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General relation between tensile strength and fatigue strength of metallic materials

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ABSTRACT

With the development of high-strength materials, the existing fatigue strength formulae cannot satisfactorily describe the relation between fatigue strength σ_w and tensile strength σ_b of metallic materials with a wide range of strength. For a simple but more precise prediction, the tensile and fatigue properties of SAE 4340 steel with the tensile strengths ranging from 1290 MPa to 2130 MPa obtained in virtue of different tempering temperatures were studied in this paper. Based on the experimental results of SAE 4340 steel and numerous other data available (conventional and newly developed materials), through introducing a sensitive factor of defects *P*, a new universal fatigue strength formula $\sigma_w=\sigma_b(C-P\bullet\sigma_b)$ was established for the first time. Combining the variation tendency of fatigue crack initiation sites and the competition of defects, the fatigue damage mechanisms associated with different tensile strengths and cracking sites are explained well. The decrease in the fatigue strength at high-strength level can be explained by fracture mechanics and attributed to the transition of fatigue cracking sites from surface to the inner inclusions, resulting in the maximum fatigue strength σ_w^{max} at an appropriate tensile strength level. Therefore, the universal fatigue strength formula cannot only explain why many metallic materials with excessively high strength do not display high fatigue strength, but also provide a new clue for designing the materials or eliminating the processing defects of the materials.

1. Introduction

Fatigue is referred to the degradation of mechanical properties leading to failure of a material or a component under cyclic loading. The fatigue strength of materials is often defined as the maximum stress amplitude without failure after a given number of cycles (e.g., 10^7 or 10^9). It is estimated that ~90% of service failures of metallic components resulted from fatigue. However, it is very time and money consuming to perform fatigue tests. Therefore, many attempts have been made to determine the fatigue strength in a cost-effective way relating fatigue strength to other mechanical properties, such as yield strength [1], tensile strength [2–4], hardness [5–7] and so on; accordingly, the relations between fatigue strength and other mechanical properties have been of more interest. Engineers and scientists have proposed many formulae to describe the relations between fatigue strength and other mechanical properties [1–7]. In 1870s, Wöhler, one of the pioneers in the fatigue field, found that the ratio of fatigue strength σ_w to tensile strength σ_b for ferrous metals followed a simple proportional relation as below [8],

$$\sigma_w=(0.4\text{–}0.5)\sigma_b \quad (1)$$

Based on the numerous data of fatigue strength and tensile strength available for steels, copper and aluminum alloys [2–4] in the past century, a more general form can be summarized as follows,

$$\sigma_w=m\sigma_b \quad (2)$$

However, it is found that the fatigue strength either maintains constant or decreases with further increasing the tensile strength [3,4]; in other words, the linear relation in Eq. (2) is no longer held at high-strength level. The critical tensile strength σ_{bc}, above which fatigue strength does not increase correspondingly, the maximum fatigue strengths σ_w^{max} and the coefficient *m* in Eq. (2) for steels, Cu and Al alloys are summarized from Refs. [2–4]. It is apparent that the linear equation cannot adequately be applied to estimate the fatigue strength of those high-strength materials.

On the other hand, in 1980s, another important finding by Murakami [5] is that there is a quantitative relationship among fatigue strength σ_w, hardness *Hv* and inclusion size $\sqrt{area}$ in high-strength steels. Soon after, many related tests have been done by ultrasonic fatigue testing machines [6,7,9–20] and some modified fatigue strength formulae were proposed by Wang et al. [9], Liu

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et al. [10] and McGreevy et al. [21]; nevertheless, no report indicated that those relations suit for other high-strength materials. In addition, the fatigue strength is found to have linear relation with hardness or the sum of tensile and yield strengths only in lower strength range [2–5]. In a word, there is also no suitable formula to satisfactorily describe the general relation between tensile and fatigue strengths of both high- and low-strength materials.

During recent decades, many new high-strength materials, such as bulk metallic glasses [22], ultrafine or nano-grained materials [23–26] and ultra-high strength steels [27] have been successfully developed; however, their fatigue strengths are found to be not as high as we expected, even become relatively lower in comparison with their higher tensile strength [27–32]. Therefore, this gives rise to two open questions for scientists and engineers: (1) Why do the materials with excessively high tensile strength not possess high fatigue strength? (2) Is there a more universal equation to describe the general relation between fatigue strength and tensile strength in a wide strength range? Therefore, in this study, SAE 4340 steel with a very wide tensile strength range, one of the excellent quenched and tempered low-alloy steels [2–5,33–36], was employed to study and establish a simple but more precise relation between fatigue strength and tensile strength of materials and provide a better clue for the design of high-performance structural materials.

2. Experimental material and procedures

In the current study, SAE 4340 steel bars were received with a diameter of 14 mm under annealing condition and its composition is given in Table 1. To gain different strength levels, five optimized heat-treatment procedures as shown in Table 2 were employed and the corresponding specimens are defined as A–E, respectively. The configurations of the tensile and fatigue specimens are shown in Fig. 1. All fatigue samples were polished in the longitudinal direction using an emery paper having a mesh of 2000#.

The tensile tests were conducted at a strain rate of $2\times10^{-4}\,s^{-1}$; very high-cycle (VHC) fatigue tests were conducted at a frequency of 20 kHz up to 10^9 cycles using a ultrasonic fatigue testing system (Shimadzu USF-2000). To avoid the sample heating, the middle section of each ultrasonic fatigue specimen was cooled by compressed air. All fatigue tests were performed with the sinusoidal wave shape under applied stress ratio of $R=-1$. The fatigue strength was determined by the staircase method in which at least six pairs of specimens were tested according to ISO12107:2003. The microstructures of the specimens with different strength levels were examined by electron backscattered diffraction (EBSD) with

Table 1
Chemical composition of SAE 4340 steel (Wt%).

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	As
0.42	0.66	0.25	0.009	0.014	0.74	1.41	0.17	0.11	0.034

Table 2
Heat-treatment procedures of SAE 4340 steel.

No.	Quenching	Tempering
A	preheating to 850 °C	180 °C tempering for 120 min
B	for 10 min and quenching in oil	250 °C tempering for 120 min
C		350 °C tempering for 120 min
D		420 °C tempering for 30 min
E		500 °C tempering for 30 min

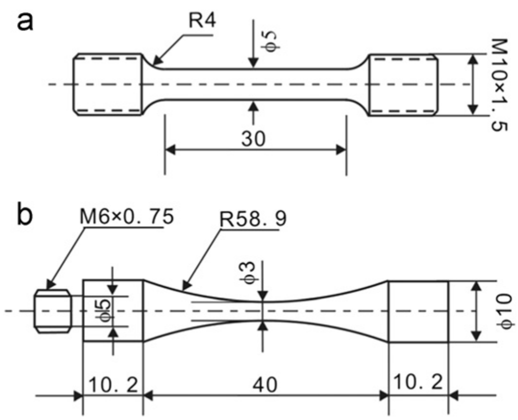

Fig. 1. Configuration of specimens tested for: (a) tensile strength; (b) VHC fatigue strength.

scanning electron microscope (LEO SUPRA35). The fatigue fractographies were observed by using a Quanta 600 scanning electron microscope (SEM).

3. Results

3.1. Microstructures

With increasing the tempering temperature, the body-centered tetragonal (BCT) martensite, which is a supersaturated solution of carbon in α-Fe, transforms to different microstructures as shown in Fig. 2. Referring to the textbook [36,37] and XRD profiles, the microstructure features of sample A–E are illustrated as follows: the sample A tempered at 180 °C contains many needle- or plate-shaped tempered martensites (see Fig. 2(a)) and some retained austenites. The sample B tempered at 250 °C consists of microstructure (Fig. 2(b)) similar to that of the sample A, but the size of retained austenite decreases because of its decomposition; however, the sample C tempered at 350 °C only displays needle- or plate-shaped tempered martensite. The samples D and E, respectively tempered at 420 °C and 500 °C, exhibit tempered troostite with plate-like appearance (Fig. 2(d) and (e)), and the lath width of troostite in sample E increases in comparison with sample D because α phase has obviously recovered after tempering above 400 °C.

3.2. Tensile properties

After different tempering procedures, the specimens A to E exhibit different tensile properties and their tensile stress–strain curves are shown in Fig. 3(a). It can be seen that the specimens A to E display different yield strength, work-hardening ability, ultimate tensile strength and elongation. Fig. 3(b) and (c) show the relations among the strength, elongation to fracture and reduction in area versus tempering temperature: it can be seen that as tempering temperature increases, tensile strength successively decreases, however, elongation to fracture and reduction in area successively increase, which are in agreement with other steels [34,35,38]. On the other hand, the yield strength first increases slightly and then decreases, which agrees with 300 M steel [39] and some other ultrahigh-strength steels tempered below 200 °C [34,35]. Fig. 3(d) demonstrates the relationships of yield strength and tensile strength versus elongation to failure of the SAE 4340 steel. As tensile and yield strengths increase, elongation to failure continuously decreases, which is consistent with the trade-offs between strength and elongation of steels [34,35]. By comparison,