Mechanical Properties of Materials

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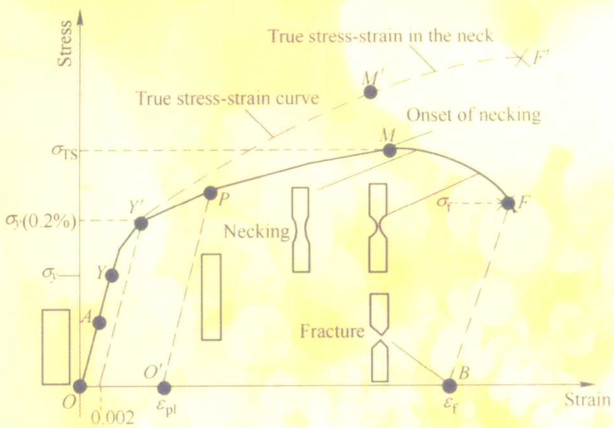

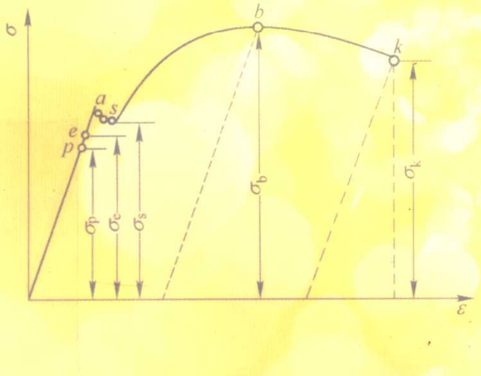

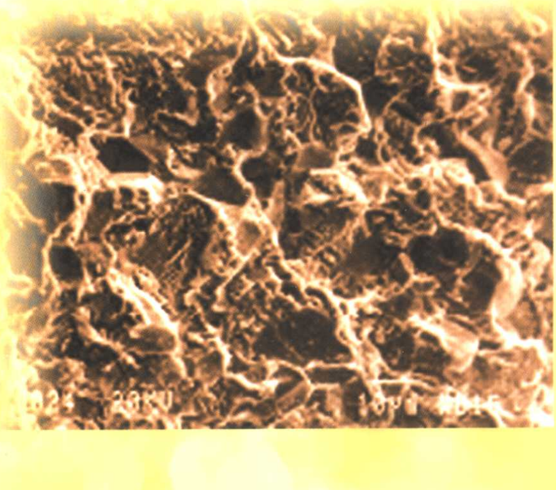

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Preface

As we know, metals are the most widely used materials in industry. Their service performances, such as physical properties, technological properties and mechanical properties, vary from metal to metal. Among them the mechanical properties for structural materials are the most important.

What do mechanical properties mean? Mechanical properties mean the behaviors of materials under external loads or combined effects of external loads with environmental factors, such as temperature, medium, loading rate and so on. Mechanical properties are also called mechanical behaviors, for example, deformation and fracture of metals caused by external loads.

Mechanical properties of materials include strength, hardness, elasticity, toughness, wear ability, notch sensitivity and so on. Briefly speaking, mechanical properties of materials mean the abilities of materials to resist deformation and fracture caused by external loads. These abilities are indicated by some parameters of mechanical property, such as parameters of strength σ_b, $\sigma_{0.2}$ and σ_{-1}, parameters of elasticity δ, ψ, parameters of toughness A_K, K_{IC} and so on. These parameters are the main criteria for proper material selecting and strength calculating in engineering design.

What are the major factors that affect mechanical properties of materials?

Often materials are subject to forces when they are used. Materials deform or break as a function of applied load, time, temperature, and other conditions. The major factors that affect mechanical properties of materials include both intrinsic and external factors. Among intrinsic factor are chemical composition, structural configuration, metallurgy quality, residual stress, surface and internal defects and so on; Among external factors are types of loading (static load and dynamic load), loading spectrum, state of stress (tension, compression, bending, torsion, combined stress and so on). There are two examples to illustrate the effect of both intrinsic and external factors on mechanical properties of materials.

First example: The stress-strain curve of a type of low carbon steel under normal static tensile test condition is illustrated in Figure p-1a. From the picture we can tell that, the low carbon steel is a metal with a great toughness and ductility in nature. But if we do the same test only under lower temperature, in this case it appears to be a brittle metal other than ductile one. This can be seen by examination of the curves in Figure p-1b. Another example: Instead of static load we impose a cyclic load on the steel specimen. It can be observed that some tiny cracks have occurred over time on the surface of the specimen, which will lead to a final fracture of the specimen. This type of failure is called fatigue fracture. In this way you can imagine the changes in mechanical properties caused by internal factor and external factors.

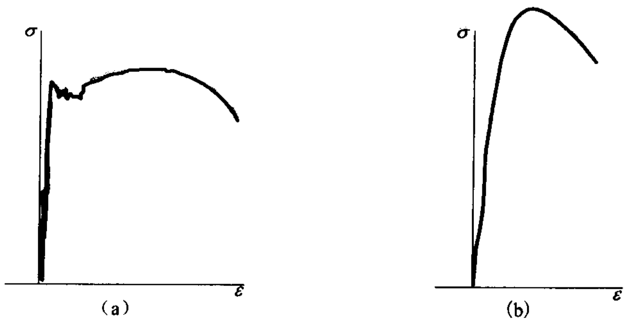

Figure p-1 Engineering stress-strain curve of low carbon steel

Mechanical Properties of Materials is categorized under experimental science. Different mechanical properties of materials are obtained through different experimentation. In microscopic terms, mechanical properties of materials are related to interactions among dislocations and interactions between dislocations and point defects. Therefore, we should study mechanical properties of materials from both macroscopic and microscopic considerations. Also we should follow some basic guidelines to study mechanical properties of materials:

1) To master the testing procedures and techniques for studying mechanical properties of materials;

2) To study the deformation and fracture phenomena and microscopic mechanism of materials under different conditions;

3) To study the essence of mechanical properties of materials, physical conceptions, actual meanings and relationships among different kinds of mechanical properties;

4) To study various affecting factors to different kinds of mechanical properties of materials;

5) To provide proper methods to improve mechanical properties of materials in the engineering practice.

Based on the fundamental theory of mechanical properties of materials, we should master the methods of proper material selection and proper design of components in order to improve the service performances of materials.

LIST OF SYMBOLS

a: distance between slip planes

a_c: critical crack length

A: amplitude ratio

A_0: original cross section area of a specimen

A_f: cross section area of a specimen at fracture

A_{ku} (A_{kv}): Charpy U (V) impact energy of the notched specimen

b: Burger's vector

COD : crack open displacement

da/dN: fatigue crack propagation rate

E_c: compressive modules of elasticity

E: modulus of elasticity in tension

E_b: modulus of elasticity in bending (flexural modulus of elasticity)

E_c: Young's modulus in compression

e: true strain

e_B: true strain at the stage of uniform deformation

e_f: true strain at fracture

F: testing force

F_{bb}: maximum bending force

F_{bc}: maximum compressive force

FATT: fracture appearance transition temperature

f: bending deflection

G : torsional modulus of elasticity (shear modulus)

G_{IC}: critical strain energy release rate

HB: Brinell hardness

HK: Knoop hardness

HRA, HRB, HRC…: Rockwell hardness

HS: Shore Hardness

HV: Vickers Hardness

IG : intergranular fracture

J, J_I: J integral

J_{Ic}: critical J integral for mode I crack

K_f: fatigue notch factor

K_t: theoretical stress concentration factor

K_I : stress intensity factor of mode I crack

K_{IC}: critical stress intensity factor (plane strain fracture toughness)
K_c: plain stress fracture toughness
ΔK_{th}: threshold of fatigue crack propagation
ΔK_I : stress intensity factor range
m': stress sensitivity exponent of dislocation motion velocity
n: strain hardening exponent
NDT: nil ductility transition
NSR: notch sensitivity ratio
N: number of fatigue cycles to failure
R: stress ratio
S: true stress
t_k: ductile-brittle transition temperature
TG: transgranular fracture
U_e: elastic strain energy
U : fracture energy
Y: dimensionless geometry factor
α: coefficient of state of stress
γ_s: effective surface energy
γ: shear strain
δ: percentage elongation after fracture
ΔT: torque increments
$\Delta\varphi$: torsion angle increments
ε: strain
$\dot{\varepsilon}$: *strain rate*
ε_e: *elastic strain*
ε_p: *plastic strain*
ε_{pb}: *given amount of non-proportional bending strain*
ν: *Poisson's ratio*
ρ: *glissile dislocation density*
$\bar{v}$: *average glissile dislocation velocity*
σ_b: *tensile strength*
σ_{bn}: *tensile strength for notched specimen*
σ_m: *mean stress*
σ_a: *stress amplitude in fatigue*
σ_{max}: *maximum stress*
σ_{min}: *minimum stress*
σ_p: *stress for a given amount of non-proportional elongation*
σ_r: *stress for a given amount of residual elongation*
σ_t: *stress for a given amount of total elongation*

σ_{pc}: *compressive stress for a given amount of non-proportional compression*

σ_{bc}: *compressive strength*

σ_{c}: *cleavage fracture stress*

σ_{sc}: *compressive yield point*

σ_{pb}: *bending stress for a given amount of non-proportional strain*

σ_{bb}: *flexural strength*

σ_{i}: *total resistance to dislocation motion*

σ_{su}: *upper yield point*

σ_{sl}: *lower yield point*

σ_{FL}: *fatigue limit.*

σ_{s}, $\sigma_{0.2}$: *yield strength (offset yield strength)*

σ_{-1}: *bending fatigue limit of the symmetric stress cycle*

σ_{-1n}: *bending fatigue limit of the symmetric stress cycle for notch specimen*

τ_{s}: *torsional yield point*

τ_{p}: *torsion stress for a give amount of non-proportional shear strain*

τ_{f}: *frictional resistance to slip.*

τ_{b}: *torsion strength*

ψ: *Percent reduction in area*

ω: *dislocation width*

CONTENTS

1

Concepts of Stress and Strain

1.1 Introduction

Engineers study the mechanics of materials mainly in order to have a means of analyzing and designing various machines and structures. Both the analysis and the design of a given structure involve determining of stresses and strains.

Stress and strain are important mechanical engineering and materials science concepts. Materials are often chosen on the basis of their response to applied force (stress). Strain is a measure of the temporary deformation such stresses can cause.

When choosing a material, there is a need to determine what properties are most important, so stress and strain that the material can undergo before permanent deformation are common factors in these decisions. As a result of action of external forces in a body there are additional (internal) forces of interaction between its separate particles. *The method of sections* is applied to reveal internal interactions between various parts of a body. In this method the body is mentally dissected by a surface (commonly, a plane) into two parts, one of which is mentally rejected, and its action is replaced with forces allocated on a surface of section.

If the body as a whole is in equilibrium, any part of it also must be in equilibrium. This consideration leads to the following fundamental conclusion: the externally applied forces to one side of an arbitrary cut must be balanced by the internal forces developed at the cut, or, briefly, the external forces are balanced by the internal forces. As a result of the equilibrium condition we may determine the resultant vector and resultant moment of internal forces that act upon the section surface. This is the essence of the method of sections.

This chapter concentrates on the fundamental concepts of stress and strain, and the relationship between stress and strain, to prepare the reader for further study of mechanical properties of metals.

1.2 Stress

Stress is defined as a force acting upon some area. Since forces are vectors, a force inclined to a plane can always be described as a combination of normal and shear forces (Figure 1-1).

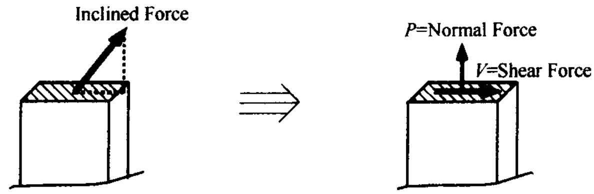

Figure 1-1　Transformation of an inclined force (F) acting upon some area (A)

If you take the normal force P on Figure 1-1 above and divide it by a cross-sectional area A, you would get the normal stress. It results in an equation

$$\sigma = \frac{P}{A} \tag{1-1}$$

where, the Greek letter σ (sigma) is used to represent normal stress that acts normally upon the reference plane of the element (Figure 1-2). The *shear stress* can be defined in a similar manner. If you take the shear force V and divide it by a cross-sectional area A, you will get the shear stress,

$$\tau = \frac{V}{A} \tag{1-2}$$

where, τ is shear stress acting in - plane of the element (Figure 1-2).

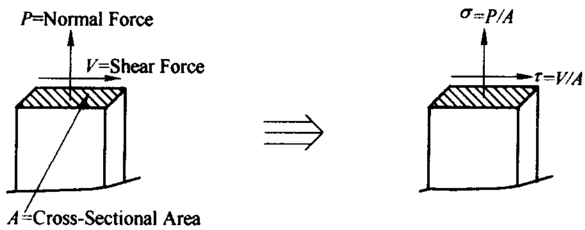

Figure 1-2　Definition of the normal and shear stresses

Stress has units of force over area. In the SI system it is newtons per square meter, and is defined as a Pascal (abbreviated Pa). In general, the internal forces acting upon infinitesimal areas of a cut are of varying magnitudes and directions. The stress upon the arbitrary infinitesimal area ΔA with normal ν (Figure 1-3) can be expressed as

$$P_\nu = \lim_{\Delta A \to 0}\left(\frac{\Delta F}{\Delta A}\right) \tag{1-3}$$

where, ΔF is a vector sum of all of the internal forces acting upon a given infinitesimal area ΔA. In other words, stress is the intensity of internal force at a point.

You can draw infinitely many planes at different orientation in space, and through a point. Stress will be different on each plane. Under static equilibrium, only nine stress components from three planes are needed to describe the stress state at a point . Figure 1-4 illustrates a general

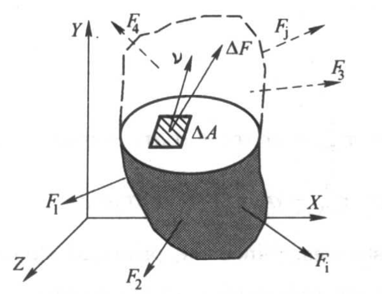

Figure 1-3 Representation of cross-section of a general body

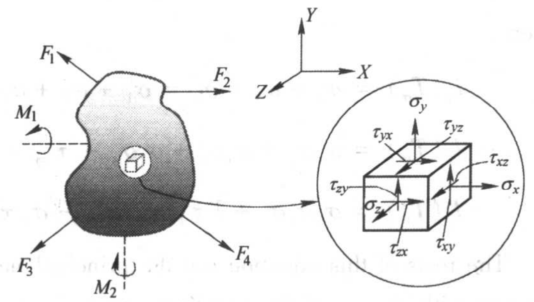

Figure 1-4 A general three-dimensional stress element

three-dimensional stress element, showing three normal stresses σ_x, σ_y and σ_z, all positive; and six shear stresses τ_{xy}, τ_{yx}, τ_{yz}, τ_{zy}, τ_{zx}, and τ_{xz}, also all positive. The element is in static equilibrium and hence

$$\tau_{xy} = \tau_{yx} \quad \tau_{yz} = \tau_{zy} \quad \tau_{zx} = \tau_{xz} \tag{1-4}$$

Outwardly directed normal stresses are considered as tension and are positive. Shear stresses are positive if they act in the direction of a reference axis. The first subscript of a shear stress component specifies the normal to the element face. The shear stress component is parallel to the axis of the second subscript. The negative faces of the element will have shear stresses acting in the opposite direction; these are also considered as positive. These nine components can be organized into the matrix:

$$T_\sigma = \begin{vmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{vmatrix} \tag{1-5}$$

This grouping of the nine stress components is known as the *stress tensor*. T_σ is symmetric and has only six independent components. We can always find some change of basis that transforms T_σ into a nice diagonal form

$$T_\sigma = \begin{vmatrix} \sigma_1 & & \\ & \sigma_2 & \\ & & \sigma_3 \end{vmatrix} \tag{1-6}$$

σ_1, σ_2, and σ_3 are called the principal stresses. The principal stresses acting in three mutually perpendicular planes, which pass through the point considered (Figure 1-5).

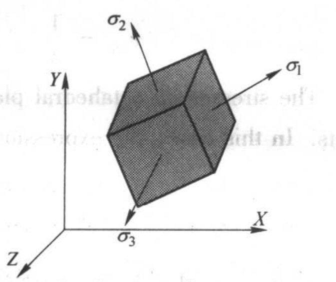

Figure 1-5 A principal stress element in rectangular system

The relation between the principal stresses at a point and the stresses on an arbitrary oriented plane passing through this point is described by the following cubic equation:

$$\sigma^3 - I_1(T_\sigma)\sigma^2 + I_2(T_\sigma)\sigma - I_3(T_\sigma) = 0 \tag{1-7}$$

where,

$$\begin{aligned} I_1(T_\sigma) &= \sigma_x + \sigma_y + \sigma_z = \sigma_1 + \sigma_2 + \sigma_3 \\ I_2(T_\sigma) &= \sigma_x\sigma_y + \sigma_y\sigma_z + \sigma_z\sigma_x - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{zx}^2 = \sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1 \\ I_3(T_\sigma) &= \sigma_x\sigma_y\sigma_z + 2\tau_{xy}\tau_{yz}\tau_{zx} - \sigma_x\tau_{yz}^2 - \sigma_y\tau_{zx}^2 - \sigma_z\tau_{xy}^2 = \sigma_1\sigma_2\sigma_3 \end{aligned} \tag{1-8}$$

The roots of this equation are the principal normal stresses. Since the principal stresses do not vary with change of the coordinate axes, i. e., they are independent of the method of their determination, the coefficients $I_1(T_\sigma)$, $I_2(T_\sigma)$, and $I_3(T_\sigma)$ from Eq. (1.7) are also independent of the choice of a coordinate system; in other words, they are stress tensor invariants with respect to choice of coordinates. In addition to expressions (1.8), there are other functions of stress tensor components that are invariant with respect to the coordinate axes. Yet all of them can be represented as functions of the three invariants presented above.

The state of stress is said to be triaxial when none of the three principal stresses is zero. For plane, or biaxial stress state one of the principal stresses equals zero. When only one principal stress is nonzero, the state of stress is called *uniaxial*. It can be shown that there are three pairs of planes where the shear stresses reach extrema. These extreme values of the shear stresses are called the principal shear stresses:

$$\tau_{12} = \frac{\sigma_1 - \sigma_2}{2}, \quad \tau_{23} = \frac{\sigma_2 - \sigma_3}{2}, \text{ and } \tau_{31} = \frac{\sigma_3 - \sigma_1}{2} \tag{1-9}$$

The plane inclined equally to the principal axes is called octahedral. The normal stress on this plane is equal to the arithmetic mean of the three principal normal stresses

$$\sigma_{oct} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} = \sigma_o \tag{1-10}$$

whereas the shear stress on the same plane is equal to the root mean square of the three principal shear stresses

$$\tau_{oct} = \frac{2}{3}\sqrt{\tau_{12}^2 + \tau_{23}^2 + \tau_{31}^2} \tag{1-11}$$

This formula can also be presented in the form

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \tag{1-12}$$

The stresses on octahedral planes can also be expressed in terms of six stress tensor components. In this case, the expressions for σ_{oct} and τ_{oct} have the form

$$\sigma_{oct} = \frac{\sigma_x + \sigma_y + \sigma_z}{3} \tag{1-13}$$

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)} \tag{1-14}$$

The stress tensor can be presented as the sum of the *hydrostatic stress* tensor (T_σ°) and of the stress deviator (D_σ) :

$$T_\sigma = T_\sigma^\circ + D_\sigma \tag{1-15}$$

where, T_σ° is composed of the components which predetermines a change in the volume of body (e. g. hydrostatic pressure):

$$T_\sigma^\circ = \begin{vmatrix} \sigma_o & 0 & 0 \\ 0 & \sigma_o & 0 \\ 0 & 0 & \sigma_o \end{vmatrix} \tag{1-16}$$

D_σ is composed of the components which are related only to distortion of the body:

$$D_\sigma = \begin{vmatrix} \sigma_x - \sigma_o & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y - \sigma_o & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z - \sigma_o \end{vmatrix} \tag{1-17}$$

and σ_o is the arithmetic mean of the normal stress:

$$\sigma_o = \frac{\sigma_x + \sigma_y + \sigma_z}{3} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} = \frac{I_1}{3} \tag{1-18}$$

Since the first invariant of the hydrostatic stress tensor coincides with the first invariant of the stress tensor

$$I_1(T_\sigma^\circ) = \sigma_o + \sigma_o + \sigma_o = 3\sigma_o = \sigma_x + \sigma_y + \sigma_z = I_1 \tag{1-19}$$

the first invariant of the stress deviator is equal to zero. The second one is given by

$$I_2(D_\sigma) = \frac{1}{6}[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)] \tag{1-20}$$

or

$$I_2(D_\sigma) = \frac{1}{6}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2] \tag{1-21}$$

In the solution of a number of problems of mechanics of materials it is convenient to use generalized stresses σ_i, which are proportional to the second invariant of the stress deviator or the octahedral shear stresses

$$\sigma_i = \sqrt{3} \cdot \sqrt{I_2(D_\sigma)} = \frac{3}{\sqrt{2}}\tau_{oct} \tag{1-22}$$

The generalized stress δ_i is called *the stress intensity*.

1.3 Strain

All structures and mechanical components deform under load. The collective displacements of points in a body relative to an external reference frame is known as deformation. Deformation describes the transformations from some initial to some final geometry. Strain is a measure of the deformation of a solid body. In strain theory are entered the normal (or axial) strain ε and shear strain γ. The normal strain is defined as the fractional change in length, or the deformation of the original length divided by the original length, and is denoted by the Greek symbol epsilon

$$\varepsilon = \frac{\Delta(\mathrm{d}l)}{\mathrm{d}l} \tag{1-23}$$

where, $\mathrm{d}l$ is the original element length, and $\Delta(\mathrm{d}l)$ is the change in length $\mathrm{d}l$, i. e. deformation. Normal strain may be compressive or tensile. Tensile strain is positive and the compressive strain is negative. Note that strain has no units, it is dimensionless. This is because we have divided one length by another. Sometimes you may see strain represented in percentage. Shear strain γ (gamma) is the change in the initial right angle between any two imaginary lines in a body. These angles are measured in radians. An example of the strains is shown in Figure 1-6. Let us consider two elementary lengths *ba* and *bc* starting from the point *b* and which are along coordinate axes *x* and *y* (Figure 1-6). As a result of deformation the lengths and original right angle between them is changed. The axial strains are equal to $\varepsilon_x = \Delta(\mathrm{d}l_x)/\mathrm{d}l_x, \varepsilon_y = \Delta(\mathrm{d}l_y)/\mathrm{d}l_y$, and the shear strain is $\gamma_{xy} = \Delta(\angle abc)$. In general an arbitrary point of a body under deformation has three axial ($\varepsilon_x, \varepsilon_y, \varepsilon_z$) and six shear ($\gamma_{xy}, \gamma_{yx}, \gamma_{yz}, \gamma_{zy}, \gamma_{zx}, \gamma_{xz}$) strains. They characterize the strain state at a point.

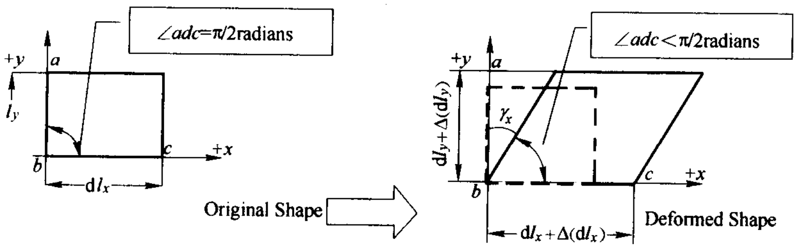

Figure1-6　Two-dimensional strained element in initial and final positions

The normal and the shear strains together define strain tensor, which is analogous to the stress tensor. The strain tensor measures the change of distances between close points in the deformed state with respect to the distances in the undeformed state. The strain tensor is symmetric and can be written as

$$T_\varepsilon = \begin{vmatrix} \varepsilon_x & \frac{\gamma_{xy}}{2} & \frac{\gamma_{xz}}{2} \\ \frac{\gamma_{yx}}{2} & \varepsilon_y & \frac{\gamma_{yz}}{2} \\ \frac{\gamma_{zx}}{2} & \frac{\gamma_{zy}}{2} & \varepsilon_z \end{vmatrix} \tag{1-24}$$