Materials behaviour in metal forming

Tensile Properties

The tensile test is the most common procedure for studying the stress-strain relationship, particularly for metals. In the test, a force is applied that pulls the material, tending to elongate it and reduce its diameter.

The starting test specimen has an original length L_o and area A_o. The length is measured as the distance between the gage marks, and the area is measured as the cross-section of the specimen. During the testing of a metal, the specimen stretches, then necks, and finally fractures, as shown in Figure. The load and the change in length of the specimen are recorded as testing proceeds, to provide the data required to determine the stress-strain relationship. There are two different types of stress-strain curves: (1) engineering stress-strain and (2) true stress-strain. **The first is more important in design, and the second is more important in manufacturing.**

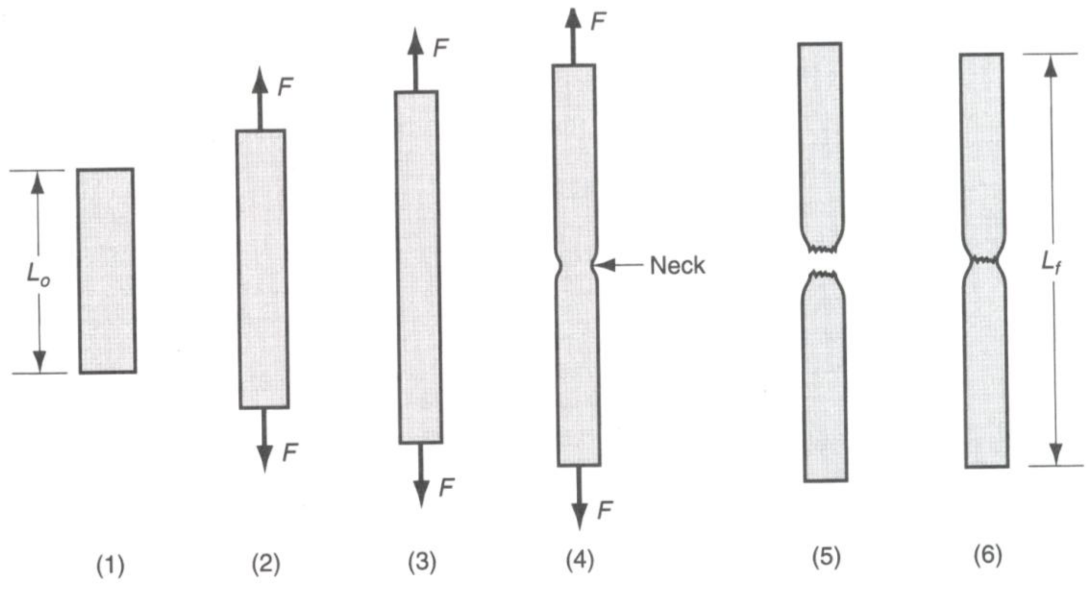


FIGURE: Typical T progress of a tensile test:(1) beginning of test, no load; (2) uniform elongation and reduction of cross-sectional area;(3) continued elongation, maximum load reached; (4) necking begins, load begins to decrease; and (5) fracture. If pieces are put back together as in (6), final length can be measured.

Engineering Stress-Strain The engineering stress and strain in a tensile test are defined relative to the original area and length of the test specimen. <u>These values are of interest in design because the designer expects that the strains experienced by any component of the product will not</u>

significantly change its shape. The components are designed to withstand the anticipated stresses encountered in service.

A typical engineering stress-strain curve from a tensile test of a metallic specimen is illustrated in Figure [shown below]. The engineering stress at any point on the curve is defined as the force divided by the original area:

$$\sigma_e = F/A_o$$

Where (σ_e = engineering stress, MPa, F = applied force in the test, N, and A_o = original area of the test specimen, mm^2. The ***engineering strain*** at any point in the test is given by

$$e = L-L_o / L_o$$

Where e = engineering strain, mm/mm; L = length at any point during the elongation, mm; and L_o = original gauge length, mm.

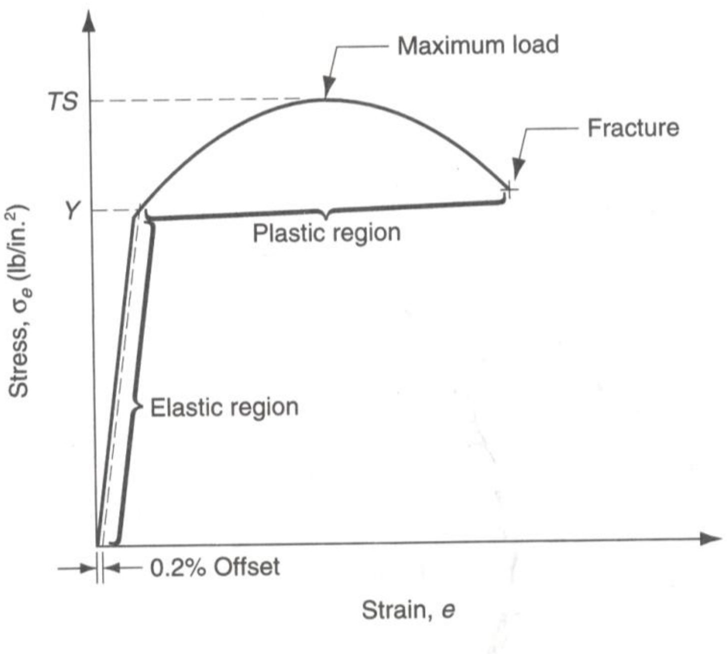


FIGURE: Typical engineering stress-strain plot in a tensile test of a metal.

The units of engineering strain are given as mm/mm, but we can think of it as representing elongation per unit length, without units.

The stress-strain relationship in Figure (shown above) has two regions, indicating two distinct forms of behavior: **elastic and plastic**. In the elastic region, the relationship between stress and strain is linear, and the material exhibits elastic behavior by returning to its original length when the load (stress) is released. **The relationship is defined by Hooke's Law:**

$$\sigma_e = Ee$$

Where ***E = modulus of elasticity***, MPa. E is a measure of the inherent stiffness of a material. It is a constant of proportionality whose value is different for different materials.

As stress increases, some point in the linear relationship is finally reached at which the material begins to yield. This yield point, **Y**, of the material can be identified in the figure by the change in slope at the end of the linear region. Because the start of yielding is usually difficult to see in a plot of test data (it does not usually occur as an abrupt change in slope), **Y** is typically defined as the stress at which a strain offset of 0.2 % from the straight line has occurred. **The yield point is a strength characteristic of the material, and is therefore often referred to as the yield strength** (other names include yield stress and elastic limit).

The yield point marks the transition to the plastic region and the start of plastic deformation of the material. **The relationship between stress and strain is no longer guided by Hooke's Law.** *As the load is increased beyond the yield point, elongation of the specimen proceeds, but at a much faster rate than before, causing the slope of the curve to change dramatically, as shown in Figure* [shown above]. Elongation is accompanied by a uniform reduction in cross-sectional area, consistent with maintaining constant volume. Finally, the applied load F reaches a maximum value, and the engineering stress calculated at this point is called the ***tensile strength or ultimate tensile strength*** of the material. We denote it as TS where

$$TS = F_{max}/A_o.$$

TS and **Y** are important strength properties in design calculations (we also use them in manufacturing calculations).

To the right of the tensile strength on the stress-strain curve, the load begins to decline, and the test specimen typically begins a process of **localized elongation known as necking**. Instead of continuing to strain uniformly throughout its length, **straining becomes concentrated in one small section of the specimen.** The area of that section narrows down (necks) significantly until failure occurs. The stress calculated immediately before failure is known as the fracture stress.

The amount of strain that the material can endure before failure is also a mechanical property of interest in many manufacturing processes. The common measure of this property is **ductility**, the ability of a material to plastically strain without fracture. This measure can be taken as either elongation or area reduction. Elongation is defined as

$$EL = L_f - L_o / L_o$$

where EL = elongation, often expressed as a percent; L_f = specimen length at fracture, mm, measured as the distance between gage marks after the two parts of the specimen have been put back together; and L_o = original specimen length, mm. Area reduction is defined as

$$AR = A_o - A_f / A_o$$

Where AR = area reduction, often expressed as a percent; A_f = area of the cross-section at the point of fracture, mm^2; and A_o = original area, mm^2.

True Stress-Strain

Thoughtful readers may be troubled **by the use of the original area of the test specimen to calculate engineering stress, rather than the actual (instantaneous) area that becomes increasingly smaller as the test proceeds.** If the actual area were used, the calculated stress value would be higher. The stress value obtained by dividing the instantaneous value of area into the applied load is defined as the ***true stress***:

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

Where $\boldsymbol{\sigma}$ = true stress, MPa; F = force, N; and A = actual (instantaneous) area resisting the load, mm^2.

Similarly, ***true strain*** provides a more realistic assessment of the "instantaneous" elongation per unit length of the material. The value of true strain in a tensile test can be estimated by dividing the total elongation into small increments, calculating the engineering strain for each increment on the basis of its starting length, and then adding up the strain values. In the limit, true strain is defined as

$$\varepsilon = \int_{L_o}^{L} \frac{dL}{L} = \ln \frac{L}{L_o}$$

Where L = instantaneous length at any moment during elongation. At the end of the test (or other deformation) the final strain value can be calculated using $\boldsymbol{L = L_f}$.

If the engineering stress-strain curve in Figure [shown above] were plotted using the true stress and strain values, the resulting curve would appear as in Figure [shown below]. **In the elastic region, the plot is virtually the same as before**. <u>Strain values are small, and true strain is nearly equal to engineering strain for most metals of interest.</u> <u>The respective stress values are also very close to each other</u>. The reason for these near equalities is that the cross-sectional area of the test specimen is not significantly reduced in the elastic region. **Thus, Hooke's Law can be used to relate true stress to true strain: $\boldsymbol{\sigma = E\varepsilon}$.**

The difference between the true stress-strain curve and its engineering counterpart lies in the plastic region. The stress values are higher in the plastic region because the instantaneous cross-sectional area of the specimen, which has been continuously reduced during elongation, is now used in the computation. **As in the previous curve, a downturn finally occurs as a result of necking. A dashed line is used in the figure to indicate the projected continuation of the true stress-strain plot if necking had not occurred.**

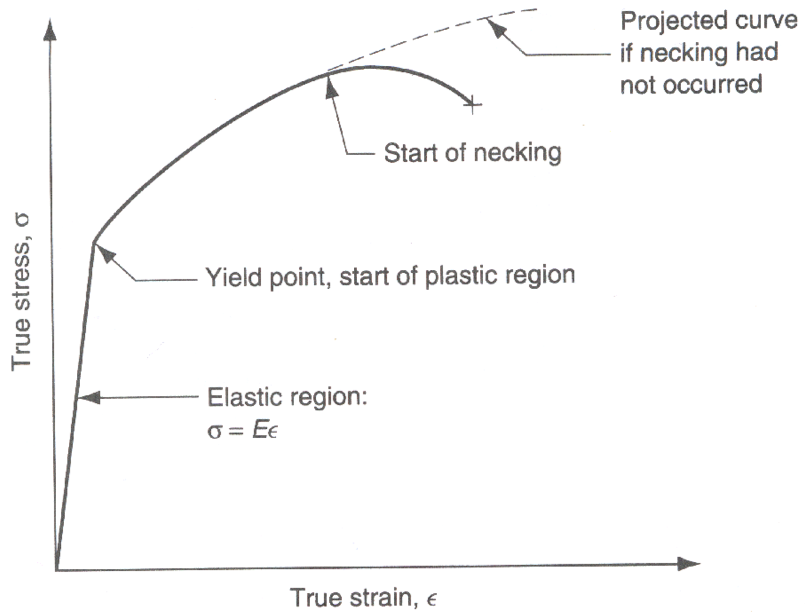


FIGURE: True stress-strain curve for the previous engineering stress-strain plot.

As strain becomes significant in the plastic region, the values of true strain and engineering strain diverge. True strain can be related to the corresponding engineering strain by $\boldsymbol{\varepsilon = ln(1 + e)}$

Similarly, true stress and engineering stress can be related by the expression

$$\boldsymbol{\sigma = \sigma_e (1+e)}$$

In Figure [shown above], we should note that stress increases continuously in the plastic region until necking begins. When this happened in the engineering stress-strain curve, its significance was lost because an erroneous [incorrect] area value was used to calculate stress. Now when the true stress also increases, we cannot dismiss it so lightly. **What it means is that the metal is becoming stronger as strain increases.** This is the property called ***strain hardening*** and it is a property that most metals exhibit to a greater or lesser degree.

Strain hardening, or ***work hardening*** as it is often called, is an important factor in certain manufacturing processes, particularly metal forming. Let us examine the behavior of a metal as it is

affected by this property. **If the portion of the true stress-strain curve representing the plastic region were plotted on a log-log scale, the result would be a linear relationship, as shown in Figure [shown below].** Because it is a straight line in this transformation of the data, the relationship between true stress and true strain in the plastic region can be expressed as:

$$\sigma = K \varepsilon^n$$

This equation is called the ***flow curve***, and it captures **a good approximation of the behavior of metals in the plastic region, including their capacity for strain hardening.** The constant K is called the ***strength coefficient***, MPa; and it **equals the value of true stress at a true strain value equal to one.** The parameter ***n*** is called the ***strain hardening exponent***, and it is the slope of the line in Figure [shown below]. Its value is directly related to a metal's tendency to work harden.

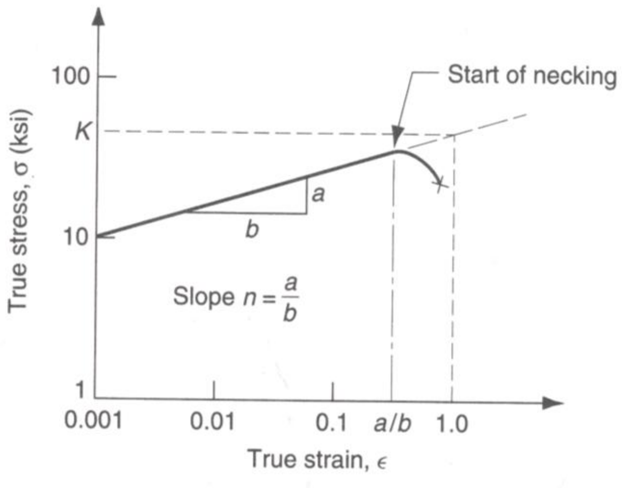


FIGURE: True stress-strain curve plotted on log-log scale.

Necking in a tensile test and in metal forming operations that stretch the work piece is closely related to strain hardening. Let us examine this relationship as it can be observed during a tensile test. <u>As the test specimen is elongated during the initial part of the test (before necking begins), uniform straining occurs throughout the length because if any element in the specimen becomes strained more than the surrounding metal, its strength increases due to work hardening, thus making it more resistant to additional strain until the surrounding metal has been strained an equal amount.</u>

Finally, the strain becomes so large that uniform straining cannot be sustained. A weak point in the length develops (due to build-up of dislocations at grain boundaries, impurities in the metal, or other factors), and necking is initiated, leading to failure. Empirical evidence reveals that necking begins for a particular metal when the true strain reaches a value equal to the strain

hardening exponent n. Therefore, a higher n value means that the metal can be strained further before the onset of necking during tensile loading.

Types of Stress-Strain Relationships

Much information about elastic-plastic behavior is provided by the true stress-strain curve. As we have indicated, Hooke's Law ($\sigma = K\,\varepsilon$) governs the metal's behavior in the elastic region, and the flow curve ($\sigma = K\,\varepsilon^n$) determines the behavior in the plastic region. Three basic forms of stress-strain relationship describe the behavior of nearly all types of solid materials, shown in Figure [shown below]:

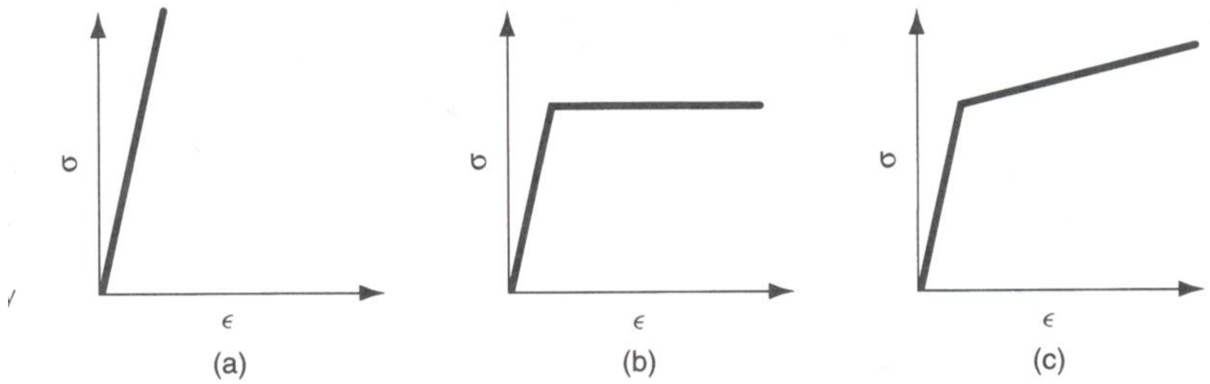


FIGURE: Three categories of stress-strain relationship (a) perfectly elastic, (b) elastic and perfectly plastic, (c) elastic and strain hardening.

(a) ***Perfectly elastic***. The behavior of this material is defined completely by its stiffness, indicated by the modulus of elasticity E. It fractures rather than yielding to plastic flow. Brittle materials such as ceramics, and many cast irons, possess stress-strain curves that fall into this category. These materials are **not** good candidates for forming operations.

(b) ***Elastic and perfectly plastic***. This material has a stiffness defined by E. Once the yield strength Y is reached, the material deforms plastically at the same stress level. The flow curve is given by K = Y and n = 0. **Metals behave in this fashion when they have been heated to sufficiently high temperatures that they recrystallize rather than strain harden during deformation.** Lead exhibits this behavior at room temperature because room temperature is above the recrystallization point for lead.

(c) ***Elastic and strain hardening***. This material obeys Hooke's Law in the elastic region. It begins to flow at its yield strength Y. Continued deformation requires an ever-increasing stress, given by a flow curve whose strength coefficient K is greater than Y and whose strain hardening

exponent n is greater than zero. The flow curve is generally represented as a linear function on a natural logarithmic plot. **Most ductile metals behave this way when cold worked.**

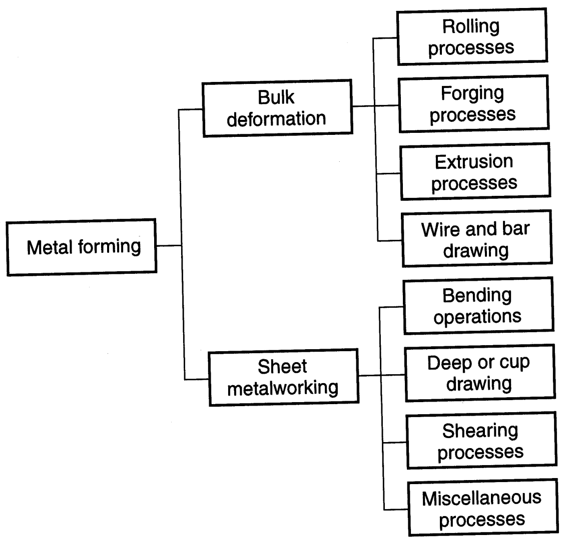
FUNDAMENTALS OF METAL FORMING

Metal forming includes a large group of manufacturing processes in which plastic deformation is used to change the shape of metal workpieces. Deformation results from the use of a tool, usually called a die in metal forming, which applies stresses that exceed the yield strength of the metal. The metal therefore deforms to take a shape determined by the geometry of the die.

Stresses applied to plastically deform the metal are usually compressive. However, some forming processes stretch the metal, while others bend the metal, and still others apply shear stresses to the metal. To be successfully formed, a metal must possess certain properties. Desirable properties for forming include low yield strength and high ductility. These properties are affected by temperature. Ductility is increased and yield strength is reduced when work temperature is raised. The effect of temperature gives rise to differences between cold working, warm working, and hot working. Strain rate and friction are additional factors that affect performance in metal forming. We examine all of these issues in this context, but first let us provide an overview of the metal forming processes.

OVERVIEW OF METAL FORMING

Metal-forming processes can be classified as (1) bulk deformation processes or (2) sheet metalworking processes. These two categories are covered in this text. Each category includes several major classes of shaping operations, as indicated in Figure.



Classification of metal forming operations.

Bulk Deformation Processes Bulk deformation processes are generally characterized by significant deformations and massive shape changes; and the surface area-to-volume of the work is relatively small. The term ***bulk*** describes the workparts that have this low area-to-volume ratio. Starting work shapes for these processes include cylindrical billets and rectangular bars. The next Figure illustrates the following basic operations in bulk deformation:

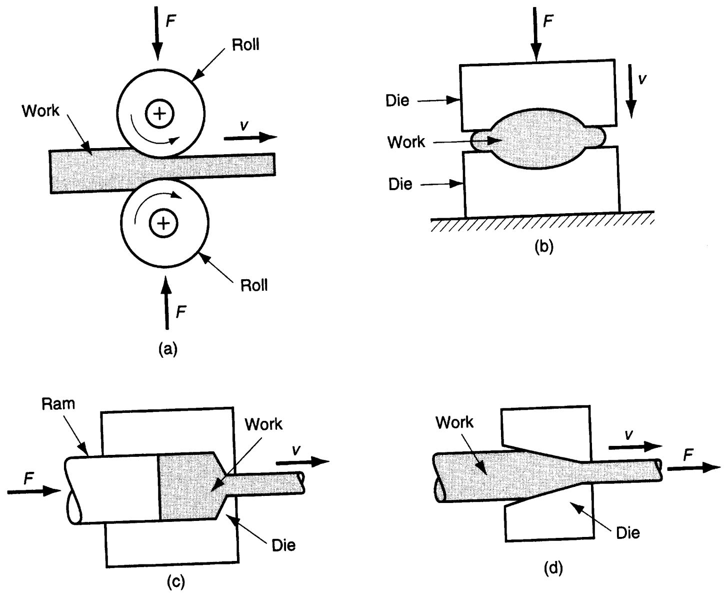


Figure: Basic bulk deformation processes.

Rolling-This is a compressive deformation process in which the thickness of a slab or plate is reduced by two opposing cylindrical tools called rolls. The rolls rotate so as to draw the work into the gap between them and squeeze it.

Forging-In forging, a workpiece is compressed between two opposing dies, so that the die shapes are imparted to the work. Forging is traditionally a hot working process, but many types of forging are performed cold.

Extrusion-This is a compression process in which the work metal is forced to flow through a die opening, thereby taking the shape of the opening as its own cross-section.

Drawing-In this forming process, the diameter of a wire or bar is reduced by pulling it through a die opening.

Sheet Metalworking Processes Sheet metalworking processes are forming and related operations performed on metal sheets, strips, and coils. The surface area-to-volume ratio of the starting metal is high; thus, this ratio is a useful means to distinguish bulk deformation from sheet metal processes. Pressworking is the term often applied to sheet metal operations because the machines used to perform these operations are presses (presses of various types are also used in other manufacturing processes). A part produced in a sheet metal operation is often called a **stamping**.

Sheet metal operations are always performed as cold working processes and are accomplished using a set of tools called a **punch** and **die**. The punch is the positive portion and the die is the negative portion of the tool set. The basic sheet metal operations are sketched in Figure and are defined as follows:

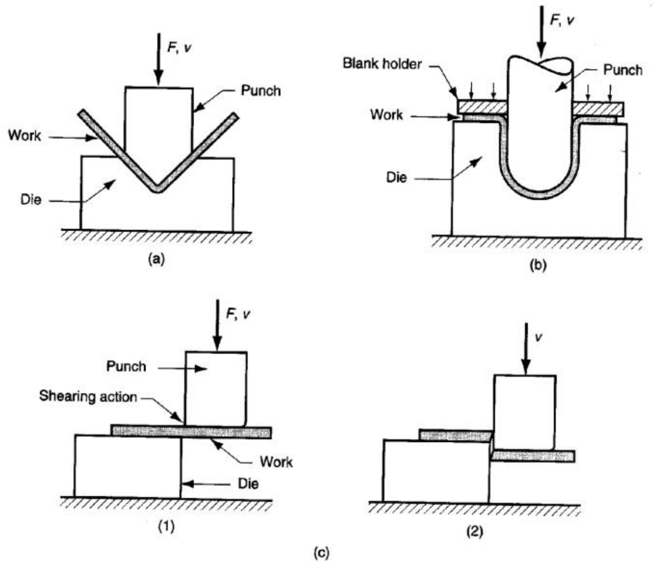


FIGURE: Basic sheet metalworking operations:
(a) bending, (b) drawing, and (c) shearing: (1) as punch first contacts sheet, and (2) after cutting. Force and relative motion in these operations are indicated by F and v.