1 Introduction

The increasing technical importance of high-temperature equipment, i.e., the urgent needs of designers and computing engineers dealing with high-temperature machinery, jet engines, and high-velocity aeronautics have resulted in a huge and rapidly growing literature in *creep mechanics* .

There is a tradition to organize IUTAM-Symposia on *Creep in Structures* every ten years: the first one was organized by N.J. HOFF in Stanford (1960), the second one by J. HULT in Göteburg (1970), the third one by A.R.S. PONTER and D.R. HAYHURST in Leicester (1980), the fourth Symposium by M. ŻYCZKOWSKI in Cracow (1990) and, finally, the fifth Symposium was organized by S. MURAKAMI and N. OHNO in Nagoya (2000).

Other events are, for instance, the traditional Conferences on *Creep and Fracture of Engineering Materials and Structures* organized by B. WILSHIRE and D.R.J. OWEN in Swansea (1981, 1984 etc. every three years).

The aim of such conferences is to bring together experimentalists, theoreticians, and engineers interested in various features of creep mechanics, in order to permit an interdisciplinary exchange of understanding, experience, and methods. Therefore, such conferences essentially contribute to the progress in *creep mechanics* . The advances have been reviewed in the Conference Proceedings from several points of view: *mathematical*, *mechanical*, *metallurgical*, etc..

Over the last two decades much effort has been devoted to the elaboration of phenomenological theories describing the relation between force and deformation in bodies of materials which obey neither the linear laws of the classical theories of elasticity nor the hydrodynamics of viscous fluids. Such problems will play a central role for mathematticans, physicits, and engineers in the future (ASTRARITA, 1979).

Material laws and constitutive theories are the fundamental bases for describing the mechanical behavior of materials under multiaxial states of stress involving creep and creep rupture. The tensor function theory has become a powerful tool (BETTEN, 1987b; 1987c) for solving such complex problems.

The mechanical behavior of anisotropic solids (which are materials with oriented internal structures produced by forming processes and manufacturing procedures or induced by permanent deformation) requires a suitable mathematical modelling. The properties of tensor functions with several argumenttensors constitute a rational basis for a consistent mathematical modelling of complex material behavior (BETTEN, 2001a; BOEHLER, 1987; RIVLIN, 1955, 1970; SPENCER, 1971; TRUESDELL and NOLL, 1965; WANG, 1971).

In creep mechanics one can differentiate between three stages: the *primary*, *secondary*, and *tertiary* creep stage (Chapter 4). These terms correspond to a decreasing, constant, and increasing creep strain rate, respectively, and were introduced by ANDRADE (1910).

In order to describe the creep behavior of metals in the primary stage *tensorial nonlinear constitutive equations involving the strain hardening hypothesis* are proposed by BETTEN et al.(1989). Based upon these general relations, the primary creep behavior of a thinwalled circular cylindrical shell subjected to internal pressure is also analysed by BETTEN et al. (1989). The *creep buckling* of cylindrical shells subjected to internal pressure and axial compression was investigated by BETTEN and BUTTERS (1990) by considering *tensorial nonlinearities* and *anisotropic primary creep* . The problem of *creep buckling* of cylindrical shells have earlier been discussed, for instance, by MURAKAMI and TANAKA (1976), OBRECHT (1977) or HAYMAN (1980).

Based upon a *creep velocity potential* JAKOWLUK and MIELESZKO (1983) formulate constitutive equations of the *primary* creep stage in comparison with experimental data on FeMnAl steel.

In Chapter 4, the secondary creep stage of isotropic and anisotropic solids in a state of multiaxial stress will be discussed. Creep deformations of metals usually remain unaffected if hydrostatic pressure is superimposed. In order to describe the secondary creep behavior of isotropic materials some authors use a *creep potential* (BETTEN, 1981a; JAKOWLUK and MIELESZKO, 1985; RABOTNOV, 1969), which is a scalar-valued function of CAUCHY's *stress tensor* . One can show that the *creep potential theory* is compatible with the *tensor function theory* provided the material is *isotropic* and additional conditions are fulfilled (BETTEN, 1985). However, the creep potential hypothesis only furnishes restricted forms of constitutive equations and, therefore, has only limited justification if the material is *anisotropic* , as has been discussed in Chapter 6.

The tertiary creep phase is also considered in Chapter 4. In this phase, the creep process is accompanied by the formation of microscopic cracks on the grain boundaries, so that damage accumulation occurs. In some cases voids are caused by a given stress history and, therefore, they are distributed anisotropically amongst the grain boundaries. Thus, the mechanical behavior will be *anisotropic* and it is therefore necessary to investigate this kind of anisotropy by introducing appropiately defined *anisotropic damage tensors* into constitutive equations. *Damage tensors* have been constructed, for instance, by BETTEN (1981b; 1983b) or by MURAKAMI and OHNO (1981). A detailed survey of several damage variables is carried out in Chapter 7.

Problems of *creep damage* have been investigated by many authors. Very extensive surveys into recent advances in *damage mechanics* are given by BODNER and HASHIN (1986), KRAJCINOVIC (1996) and KRAJCINOVIC and LEMAITRE (1987), for instance. Further contributions to the theory of *Continuum Damage Mechanics* should be mentioned in the literature, for example, AL-GADHIB et al (2000), BETTEN (1983b; 1986a; 1992), CHABOCHE (1984; 1999), CHRZANOWSKI (1976), HAYAKAWA and MURAKAMI (1998), JAKOWLUK (1993), KRAJCINOVIC (1983), LEMAITRE (1992; 1996), LEMAITRE and CHABOCHE (1990), LITEWKA and HULT (1989), LITEWKA and MORZÝNSKA (1989), MURAKAMI (1983; 1987), MURAKAMI and KAMIYA (1997), MURAKAMI and OHNO (1981), MURAKAMI and SAWCZUK (1981), MURAKAMI, SANOMURA and SAITOH (1986), MURAKAMI, HAYAKAWA and LIU (1998), ONAT (1986), and SKRZYPEK (1999).

In the past two decades there has been considerable progress and significant advances made in the development of fundamental concepts of damage mechanics and their application to solve practical engineering problems. For instance, new concepts have been effectively applied to characterize creep damage, low and high cycle fatigue damage, creep-fatigue interaction, brittle/elastic damage, ductile/plastic damage, strain softening, strain-rate-sensitivity damage, impact damage, and other physical phenomena. The materials include rubbers, concretes, rocks, polymers, composites, ceramics, and metals. This area has attracted the interest of a broad spectrum of international research scientists in micromechanics, continuum mechanics, mathematics, materials science, physics, chemistry and numerical analysis. However, sustained rapid growth in the development of damage mechanics requires the prompt dissemination of original research results, not only for the benefit of the researchers themselves, but also for the practising engineers who are under continued pressure to incorporate the latest research results in their design procedures and processing techniques with newly developed materials.

In this context an excellent book, recently published by SKRZYPEK and GANCZARSKI (1999), should be recommended. This book is an extensive and comprehensive survey of one- and three- dimensional damage models for elastic and inelastic solids. The state–of-the-art is reported by more than 200 references. The book not only provides a rich current source of knowledge, but also describes examples of practical applications, numerical procedures and computer codes. The style of the presentation is systematic, clear, and concise, and is supported by illustrative diagrams.

Because of the broad applicability and versatility of the concept of damage mechanics, the research results have been published in over thirty English and non-English technical journals. This multiplicity has imposed an unnecessary burden on scientists and engineers alike to keep abreast with the latest development in the subject area. The new *International Journal of Damage Mechanics* has been inaugurated to provide an effective mechanism hitherto unavailable to them, which will accelerate the dissemination of information on damage mechanics not only within the research community but also between the research laboratory and industrial design department, and it should promote and contribute to future development of the concept of damage mechanics.

Furthermore, one should emphasize that special *Conferences on Damage Mechanics* has contributed significantly to the development of theories and experiments in Damage Mechanics, for instance, the Conference on *Damage Mechanics* held in Cachan (1981) or the IUTAM-Symposium on *Mechanics of Damage and Fatigue* held in Haifa and Tel Aviv (1985), CEEPUS Summer School on *Analysis of Elastomers and Creep and Flow of Glas and Metals* held in Zilina,Slovakia (1996), CISM Advanced School on *Applications of Tensor Functions in Solid Mechanics* held in Udine (1984) and in Bad Honnef (1986), CISM Advanced School on *Modelling of Creep and Damage Processes in Materials and Structures* held in Udine (1998), Workshop on Modelling of *Damage Localisation and Fracture Processes in Engineering Materials* held in Kazimierz Dolny, Poland(1998), Symposium on *Anisotropic Behaviour of Damaged Materials*, held in Kraków-Przegorzaly, Poland (2002), to name just a few, gave many impulses. The keynote lectures delivered during the last Symposium in Kraków have been printed in a new book, edited by SKRZYPEK and GANCZARSKI (2003).

This book provides a survey of various damage models focusing on the damage response in anisotropic materials as well as damage-induced anisotropy. There was a lack of such a book that would deal with the anisotropic damage mechanics with micro-mechanical aspects and thermo-mechanical coupling involved.

The book is divided into three parts. Part I *General description of anisotropically damaged materials* contains the Chapters 1-4 on: the mathematical bases of tensor functions application to damage anisotropy (J. BETTEN, *Technical University of Aachen*); the multi-scale damage mechanics (J.-L. CHABOCHE, *ONERA*, Chatillon, co-author N. CARRÈRE); an alternative approach to anisotropic damage via critical plane concept (Z. MRÓZ, *IPPT PAN*, Warsaw, co-author J. MACIEJEWSKI) and a formal description of damage induced anisotropy (J. GRABACKI, *Cracow University of Technology*, Kraków)

Part II *Phenomenological- and micro-mechanical-based approaches to anisotropic damage and fracture in brittle materials* includes Chapters 5-7 on: anisotropic elastic-brittle damage and fracture description based on irreversible thermodynamics (J. J. SKRZYPEK, *Cracow University of Technology*, Kraków, co-author H. KUNU-CISKAL); experimental nnd theoretical investigations of anisotropic damage in concrete and fiber reinforced concrete (A. LITEWKA et al., *Universidade da Beira Interior*, Covilha) and micro-mechanical damage model in rock-like solids (M. BASISTA, *IPPT PAN*, Warsaw).

Part III *Damage induced creep anisotropy of metallic materials under thermo- mechanical loadings* consists of Chapters 8-10 on: an extension of isotropic creep damage theories to anisotropic materials (H. ALTENBACH, *Martin-Luther-University*, Halle-Wittenberg); experimental investigations of creep fracture anisotropy in weld metal at elevated temperature (T. H. HYDE et al.,*University of Nottingham*) and non-classical problems of coupled thermo-damage fields (A. GANCZARSKI, *Cracow University of Technology*, Kraków),

To summarize the scope of this book as well as to briefly present other directions of research and future trends the Editors decided to include to the book additional concluding remarks (M. ZYCZKOWSKI, *Cracow University of Technology*, Kraków).

The best way to give a quick overview of some important works in damage mechanics may be in form of a table as has proposed by MURAKAMI (1987). The following Table 1.1 based upon MURAKAMI's scheme (1987) has been modified by SKRZYPEK and GANCZARSKI (1999) and by BETTEN (2001b).

Table 1.1: Classification of material damage, microscopic mechanisms and chararacteristic features

References	Microscopic mechanisms and characteristic features
Elastic-brittle damage	
GRABACKI (1994) KRAJCINOVIC and FONSEKA (1981) KRAJCINOVIC (1984; 1996) LEMAITRE and CHABOCHE (1990) LITEWKA (1985; 1989) LITEWKA and HULT (1989) MARIGO (1985) MURAKAMI and KAMIYA (1997) NAJAR (1994)	Nucleation and growth of microscopic cracks caused by elastic deformations. Change of effective stiffness and compliance due to the strength reduction and elastic modulus drop with damage evolution. (Metals, rocks, concrete, composites).
Elastic-plastic damage	
TVERGAARD (1988) CHOW and LU (1992) DRAGON (1985) LEMAITRE (1985) MURZEWSKI (1992) MOU and HAN (1996) SAANOUNI (1994) VOYIADJIS and KATTAN (1992)	Nucleation, growth, and coalescence of microscopic voids caused by the (large) elastic-plastic deformation. Intersection of slipbands, decohesion of particles from the matrix material, cracking of particles. Void coalescence of shear bands formation. (Metals, composite, polymers).
Spall damage	
DAVISON et al. (1977; 1978) GRADY (1982) JOHNSON (1981) NEMES (1990) PERZYNA (1986)	Elastic and elastic-plastic damage due to impulsive loads. Propagation of shock plastic waves. Coupling between nucleation and growth of voids and stress waves. Coalescence of microcrack prior to the fragmentation process. Full separation resulting from macrocrack propagation through heavily damaged material.
Fatigue damage	
COFFIN (1954) CHABOCHE (1974) DUFAILLY and LEMAITRE (1995) KRAJCINOVIC (1996) LEMAITRE (1992) LEMAITRE and CHABOCHE (1990) MANSON (1979) NAJAR (1994) SKOCZEN (1996)	Nucleation and growth of microscopic transgranular cracks in the vicinity of surface. High cycle fatigue (number of cycles to failure larger than 10^5): effect of macroscopic plastic strain is negligible. Very low cycle fatigue (number of cycles below 10): crack initiation in the vicinity of surface in the slip bands in grains prior to the rapid transgranular mode in the slip planes.

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Table 1.1: Classification of material damage, microscopic mechanisms and chararacteristic features

References	Microscopic mechanisms and characteristic features
Creep damage	
BETTEN (1983b; 1992) BETTEN et al. (1999) CHABOCHE (1981; 1988) H.ALTENBACH et al. (1990; 1997) HAYHURST and LECKIE (1973) HAYHURST et al.(1984) J.ALTENBACH et al. (1997) KACHANOV (1958) KOWALESKI (1996a,b,c) KRAJCINOVIC (1983; 1996) LECKIE and HAYHURST (1974) MURAKAMI (1983) NAUMENKO (1996) NEEDLEMAN et al. (1995) QI (1998) QI and BERTRAM (1997) RABOTNOV (1969) STIGH (1985) TRAMPCZYNSKI et al. (1981) ZHENG and BETTEN (1996)	Nucleation and growth of microscopic voids and cracks in metal grains (ductile transgranular creep damage at low temperatures), or on intergranular boundaries (brittle intergranular damage at high temperatures) mainly due to grain boundaries sliding and diffusion.
Creep-fatigue damage	
CHRZANOWSKI (1976) DUNNE and HAYHURST (1994) HELLE and TVERGAARD (1998) JAKOWLUK (1993) LEMAITRE and CHABOCHE (1975; 1990) WANG (1992)	Damage induced by repeated mechanical and thermal loadings at high temperature. Coupled creep-cyclic plasticity damage. Nonlinear interaction between intergranular voids and transgranular cracks. Slip bands formation due to plasticity (low temperature) combined with microcrack development due to creep (high temperature). (Metals, alloy steels, aluminum alloy, copper).
Irradiation damage	
GITTUS (1978) MURAKAMI and MIZUNO (1992) TETELMAN and MCEVILY (1970)	Damage caused by irradiation of neutron particles and α rays. Knock-on of atoms, nucleation of voids and bubbles, swelling. Ductile behavior of creep under irradiation and brittle behavior on post-irradiation creep.

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Table 1.1: Classification of material damage, microscopic mechanisms and chararacteristic features

References	Microscopic mechanisms and characteristic features
Anisotropic damage	
BETTEN (1992) CHABOCHE (1993) CHABOCHE et al. (1995) CHEN and CHOW (1995) CHOW and WANG (1987a,b) LADEVEZE (1990) LIS (1992) LITEWKA (1985) MATZENMILLER and SACKMANN (1994) MURAKAMI and KAMIYA (1997) SIDOROFF (1981) VOYIADJIS and VENSON (1995) ZHENG and BETTEN (1996)	Damage induced anisotropy of solids or damage anisotropic materials (composites). Unilateral damage (opening/closure effect). Anisotropic elastic-brittle damage. Nonproportional and cyclic loadings. Effective state variables and damage effect tensor. (Concrete, anisotropic ceramic composites).
Thermo-creep damage	
GANCZARSKI and SKRZYPEK (1995; 1997) KAVIANY (1995) SAANOUNI et al. (1994) SKRZYPEK and GANCZARSKI (1998)	Thermo-elastic-viscoplastic damage (fully coupled approach). Damage effect on heat flux in solids. Change of temperature gradient due to damage evolution.

Further reviews should be mentioned, for instance, the extended reports by ZHENG (1994), KRAJCINOVIC (1984), MURAKAMI (1987), ZYCZKOWSKI (1988; 1996) or the comprehensive surveys in the monographs and textbooks published by KRAJCINOVIC and LEMAITRE (1987), KACHANOV (1986), KRAJCINOVIC (1996), LEMAITRE and CHABOCHE (1990), LEMAITRE (1992), SKRZYPEK and GANCZARSKI (1999), to name but a few.

The different types of material damage listed in Table 1.1 have (more or less) a significant influence on the mechanical properties of the material, e.g., on the elasticity modulus, the elastic stiffness, the velocities of elastic waves, the plastic properties, the strength of materials, the fatigue strength, the creep rupture time, etc.. Thus, damage mechanics and their application play a central role in solving practical engineering problems.

Before formulating some basic equations of continuum mechanics and constitutive equations for materials under multi-axial states of stress and creep conditions, a short outline of tensor algebra should be given in the next chapter.