1

Introduction on Very High Cycle Fatigue

This chapter is a summary of several decades of reasearch on gigacycle fatigue of metals. For more detail please see references [BAT 04] and [BAT10].

1.1. Fatigue limit, endurance limit and fatigue strength

Fatigue limit, endurance limit and fatigue strength are all expressions used to describe a property of materials under cyclic loading: the amplitude (or range) of *cyclic stress* that can be applied to the material without causing *fatigue failure.* In these cases, a number of cycles (usually 10^7) are chosen to represent the fatigue life of the material.

According to the American Society for Testing and Materials (ASTM) Standard E 1150, the definition of *fatigue* is summarized as follows: "The process of progressive localized permanent structural damage occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations". The plastic strain resulting from cyclic stress initiates the crack; the tensile stress promotes crack growth propagation. Microscopic plastic strains also can be present at low levels of stress where the strain might otherwise appear to be totally elastic. The ASTM defines *fatigue strength*, S_{Nf}, as the value of stress at which failure occurs after N_f cycles, and *fatigue limit*, S_f, as the limiting value of stress at which failure occurs as N_f becomes very large. The ASTM does not define *endurance limit*, the stress value below which the material will withstand many load cycles, but implies that it is similar to fatigue limit.

Some authors use *endurance limit* for the stress below which failure never occurs, even for an indefinitely large number of loading cycles, as in the case of steel, and *fatigue limit* or *fatigue strength* for the stress at which failure occurs after a specified number of loading cycles, such as 500 million, as in the case of aluminum. Other authors do not differentiate between the expressions even if they do differentiate between the face center cubic (FCC) metals and the base center cubic (BCC) metals [BAT 10].

Since the word "fatigue" was used by Braithwaite, A. Wöhler established the first basic approach to the fatigue life of metals, in the mid-1800s, when the main industrial applications were railcar axles and steam engines for railways and boats [BAT 10]. The slow rotation of a steam engine was about 50 cycles per minute, more or less. Thus, the fatigue limit was defined by Wöhler to be between 10^6 and 10^7 cycles, but it seems that the quasi-hyperbolic stress number of cycle (SN) curve was suggested by Basquin [BAS 10]. Today, the fatigue life of a high-speed train ranges in the gigacycle, 10^9, regime and for an aircraft turbine it is of the order of 10^{10} cycles, according to the rotation speed of several thousand turns per minute.

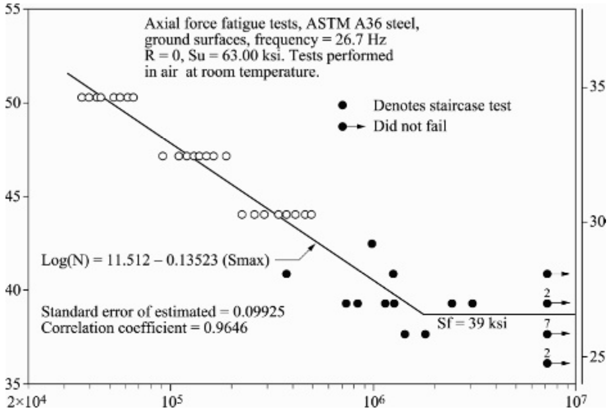

Figure 1.1. *International standard for SN curve and fatigue limit*

The fatigue curve or SN curve is usually defined in reference to carbon steel. The SN curve is generally limited to 10^7 cycles and it is acknowledged, according to the standard, that a horizontal asymptote allows us to determine a fatigue limit value for an alternating stress between 10^6 and 10^7 cycles. Beyond 10^7 cycles, the standard considers that the fatigue life is infinite. For other alloys, it is assumed that the asymptote of the SN curve is not horizontal.

A few results for fatigue limit based on 10^9 cycles can be found in the literature [BAT 10]. Using standard practice, the shape of the SN curve beyond 10^7 cycles is predicted using the probabilistic method, and this is also true for the fatigue limit. In principle, the fatigue limit is given for a number of cycles to failure (Figure 1.1). Using, for example, the staircase method, the fatigue limit is given by the average alternating stress σ_D and the probability of fracture is given by the standard deviation of the scatter (s). The classical way to determine the infinite fatigue life is to use a Gaussian function. Roughly speaking, it is said that σ_D minus $3s$ gives a probability of fracture close to zero. Assuming s is equal to 10 MPa, the true infinite fatigue limit should be $\sigma_D - 30$ MPa. However, experiments show that between σ_D for 10^6 and σ_D for 10^9, the difference is greater than 30 MPa for many alloys.

The so-called standard deviation (SD) approach to the average fatigue limit is certainly not the best way to reduce the risk of rupture in fatigue. When one is conscious that it is the last resort, only experience can remove this ambiguity by appealing to some tests of accelerated fatigue. Today some piezoelectric fatigue machines are very reliable, capable of producing 10^{10} cycles in less than one week, whereas the conventional systems require more than 3 years of tests for only one sample.

To summarize the present situation, it is acknowledged that the concept of a fatigue limit is bound to the hypothesis of the existence of a horizontal asymptote on the SN curve between 10^6 and 10^7 cycles (Figure 1.1). Thus, a sample that reaches 10^7 cycles and is not broken is considered to have an infinite life; that is, in fact, a convenient and economical approximation but not a rigorous approach. It is important to understand that if the staircase method is popular today to determine the fatigue limit, this is because of the convenience of this approximation. A fatigue limit determined by this method to 10^7 cycles requires 30 h of tests to get only one sample with a machine working at 100 Hz. To reach 10^8 cycles, 300 h of tests would be required, which is expensive. Using a 20 kHz piezoelectric fatigue machine, it takes around 14 h to obtain 10^9 cycles, 6 days for 10^{10} cycles and 58 days for 10^{11} cycles. The basic design of the piezoelectric fatigue machine is the same at 30 kHz as a 20 kHz piezoelectric fatigue machine, where the vibration of the specimen is induced by a piezoceramic converter, which generates acoustic waves in the specimen through a power concentrator (horn) in order to obtain desired displacement and an amplification of the stress [WU 93]. The resonant specimen dimension and stress concentration factor were calculated by the Finite Element Method (FEM) subject to 20 and 30 kHz [WU 93]. Such computer-controlled piezoelectric fatigue machines are able to work in tension-compression, tension-tension-tension, bending and torsion loading (Figure 1.2). It is of importance to note that the temperature of the specimen and the amplitude of the stress must stay constant during a standard test at 20 kHz to keep the comparison with low-frequency testing. A complete description of the procedure is given in [BAT 04].

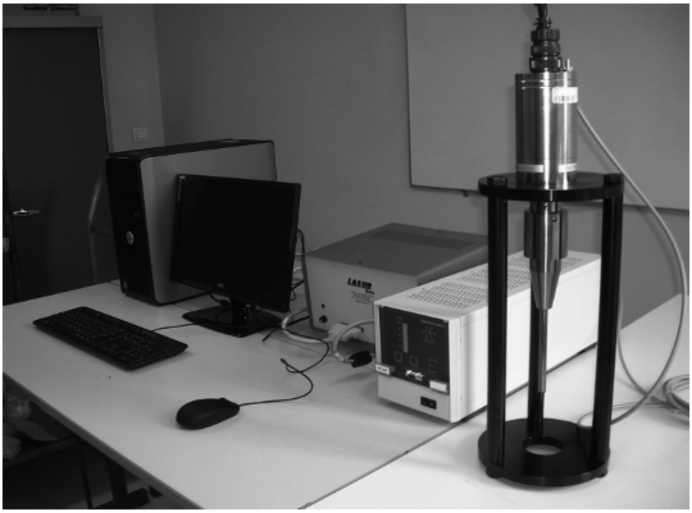

Figure 1.2. *Experimental system for ultrasonic fatigue at 20 kHz*

1.2. Absence of an asymptote on the SN curve

Generally speaking, it is assumed that the steel SN curves are different from the others. To get an overview of the gigacycle behavior, many alloys, including steel, are considered in this chapter. For results of fatigue SN curves based on 10^9 cycles, a few results are available in the literature. Many of those results come from our laboratory [BAT 04]. The other results come from Japanese researchers such as Naito [NAI 84], Kanazawa [NIS 97], Murakami [MUR 99] and Sakai [SAK 07]. They are limited to 10^8 cycles. Also, some SN curves for light alloys come from the laboratory of S. Stanzl-Tschegg and H.R. Mayer [STA 99]. They are limited to 10^9 cycles.

Safe-life design based on the infinite life criteria was initially developed from the Wöhler approach, which is the stress-life or SN curve related to the asymptotic behavior of steel. Some materials display a fatigue limit or an "endurance" limit at a high number of cycles (typically $>10^6$). Most other materials do not exhibit this response; instead, they display a continuously decreasing stress-life response, even at a large number of cycles (10^6–10^9), which is more correctly described by fatigue strength at a given number of cycles.

The actual shape of the SN curve between 10^6 and 10^{10} cycles is a better way to help the prediction of risk in fatigue cracking (Figure 1.3).

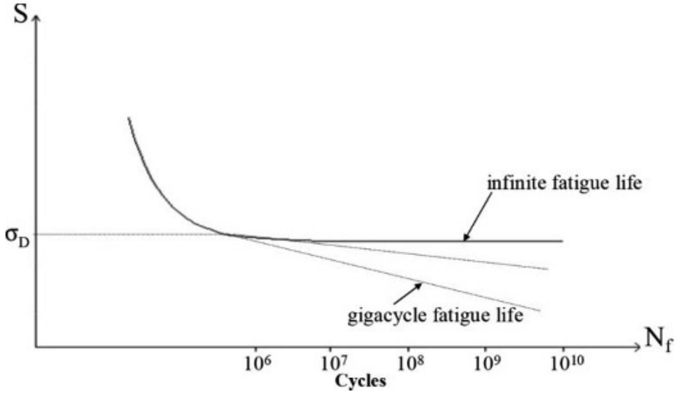

Figure 1.3. *The concept of gigacycle fatigue SN curve*

Since Wöhler, the standard has been to represent the SN curve by a hyperbole more or less modified as indicated below.

Hyperbole Ln Nf = Log a - Ln σ a, while other methods may be listed as:

– Wöhler Ln Nf = $a - b\ \sigma a$;

– Basquin Ln Nf = $a - b$ Ln σa;

– Stromeyer Ln Nf = $a - b$ Ln $(\sigma a - c)$;

Only the exploration of the life range between 10^6 and 10^{10} cycles will create a safer approach to modeling.

1.3. Initiation and propagation

It is of great importance to understand and predict a fatigue life in terms of crack initiation and small crack propagation. It has been generally accepted that at high stress levels, fatigue life is determined primarily by crack growth, while at low stress levels, most of the life is consumed by the process of crack initiation. In low cycle fatigue, it is generally understood that about 50% of the life is devoted to initiation of the micro crack. But many authors demonstrated that the portion of life attributed to crack nucleation is the upper 90% in the high cycle regime (10^6–10^7 cycles) for steel, aluminum, titanium and nickel alloys. In the case for which the crack nucleates from a defect, such as an inclusion or pore, it is said that a relation must exist between the fatigue limit and the crack growth threshold.

However, the relation between the crack growth and initiation is not obvious for many reasons. First, it is not certain that a fatigue crack grows immediately at the first cycle from a sharp defect. Second, when a defect is small, a short crack does not grow as a long crack. In particular, the effect of ratio *R* or the closure effect depends on the crack length. Thus, the relationship between ΔK_{th} and σ_D is still to be discussed (BAT 00).

Another important aspect is the concept of infinite fatigue life. It is understood that below ΔK_{th} and below σ_D the fatigue life is infinite. In fact, the fatigue limit σ_D is usually determined for Nf = 10^7 cycles. Since the fatigue failure can appear up to or beyond 10^9 cycles, the fatigue strength difference at 10^7 and 10^9 cycles could be more than 100 MPa. This means that the relationship between σ_D and ΔK_{th} must be established in the gigacycle regime if any relation exists.

1.4. Fatigue limit or fatigue strength

How can we model the fatigue limit or the gigacycle fatigue strength of industrial alloys?

The procedure is given below.

First, a new SN curve must be determined up to 10^{10} cycles, which is, in fact, more than the fatigue life of most technological machines.

Second, new fatigue strength at 10^9 cycles has to be predicted using regular statistical method.

In more detail, the prediction of gigacycle fatigue is based on two different mechanisms:

– Initiation is related to flaws (inclusions, defects, pores): prediction is derived from stress concentration, fracture mechanics or short crack approaches.

– Initiation is not related to defect: in this case, microstructure is a key parameter, such as grain size, interface, load transfer and microplasticity.

Thus, the discussion of gigacycle fatigue prediction is split into two parts. The first part is devoted to alloys with flaws.

1.5. SN curves up to 10^9 cycles

In specialized literature, few results were given on this topic until "Euromech 382" was held in Paris in June 1998. Typical gigacycle SN curves are given below as examples.

The experimental results (Figures 1.4–1.6) show that specimens can fail up to 10^9 and beyond. It means the SN curve is not an asymptotic curve. Thus, the concept of infinite life fatigue is not correct and the definition of a fatigue limit at 10^6–10^7 cycles is not conservative [BAT 99]. In Figures 1.4–1.6, it is shown that fatigue failure can occur after 10^{10} cycles in cast aluminum, in SG cast iron and in bearing steel. Depending on the alloy, the difference between the fatigue strength at 10^6 and 10^9 cycles can range from 50 to 200 MPa. From the practical point of view, the gigacycle fatigue strength becomes the most realistic property for predicting very long life [BAT 10].

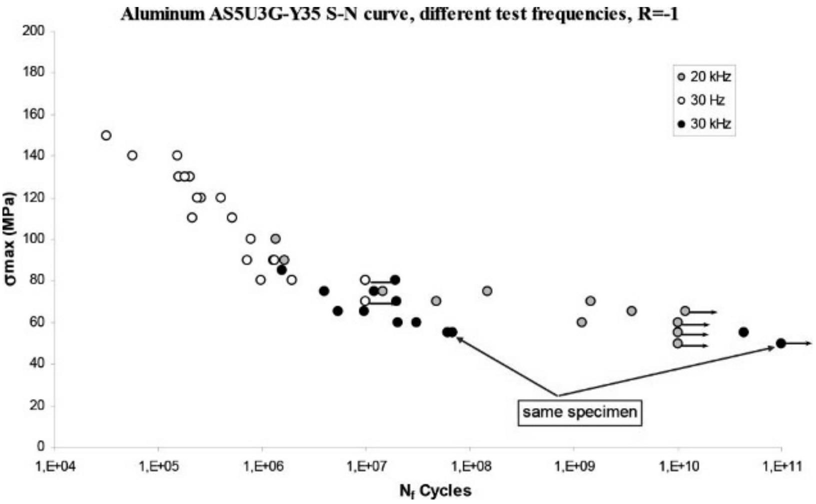

Figure 1.4. *Gigacycle SN curve for a cast aluminum alloy*

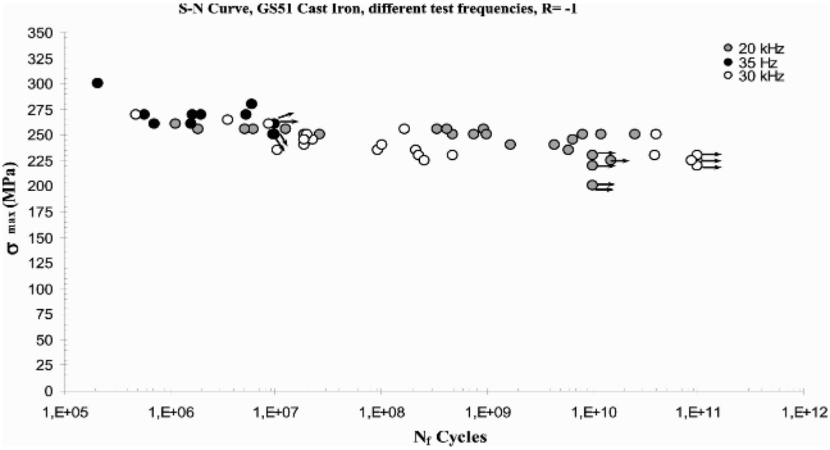

Figure 1.5. *Gigacycle SN curve for an SG cast iron R = –1*

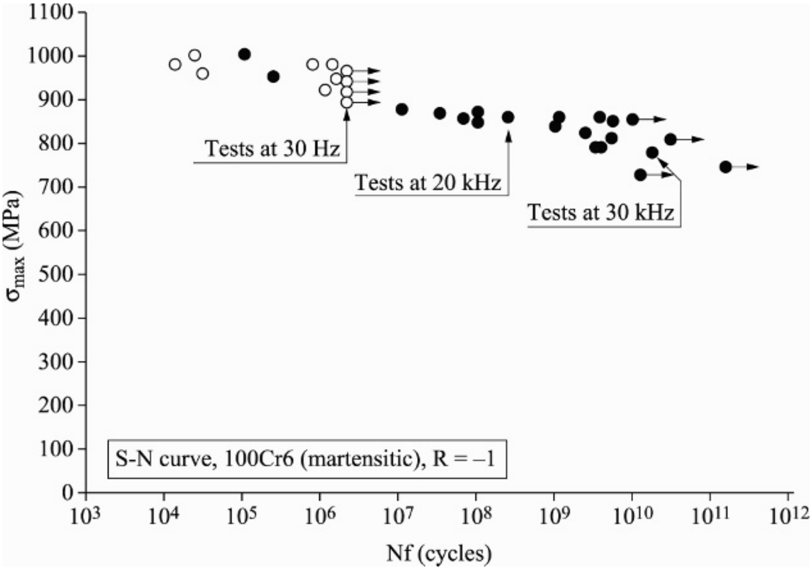

Figure 1.6. *Gigacycle fatigue, 51200 bearing steel. R= –1*

There are only two ways to obtain fatigue data in the gigacycle regime: the rotating bending test (limited to 10^8 cycles) or the high-frequency test. On the contrary, all the fatigue results in the megacycle regime are obtained with low-frequency fatigue machines (1 to 100 Hz). Thus, several questions arise:

– What is the effect of frequency at 20 kHz?

– What is the effect of temperature increase at 20 kHz?

– What is the metal response at high frequency?

– What is the effect of bending, if any, in rotating bending, well known to emphasize the surface plasticity?

These questions need to be clarified and perhaps a new standard needs to be agreed to determine the complete SN curve.

Very often, there is a subsurface initiation site transition beyond 10^7 cycles when inclusion or microstructural defects are operating. Before 10^6 cycles, the initiation of the crack occurs at the surface. But this mechanism is not unique. It means that the surface damage is not always the key mechanism as it is often said, but, in case of no critical defect at this interior, the initiation can appear at the surface in the gigacycle fatigue regime, for example, in pure copper or in pure iron.

1.6. Deterministic prediction of the gigacycle fatigue strength

From a practical point of view, it can be said that the infinite fatigue life for many components is 10^9 or 10^{10} cycles. Thus, it seems that the gigacycle fatigue strength is a crucial property of metal. These data can be determined either by using a statistical approach (staircase) or by using a deterministic relation between stress and defect.

Few models are able to predict the effect of non-metallic inclusions on fatigue strength. This may be because adequate reliable quantitative data on non-metallic inclusions are hard to obtain. Murakami *et al.* [MUR 99] have investigated the effects of defects, inclusions and flaws on fatigue strength of high-strength steel and expressed the fatigue limit as functions of Vickers hardness (HV) (Kgf/mm^2) and the square root of the projection area of an inclusion or small defect: √area (μm). The fatigue limit prediction equation proposed by Murakami is as follows:

$$\sigma_w = \frac{C(HV + 120)}{(\sqrt{area})1/6}\left[\frac{(1-R)}{2}\right]\alpha$$

C = 1.45 for a surface inclusion or defect;

C = 1.56 for interior inclusion or defect;

$\alpha = 0.226 + \text{HV} \times 10^{-4}$.

The model does not specify the number of cycles for which the stress σ_w is represented.

According to experimental data, a modified empirical equation, based on Murakami's model, was proposed to estimate the gigacycle fatigue initiation from inclusion and small defects. This model is especially accurate for high-strength steel [WAN 99]. Murakami's parametrical model is an interesting and practical approximation for engineers. Nevertheless, we can see in the results that the error between experience and prediction can sometimes reach up to 26% and it is often about 10%. One difficulty is the estimation of the size of the defect using the square root of the projected area. Table 1.1 shows a comparison between the fatigue strength predicted by the Murakami equation and the experimental results (staircase method) in the gigacycle regime.

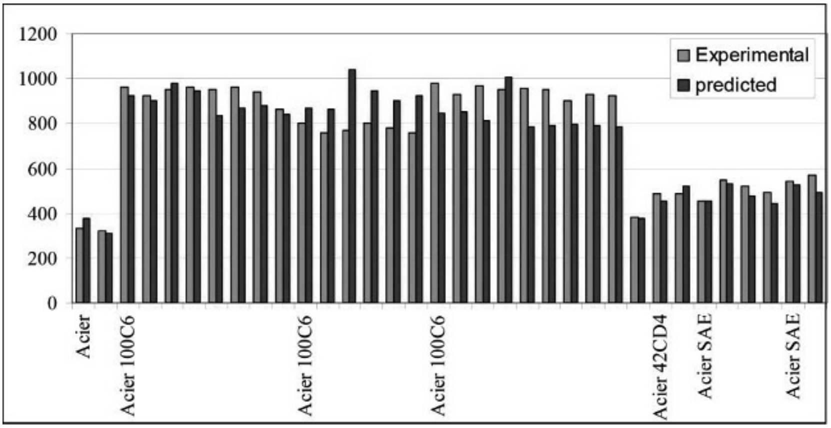

Table 1.1. *Comparison between predicted and experimental fatigue strength at 10^9 cycles*

1.7. Gigacycle fatigue of alloys without flaws

What happens in alloys without inclusion in the gigacycle fatigue regime?

It is well known that in titanium alloys there is not any inclusion or porosity. In this condition, initiation of fatigue crack cannot nucleate from defects; but in titanium alloys, it is found that crack initiation can occur up to 10^9 cycles, despite there not being any inclusion or pore. Figure 1.7 presents SN curves depending on the thermal processing of a Ti 6246 alloy.

It is emphasized that the gigacycle fatigue regime is not always correlated with defects such as inclusions or pore. For Ti 6246, the gigacycle fatigue strength is associated with the transformed amount and secondary alpha volume fraction. Internal fatigue initiation with quasi-cleavage facets in primary alpha phase has been shown [JAG 99, TAO 96].

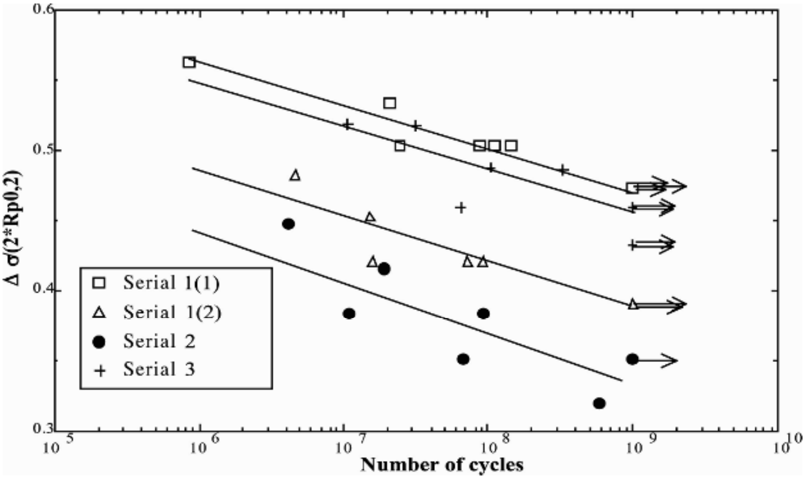

Figure 1.7. *SN curves for Ti alloy with several microstructures [JAG 99]*

1.8. Initiation mechanisms at 10^9 cycles

What remains is to specify how and why some fatigue cracks can initiate inside the metal in gigacycle fatigue. The explanation of the phenomenon is not obvious. It seems that the cycle plastic deformation in plane stress condition becomes very small in the gigacycle regime. In this case, internal defects or large grain size play a role, in competition with the surface damage. It also means that the effect of the environment is quite different in the gigacycle regime since the initiation of short cracks is inside the specimen. Thus, the surface of technological alloys plays a minor role if it is smooth. The effect of plane stress plasticity is evanescent compared to microplasticity due to defects or microstructure misfits. It means that internal initiation is correlated with stress concentration or load transfer.

1.9. Conclusion

It is shown that beyond 10^7 cycles, fatigue rupture can still occur in a large number of alloys. In some cases, the difference of fatigue resistance can decrease by 100, even 200 MPa, between 10^6 and 10^9 cycles to failure. According to our observations, the concept of an infinite fatigue life on an asymptotic SN curve is not correct. Under these conditions, a fatigue limit defined with a statistical analysis between 10^6 and 10^7 cycles cannot guarantee an infinite fatigue life.

Assuming that the fatigue life of engineering components and structures can range above 10^8 cycles, it is very important to determine safe fatigue strength for 10^9 cycles for predicting very long fatigue life of modern components. From a practical point of view, the only way is to use a piezoelectric fatigue machine.

1.10. Bibliography

[BAS 10] BASQUIN O.H., "The exponential law of endurance tests", *Proceedings of the American Society for Testing and Material*, vol. 10, pp. 625–630, 1910.

[BAT 99] BATHIAS C., "There is no infinite fatigue life in metallic materials", *Fatigue and Fracture of Engineering Materials and Structures,* vol. 22, pp. 559–565, 1999.

[BAT 00] BATHIAS C., "Relation between endurance limits and thresholds in the field of gigacycle fatigue", *American Society for Tetsing and materials/Special Technical Publication*, vol. 1372, pp. 135–154, 2000.

[BAT 04] BATHIAS C., PARIS P.C., *Gigacycle Fatigue in Mechanical Practice*, Section 7, Marcel Dekker, 2004.

[BAT 10] BATHIAS C., PINEAU A., *Fatigue of Materials and Structures*, ISTE, London and John Wiley and Sons, New York, 2010.

[JAG 99] JAGO G., BECHET J., "Relation between microstructure and properties in Ti alloys", *Fatigue and Fracture of Engineering Materials and Structures*, vol. 22, pp. 647–655, 1999.

[KAN 97] KANAZAWA K., NISHIJIMA S., "Fatigue fracture of low alloy steel at ultra-high cycle regime under elevated temperature conditions", *Journal of the Society for Materials Science,* vol. 46, no. 12, pp. 1396–1401, 1997.

[MUR 99] MURAKAMI Y., NAMOTO T., UEDA T., "Factors influencing the mechanism of superlong fatigue failure in steels", *Fatigue and Fracture of Engineering Materials and Structures*, vol. 22, pp. 581–590, 1999.

[NAI 84] NAITO T., UEDA H., KIHUSHI M., “Fatigue behavior of carburized steel with internal oxides and nonmartensitic microstructure near the surface,” *Metall. Trans. A*, vol. 15, no. 7, pp. 1431–1436, 1984.

[SAK 07] SAKAI T., “Review and prospects for current studies on very high cycle fatigue of metallic materials for machine structural use”, *4th International Conference on Very High Cycle Fatigue (VHCF-4),* TMS (The Minerals, Metals & Materials Society), 2007.

[STA 99] STANZL-TSCHEGG S., “Fracture mechanisms and fracture mechanics at ultrasonic frequency”, *Fatigue and Fracture of Engineering Materials and Structures*, vol. 22, pp. 567–579, 1999.

[TAO 96] TAO H., Ultrasonic fatigue at cryogenic temperature, PhD Thesis, CNAM, Paris, 1996.

[WAN 99] WANG Q.Y., BERARD J.Y., BATHIAS C., “Gigacycle fatigue of ferrous alloys”, *Fatigue and Fracture of Engineering Materials and Structures,* vol. 22, no. 8, pp. 667–672, 1999.

[WU 93] WU T.Y., NI J.G., BATHIAS C., “Automatic in ultrasonic fatigue machine to study low crack growth at room and high temperature”, *ASTM STP*, vol. 1231, pp. 598–607, 1993.