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Short Communication

Fatigue life prediction of FV520B with internal inclusions

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ABSTRACT

Fatigue life prediction of high strength material such as FV520B is a primary concern in remanufacturing engineering theory and research development, is an important research topic in the field. However, few studies about FV520B fatigue property exist in literature. This paper discusses a fatigue experiment for life prediction model conducted in the UFTS (Ultrasonic Fatigue Test System) at 20 kHz. Based on the obtained fatigue failures, test data, and observed GBF (Granular Bright Facet) and "fish-eye", the analysis results prove that inclusions can be a principal cause of the fatigue failure in giga-cycle stage. After employing a fitting algorithm and determining the model unknown parameters, based on the fatigue data including life and inclusion size, an FV520B empirical life prediction model is identified. Model validation is performed through the analysis of errors between the model and experimental data, which are shown within an accepted tolerance for its engineering applicability. The model applicable for the FV520B life prediction and is an influences to the life study of high strength materials. It is highly beneficial to the research development in remanufacturing engineering as well.

1. Introduction

Fatigue failure is usually the predominant failure mode for mechanical parts, and fatigue failure may account for 50% of all these predominant failure modes, even reaches 90% in some special circumstances [1]. Now, the international mechanical industry is trending to large-scale and complex high-speed and high-temperature tolerances. This is especially the case in the fields of aerospace, centrifugal compressors, the automobile industry, railways and bridge constructions [2]. Material used in the manufacturing process is required to have high mechanical properties, such as the high strength steel FV520B in this paper. Unfortunately, it is quite complicated and expensive to analyze these materials for the fundamental properties. For these reasons, the mechanical part fatigue life should exceed 10^7 cycles, which is known as the "giga-cycle fatigue level" [3–5]. Consider that during the usage, fatigue failure can be caused by many factors, but one of these factors that researchers most commonly choose to study on is known as fatigue damage which is also called fatigue crack [6–8]. Inclusions at the subsurface level are common sites for fatigue crack nucleation in these materials [9] when life reaches the giga-cycle fatigue level. These inclusions are the results of deoxidation additions, impurities or some external substances. In low cycle fatigue, life was mainly affected by inclusions in surface, but when life reaches giga-cycle fatigue level, more and more research data show that fatigue cracks initiate from the specimen subsurface and inclusion on the subsurface is the key factor in fatigue crack nucleation. An external force will cause a concentration of high stress in the position of inclusion and create cracks because of the significant property differences between inclusion and matrix material [10,11]. This effect will lead to the crack nucleation, and it is significant for high strength material as FV520B, which is often used to manufacture impellers of centrifugal compressors or some other expensive, mechanical units. These cracks will continue propagating and lead to fatigue failure, eventually. Usually the fatigue failure happens instantaneously and without warning; this is also irreversible. Thus, fatigue failure can easily cause serious accidents, significant economic losses, have a serious impact on mechanical systems, and possibly cause accidents affecting human life.

Predicting the fatigue life of high strength steel as FV520B with inclusion on the subsurface is an important research topic, especially for those who can use the information to improve the manufacturing of mechanical equipment. This research is beneficial to improving engineering quality, safety and economic efficiency.

Many theories have been developed to predict fatigue life with subsurface cracking in the past a few years. These theories include Miner's linear cumulative damage theory, Janson's damage mechanics during the crack initiation process [12], equivalent strain energy life prediction [13], and total life prediction based on small-crack theory [14]. There is also corrosion life prediction and multi-axial fatigue life prediction (which involve the temperature, corrosion load form, and some other environment factors) [15]. Stress-Life theory is based on the S–N curve and fatigue

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endurance limit which were proposed by Wohler, and this theory is usually used for the infinite fatigue life design. Based on these methods and theories researchers have established many life prediction models. Mughrabi has investigated the irreversible slip change behavior of giga-cycle fatigue and assumed that the Manson-Coffin model was still available in this situation. He established a life prediction model used for the situation when local cumulative plastic strain reached the critical value. Tanaka & Mura proposed their life prediction model based on the grain sliding theory. When the dislocation repulsion exceeds the critical value then the crack will begin to initiate [16]. By using the crack growth rate model, Paris established the crack propagation life prediction model [17]. Both of these models are widely used to predict fatigue life. Wang established a metal giga-cycle fatigue life prediction model based on both Tanaka & Mura and Paris's theories and has been tested on many different materials [9,18]. Shrikant and Morris got the relationship between the crack nucleation size and fatigue life based on Mura's and some other researchers' results [19]. As the dispersion of the crack initiation and propagation, Lei thought that structural fatigue life is determined by the crack containing part, so he proposed a probability model based on the density of micro-crack volume. Provan deduced a crack initiation model based on the study of mechanical properties of the grain boundary, this model is fit for the situation that crack size is Gauss distribution.

These theories and models have made a significant contribution to the life prediction in remanufacturing as well as to strengthen the theoretical foundation. But life prediction in engineering practice is a very case-oriented—different theory and models are specifically for desired application and condition. Parameters of the model are not the same when applying to dissimilar material modeling. In order to ensure the accuracy of the result the prediction models should be analyzed before applying. Doing this will help make sure that every possible factor has been considered and included in the model. The next step is to calibrate the parameters of the model for the given material. After calibration, a new life prediction model for the given material is then established.

The material tested for study in this paper was FV520B. FV520B is a very important and popular engineering material and is widely used in the manufacture of mechanical equipment such as centrifugal compressor impellers [20]. FV520B has good corrosion resistance, high hardness, and good welding property. However, the investigation of the fatigue property of FV520B is still shallow and lacks enough fatigue life data. So the fatigue experiment for FV520B was carried out to get the fatigue data and phenomenon to establish the specific model of FV520B. The fatigue experiment in this paper was conducted to obtain FV520B life performance, inclusions and fracture characteristics were observed. These experiment data will be used for base model unknown constant parameters estimation, and another set of data will be used to validate the model for its applicability and accuracy. This is how the specific model for FV520B was established in this paper. The results from this research study for FV520B fatigue property have applied to centrifugal compressor and other mechanical systems with FV520B for the improvement of performance, quality, and the system security from preventing catastrophic accidental failures. FV520B fatigue life prediction is difficult in theory, but useful in practical engineering. It has a high value in the study of remanufacturing and also the remanufacturing engineering.

2. FV520B fatigue experiment

The fatigue experiment was carried out with Pro. Wang and Mr. Zhang who belong to the same subject research team with authors. After the experiment, experimental phenomenon and data were recorded, such as Figs. 1a and 1b, Figs. 2a and 2b and Table 2 [21]. Based on these phenomenon and analysis of the mechanism of fatigue failure, the fatigue life model of FV520B was established which is the main work of this paper.

Ultrasonic fatigue technology has been rapidly developed these years, for its high efficiency and low energy consumption, so Ultrasonic Fatigue Test has been widely used to investigate the metal fatigue property, also the fatigue experiment of FV520B in this paper.

The chemical compositions of the specimen are displayed in Table 1.

The FV520B fatigue experiment in this paper was carried out according to ASTM (American Society for Testing Material) standards, using an Ultrasonic Fatigue Test System operating at 20 kHz with zero mean stress which allows us to obtain fatigue properties completely reliable. The experiment was conducted in an open environment similar to the practical engineering working condition, to make sure the experimental phenomena and data are close to the actually situation. The specimen used in the test has an hourglass shape with a radius curvature of the reduced section (notch radius) of 58.9 mm, and their minimum diameter is 3 mm. The experiment observations, especially on the fracture characteristics, were investigated and measured by a Scanning Electron Microscope (SEM) and Optical Microscope (OM). Experimental results included inclusion size and fatigue life data.

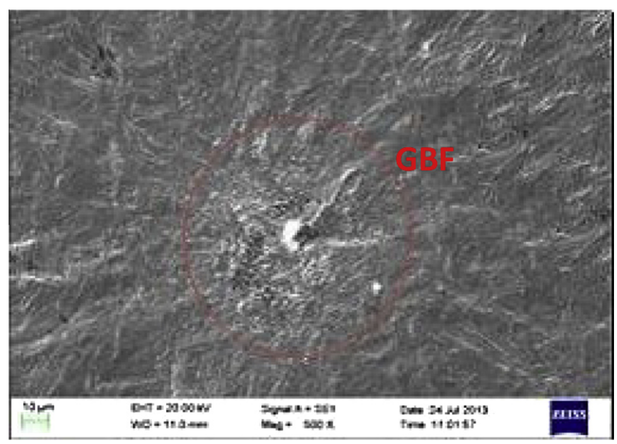

Fig. 1a. GBF caused by inclusion (SEM).

Fig. 1b. GBF caused by inclusion (OM).