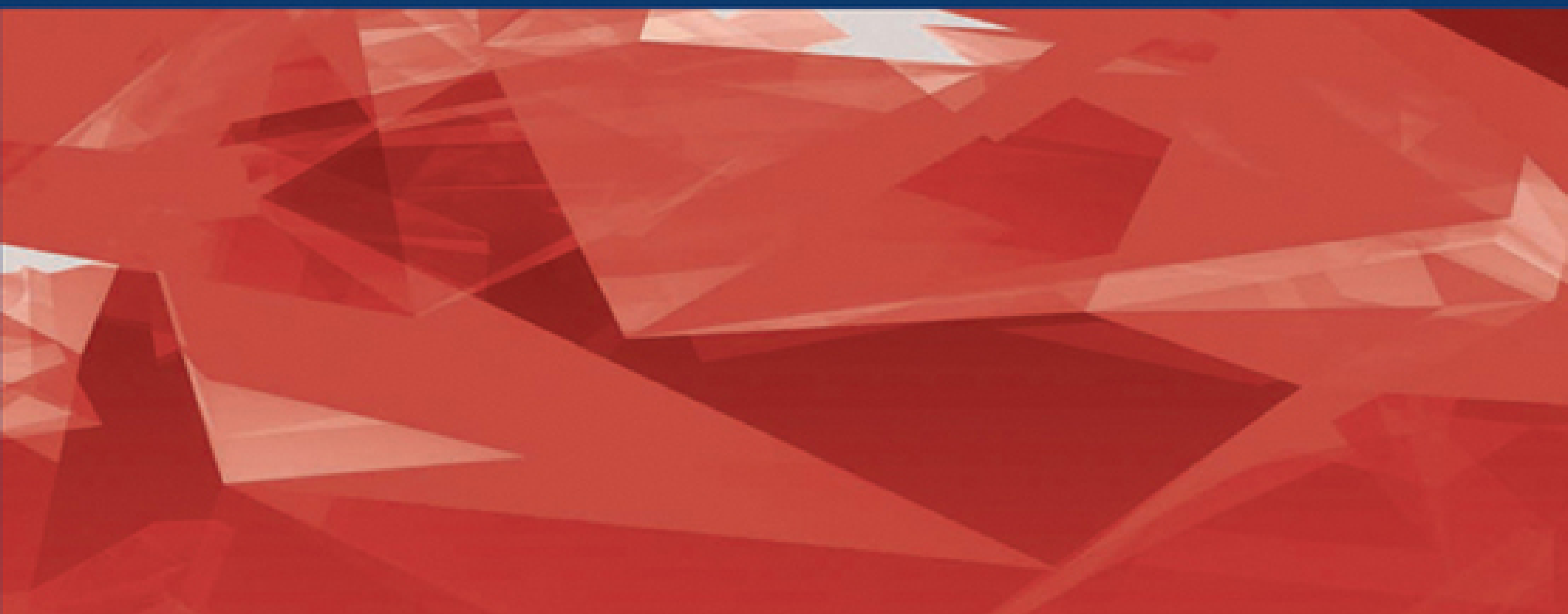
Fatigue of Materials and Structures

Application to Damage and Design

Edited by
Claude Bathias and André Pineau



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Foreword

This book on fatigue, combined with two other recent publications edited by Claude Bathias and André Pineau[1], are the latest in a tradition that traces its origins back to a summer school held at Sherbrooke University in Quebec in the summer of 1978 which was organized by Professors Claude Bathias (then at the University of Technology of Compiegne, France) and Jean Pierre Bailon of Ecole Polytechnique, Montreal, Quebec. This meeting was held under the auspices of a program of cultural and scientific exchanges between France and Quebec. As one of the participants in this meeting, I was struck by the fact that virtually all of the presentations provided a tutorial background and an in-depth review of the fundamental and practical aspects of the field as well as a discussion of recent developments. The success of this summer school led to the decision that it would be of value to make these lectures available in the form of a book which was published in 1980. This broad treatment made the book appealing to a wide audience. Indeed, within a few years, dog-eared copies of “Sherbrooke” could be found on the desks of practicing engineers, students and researchers in France and in French-speaking countries. The original book was followed by an equally successful updated version that was published in 1997 which preserved the broad appeal of the first book. This book represents a part of the continuation of the approach taken in the first two editions while providing an even more in-depth treatment of this crucial but complex subject.

It is also important to draw attention to the highly respected “French School” of fatigue which has been at the forefront in integrating the solid mechanics and materials science aspects of fatigue. This integration led to the development of a deeper fundamental understanding thereby facilitating application of this knowledge to real engineering problems from microelectronics to nuclear reactors. Most of the authors who have contributed to the current edition have worked together over the years on numerous high-profile, critical problems in the nuclear, aerospace, and power generating industries. The informal teaming over the years perfectly reflects the mechanics/materials approach and, in terms of this book, provides a remarkable degree of continuity and coherence to the overall treatment.

The approach and ambiance of the “French School” is very much in evidence in a series of bi-annual international colloquia. These colloquia are organized by a very active “fatigue commission” within the French Society of Metals and Materials (SF2M) and are held in Paris in the spring. Indeed, these meetings have contributed to an environment which fostered the publication of this series.

The first two editions (in French), while extremely well-received and influential in the French-speaking world, were never translated into English. The third edition was recently published (again in French) and has been very well received in France. Many English-speaking engineers and researchers with connections to France strongly encouraged the publication of this third edition in English. The current three books on fatigue were translated from the original four volumes in French[2] in response to that strong encouragement and wide acceptance in France.

In his preface to the second edition, Prof. Francois essentially posed the question (liberally translated), “Why publish a second volume if the first does the job?” A very good question indeed! My answer would be that technological advances place increasingly severe performance demands on fatigue-limited structures.

Consider, as an example, the economic, safety and environmental requirements in the aerospace industry. Improved economic performance derives from increased payloads, greater range and reduced maintenance costs. Improved safety, demanded by the public, requires improved durability and reliability. Reduced environmental impact requires efficient use of materials and reduced emission of pollutants. These requirements translate into higher operating temperatures (to increase efficiency), increased stresses (to allow for lighter structures and greater range), improved materials (to allow for higher loads and temperatures) and improved life prediction methodologies (to set safe inspection intervals). A common thread running through these demands is the necessity to develop a better understanding of fundamental fatigue damage mechanisms and more accurate life prediction methodologies (including, for example, application of advanced statistical concepts). The task of meeting these requirements will never be completed; advances in technology will require continuous improvements in materials and more accurate life prediction schemes. This notion is well illustrated in the rapidly developing field of gigacycle fatigue. The necessity to design against fatigue failure in the regime of 10^9 + cycles in many applications required in-depth research which in turn has called into question the old, comfortable notion of a fatigue limit at 10^7 cycles. New developments and approaches are an important component of this edition and are woven through all the chapters of the three books.

It is not the purpose of this preface to review all of the chapters in detail. However, some comments about the organization and over-all approach are in order. The first chapter in the first book[3] provides a broad background and historical context and sets the stage for the chapters in the subsequent books. In broad outline, the experimental, physical, analytical and engineering fundamentals of fatigue are developed in this first book. However, the development is done in the context of materials used in engineering applications and numerous practical examples are provided which illustrate the emergence of new fields (e.g. gigacycle fatigue) and evolving methodologies (e.g. sophisticated statistical approaches). In the second[4] and third[5] books, the tools that are developed in the first book are applied to newer classes of materials such as composites and polymers and to fatigue in practical, challenging engineering applications such as high temperature fatigue, cumulative damage and contact fatigue.

These three books cover the most important fundamental and practical aspects of fatigue in a clear and logical manner and provide a sound basis that should make them as attractive to English-speaking students, practicing engineers, and researchers as they have proved to be to our French colleagues.

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December 2010

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1. C. BATHIAS, A. PINEAU (eds.), *Fatigue of Materials and Structures: Fundamentals*, ISTE, London and John Wiley & Sons, New York, 2010.
C. BATHIAS, A. PINEAU (eds.), *Fatigue of Materials and Structures: Application to Design*, ISTE, London and John Wiley & Sons, New York, 2011.

2. C. BATHIAS, A. PINEAU (eds.), *Fatigue des matériaux et des structures*, Volumes 1, 2, 3 and 4, Hermes, Paris, 2009.

3. C. BATHIAS, A. PINEAU (eds.), *Fatigue of Materials and Structures: Fundamentals*, ISTE, London and John Wiley & Sons, New York, 2010.

4. This book.

5. C. BATHIAS, A. PINEAU (eds.), *Fatigue of Materials and Structures: Application to Design*, ISTE, London and John Wiley & Sons, New York, 2011.

Chapter 1

High Temperature Fatigue [1]

1.1. Introduction and overview

1.1.1. *Introductory remarks*

It is a basic consequence of thermodynamics that the efficiency of heat engines, regardless of their type, increases with increasing temperature. In the power generation industry (nuclear industry, coal-fired and/or oil-fired plants), any increase in working temperature leads to a decrease in fuel consumption, pollution and operating costs. In the jet engine industry, increased operating temperatures lead to improved performances, such as the combinations of heavier payloads, a greater speed and a greater range.

For the power generation industry, lower fuel consumption, reduced pollution and lower costs are important. However, as operating temperatures are increased, additional problems to those encountered at lower temperatures arise. Regardless of its type, all engines have moving parts that experience variable loading during each operating cycle. In general, loading above a certain level causes microscopic rearrangements at the atomic level, which can lead to an important damage. With continued operation (i.e. cyclic loading) damage accumulates and eventually leads to the fracture of the component. This scenario can be viewed as a working definition of fatigue. Many practical and theoretical investigations have been carried out over the past two centuries to experimentally characterize failure by fatigue and to predict the lives of components subjected to fatigue loading. Wöhler [WÖH 1860], going back more than a century, demonstrated that the fatigue life of a component may be represented in terms of stress, which eventually leads to the well-known and widely used S/N curve methodology, which was discussed in Claude Bathias and André Pineau's *Fatigue of Materials and Structures: Fundamentals*. Even if fundamentaland practical difficulties are still encountered using this approach, the stress-based method is applicable to this day to make preliminary life estimates of some components.

1.1.2. *A little history*

1.1.2.1. *Effects of temperature*

At higher temperatures such as those found in the power generation and jet engine industries, not only is there repeated loading, but depending on strain rates and hold times, time-dependent damage processes such as creep and environmental attack become important. Two major advances in understanding high temperature fatigue from an engineering perspective were made in the 1950s and 1960s at NASA Lewis by Manson and coworkers (see e.g. [MAN 53]) and at General Electric by Coffin and coworkers [COF 54]. The first was in terms of conceptualizing the fatigue process in a more physically acceptable, albeit very general, manner. The second major advance was associated with advances in control technology. The rapid advances in "controls" paved the way for the development of closed-loop test machines, much more reliable data, and vastly improved life prediction capabilities. These are discussed in greater detail below.

1.1.2.2. *Problems with the S/N approach: strain as a driver of damage*

Attempts to predict the lives of high-temperature components in jet engines and nuclear power generation facilities using the S/N approach lacked sufficient precision and required the use of significant safety factors. Two factors limited the utility of the traditional approaches:

– dynamic changes in the material (intrinsic and extrinsic) are not captured in the traditional S/N approach (this aspect is a major focus of this chapter and is discussed in detail in subsequent sections).

– stress is not a physically meaningful damage function in itself.

The second limitation is easily understood in terms of basic physics. It is not possible to “measure” a stress (or equivalently a force) without some reference to displacement and a relationship defining stress (or force) in terms of strain (or displacement). Strains and displacements are real, while stresses and forces represent mathematical conveniences. Real damage in a material will always depend upon some kind of displacement or physical change within the material.

In a structural crystalline material, it is intuitively appealing to associate damage with strain. The more strain, the more dislocation movement. The more dislocation movement, the greater the possibility of dislocation intersections and pile-ups. These obviously produce various forms of damage such as vacancies, interstitials, cells, tangles and increased dislocation densities (see e.g. [HUL 01] for a detailed discussion of dislocation interactions and debris). In fatigue, we are thus led to think in terms of the reversed plastic strain, $\Delta\varepsilon_p$. In addition, elastic strains, denoted by $\Delta\varepsilon_e$, can be damaging in the sense that they may produce microplasticity or elastic displacements that may be sufficient to cause cracking of brittle inclusions. Both Coffin [COF 54] and Manson [MAN 53], working independently, adopted the working hypothesis that plastic strain range was the real driver of fatigue damage and hence determined the fatigue life. Using the then recently developed closed-loop test equipment they were able to carry out experiments in which the strain range was controlled. For relatively high strains, they found that when the plastic strain range was plotted against the cyclic life, a straight line on a log-log plot was produced, independent of material. The result was the well-known Coffin-Manson Law:

[1.1] $N_f^{\beta} \cdot \Delta\varepsilon_p = C_D$

These terms are defined in [BAT 10] and will not be discussed here, other than to emphasize that the exponents and constants are dependent upon the material and testing conditions. Most of the currently used high-temperature life prediction methodologies use equation [1.1] as a starting point and modify it in some way to account for time-dependent processes, such as creep and environment effects.

1.1.2.3. *Total strain approach to life prediction – advantages and critique*

Manson [MAN 65] and his coworkers [HAL 78] at NASA recognized that putting life in terms of total strain was more convenient from an engineering perspective. This was done by noting that the total strain range, $\Delta\varepsilon_t$, was the sum of the elastic and plastic ranges and that a correlation similar to equation [1.1] could be made. Adding up the elastic and plastic strain ranges gives:

[1.2] $\Delta\varepsilon_t = C_D \cdot N_f^{-\beta} + C_E \cdot N_f^{-\alpha}$

The second set of quantities on the right-hand side corresponds to the elastic strain component. For many materials, the values of β and α are approximately 0.6 and

0.12 [PIN 10] respectively. However, since these are only approximate values, their use is limited to scoping calculations. Due to the form of equation [1.2] and the values of β and α, the first component dominates for high strains and the second component dominates for low strains. Thus, life prediction may be viewed in terms of low cycle fatigue (high strain ranges) or high cycle fatigue (low strain ranges). Only when the elastic and plastic strains are essentially equal must we consider both terms.

While the strain-life equation [1.2] is frequently used, there are two problems with this equation and with equation [1.1]. The first one is that life is traditionally represented in terms of cycles to failure, N_f. Clearly this introduces geometric dependence into the problem and implicitly incorporates a process that was not addressed – the process of crack propagation. Many researchers have attempted to address this situation by using cycles to initiation, defined as a given load drop in a strain-controlled test. The relationship between load drop and crack size is easily developed. It is given by:

[1.3] $A_c = 100(\%LD)A_0$

where A_C is area of the crack, A_0 is the initial cross-sectional area of the sample, and % LD is the percentage load drop.

With a specimen 6.35 mm in diameter, a 1% load drop corresponds to a crack with a characteristic linear dimension of about 560 µm[1]. For most polycrystalline materials, this corresponds to at least 10 grains and it is difficult to consider a crack of such a size as relating entirely to initiation. The size of the crack detected via this method may be decreased by reducing both the load drop and the specimen's diameter. Clearly distinguishing the initiation phase (e.g. limiting initiation to a physically meaningful dimension) remains a challenge in high temperature fatigue.

The second problem is that by representing the fatigue life (or more correctly the cycles to initiation) by equation [1.2], the dependent and independent variables are confounded in such a way that equation [1.2] cannot be restructured to make life a function of strain; a more rational dependence. Equation [1.2] can easily be solved using numerical iteration techniques. It does not present any difficulty from an engineering perspective. However, the form of the equation does present scientific difficulties. A fundamental model of fatigue would have to have the following form:

[1.4] $N_i = f(D_{\Delta\varepsilon_p}(N))$

where N_i is the number of cycles to initiation, D is the damage state which depends on the current cycle number for given plastic strain range, $\Delta\varepsilon_p$, and N is the current cycle number.

Equation [1.2] and its variants should be regarded as an engineering convenience and not as a scientific basis for a deep understanding of fatigue.

1.1.3. *High temperature testing closed-loop control and extensometry*

The closed-loop approach to mechanical testing, in its simplest form, means that what is desired is actually delivered. This topic is discussed in more detail elsewhere [ANT 00] but a brief description is important here, not only for the historical context, but for its centrality in high temperature low cycle fatigue (LCF). In broad outline, a program for stress or strain as a function of time is programmed for a specimen. The closed-loop control system compares the command value to the measured value and makes a rapid adjustment to bring the system into dynamic equilibrium. In this way, we may obtain test results with a high degree of accuracy and precision for precisely controlled conditions. In high temperature studies, it is customary to use plastic strain control since it directly affects damage. In practice, the upper and lower plastic strain limits are set along with the loading rates and hold times (i.e. the loading profile) and the test is conducted in this way. The appeal of this approach is that it corresponds to the real physical quantity, which is closely related to damage.

Implicit in this approach is the ability to measure and control temperature, which can also be done using a feedback system with inductive or radiative heating. Some care must be exercised here to avoid convective effects and to make sure that thermocouples, if used with inductive heating, do not have a significant loop cross section normal to the flux lines lest extraneous EMF (Electromagnetic force) be generated. High-temperature extensometry must be employed, adding a further complication. If mechanical contact is made between the specimen and the extensometer, such contact must be firm enough to prevent the extensometer from slipping (and causing undesired loading) but not so firm as to cause crack initiation and premature fatigue failures at the point of extensometer contact. Extremely simple, cost-effective and accurate high-temperature extensometers have been developed that completely avoid these problems [MIL 88]. Another method involves the use of laser extensometry. Due to changes in the surface at high temperatures and slower response rates, however, lasers are best used for measuring rather than controlling. In addition, laser extensometers are at least 30 times more expensive than the mechanical extensometers discussed above and are not easily replaced.

1.1.4. *Damage mechanisms and interactions in high-temperature fatigue*

In addition to the damaging effects of reversed plasticity, creep and environmental effects (usually in the form of oxidation) must be considered at high temperatures. Furthermore, interactions among these mechanisms must be measured as well as the stability of the underlying microstructure and dislocation substructure. As a simple example, slip bands may impinge upon oxygen-poisoned boundaries causing early cracking. In addition, the ingress of oxygen atoms may affect the way in which fundamental fatigue deformation processes occur. Complicating matters further is the fact that in many real-world applications, the mechanical strains and temperature vary independently (so-called thermomechanical fatigue, or TMF, discussed in more detail in Chapter 7 of [BAT 11]) leading to damage mode interactions that probably never occur in isothermal fatigue. Any physically meaningful life prediction equation must be such that its form and physical parameters correspond to physical reality. This aspect of life prediction is discussed in detail in this chapter.

1.1.5. *Organization of this chapter*

This chapter starts out with an overview of several existing models for high-temperature fatigue to provide background and context. High-temperature fatigue is a vast and complex problem in which many materials are considered. Such materials are so vast in number that an intelligent limitation must be made while still elucidating important principles. In order to do this, we have decided to use the following three important and representative classes of material to achieve this goal:

– austenitic stainless steels (power generation industry);

– Cr-Mo steels (power generation industry);

– Ni-base superalloys (gas turbines in the jet engine industry).

In addition to their industrial importance, these materials were selected for in-depth discussion because their different microstructures, deformation characteristics, and damage mechanisms fully illustrate the challenges of high-temperature fatigue. With some caution, the principles developed in this chapter may be applied to other material systems. In the section on each of these materials, the basic microstructure, fundamental deformation mechanisms, basic fatigue damage mechanisms and their interactions are discussed. In some cases, TMF is also included. Models based on dominant mechanisms are presented in several cases. Some of the more widely used engineering models are discussed with respect to the physics-based models (which are the main focus of this chapter) in terms of functional form and sensitivity of parameters to temperature, strain rate and environment.

An important theme running throughout this chapter, for both LCF and fatigue crack propagation (FCP), is the dynamic nature of materials with respect to the stability of the microstructure and dislocation substructure as a function of temperature, level of deformation and strain rate.

1.1.6. *Goals*

The goals of this chapter are:

– to review mechanisms of cyclic deformation, damage accumulation and crack propagation in austenitic stainless steels, Cr-Mo steels, and superalloys (both Nibase and Fe-Ni base);

– to relate these mechanisms to engineering applications;

– to review life prediction methodologies appropriate to these applications and mechanisms;

– to point out current and likely future trends in the development of more fatigue-resistant materials and improved life prediction methodologies.

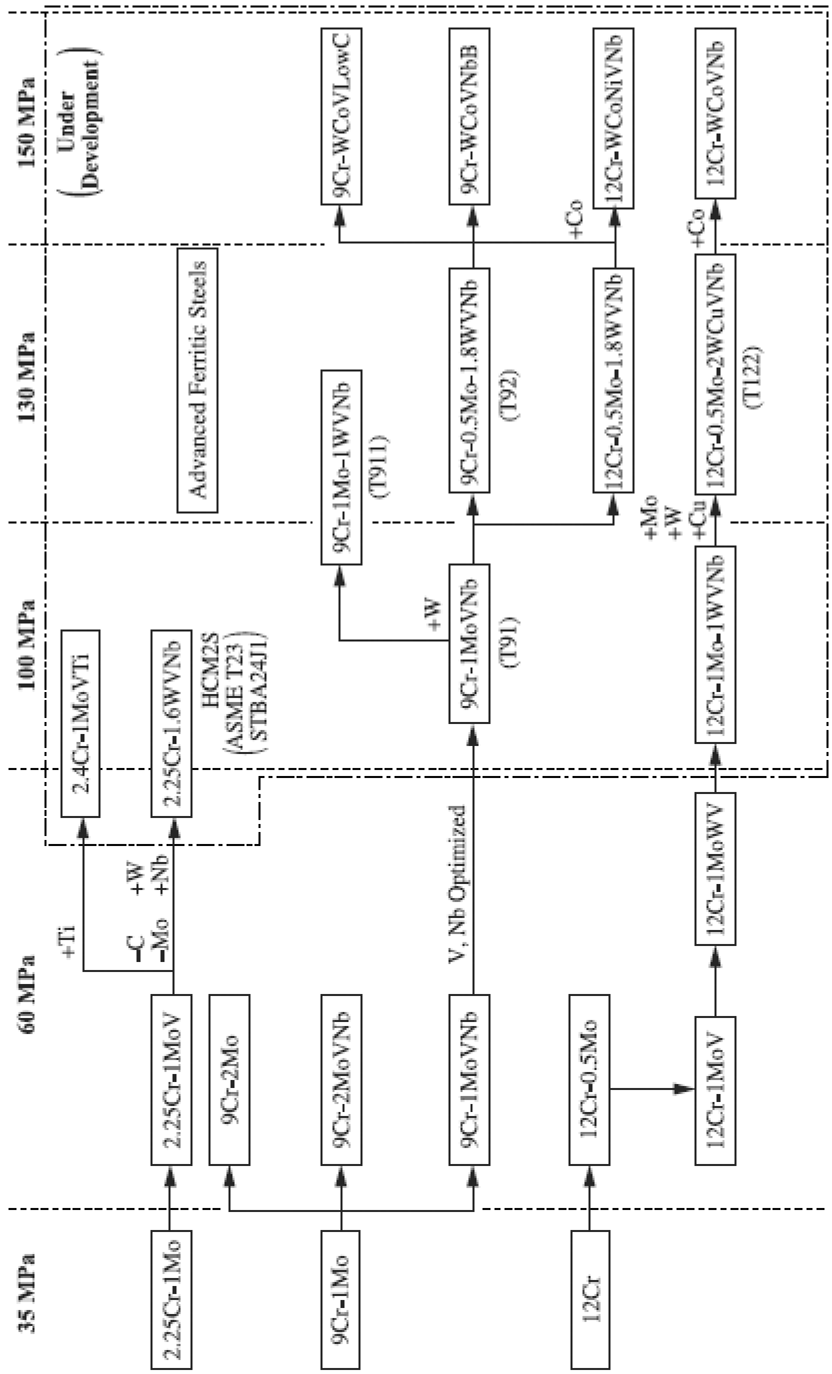
1.2. 9 to 12% Cr steels

1.2.1. *Introduction*

Martensitic steels of the 9–12% Cr variety are widely used in the thermal power generation industry where operational temperatures are in the neighborhood of 550°C. The desire for increased operating temperatures led to the development of compositional modifications in these materials. The first of these modifications was the addition of 1% molybdenum followed by tungsten, vanadium and nitrogen. Most of the structures in this industry are subject to creep loading. Table 1.1 summarizes the various compositions that have been developed and gives the 600°C creep rupture stress. Considerable hope is vested in the most advanced compositional modifications for the fabrication of components to be used in fourth-generation electro-nuclear fusion reactors scheduled to come on line around 2030–40. This timeframe requires a demonstration reactor to be available around 2020. This means that most technical solutions must be well in hand around 2012. In the same vein, we can also consider the possibility of using these steels for fusion reactors whose industrial debut is further in the future.

Compared to austenitic stainless steels, these steels in addition to other advantages have superior thermal conductivity, a lower coefficient of thermal expansion and less sensitivity to radiation-induced swelling, especially the ODS (Oxide Dispersion Strengthened) versions that are produced by mechanical grinding using ball milling. To design these reactors, it is imperative to have a detailed understanding of the fatigue and creep-fatigue properties of these steels since cycling is related to maintenance-related shutdowns and startups, and to a lesser extent on the demands of the power grid. The major problem associated with the design rules for components used in the nuclear power generation industry lies in the necessity of extrapolating the data upon which these rules are based. The totality of these technical requirements explains the renewed interest in studying these materials in the past few years.

Table 1.1. *Chromium-bearing ferritic and martensitic steels showing the evolution in chemistry and improvement in 100,000-hour creep strength at 600°C*

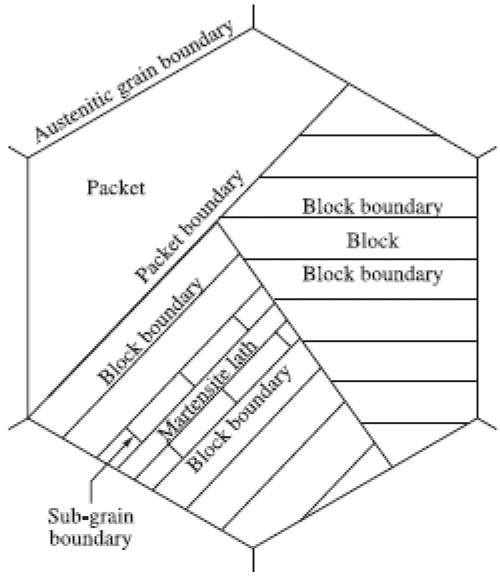


In this chapter, a classical approach to considering fatigue and creep fatigue properties is followed. After a discussion of the microstructure, classical fatigue behavior is considered. It is shown that the particularities of the microstructure lie at the heart of the important phenomenon of cycling softening that is often observed. Next, the subject of fatigue damage is considered. The discussion of steels is centered on those with compositions of 9% Cr and 1% Mo (P91). However, changes in behavior associated with compositional modifications and microstructural changes are discussed, as far as is possible. A number of excellent recent review papers are available on these steels. For example, the review of Klueh and Nelson [KLU 07] can be consulted on this topic. This section relies heavily upon the thesis by Fournier [FOU 07], which was the basis of several recent publications: [FOU 06a, FOU 06b, FOU 08a, FOU 08b, FOU 08c, FOU 09a, FOU 09b]. Fournier studied a composition characteristic of these steels (C = 0.088, N = 0.043, Cr = 8.78, Mo = 0.92, Mn = 0.35, Si = 0.33, Nb = 0.78, V = 0.191 in percentage weight). This steel was austenitized at 1,050°C for 30 minutes, quenched and then aged at 780°C for one hour. The results obtained on this steel serve as the basis for the following discussion. The results for other steels in this family, notably those containing 12% Cr, are discussed.

1.2.2. *Microstructures of 9–12% Cr steels*

The microstructure of these steels must be considered at several size scales, see Figure 1.1.

Figure 1.1. *Various significant size scales for quenched and tempered 9–12% Cr steels [FOU 07]*



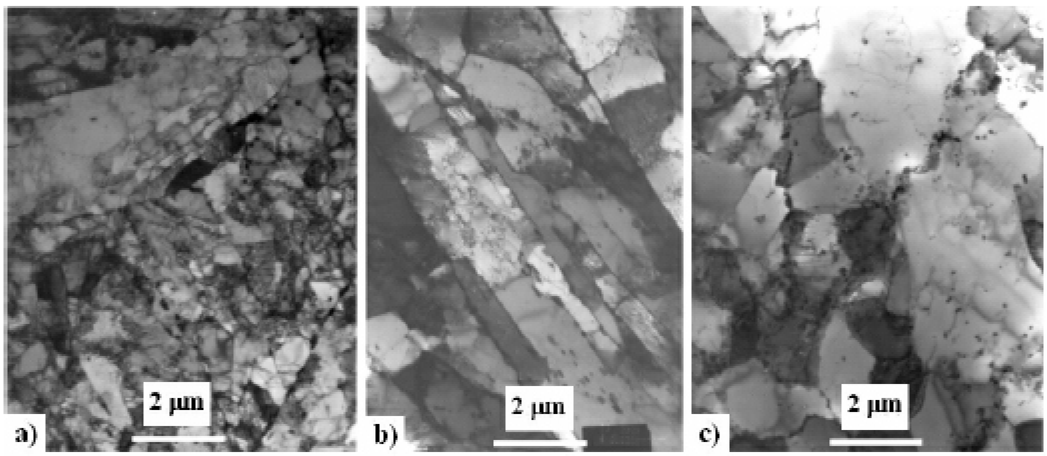
At the optical microscopy level, entangled packets resulting from the martensitic phase transformation can be seen in prior austenite grains (d~10–60 µm). These packets are subdivided into blocks of laths, which have the same $\{111\}_{\gamma}$ habit plane.

The laths have a variable thickness but are generally in the order of several microns. During quenching, subgrains are formed in the interior of these laths (see Figure 1.2). These subgrains also have a variable size but are generally in the order of about 500 nm. The microstructure and crystallography of the martensite lath obtained from quenching these steels is very well described in the article by Kitahara *et al*. [KIT 06].

All of the steels have carbides after ageing whose dimensions vary significantly with composition and the thermal treatment. Chromium carbides of the $M_{23}C_6$ type are the first to form and are quite often preferentially precipitated upon boundaries, including former γ grain boundaries and others (see e.g. [EFF 89]).

Figure 1.2. *P91 steel. Transmission electron microscopy observations: a) initial condition (quenched and tempered); b) cyclically deformed in pure fatigue ($\Delta\varepsilon_{fat}$ = 0.70%), T = 550°C; c) tested in hold-time fatigue ($\Delta\varepsilon_{fat}$ =0.70%), T=550°C.*

Note the progressive coarsening of the structure from a) to c) [FOU 88]



Moreover, these steels contain very fine carbides (and carbo-nitrides) of the MX type that are distributed uniformly throughout the microstructure. More details are provided elsewhere (see, e.g. [GAF 05] and [BRA 91]).

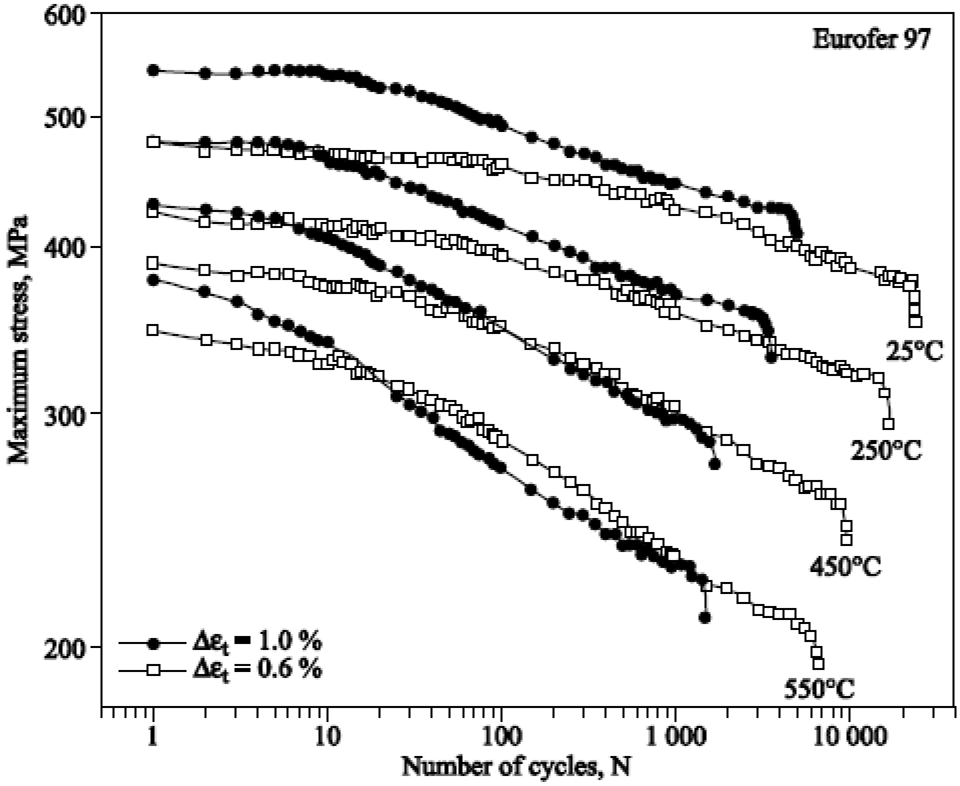
1.2.3. *Mechanical behavior*

In the following, the mechanical behavior of 9–12% Cr steel during fatigue and creep-fatigue are discussed.

1.2.3.1. *Behavior in pure fatigue*

Typical fatigue behavior for a 9–12% Cr steel is shown in Figure 1.3 [ARM 04]. It is seen that the maximum stress decreases continually at both low ($\Delta\varepsilon_t$ = 0.6%) and high ($\Delta\varepsilon_t$ = 1.0%) strains. This softening becomes more pronounced as the temperature increases. Thus, at T=550°C and at half of the fatigue life, the stress is practically cut in half. A detailed study by Fournier [FOU 07] on a P91 steel showed that this cyclic softening seen at 550°C (Figure 1.4), affects the kinematic component of hardening whereas the isotropic component is hardly affected over the strain range that was studied (0.4%< $\Delta\varepsilon_t$ <0.6%) [FOU 06]. This observation suggests that microstructural modifications occur during cycling that affect the long-range internal stresses associated with the arrangement of dislocations.

Figure 1.3. *Eurofer 97 steel. LCF tests at various temperatures (25°C, 250°C, 450°C and 550°C) at two strain levels* $-\Delta\varepsilon_t$ *=0.60% and 1%. The variation of stress with the number of cycles is shown [ARM 04]*



Transmission electron microscopy (TEM) examinations revealed a significant modification of the dislocation substructure, especially when a creep component is imposed on a pure fatigue test, Figure 1.2. The density of dislocations decreases and dislocations re-arrange themselves into larger cells. The relationship between the cell size and saturation stress (or the stress at half-life) is shown in Figure 1.5 [KLM 88]. It thus appears as if the microstructure of 9–12% Cr steels is highly unstable under cyclic loading. Recent studies on steels produced by ball milling systematically seem to show that the presence of very fine particles in the matrix strongly reduce or even suppress this softening phenomenon [UKA 07].

Figure 1.4. *P91 steel: a) variation in the stress amplitude with the number of cycles in continuous fatigue; b) variation of the kinematic component, X, of hardening with the number of cycles. The total applied strain amplitude at 550°C is indicated on each figure [FOU 06]*

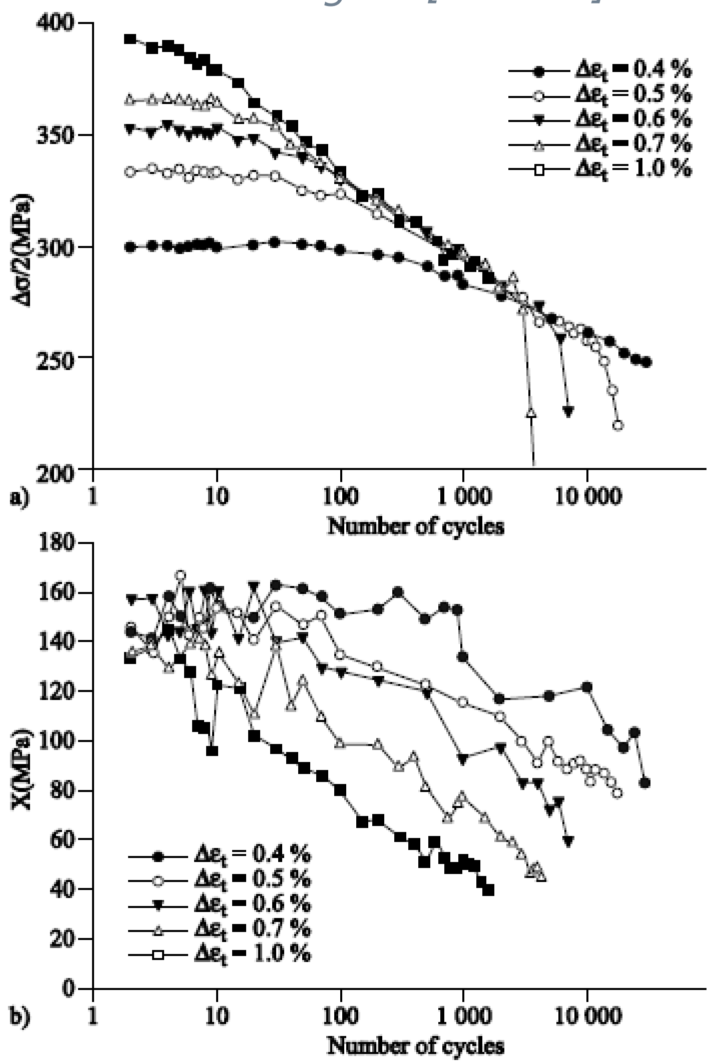
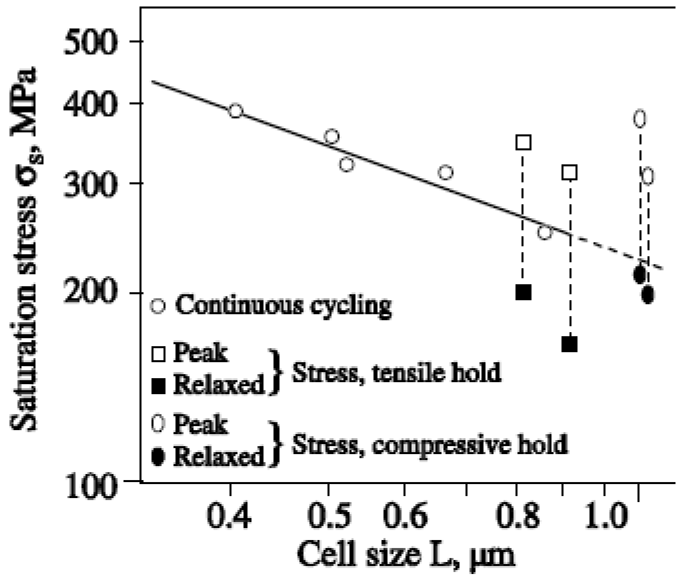


Figure 1.5. *Correlation between cyclic softening and microstructural coarsening for a P91 steel fatigued at 593°C [KIM 88]*



1.2.3.2. *Creep fatigue behavior*

The principle of creep-fatigue testing with a hold time is shown in Figure 1.6. In relaxation fatigue tests, Figure 1.6a, a hold is applied at the maximum strain (tension) or the minimum strain (compression). During this hold period, stress relaxation occurs by a mechanism of viscous deformation process in which elastic strain is converted into plastic strain.

In an actual creep-fatigue test a hold time is imposed at the maximum (or minimum) stress, which is held constant, until the desired level of strain is attained, see Figure 1.6b. During this hold time, a creep strain, ε_{creep}, occurs either in tension or in compression. These creep-fatigue tests are more revealing of the behavior, in as much as an increasing amount of creep strain is applied on a cycle-by-cycle basis. These tests lead to the development of a mean stress in tension for a compressive hold and a compressive mean stress for a tensile hold, as seen in Figure 1.7. A very strong softening effect is seen in Figure 1.7.