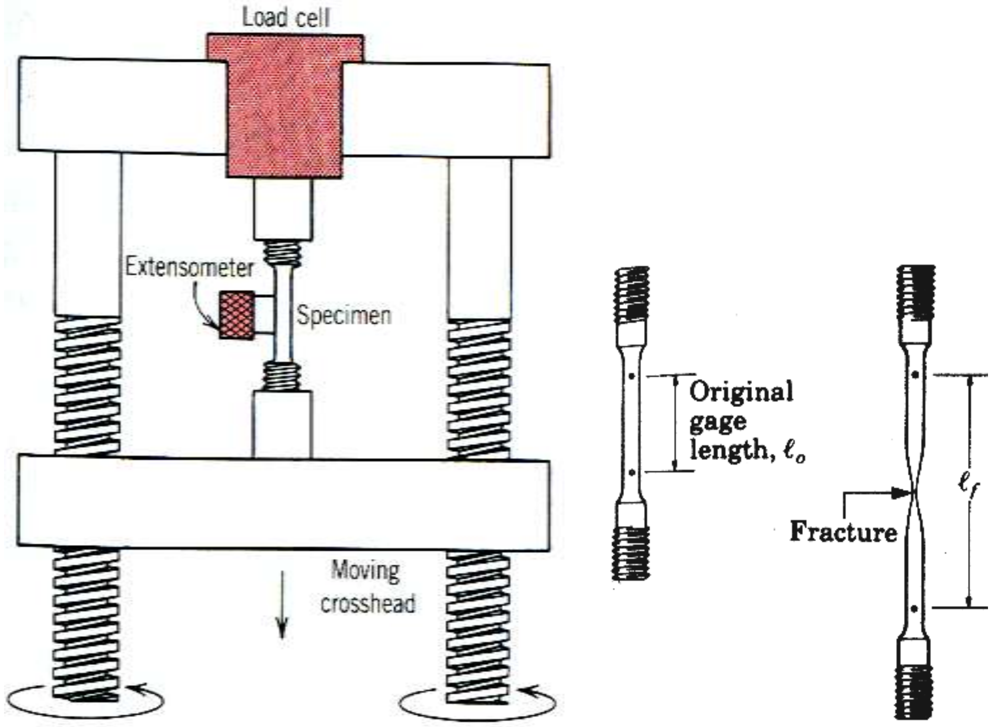


Figure 3. Schematic representation of the apparatus used to conduct tensile stress strain tests and shape of specimen.

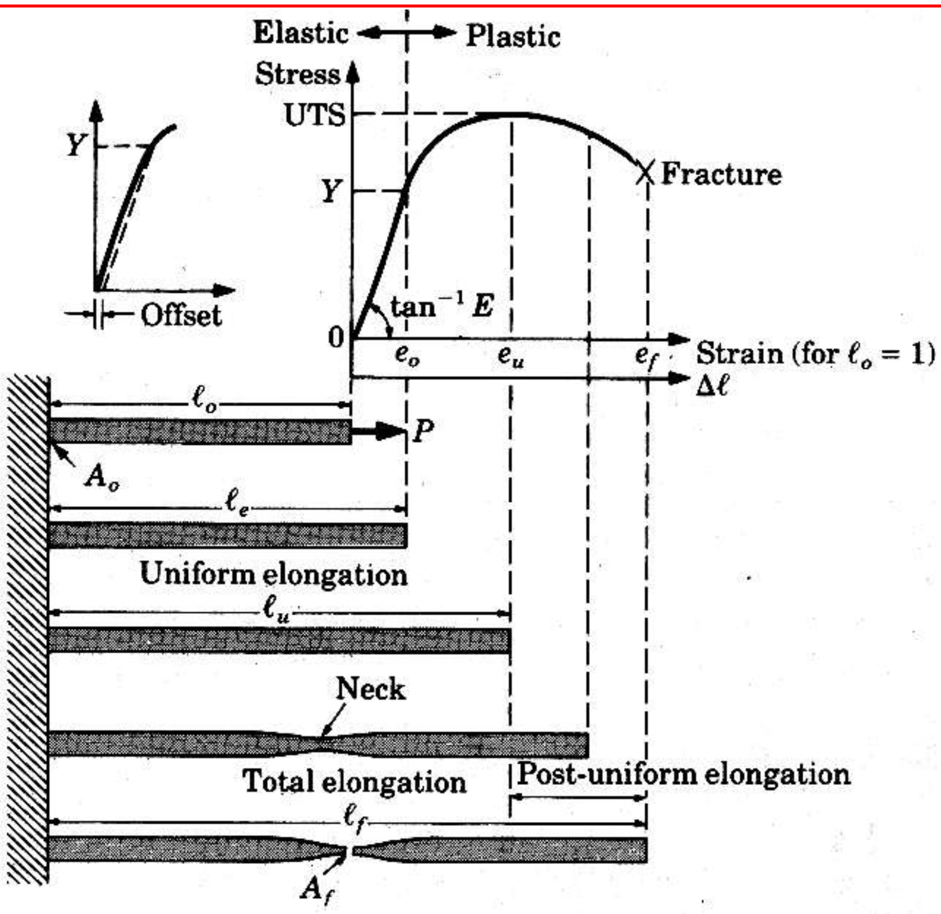


Figure 4. Outline of a tensile-test sequence showing different stages in the elongation of the specimen.

4. Hooke's Law

Deformation in which stress and strain are proportional is called elastic deformation; a plot of stress versus strain results in a linear relationship. Stress and strain are proportional to each other through the relationship.

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

This is known as Hook's law, and the constant of proportionality E (psi or MPa) is the modulus of elasticity, or Young's modulus .Values of the modulus of elasticity for ceramic materials are characteristically higher than for metals; for polymers, they are lower. These differences are a direct consequence of the different types of atomic bonding in the materials types. Furthermore, with increasing temperature, the modulus of elasticity diminishes.

There are some materials (e.g., gray cast iron and concrete) for which this initial elastic portion of the stress-strain curve is not linear; hence, it is not possible to determine a modulus of elasticity as described above. For this nonlinear behavior, either tangent or secant modulus is normally used.

5. Anelasticity or viscoelastic behavior

In most engineering materials, however, there will also exist a time-dependent elastic strain component. That is, elastic deformation will continue after the stress application, and upon load release some finite time is required for complete recovery. This time-dependent elastic behavior is known as anelasticity, and it is due to time-dependent microscopic and atomistic processes that are attendant to the deformation. For metals the anelastic component is normally small and is often neglected. However, for some polymeric materials its magnitude is significant; in this case it is termed viscoelastic behavior.

6. Poisson's ratio

When a tensile stress is imposed on a metal specimen, an elastic elongation and accompanying strain ε_z result in the direction of the applied stress (arbitrarily taken to be the z direction), as indicated in Figure 5. As a result of this elongation, there will be constrictions in the lateral (x and y) directions perpendicular to the applied stress; from these contractions, the compressive strains ε_x and ε_y may be determined. If the applied stress is uniaxial (only in the z direction), then $\varepsilon_x = \varepsilon_y$. A parameter termed Poisson's ratio v is defined as the ratio of the lateral and axial strains, or

$$v = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z} \qquad (4)$$

The negative sign is included in the expression so that v will always be positive, since ε_x and ε_z will always be of opposite sign. Theoretically, Poisson's ratio for isotropic materials should be ¼; furthermore, the maximum value for v (or that value for which there is no net volume change) is 0.50. Shear and elastic moduli are related to each other and to Poisson's ratio according to

$$E = 2G(1+V) \qquad (5)$$

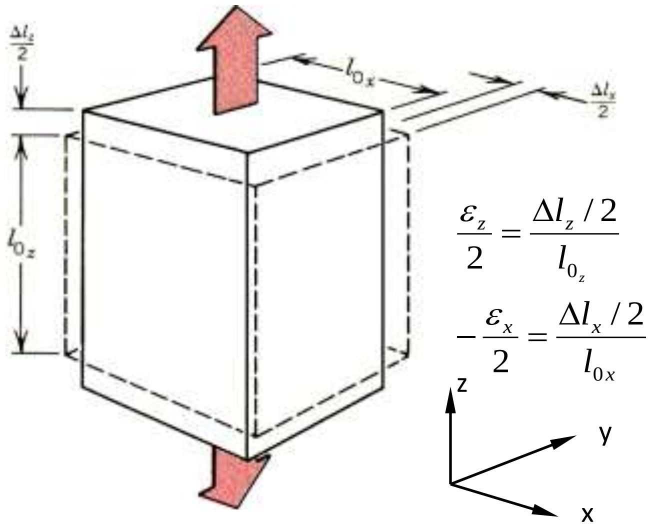


Figure [5]: Axial (z) elongation (positive strain) and lateral (x and y) contractions (negative strains) in response to an imposed tensile stress. Solid lines represent dimensions after stress application; dashed lines, before.

7. Isotropic and anisotropic

Many materials are elastically anisotropic; that is, the elastic behavior (e.g., the magnitude of E) varies with crystallographic direction. For these materials the elastic properties are completely characterized only by the specification of several elastic constants, their number depending on characteristics of the crystal structure. Even for isotropic materials, for complete characterization of the elastic properties, at least two constants must be given. Since the grain orientation is random in most polycrystalline materials, these may be considered to be isotropic; inorganic ceramic glasses are also isotropic.

8. Modulus of resilience and the specific energy

The area under the stress-strain curve up to the yield point Y of a material is known as the modulus of resilience, or the specific energy that the material can store elastically. This area has the unit of energy per unit volume.

$$\text{Modulus of Resilience} = \frac{Ye_o}{2} = \frac{Y^2}{2E} \qquad (6)$$

9. Yielding and yield stress

For most metallic materials, elastic deformation persists only to strains of about 0.002(0.2% for linear elastic behavior); other offset strains may also be in used (0.5% for non-linear elastic behavior) and should be specified when reporting the yield stress of a material. As the material is deformed beyond this point, the stress is no longer proportional to strain and permanent, non-recoverable, or plastic deformation occurs.

From an atomic perspective, plastic deformation corresponds to the breaking of bonds with original atom neighbors and then reforming bonds with new neighbors as large numbers of atoms or molecules move relative to one another; upon removal of the stress they do not return to their original positions. The mechanism of this deformation is different for crystalline and amorphous materials. For crystalline solids, deformation is accomplished by means of a process called slip, which involves the motion of dislocations. Plastic deformation in no crystalline solids (as well as liquids) occurs by a viscous flow mechanism.

Most structures are designed to ensure that only elastic deformation will result when a stress is applied. It is therefore desirable to know the stress level at which plastic deformation begins, or where the phenomenon of yielding occurs. For metals that experience this gradual elastic-plastic transition, the point of yielding may be determined as the initial departure from linearity of the stress-strain curve; this is sometimes called the proportional limit. In such cases the position of this point may not be determined precisely. As a consequence, a convention has been established where in a straight line is constructed parallel to the elastic portion of the stress-strain curve at some specified strain offset, usually 0.002. The stress corresponding to the intersection of this line and the stress-strain curve as it bends over in the plastic region is defined as the yield strength σ_y.

For those materials having a nonlinear elastic region, use of the strain-offset method is not possible, and the usual practice is to define the yield strength as the stress required to produce some amount of strain (e.g., $\varepsilon = 0.005$).

Some steels and other materials have upper and lower yield points. The elastic-plastic transition is very well defined and occurs abruptly in what is termed a yield point phenomenon. At the upper yield point, plastic deformation is initiated with an actual decrease in stress. Continued deformation fluctuates slightly about some constant stress value, termed the lower yield point; stress subsequently rises with increasing strain. For metals that display this effect, the yield strength is taken as the average stress that is associated with the lower yield point, since it is well defined and relatively insensitive to the testing procedure. Thus, it is not necessary to employ the strain-offset method for these materials.

10. Tensile strength

After yielding, the stress necessary to continue plastic deformation in metals increases to a maximum, point M in Figure 6, and then decreases to the eventual fracture, point F. The tensile strength TS (psi or MPa) is the stress at the maximum on the engineering stress-strain curve (Figure

6). This corresponds to the maximum stress that can be sustained by a structure in tension; if this stress is applied and maintained, fracture will result. All deformation up to this point is uniform throughout the narrow region of the tensile specimen. However, at this maximum stress, a small constriction or neck begins to form at some point, and all subsequent deformation is confined at this neck, as indicated by the schematic specimen insets in Figure 6. This phenomenon is termed "necking," and fracture ultimately occurs at the neck. The fracture or rupture strength corresponds to the stress at fracture. Tensile strengths may vary anywhere from 7000 psi (50 MPa) for an aluminum to as high as 450,000 psi (3000 MPa) for the high-strength steels. Ordinarily, when the strength of a metal is cited for design purposes, the yield strength is used. This is because by the time a stress corresponding to the tensile strength has been applied, often a structure has experienced so much plastic deformation that it is useless. Furthermore, fracture strengths are not normally specified for engineering design purposes.

11. Ductility

Ductility is another important mechanical property. It is a measure of the degree of plastic deformation that has been sustained at fracture. A material that experiences very little or no plastic deformation upon fracture is termed brittle. The tensile stress-strain behaviors for both ductile and brittle materials are schematically illustrated in Figure 7. Ductility may be expressed quantitatively as either percent elongation or percent area reduction. The percent elongation %EL is the percentage of plastic strain at fracture, or

$$\%EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100 \quad (9)$$

A second measure of ductility is reduction of area, defined as

$$\text{Reduction of area} = \left(\frac{A_0 - A_f}{A_0}\right) \times 100 \quad (8)$$

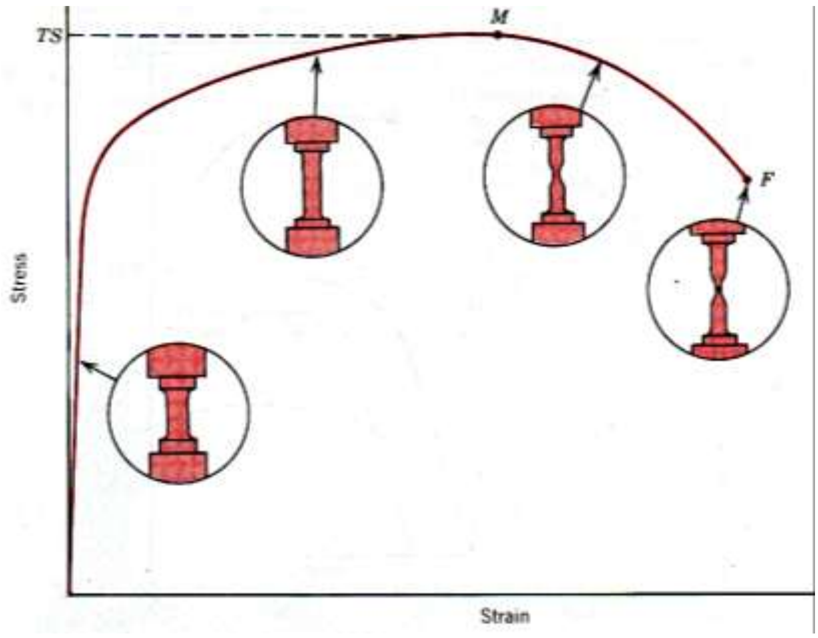


Figure 6. Typical engineering stress-strain behaviors to fracture, point F. The tensile strength TS is indicated at point M. The circular insets represent the geometry of the deformed specimen at various points along the curve.

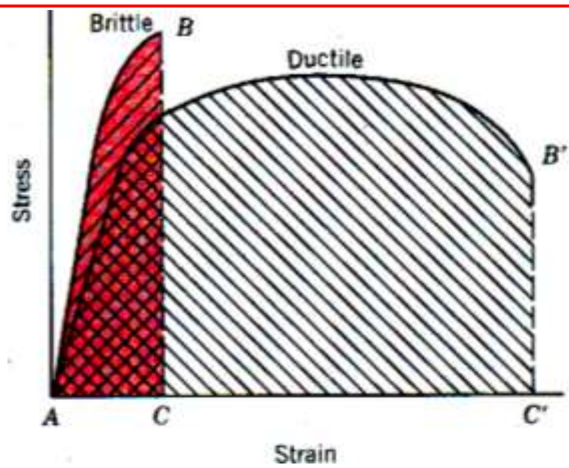


Figure 7: Schematic representations of tensile stress-strain behavior for brittle and ductile materials loaded to fracture.

12. The true stress- true strain curve

True stress σ = F/ A, where A is the instantaneous cross sectional area of the test specimen. We can define true strain; natural or logarithmic strain ε as:

$$\varepsilon = \int_{l_o}^{l} \frac{dl}{l} = ln\left(\frac{l}{l_0}\right) \qquad (9)$$

Within the uniform deformation the true strain can be expressed as:

$$\varepsilon = ln\left(\frac{l}{l_0}\right) = ln\left(\frac{A_0}{A}\right) = ln\left(\frac{D_0}{D}\right)^2 = 2\,ln\left(\frac{D_0}{D}\right) \qquad (10)$$

The relationship between the engineering strain and true strain can be found from the following expression:

$$e = \frac{\Delta l}{l_0} = \frac{l - l_0}{l_0} = \frac{l}{l_0} - 1 \qquad (11)$$

$$\therefore \frac{l}{l_0} = e + 1 \qquad (12)$$

$$\varepsilon = ln(1 + e) \qquad (13)$$

The Strength of material can be expressed in terms of true stress as:

$$\sigma = K\varepsilon^n \qquad (14)$$

Where K is the strength coefficient and n is the strain-hardening exponent. These can be determined experimentally as shown in figure 8, which reflects the true stress versus true strain curve in logarithmic scale, according to equation (15)

$$Log\ \sigma = log\ K + n\ Log\ \varepsilon \qquad (15)$$

The area under the true stress- true strain curve is known as toughness and can be expressed as:

$$Toughness = \int_{0}^{\varepsilon_f} \sigma . d\varepsilon \qquad (16)$$

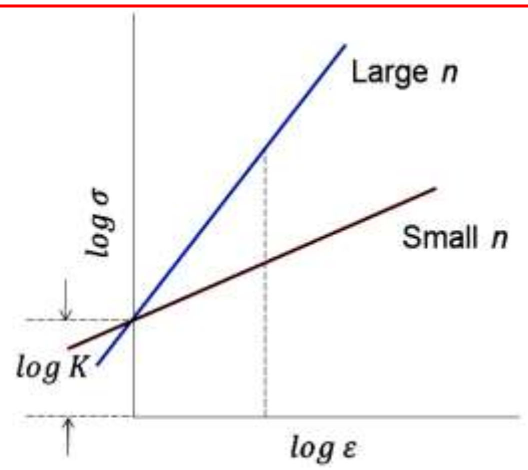


Figure 8. The true stress versus true strain curve (in logarithmic scale) for metals with large and small n-values.

13. Numerical Example:

An annealed bar of copper alloy is subjected to a deformation load has a stress - strain curve given by $\boldsymbol{\sigma = 100\varepsilon^{0.5}}$ **MPa**. The diameter of the bar is 10 mm, and the length is 500 mm. At the onset of necking calculate the following.

1. The ultimate true tensile strength.
   $\varepsilon = \mathrm{n} = 0.5 \Rightarrow \sigma = K.\varepsilon^{n} = 100(0.5)^{0.5} = UTS_{True} = 70.7MPa$

2. The initial cross sectional area of the bar.
   $$\mathrm{A_o} = \pi\left(\frac{10}{2}\right)^2 = 78.5\,mm^2 = 7.8\times10^{-5}\ \mathrm{m}^2$$

3. The maximum load can be applied,
   $$ln\left(\frac{A_o}{A_{neck}}\right) = n \Rightarrow ln\left(\frac{78.5}{A_{neck}}\right) = 0.5$$
   $$A_{neck} = \frac{78.5}{e^{0.5}} = \frac{0.00196}{e^{0.5}} = 47.6\ \mathrm{mm}^2$$
   $$P = \sigma.A_{neck} = UTS_{true}\cdot A_{neck} = (70.7MPa)(47.6m\mathrm{m}^2) = 3.4KN$$
   $1\,\mathrm{MPa} = 1000\ \mathrm{KN/m^2}$

4. Find the ultimate engineering tensile strength.
   $$\mathrm{UTS_{Engineering}} = \frac{P}{A_o} = \frac{3.4KN}{78.5mm^2} = 43312KN/m^2$$

5. The change in the length of the tube.

$$\frac{\Delta L}{L_o} = e$$

$$\varepsilon = \ln(1+e) = 0.5 \Rightarrow e^{0.5} - 1 = e = 0.6487$$

$$0.6487 = \frac{\Delta L}{L} \Rightarrow \Delta L = (0.6487)(500) = 324\text{mm}$$

Or $$\varepsilon = 0.5 = \ln\left(\frac{L}{L_O}\right) \Rightarrow e^{0.5} = \frac{L}{500} \Rightarrow L = 824$$

$$\Delta L = L - L_o = 824 - 500 = 324mm$$

14. Materials

Two standard tensile specimens are required according to the international standards, as shown in Figure 2. One made from steel and the other from Brass.

15. Tools and Equipment.

Universal testing machine to conduct the tensile stress strain tests and Vernier Caliper for taking some measurements are required.

16. Procedures.

1. Select an Aluminum bar of 1.5 in. diameter
2. Prepare a circular standard tensile specimen, according to the specifications in Figure.2, and table 2.
3. Sketch the prepared specimen by hand on an A4 blank page.
4. Highlight on the sketch all the specimen dimensions, in particular;
    - the length on the reduced section,
    - the gauge length
    - the diameter of the specimen within the gauge length
5. Mark the two lengths on the tensile specimen.
6. Set the testing machine and prepare it to be ready for performing the test, that implies; checking the electrical connections, switching on the machine, switching on the pressure pump and wait tell the pressure reach the needed value.
7. Mount the specimen by its ends into the holding grips of the testing apparatus shown in figure 3.
8. Switch on the loading button of the testing machine. The machine gradually increasing tensile load that is applied uniaxial along the long axis of a specimen until the specimen fractured.
9. Remove the load-deflection table (curve if available) from the printer of testing machine control unit.
10. Assemble the fractured specimen (fix the two half's together precisely) and measure the final diameter, the final reduced section, and the final gauge length of the deformed specimen.
11. Answer all the requirements listed in the next section.

17. Requirements.

1. Draw the engineering stress-engineering strain curve of the tested materials.
2. Draw the true stress-true strain curve of the tested materials
3. Draw the logarithm relation between true stress true strains then find the strength coefficient (K) and the strain-hardening exponent (n).
4. For the tested materials, determined from the drawn stress-strain curves the following:
    a. Modulus of elasticity
    b. Proportional limit
    c. Elastic limit
    d. Yield strength
    e. Elastic specific energy per unit volume
    f. Ultimate tensile strength
    g. Fracture stress
    h. Toughness
    i. Elongation
    j. Ductility

18. Sample Calculation Example

A round bar of 8 mm diameter and original gage length of 110 mm is subjected to a tensile test, the following data were recorded.

Load (KN)	Deflection (mm)
0	0.0
3	0.5
26	3.0
30	8.0
30	10.0
29	14.0
30	17.0
30	21.0
31	25.0
32	31.0
33	34.0
34	38.0
35	42.0
33	46.0
30	50.0

1. Draw the load deflection (elongation) curve
2. Draw the engineering stress-engineering strain curve.
3. Draw the true stress-true strain curve
4. Draw the logarithm relation between true stress true strains then find the strength coefficient (K) and the strain-hardening exponent (n).
5. Determined the following: Modulus of elasticity, Proportional limit, Elastic limit, Yield strength, Elastic specific energy per unit volume, Ultimate tensile strength, Fracture stress, Toughness , Over all Elongation percentage %, and evaluate Ductility

Solution:

Original diameter D_0 = 8 mm → original area A_0 = 50.27 mm^2. Original length L_0 = 110 mm^2,

Engineering stress (KN/mm^2) = Load/ A_0, Engineering stress (Kpa) = Engineering stress (KN/mm^2) x 1000

Engineering strain = Deflection/ L_0 = Deflection/ 110.

Instantaneous length (mm) = Original length + Deflection = 110 + Deflection

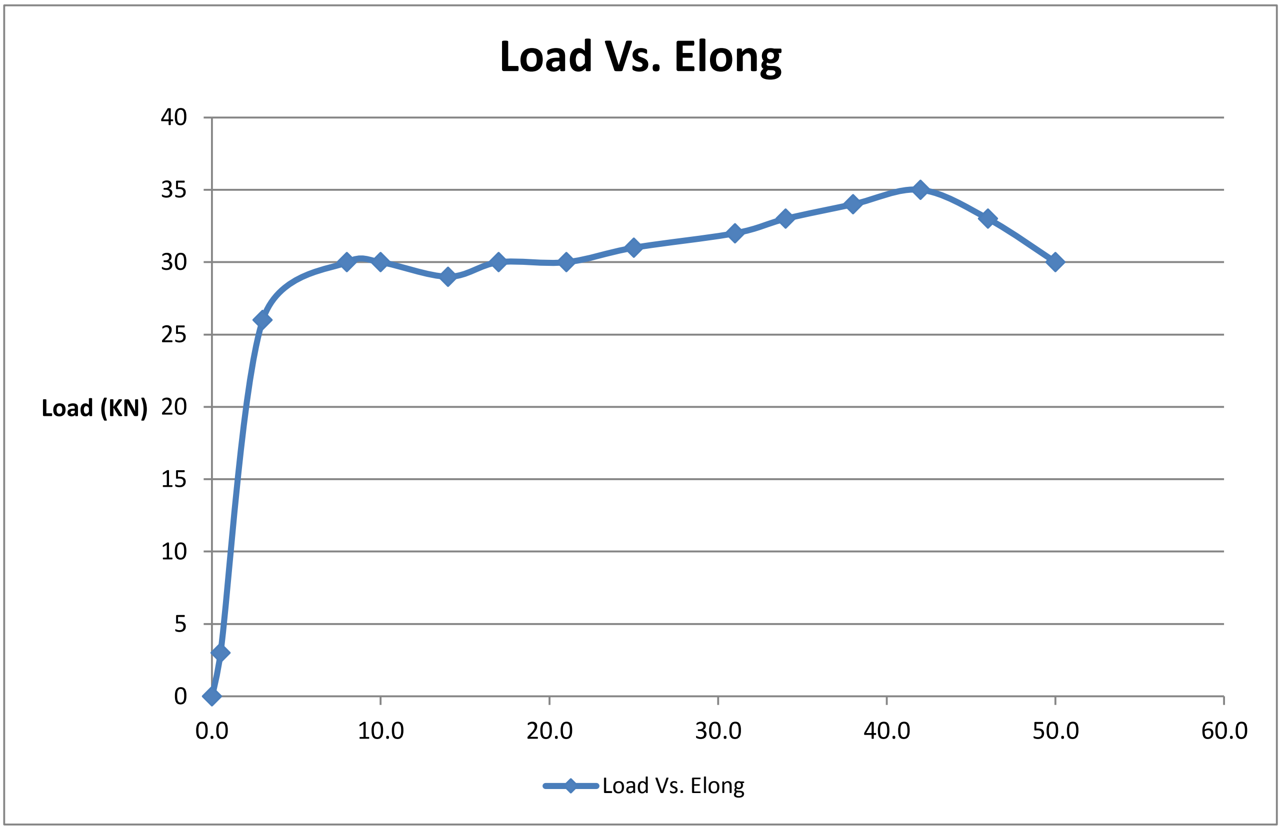
Instantaneous area (mm^2) = (Original area x Original length)/ Instantaneous length = (50.27x110)/ Instantaneous length

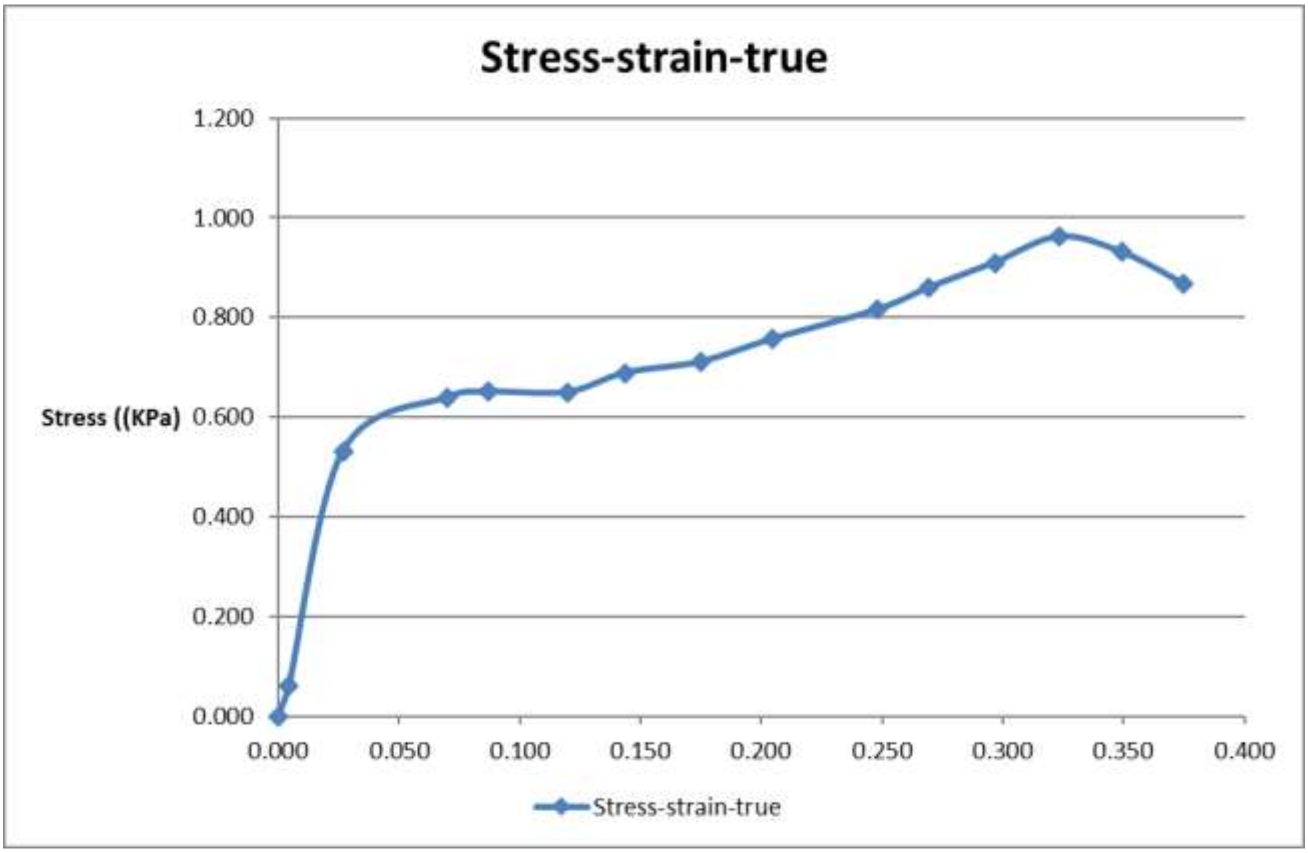
True Stress (KN/mm^2) = Load (KN) / Instantaneous area (mm2)

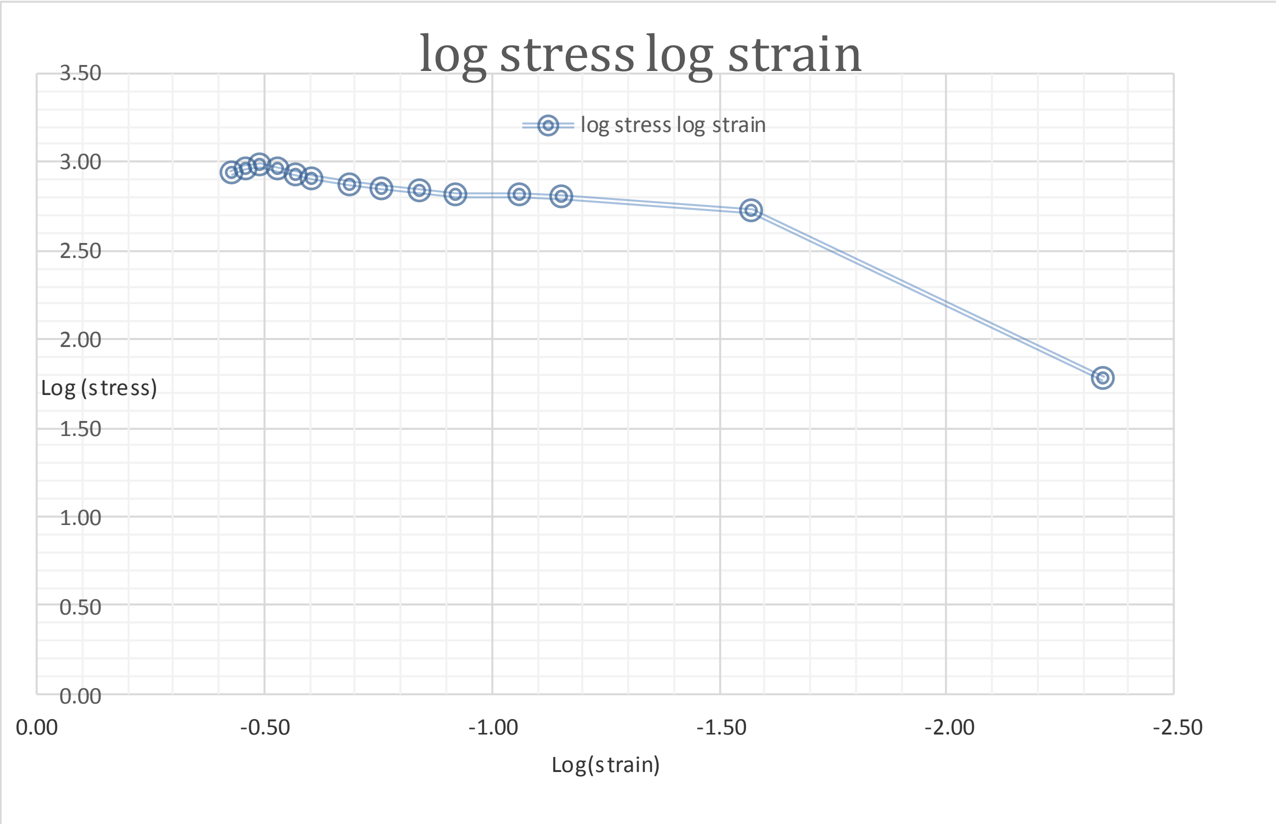
True Stress (Kpa) = True Stress (KN/mm2)x 1000

True strain = Lin (Instantaneous length/ Original length) = Lin (Instantaneous length/ 110)

Load	Deflc	Engineering			Instantaneous		True			Log σ	Log ε
		Stress σ_e		Strain	length	Area	Stress σ		Strain	Kpa	
KN	(mm)	KN/mm^2	Kpa	e	mm	mm^2	KN/mm^2	Kpa	ε		
0	0.0	0.000	0	0.000	110.0	50.27	0.000	0	0.000	-	-
3	0.5	0.060	60	0.005	110.5	50.04	0.060	60	0.005	1.78	-2.3
26	3.0	0.517	517	0.027	113	48.94	0.531	531	0.027	2.73	-0.27
30	8.0	0.597	597	0.073	118	46.86	0.640	640	0.070	2.81	-1.15
30	10.0	0.597	597	0.091	120	46.08	0.651	651	0.087	2.81	-1.06
29	14.0	0.577	577	0.127	124	44.59	0.650	650	0.120	2.81	-0.92
30	17.0	0.597	597	0.155	127	43.54	0.689	689	0.144	2.84	-0.84
30	21.0	0.597	597	0.191	131	42.21	0.711	711	0.175	2.85	-0.76
31	25.0	0.617	617	0.227	135	40.96	0.757	757	0.205	2.88	-0.69
32	31.0	0.637	637	0.282	141	39.22	0.816	816	0.248	2.91	-0.61
33	34.0	0.656	656	0.309	144	38.40	0.859	859	0.269	2.93	-0.57
34	38.0	0.676	676	0.345	148	37.36	0.910	910	0.297	2.96	-0.53
35	42.0	0.696	696	0.382	152	36.38	0.962	962	0.323	2.98	-0.49
33	46.0	0.656	656	0.418	156	35.45	0.931	931	0.349	2.97	-0.46
30	50.0	0.597	597	0.455	160	34.56	0.868	868	0.375	2.94	-0.43


Load Vs. Elong
40
35
30
25
Load (KN) 20
15
10
5
0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
Load Vs. Elong


Stress-strain-true
1.200
1.000
0.800
Stress ((KPa) 0.600
0.400
0.200
0.000
0.000
0.050
0.100
0.150
0.200
0.250
0.300
0.350
0.400
Stress-strain-true



Slope n	n	0.526	
Intercept	log K	3.266	
	K	26.216	Kpa
	K	0.0262	(KN/mm2)

$\sigma = 26\varepsilon^{0.526}$ KPa

6. At the onset of necking calculate the following.
   Now: $\sigma = 26\varepsilon^{0.526}$ KPa
   The following can be solved in the same manner as in section **13** of this guide.
   k. The ultimate true tensile strength.
   l. The initial cross sectional area of the bar.
   m. The maximum load can be applied,
   n. Find the ultimate engineering tensile strength.
   o. The change in the length of the tube.
   p. The ideal energy required for homogeneous deformation

18. Answer the following Questions

Q1. Consider the engineering stress-strain curve, the curve after necking goes down and the engineering stress decreases with the increase of engineering strain. Explain why?

Q2. Discuss the effects of; temperature; strain rate; and deformation rate on the shape of the true stress-true strain curve.

Q3. The true strain can be expressed as: $\varepsilon = ln\left(\frac{1}{1-r}\right)$ where r is the percentage reduction of area. Prove this relation.

19. References

[1] William Callister, David G.Rethwisch, Material Science and Engineering an Introduction. 8th edition. John Wiley and Sons Inc.

[2] Kalpakjian and Schmid, Manufacturing Processes for Engineering Materials, 5th edition. ,2008 © Pearson Education ISBN No. 0-13-227271-7.

[3] Murthy, S. Trymbaka. Textbook of Elements of Mechanical Engineering. ISBN 978-9380578576.

[4] Degarmo, E. Paul; Black, J T.; Kohser, Ronald A. (2003), Materials and Processes in Manufacturing (9th ed.), Wiley, ISBN 0-471-65653-4.