Experiment 1

Tensile Test of Mild Steel Rod

Aim: To determine the yield strength, ultimate strength, breaking strength and Young's modulus.

Apparatus Required:

1. Tensile test specimen
2. Scale
3. Micrometer/Vernier caliper
4. Extensometer
5. Universal tensile testing machine (UTM)

Theory: Whenever a test specimen (Figure 1) is pulled axially with load *P* at both ends, the rod is subjected to tensile stress, σ_o, which is uniformly distributed throughout the rod cross-section and is given by

$$\sigma_o = \frac{P}{A_o} = \frac{4P}{\pi d_o^2} \qquad (1)$$

where A_o represents the cross-sectional area of the rod before deformation and is obviously

$$A_o = \frac{\pi d_o^2}{4}$$

where, d_o being the original rod diameter. As a result of the stress developed in the rod, it elongates. Two predefined points are marked on the rod separated by the distance L_o which is known as the *gauge length*.

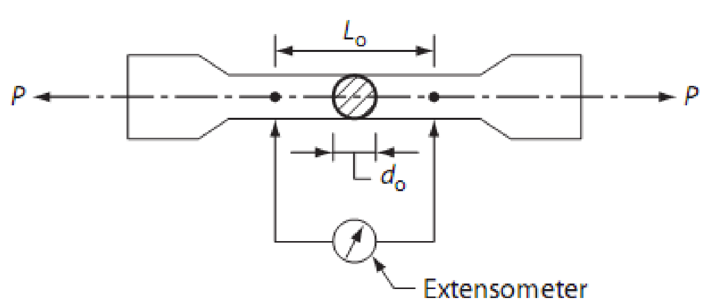

Figure 1 Tensile test specimen.

An instrument, known as the *extensometer*, is used to measure the elongation of the rod ΔL of the rod and to calculate the *engineering strain*, $\in_E$ as

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

If we go on applying the load by gripping the specimen in a dedicated machine, known as *universal tensile testing machine* or commonly called *UTM*, we can directly measure P and ΔL from the machine console. A special unit of UTM directly plots P vs. ΔL graph. Figure 2 shows the setup schematically:

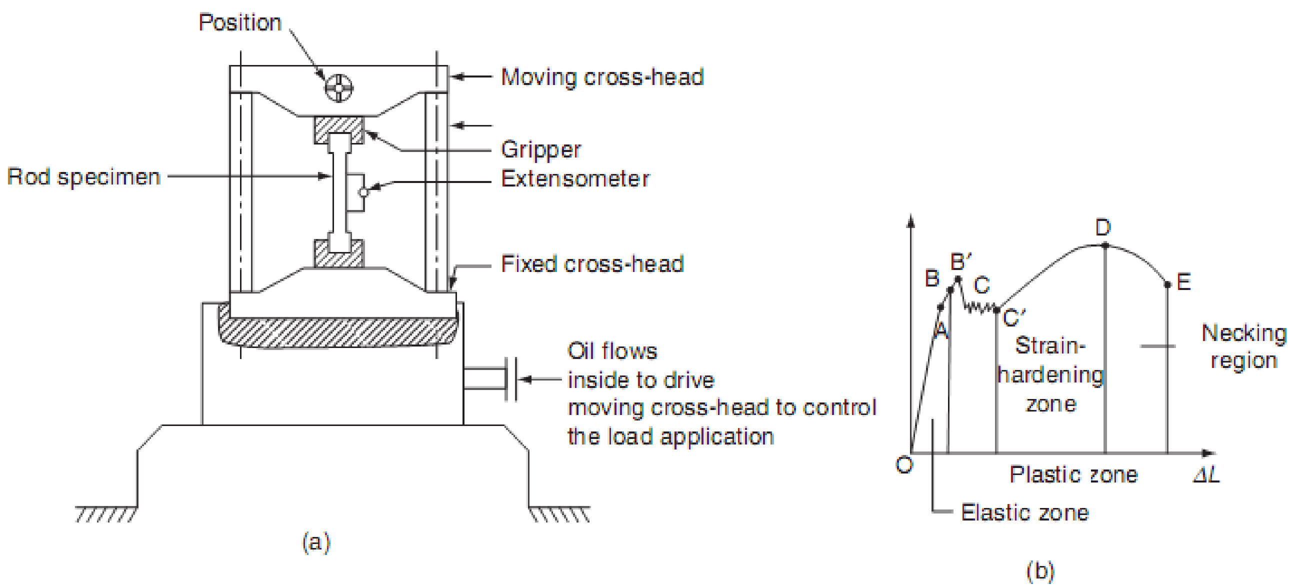

Figure 2 Essentials of tensile test.

As the load is increased, elongation also increases proportionally and this continues upto point A in Figure 2(b). The point A upto which this proportionality holds, is known as the proportional limit (PL) and the stress corresponding to this load is called proportional limit stress (σ_{PL}) which is derived as

$$\sigma_{PL} = \left(\frac{P}{A_o}\right)_A$$

The subscript A in the above equation represents the point where this equation has been evaluated. If load is applied beyond A, it soon reaches point B upto which the rod remains elastic. That is, if the load is removed, the elongation also vanishes and this happens anywhere from O to B. Stress corresponding to that point is known as the *elastic limit*. If loading is continuously applied on the rod, it enters the yielding zone, from where all elongations of the rod are plastic. If load is removed beyond point B′ (which for mild steel represents upper yield point), permanent set occurs as shown Figure 3:

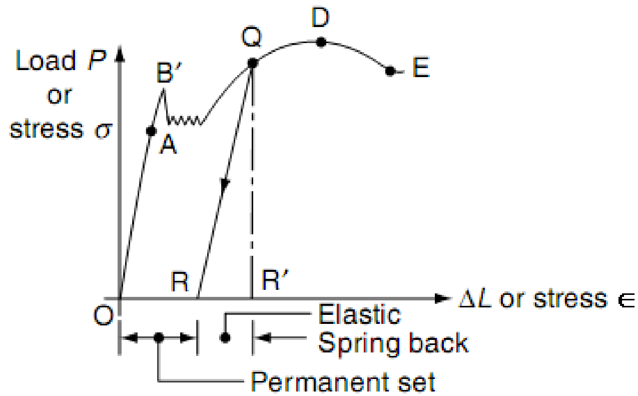

Figure 3 Permanent set.

Suppose at any point Q beyond the yield point load is removed, then unloading occurs along line QR which is parallel to the initial linear portion OA of the curve. As load becomes zero, elongation OR remains permanent and is known as the permanent set. Portion of elongation represented by RR′ is called the elastic spring-back and it vanishes as load becomes zero.

For the mild steel specimen, point B′ in Figure 2(a) is the upper yield point and if loading is kept on increasing, momentarily it drops to point C and moves to point C′ indicating significant elongation of the rod without having corresponding increase in load *P*. Point C is known as the lower yield point. The portion CC′ is known as yield plateau. In reality, however, load does not remain constant over portion CC′. Instead, it fluctuates up and down with respect to CC′ line. It is to be carefully noted that not all materials show these upper and lower yield points. In fact, cold-worked steel and alloy steel do not exhibit this feature. Some materials like aluminium do not show any sharply defined yield point and instead, shows a smooth transition from linear to non-linear zones of the curve as shown in Figure 4.

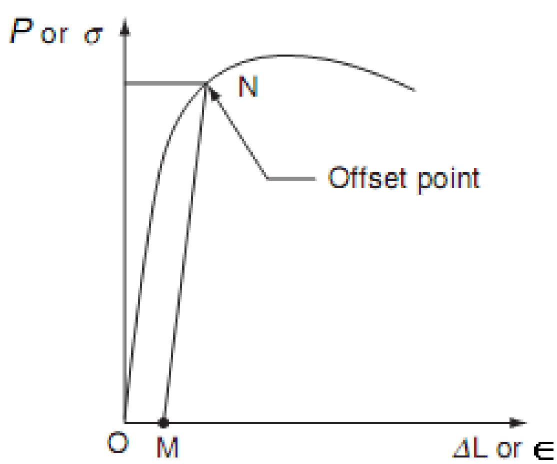

Figure 4 Load elongation or stress–strain curve for aluminium.

For such cases, we consider the concept of offset or proof stress. According to this concept, a strain of 0.2% (i.e. 0.002) is considered on the elongation (strain) axis and a line parallel to the initial linear portion of the curve is drawn to intersect the curve, which corresponds to the offset load (stress).

If we go on increasing the loading beyond C′, it is noted that the material becomes strain hardened, that is, continuously increasing loading is required to cause more elongation of the rod. This continues up to the point D where the ordinate of the curve becomes maximum. This point D corresponds to the ultimate point and the stress corresponding to point D is called the *ultimate tensile stress* or *UTS*. For example, this value is around 200 MPa for mild steel specimen. The portion C′D of the curve is called *strain-hardening zone*. If loading is increased further beyond D, it is observed that load required to cause further elongation decreases and ultimately, the specimen fractures at the lower load at point E, which is known as the failure point. The stress σ_E corresponding to this point is known as failure stress, where

$$\sigma_E = \frac{P_E}{A_o} = \left(\frac{P}{A_o}\right)_E$$

To explain this seemingly strange behavior that failure occurs at a lower load than the ultimate or maximum load carried by the rod, it is observed that as the specimen continues to elongate plastically, the cross-section of the specimen decreases continuously since the process is *isochoric* (or constant volume). This decrease in the area of specimen is termed as *necking*. As the area of the specimen decreases, its effective load-bearing capacity also decreases but the rate of decrease of area is small until we reach point D, where the above rates become equal. However, on reaching point D, the erstwhile elongation of the rod and the subsequent reduction of the cross-section becomes localised to a point which is generally the weakest location in the entire specimen. In reality, this location corresponds to the region where already *microcracks*, *voids*, *flaws*, etc., exist in the microstructure level. If the loading is further continued beyond this location, rate of decrease of the area becomes faster. Obviously, due to this rapid reduction in cross-sectional area, load-bearing capacity also starts decreasing but at a rate which is smaller than the rate of area reduction. Consequently the specimen fractures at a lesser load at point E, which is considerably lower than the maximum load at D. Portion DE of the curve is termed the *necking zone*. Necking itself is a complex phenomenon and is considered to be an example of *instability*, or more precisely, *plastic instability*. Studies have indicated that a complex three-dimensional state of stress exists in the necking region. On fracture, a typical fractured geometry known as the *cup-and-cone* geometry is obtained for mild steel specimen as shown in Figure 5.

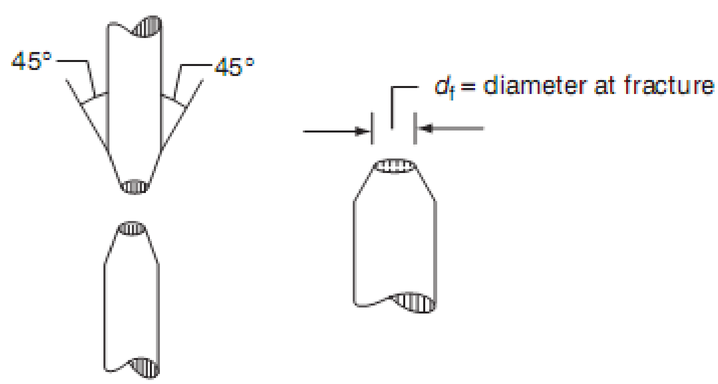

Figure 5 Cup-and-cone fracture.

This fractured geometry is typical for a ductile material. The cone forms 45° locations as shown in Figure 6.

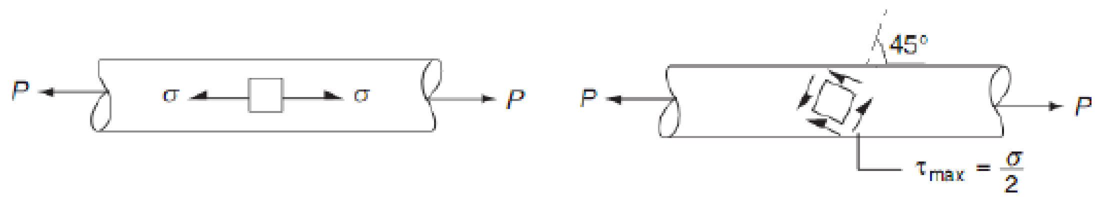

Figure 6 Maximum shear stress on rod subjected to uniaxial stress.

It is noted that so far in the above deliberations, we have mentioned about stress given by Eq. (1) and strain as given by Eq. (3), and they are called *engineering stress* or, *nominal stress* and *engineering strain*, respectively. Another alternative way to express these parameters is to determine *true stress* and *true strain*. In these definitions, *current geometrical parameters of the specimen* are used. Accordingly, *true stress* σ_{T} is given by

$$\sigma_{\mathrm{T}} = \frac{P}{A} \tag{5}$$

where *P* and *A* represent instantaneous load and area, respectively. If *L* be the instantaneous length, then in the plastic region:

$$A_{\mathrm{o}} L_{\mathrm{o}} = AL \tag{6}$$

since it is a constant volume process. Here A_o and L_o are respectively, the *initial* values of area and length. Now, from Eqs. (5) and (6), we get

$$\sigma_{\mathrm{T}} = \frac{P}{A_{\mathrm{o}}} \cdot \frac{L}{L_{\mathrm{o}}}$$

or

$$\sigma_{\mathrm{T}} = \sigma_{\mathrm{o}} \left(\frac{L}{L_{\mathrm{o}}} \right) \tag{7}$$

Upto the ultimate point D in the stress–strain diagram, there is no appreciable difference between the true stress and the engineering strain. Now, true strain, $\in_{\mathrm{T}}$ is given by

$$\in_{\mathrm{T}} = \int_{L_{\mathrm{o}}}^{L} \frac{\mathrm{d}L}{L}$$

or

$$\in_{\mathrm{T}} = \ln \left(\frac{L}{L_{\mathrm{o}}} \right) \tag{8}$$

Equations (7) and (8) can further be written in terms of the engineering strain $\in$ by noting that

$$L = L_{\mathrm{o}}(1 + \in)$$

Hence,

$$\sigma_T = \sigma_o(1+\in) \quad (9)$$

and
$$\in_T = \ln(1+\in) \quad (10)$$

Hence if σ_T and $\in_T$ are plotted on the graph of σ vs. $\in$, we obtain the following stress–strain diagram as shown in Figure 7:

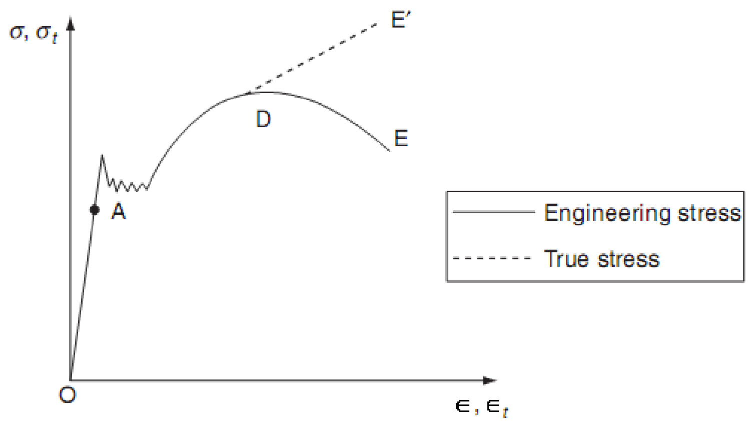

Figure 7 True stress–strain and engineering stress–strain diagram.

From the above diagram, it is observed that true stress differs from point D, where the reduction in area is significant. And instead of lower stress at E, we will reach a higher true value of stress at E′ since now instantaneous area has been used to define stress as given by Eq. (5). Apart from this usual information given by stress–strain curve, we can get further useful data as follows:

1. **Modulus of elasticity, *E*:** It is known that stress is proportional to strain upto the proportional limit (Hooke's law). The proportionality constant is known as the modulus of elasticity and can be obtained as

$$E = \frac{\sigma_o}{\in} \quad (11)$$

   For mild steel specimen, this value is around 200 GPa. So modulus of elasticity is equal to the slope of the initial linear portion, OA of the curve in Figure 7.

2. **Measure of ductility:** Ductility refers to the property of a material by virtue of which it can deform plastically before fracture. Quantitatively, it can be measured by the *percentage elongation* and *percentage reduction in area*. They are defined as:

$$\text{Percentage elongation} = \frac{L_f - L_o}{L_o} \times 100 \quad (12)$$

   and
$$\text{Percentage reduction in area} = \frac{A_o - A_f}{A_o} \times 100$$

In the above expressions, L_o and A_o represent the initial length and initial area, while L_f and A_f represent the final length and final area upto fracture, respectively. By definition, a material is said to be ductile, if its percentage elongation is more than 5%, otherwise it is said to be brittle.

3. **Modulus of resilience:** Area under stress–strain curve represents the energy adsorbed by the material per unit volume as it is continuously deformed under load. Typically, area under the stress–strain diagram upto the proportional limit is termed as the modulus of resilience. Physically, this is the energy which can be released upon unloading the specimen.
4. **Modulus of toughness:** Total area under the stress–strain diagram represents, physically, the energy adsorbed by a specimen upto the point of fracture, per unit volume. If a specimen is more ductile, it has higher modulus of toughness.
5. **Examination of fractured surface:** Upon examination of the fractured surface of the specimen, it is revealed that fibrous surface exists at fracture point. This represents an evidence of lot of plastic deformation of the material. If we consider a brittle material specimen, there will be shiny surface at the fracture zone showing almost no existence of plastic deformation.

Finally, we must note that metallurgical properties of steel greatly affect the stress–strain diagram as shown in Figure 8.

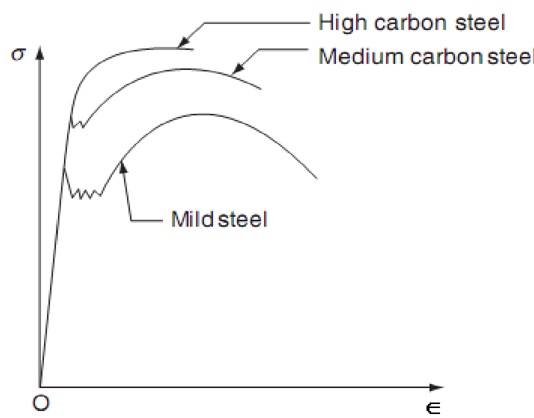

Figure 8 Stress–strain diagram of steel with various carbon content.

The figure shows that as the carbon content of steel are increased significantly from mild steel specimen to high-carbon steel, its ductility decreases and the yield point is raised significantly. Also, it is noted that steel with high carbon content, the difference between lower and upper yield points gradually vanishes.

The experimental results also depend very much on the rate of loading. If the rate is high, it has been observed that the ductility of the specimen is considerably reduced. We have already mentioned how the specimen behaves if loading is withdrawn at a point beyond the yield point (refer to Figure 3). Further to that, it is observed that if the material is reloaded again in the tensile manner, the yield point is increased considerably as shown in Figure 9.

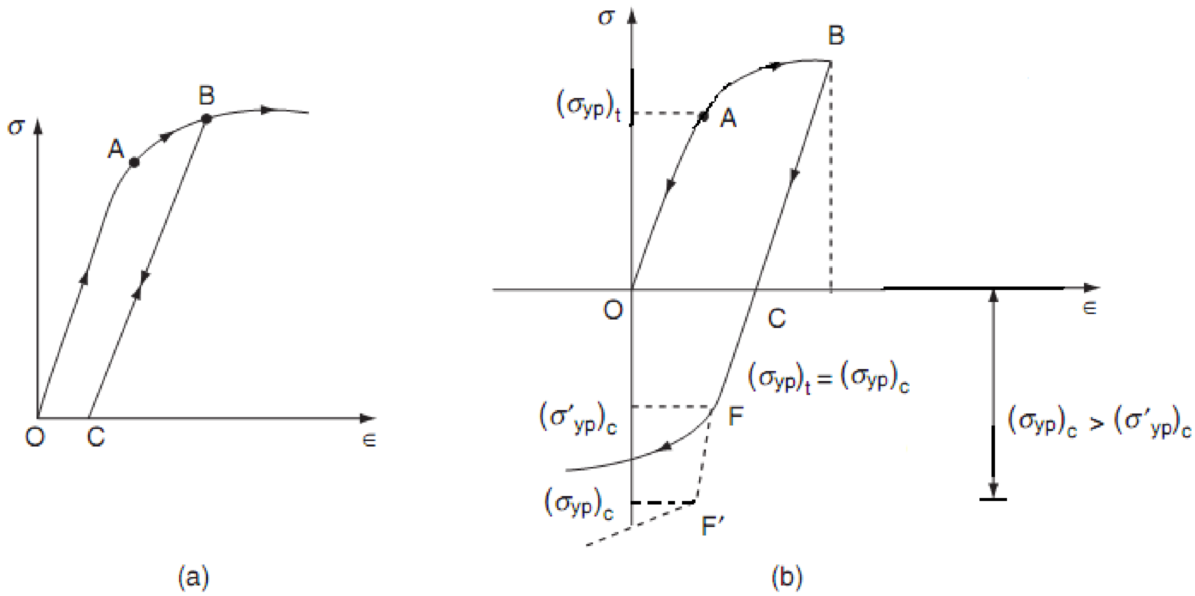

Figure 9 Stress–strain diagrams.

The figure shows that the specimen is unloaded from point B which is beyond the yield point A. It is further loaded in the same direction and the reloading follows the path CB, which is parallel to the initial linear portion of stress vs. strain curve. Subsequently, the yield point is raised to point B beyond which it continues to follow the same curve which would have been followed by the specimen, had there been no unloading at point B. This phenomenon of increasing the yield point is also known to be strain-hardening. However, it is to be carefully noted that the increase in the yield point of the specimen takes place in the direction along which the specimen has been loaded initially, that is, yield point in tension has been increased because of loading–unloading–reloading cycle. If the material is continued to be loaded beyond C but this time, in the reverse direction (i.e., compressive load is applied on the specimen), the material soon starts yielding at F, which is the new yield point $(\sigma'_{\text{yp}})_C$ in compression. If we assume that the yield point is same both in tension and compression, the specimen then would have followed the dashed curve as shown in Figure 9(b). That the effect of loading and unloading on the directional properties of the yield point is different is termed as *Bauschinger effect*.

We will close down our theoretical deliberation after mentioning another phenomena that occurs in steel specimens particularly when it reaches yield point while carrying out tensile testing. It is noted that at yield point, on the polished surface of the specimen, 45° lines appear as shown in Figure 10.

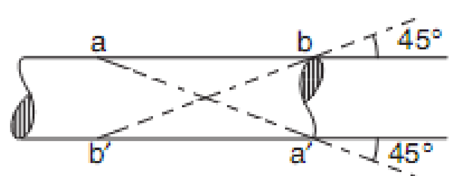

Figure 10 Lüders' lines.

Initially, these lines appear on one location and gradually more such lines appear along the entire surface of the specimen. These lines are termed as *Lüders'* lines or stretcher's lines or *Hartmann lines* or *Piobert lines*. Studies have indicated that appearance of Lüders' lines mark the yielding initiation, and subsequent appearance of more Lüders' lines on the specimen surface indicates progressive yielding across the entire specimen. In fact, it is even understood that for mild steel specimen, the fluctuation of the stress with respect to the lower yield point is because of the consecutive appearance of Lüders' lines on the specimen surface.

Test procedure:

1. The initial diameter and length readings are taken. First gauge length markers are put on the specimen over which strain calculation needs to be carried out.
2. Mount the specimen between two holders/fixtures of the testing machine. A typical testing machine is shown in Figure 11.
3. After ensuring firm gripping, extensometer is mounted on the specimen to record elongation. The figure of a typical contact-type extensometer is shown in Figure 12. Ensure 'O' setting on the dual dial gauge of the extensometer.

Figure 11 Tensile testing machine.

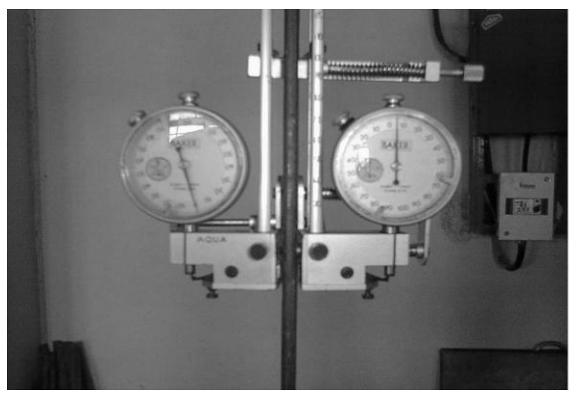

Figure 12 Extensometer.

(*Photo Courtesy*: Applied Mechanics Laboratory, Mechanical Engineering Department, Jadavpur University, Kolkata)

4. Machine console is started to apply uniaxial centric tensile load on the specimen. Autographic recorder of the testing machine automatically records the load–elongation curve. At regular intervals, load–elongation data are recorded. On getting sufficient data for the linear portion of the diagram, further loading is applied until we reach a point where a visual elongation is noted with minor load increment. Thus, the yield point is arrived.
5. At this stage, the extensometer is strapped off from the specimen and loading is continuously applied. Soon we reach the ultimate point.

6. On further increment of load, visually lateral thinning down of the specimen is noted. This is called necking. With further addition of loading, subsequently the specimen is broken.
7. After careful recording of the loadings in all the above stages, the broken pieces of the specimen are collected to measure:
    - The length between gauge marks upon fracture. This is denoted as L_f.
    - The diameter d_f of the minimum diameter at the fractured location.

Precautions:

1. Test specimen surface must be polished and free from scaling, dirts, rusts, etc.
2. Specimen should be firmly gripped in the clutches of the machine so that no slipping takes place.
3. Extensometer setting should be carefully checked.
4. Observation data should be collected so that no parallax error takes place.

In modern machines, such as the one shown in Figure 11, data acquisition takes place electronically, they are automatically stored in computers, and subsequent post-processing is done very easily.

Results:

Observed Data

Initial diameter of specimen, d_o = ___ Room temperature: ___°C

Initial gauge length of specimen, L_o = ___

Sl. No.	***Load (N)***	***Extensometer Reading (mm)***

Calculated Data

Sl. No.	***Stress (MPa) = σ = P/A_o***	***Strain = Elongation/Gauge Length***

Instruction:

- Plot of P vs. ΔL curve
- Plot of σ vs. $\in$ curve