The basic principles of the physical mesomechanics of materials are formulated. This new scientific discipline relates the physics of plasticity (the micro level), the mechanics of a deformable solid (the macro level), and physical materials science. Plastic deformation and subsequent failure of a loaded solid develops as the successive evolution of shear-stability loss at the micro, meso, and macro levels. The deformation laws at the different scale levels are scale-invariant. To study the deformation mechanisms at the meso level, engineering viewing methods may be used. It is shown that, in deformable materials, a basic stress concentrator always appears at the point of application of an external load; this plays the fundamental role in the meso-level development of deformation. The basic carriers of plastic flow at the meso level are volume elements of various sizes; their motion occurs by a shear + rotation mechanism. In a structurally inhomogeneous medium, stress mesoconcentrators arise at internal boundaries; these form dissipative substructures and result in fragmentation of the material at the meso level. Electron-microscopic data on the basic types of meso-level substructures for high-strength materials indicate that, at the substructure boundaries, high-energy states that are in structural disequilibrium are formed at the substructure boundaries; these states are characterized by crystal-lattice curvature of up to 1 deg/μm and a high disclination density. A new structural state is observed: a substructure with a continuum disclination density, characterized by crystal-lattice curvature of up to 40 deg/μm. The methodological aspects of a unified theory of a deformable solid are discussed, and a theoretical approach that may be used to model the deformation and failure of materials with a complex internal structure at different scale levels, on the basis of continuum-mechanics methods, is proposed. This approach allows defining equations for the description of plastic deformation at the micro, meso, and macro levels to be written, taking account of the contribution of the accumulated strain at the lower levels to the strain at the upper levels. The theoretical results are in good agreement with experimental data.

INTRODUCTION

The Center of Fundamental Research and Elite Education (CFREE) devoted to the physical mesomechanics and computer design of new materials was founded on the basis of the existing scientific and educational complex that includes: the Institute of Strength and Materials Physics (ISMP), Siberian Branch, Russian Academy of Sciences; the V. D. Kuznetsov Siberian Physicotechnical Institute (SPI), Tomsk State University; and the physics and physical-engineering faculties at Tomsk State University (TSU). The Tomsk school of solid-state physics dates back to the efforts of V. D. Kuznetsov and M. A. Bol’shanina in the mid-1930s. Since the early 1960s, world-class research on the physics of the plasticity and strength of solids has been conducted in Tomsk on the basis of physical models, using the theory of dislocations and other structural defects. In the course of this research, it was found that the use of dislocational theory (the micro level) is inadequate to explain the mechanical and strength properties of solids at the macro level.
In the last two decades, a new scientific discipline has been developed at Tomsk: the physical mesomechanics of materials [1-12], which corresponds to the intersection of continuum mechanics, the physics of plasticity and strength (dislocation theory), and physical materials science.

The principles of physical mesomechanics differ significantly from traditional approaches to continuum mechanics and dislocation theory. The new paradigm has been widely discussed at annual international conferences organized in Tomsk by ISMP. At the Mesofracture '96 conference, the decision was made to hold international conferences on physical mesomechanics in different countries. The Mesomechanics '98 conference was held in Tel Aviv (Israel). The next conferences are planned for Berlin (Germany) in 1999 and Sian (China) in 2000. An international journal devoted to physical mesomechanics is being published in Tomsk, in Russian and English; in collaboration with Stuttgart University, an international center on physical mesomechanics has been founded.

The scientific and educational complex on the physical mesomechanics of materials, with its unique resources of personnel and equipment, permits collaborative fundamental and applied research by ISMP, PIS, and TSU, as well as the education of specialists in this new discipline.

On the basis of mesomechanics, new nondestructive monitoring methods have been developed, and principles have been formulated for the creation of metallic, ceramic, and polymer materials with multilevel damping, characterized by high strength and wear resistance. Furthermore, mesomechanics permits the computerized optimization of various technological processes for applying high-strength, wear-resistant, and corrosion-resistant composite coatings to machine parts. Physics is an experimental science. Over time, our understanding of the behavior of solids at the meso level under various loads becomes deeper, and we develop theoretical methods that provide quantitative relationships between the micro-level motion of dislocations and the integral mechanical characteristics at the macro level, taking the evolution of the solid's internal structure into account. The basic results obtained by the CFREE in the last two years on the physical mesomechanics of materials are summarized in the present work, and predictions are made regarding future developments.

1. FUNDAMENTAL PRINCIPLES OF PHYSICAL MESOMECHANICS

The following fundamental principles of the physical mesomechanics of materials may be stated [8, 9].

1. A loaded solid is a self-organizing multilevel system with a high degree of disequilibrium. Its plastic flow develops as the synergetic evolution of shear-stability loss at the micro, meso, and macro levels.

2. At the micro level, shear-stability loss of the crystal lattice occurs in local stress-microconcentrator zones. The basic crystal-lattice defect is a dislocation, which arises as the result of local structural change in the crystal lattice within the stress-microconcentrator gradient field. The core of the dislocation is a fragment of a new structure, which is of higher energy than the initial crystal lattice.

3. At the meso level, shear-stability loss occurs in local zones of the loaded sample as a whole. The basic mesodefect is a mesoband, creating stress mesoconcentrators in local zones and propagating in the directions of maximum tangential stress $\tau_{\text{max}}$, regardless of the crystallographic orientation of the lattice.

4. The basic plastic-flow carrier at the meso level is a three-dimensional mesovolume: cells of dislocational substructure, deformational domains, subgrains, grains, their conglomerates, etc. Their motion is by the shear + rotation mechanism.

5. A crystalline material capable only of translational shear forms a hierarchy of dissipative substructures at the meso level, with deformation by the shear + rotation mechanism. This process leads to fragmentation of the material at the meso level.

6. Failure is the appearance of global stability loss of the loaded sample, with the appearance of a stress macroconcentrator responsible for the transition of sample fragmentation from the meso level to the macro level. Two macrobands of localized deformation (parallel to $\tau_{\text{max}}$ or in conjugate directions) propagate through the whole sample cross section, culminating in the limiting case of macro-level fragmentation: splitting of the sample into two parts.

7. The plastic flow mechanisms and carriers and the corresponding stages of the stress—strain curve are scale-invariant (the scaling principle).

8. By physical-mesomechanics methods, all the information on the loaded material may be entered in a computer, and computer design of materials with specified mechanical properties (the inverse problem) is also possible.