International Journal of Fatigue 48 (2013) 48–54

Contents lists available at SciVerse ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Fatigue strength prediction for inhomogeneous face-centered cubic metal based on Vickers hardness

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A R T I C L E I N F O

Article history:
Received 27 April 2012
Received in revised form 11 September 2012
Accepted 14 September 2012
Available online 17 October 2012

Keywords:
Hardness
Fatigue limit
Fatigue strength
Stainless steel
Statistics

A B S T R A C T

To find the Vickers hardness (*HV*) value for predicting the fatigue strength of inhomogeneous face-centered cubic (FCC) metals, *HV* tests were performed on SUH660 stainless steel. The results indicate that the intrinsic hardness distribution can be obtained from the *HV* distribution in test zones according to the Vickers hardness definition. The soft zone greatly affects the fatigue strength of an inhomogeneous FCC metal. Therefore, for another inhomogeneous FCC metal in which fatigue cracks initiate and propagate easily in the softest zone, the fatigue limit can be predicted using the mean *HV* value of the softest zone.

1. Introduction

It is widely known that the fatigue limit of metal can be predicted by its hardness. For steel with a Vickers hardness of approximately 400 or less, the following equation [1–4] is effective:

$$\sigma_w = 1.6HV \pm 0.1HV \quad (1)$$

where σ_w (MPa) is the predicted fatigue limit and *HV* (kgf/mm^2) is the Vickers hardness. The fatigue limit of metal that has a defect can be predicted by the following equation proposed by Murakami et al. [5,6]:

$$\sigma_w = \frac{1.43(HV + 120)}{(\sqrt{area})^{1/6}} \quad (2)$$

where $\sqrt{area}$ (μm) is the square root of the defect area projected onto the plane perpendicular to the first principal stress.

When predicting a fatigue limit using the above equations, Vickers hardness is measured and used; however, the following two questions arise. (1) What load should be used for the Vickers hardness measurement? (2) Which of the varying measured values should be used? In the present paper, question (2) is discussed. About question (1), it can be thought that the intrinsic hardness should be measured in a domain about the size of a non-propagating crack because the fatigue limit is the state at which a small crack starts and becomes a non-propagating crack due to plasticity-induced fatigue crack closure. In addition, for SUH660 stainless steel that was tested in this study, a fatigue crack initiated or non-propagated, and no inclusion was seen where the crack initiated [7]. The effect on the intrinsic hardness of the grain boundary, second phase, and inclusion is not discussed.

The intrinsic hardness of a metal should not vary if thermomechanical treatment is performed correctly. However, as a method of evaluating intrinsic hardness, the Vickers hardness, an indenter is pressed into a metal and the resulting plastic deformation is evaluated. In the case of this evaluation, the relationship between the direction of the indentation (or the direction of plastic deformation) and the crystal orientation of a metal varies relative to the plane of the measured specimen, the obtained Vickers hardness varies. Because there are many slip systems in the case of body-centered cubic (BCC) metal, this scatter is small compared to that of face-centered cubic (FCC) metal; however, because there are few slip systems in the case of FCC metal, the scatter in Vickers hardness becomes greater compared to BCC metal. Furthermore, when an inhomogeneous metal has a scatter in its intrinsic hardness, Vickers hardness indicates that scatter. Therefore, the Vickers

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http://dx.doi.org/10.1016/j.ijfatigue.2012.09.021

hardness value used to predict a fatigue limit has not been clarified.

SUH660 (A286) is an austenitic heat-resistant precipitation-hardening stainless steel [8–11]. In previous research by the present authors, a very large scatter in Vickers hardness compared to common homogeneous metals was found in SUH660 stainless steel, and the relationship between this very large scatter in Vickers hardness and a lower fatigue strength ratio compared to carbon steel was confirmed. Therefore, SUH660 stainless steel is an inhomogeneous FCC metal.

In the present paper, according to the definition of Vickers hardness and intrinsic hardness of an inhomogeneous FCC metal, the intrinsic hardness distribution of the fatigue specimen is obtained from Vickers hardness distribution in several test zones. Then, the influence of intrinsic hardness of the softest zone on fatigue behavior is discussed to find the *HV* value that can be used to predict the fatigue limit by Murakami's approach [5,6] for an inhomogeneous FCC metal.

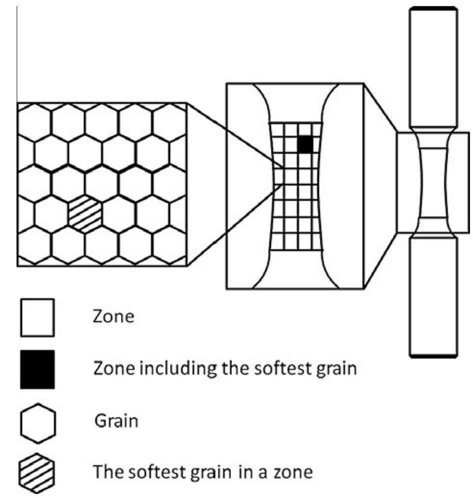

Fig. 2. Fundamental point of view for intrinsic hardness distribution.

2. Proposed experimental principle

To determine the influence of the intrinsic hardness of the softest zone on the fatigue limit of an inhomogeneous FCC metal, the average *HV* value of the softest zone should be obtained. However, the location of the softest zone in the specimen is not known, thus the average *HV* value of the softest zone cannot be obtained by an *HV* test. Therefore, to solve this problem, a new experimental procedure for predicting the average *HV* value was developed, which is shown in Fig. 1. In this experiment, a statistical method is used to predict the average *HV* value of the softest zone. Fig. 2 shows the fundamental point of view of the intrinsic hardness distribution. For an inhomogeneous FCC metal, the intrinsic hardness and the Vickers hardness are homogeneous within a grain. However in a zone, the intrinsic hardness is homogeneous but the Vickers hardness is inhomogeneous because in an *HV* test, the crystal orientation varies according to the indented direction (or the direction of plastic deformation). When an *HV* test is performed in a test zone, the Vickers hardness distribution is obtained for the test zone, and then the *HV* value of the softest grain in the test zone would be predicted by a statistical method. After *HV* tests in several test zones, the *HV* value of the softest grain in the specimen surface would be predicted by statistics of extreme [12] using the *HV* values of the softest grain in each of several test zones. Meanwhile the average Vickers hardness variability would be obtained from the Vickers hardness variability of the several test zones. Therefore, according to the *HV* value of the softest grain and average Vickers hardness variability of the specimen surface, the Vickers hardness distribution in the softest zone can be obtained, thus the average *HV* value of the softest zone can be predicted.

3. Experimental methods

In this study, SUH660 stainless steel was used as the inhomogeneous FCC metal to predict the fatigue limit. Table 1 shows the chemical composition of SUH660 stainless steel samples. The SUH660 stainless steel samples were solution treated (ST) for 1 h at 980 °C, air cooled, aged (A) 16 h at 720 °C, and then air cooled again.

The *HV* tests were performed on the surface of the SUH660 stainless steel specimen. The indentation load was 0.49 N, and the indentations were made at the center of the grain to avoid any grain boundary effects. The size of the indentation was approximately 15 μm. SUH660 stainless steel is an inhomogeneous FCC metal, and although the Vickers hardness test indicated approximately the same value within a distance of several crystal grain sizes from the first measurement position, measurement positions located 1 mm or more from each other had significantly different *HV* values. The intrinsic hardness varied on the surface of SUH660, whereas carbon steel, which is a homogeneous FCC metal, has a constant intrinsic hardness. To discuss the intrinsic hardness scatter, which depends on the measurement position, a region of 600 μm × 450 μm was then defined as a zone, which is the size of the field of view of the 200× optical microscopes used in this study. Fig. 3 shows the microstructure of a zone on the test speci-

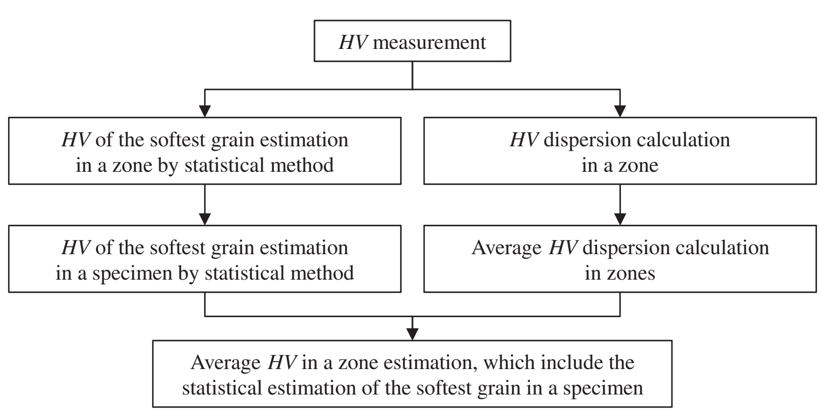

Fig. 1. Experimental procedure for predicting average *HV*.