材料科学与工程著作系列
HEP Series in Materials Science and Engineering

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王仲仁　胡卫龙　苑世剑　王小松　著

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Preface

With enormous pleasures, I, on behalf of all of the authors of the book, feel deeply honored to contribute our years of attained experience of research and teaching work through the book in English version to the readers who are engaged in the engineering plasticity regarding metal forming.

This book makes detailed introductions of authors' academic contributions: the sequential correspondence law between stress and strain components, the zoning of yield graphics under plane stress states and three-dimensional stress states, the prediction of the dimensional variation tendency of work pieces, the general yield criterion,the graphical description of the anisotropic yield criterion and also shell hydro-forming for manufacturing large vessels.

This book performs mechanical analyses of a couple of special forming technologies, which include, rotary forging, viscous pressure forming, multipoint sandwich forming, and isothermal forging.

For decades, the authors of this book actively took part in the international academic exchanges and published a great number of academic papers. This book systematically summarized a number of scattered papers that were published on various periodicals, on conference proceedings and on the *Journal of Material Processing Technology,* in 2004 published a Special Issue dedicated to Professor Z. R. Wang on the occasion of his issued 70th birthday.

It is quite difficult to get real understanding of many concepts in the theory of plasticity, such as the concept that the values of stress are dependent on the orientation of the plane acted on, that the equivalent stresses and equivalent strains are the extension from the strength theory, that the yielding function is different from the plastic potential, and others. The book is meant to hammer them home.

The ever-increasing requirement to raise the precision of theoretical analysis in engineering practices creates the demands for, apart from the yield function and the plastic potential function, the hardening model able to describe the nonisotropic hardening characteristics of materials. The book discusses this issue in depth.

The chapter and section authors: Chapter 1, W. L. Hu and Z. R. Wang; Chapters 2 and 3, X. S. Wang; Chapters 4, 5, and 6 and Section 7 of Chapter 11, W. L. Hu; Chapters 7 and 8, Z. R. Wang; Chapter 9 and most of Chapter 11, S. J. Yuan; Chapter 10, L. Yuan and Z. R. Wang; Section 7 of Chapter 10, G. Liu; Sections 4, 5, and 6 of Chapter 11, X. Y. Wang, Q. Zhang, and Z. B. He, separately. Also, W. W. Zhang, X. L. Cui, Y. L. Lin, and X. L. Zhang joined in part of the translation work. X. S. Wang and Y. Z. Chen edited the manuscripts of the book according to the request of publication.

I'm obliged to express my special thanks to Ms. Jianbo Liu and Ms. Xueying Zou, editors for the Higher Education Press. It is their precious recommendations that helped bring this book to publication. Sincere thanks also go to Prof. Z. Q. Du, who, as an elder English editor and writer for technical journals, examined almost every sentence of the book in an attempt to ensure the literal suitability. I believe his endeavor will surely be conducive to improving the readability of the book.

Z.R. Wang

2017.5

Contents

1

Fundamentals of Classical Plasticity

1.1 Stress

1.1.1 The Concept of Stress Components

When a set of directional forces $P_1, P_2, P_3, \cdots$ acts on a deformable material element (see Figure 1.1) and remains balanced without causing a displacement and/or rotation, a set of balanced internal stresses must be generated because of the deformation taking place in the material element. Generally, if stress components distribute uniformly on a plane, the stress unit is equal to the force per unit area. Despite an inherent relation that exists between the stress and the acting force, the stress and the force are entirely different in their physical concepts that we could not confuse.

In analyzing displacement and rotation of a rigid body, all acting forces are vectors and can be converted into a single one. For example, the forces $P_1, P_2, P_3, \cdots$ shown in Figure 1.1 can be turned into a single vector P:

$$P = P_1 + P_2 + P_3 + \ldots \tag{1.1}$$

Equation (1.1) means that if $P \neq 0$, this loaded body must move and if P does not pass the body's center, the body must rotate simultaneously.

However, it is incorrect to use the force P resulted from vector addition to analyze the elastic or plastic changes in shape of the material element. Different sets of directional forces will respond to different stress distribution on a plane cut out of this material element even if they have the same vector composition. Figure 1.2 illustrates the case of a simple uniaxial tension.

Stress components on different planes of this loaded material element are different. For example, the stress component on the plane vertical to the axis in Figure 1.2 can be expressed by

$$\sigma_0 = P/S_0 \tag{1.2}$$

where P is the axial force, and S_0 is the cross section.

If this material element is a unit body with each edge equal to 1 unit, Equation (1.2) becomes

$$\sigma_0 = P \tag{1.3}$$

Equation (1.3) builds up a relationship between the force and the stress, however, it holds true only in the analysis of equilibrium system. Their physical concepts are essentially different. The force is mainly to make the forced material element to move or move with rotation, and the stress deals with the "shape changing" of the stressed material element.

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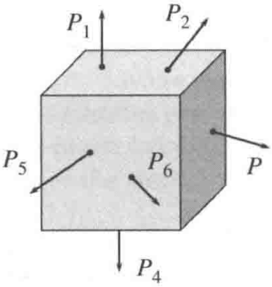

Figure 1.1 Directional forces acting on a unit element.

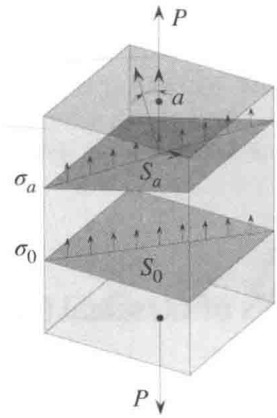

Figure 1.2 Relationship between forces and stresses on a plane cut out of a loaded body under uniaxial tension.

On a cut plane tilting at an angle α against the axis, when the area of the plane increases from S_0 to $S_0/\cos\alpha$, the stress on it becomes

$$\sigma_\alpha = P\cos\alpha \tag{1.4}$$

With the angle α increasing, the cut plane should get more inclined to decrease the stress σ_α so as to maintain the force in equilibrium. Equation (1.4) indicates that the value of stress σ_α is completely predicated on the orientation of the cut plane. But variation of the stress value σ_α does not bring any influences upon the deformation type of the uniaxial tension, which means that the strain state of the element remains unchanged.

1.1.2 Description of the Stress State

It should thus be clear that the stress state is very important—we must understand how the material element responds to the deformation caused by the stress components. On the other hand, in the case of inhomogeneous stress distribution on cut planes, which is most common in reality, it is required to analyze the stress state of a deforming body from one point inside the body to the other. Generally, the stress condition of a point inside a deforming body is often defined by a cubic element. Further understanding stress components in relation to any complex stress state would be essential to fully grasp the stress and stress tensor concepts.

1.1.2.1 Stresses on an Arbitrary Inclined Plane

Let's investigate the necessary condition by analyzing the stress state at a point inside the deformable body. Suppose that the point to be analyzed is O. Usually, three mutually perpendicular planes XOY, YOZ, and ZOX (see Figure 1.3) are set up to analyze its stress state. Stress components on each plane are divided into one normal stress, symbolized by σ, vertical to the plane and two shear stresses by τ, parallel to the coordinate axes. In order to identify what plane the stress components act on, one subscript is used for the normal stress and two subscripts for each of the shear stresses. The subscript for the normal stress denotes its acting direction.

The first of the two subscripts of the shear stress denotes the normal direction of the acting plane of the shear stress, and the second the acting direction of the shear stress (see Figure 1.3). The value of all stress components is not arbitrary but is determined by the equilibrium

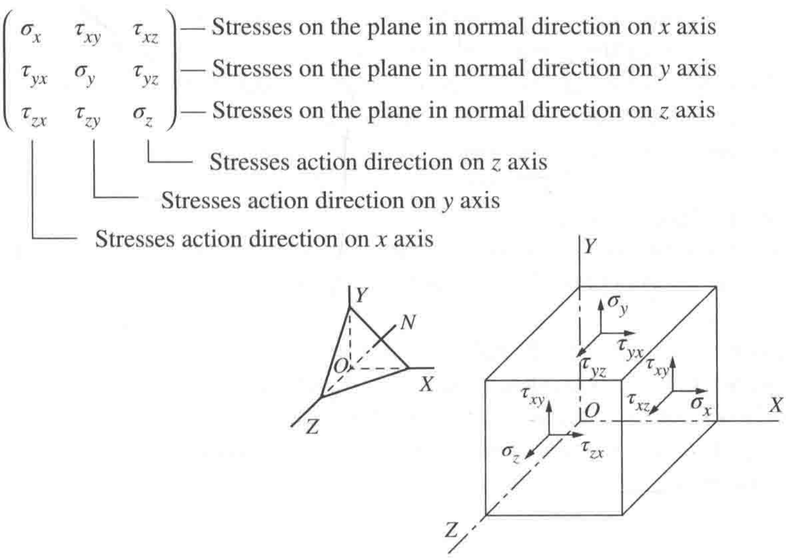

Figure 1.3 Stress components on three mutually perpendicular planes.

between stress components on the cut plane and the associated external force (see the example in Figure 1.2). Customarily, positive normal stresses are supposed to be tensile ones and negative normal stresses are compressive. Normally, it doesn't matter whether a shear stress is positive or negative, because shear stresses always exist in pairs. Nevertheless, because some materials show anisotropic yield behavior and/or strength differential in tension and compression, the change in loading direction or stress state might change the yielding behavior in value of the shear stresses. Therefore, for some materials, when the stress direction changes (e.g., from tension to compression or vice versa), we must still define whether the shear stresses are positive or negative, based on the action direction. Namely, when the second subscript of shear stress implies the positive direction of the axis, this shear stress is positive, and vice versa. Thus, stress components on three planes in a *xyz* coordinate system can be expressed in the matrix form (see Figure 1.3).

From Figure 1.3, we know that the nine stress components on the three mutually perpendicular planes share a common feature. That is, shear stresses exist in pairs with the same value and the subscripts composed of two identical English letters in opposite order. Namely,

$$\tau_{xy} = \tau_{yx},\ \tau_{yz} = \tau_{zy},\ \tau_{zx} = \tau_{xz} \tag{1.5}$$

Equation (1.5) means that there are only six independent stress components in a symmetric form (Figure 1.3), which can be represented by a matrix as follows:

$$\begin{pmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ & \sigma_y & \tau_{yz} \\ & & \sigma_z \end{pmatrix} \tag{1.6}$$

In the case that, on the three mutually perpendicular planes, there are only three normal stresses, called the principal stresses: σ_1, σ_2, and σ_3, without any shear stress, Equation (1.6) becomes

$$\begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix} \tag{1.7}$$

which represents the principal coordinate system.

Obviously, once the six stress components at the point O are given with respect to the x, y, and z coordinate axis, the stress state at the point O is fixed. Any change in the value of one of the stress components, as long as it is not due to the conversion of coordinate system, would mean a change in the stress state at the point O. In other words, the stress state at a point must be described with six stress components or three principal stresses.

1.1.2.2 Stress Components on an Oblique Plane

It has been proved that given six stress components or three principal stresses at a point, the normal and shear stresses on any oblique plane relative to the x, y, and z coordinate axes can be determined.

On the oblique plane represented by a triangle ABC (see Figure 1.4), the normal N (ON) is denoted by directional cosines (l、m、n) with three angles α_x, α_y and α_z formed between ON and separately OX, OY, and OZ. Let ΔA denote the area of the triangle ABC, ΔA_x, ΔA_y, and ΔA_z the areas formed by projecting ΔA, respectively, on the three coordinate surfaces:

$$\begin{aligned} \Delta A_x &= \Delta A \cdot l \\ \Delta A_y &= \Delta A \cdot m \\ \Delta A_z &= \Delta A \cdot n \end{aligned} \tag{1.8}$$

Let the resultant stress on the triangle ABC be denoted by S, which has a direct stress component σ_N normal to the plane ABC and a shear stress component τ on it. Thus, the equilibrium of the forces on the tetrahedron $OABC$ in the direction OX, OY, and OZ, respectively, can be described by

$$\left.\begin{aligned} S_x \cdot \Delta A &= \sigma_x \cdot \Delta A \cdot l + \tau_{yx} \cdot \Delta A \cdot m + \tau_{zx} \cdot \Delta A \cdot n \\ S_y \cdot \Delta A &= \tau_{xy} \cdot \Delta A \cdot l + \sigma_y \cdot \Delta A \cdot m + \tau_{zx} \cdot \Delta A \cdot n \\ S_z \cdot \Delta A &= \tau_{xz} \cdot \Delta A \cdot l + \tau_{yz} \cdot \Delta A \cdot m + \sigma_z \cdot \Delta A \cdot n \end{aligned}\right\} \tag{1.9}$$

where S_x, S_y, and S_z are the components of the resultant stress S in parallel with OX, OY, and OZ, respectively.

Simplification of Equation (1.9) gives

$$\left.\begin{aligned} S_x &= \sigma_x \cdot l + \tau_{yx} \cdot m + \tau_{zx} \cdot n \\ S_y &= \tau_{xy} \cdot l + \sigma_y \cdot m + \tau_{zx} \cdot n \\ S_z &= \tau_{xz} \cdot l + \tau_{yz} \cdot m + \sigma_z \cdot n \end{aligned}\right\} \tag{1.10}$$

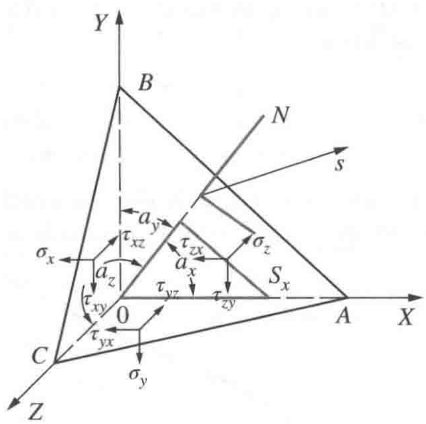

Figure 1.4 Stress components on an oblique plane.