Magnetic Barkhausen emission to evaluate fatigue damage in a low carbon structural steel

S. Palit Sagar\textsuperscript{a,\*}, N. Parida\textsuperscript{a}, S. Das\textsuperscript{a}, G. Dobmann\textsuperscript{b}, D.K. Bhattacharyya\textsuperscript{a}

\textsuperscript{a}National Metallurgical Laboratory, MST Division, Jamshedpur 831007, India
\textsuperscript{b}Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren, IZFP, Germany

Received 23 July 2003; received in revised form 28 April 2004; accepted 1 June 2004

Abstract

The various stages of fatigue damage in low carbon structural steel have been characterized using magnetic Barkhausen emission (MBE) signal analysis technique during high cycle fatiguing. The observed trends in the variation in MBE peak voltage showed an initial increase followed by a decrease. After that a sharp increase was found during online monitoring of fatigue till failure. The variation of MBE peak voltage with mechanical deformation was correlated with the microstructural changes at different stages of fatigue damage. The state-of-the-art of microstructural changes at various stages of fatigue damage has been established using transmission electron microscopy (TEM) to correlate the changes in the magnetic Barkhausen parameters with the microstructural changes.

\textcopyright{} 2004 Elsevier Ltd. All rights reserved.

Keywords: Magnetic Barkhausen emission; Fatigue; Microstructural change; Transmission electron microscopy; Dislocation cell structure; Persistent slip bands

1. Introduction

Fatigue is one of the most common materials degradation mechanisms in industry that occurs when material experiences repeated or cyclic stresses for a long duration of time. It has long been reported that nearly 90\% of industrial components failure takes place due to fatigue and it occurs suddenly without any warning \cite{1}. The phenomenon is broadly categorized into two types, namely, high cycle fatigue (HCF) and low cycle fatigue (LCF). The maximum stress level in the former does not exceed the yield stress, while in the later, it exceeds it during the load cycles \cite{1}. The fatigue life of a component may be divided into three broad stages, namely, microstructural changes leading to crack initiation, growth of micro-crack beyond the critical length, followed by the third stage of rapid fracture and failure. In the case of HCF, the portion of fatigue life attributed to crack initiation is often more than 90\% of the total life \cite{2,3}. In other words, the life is crack initiation controlled. In the case of LCF, though the damage processes and the sequences are broadly similar to those in HCF, the crack growth stage is often more important than the crack initiation stage. Because of the importance of the failure mode and because of the predominating role that crack initiation stage plays in HCF failures, it is important to have suitable nondestructive test (NDT) techniques to characterize the progression of the damage till cracks are initiated \cite{3–17}. An important problem that the NDT technique needs to address is the scatter related to the dependence of fatigue life on surface finish, stress level, etc. \cite{1,18,19}. It is therefore necessary that the NDT parameters and the methodology used should be ‘insensitive’ to the parameters that are associated with the scatter in the fatigue life.

This paper deals with the assessment of damage due to HCF (till crack initiation) in a low carbon steel by a magnetic NDT technique based on Barkhausen emission signal analysis. Some other NDT techniques are possible for the same purpose, namely, X-ray diffraction peak broadening, ultrasonic attenuation and velocity, positron annihilation, etc. These are not discussed here for the sake of brevity. It should suffice to say that magnetic techniques are
During fatigue, microstructures of materials experience continuous changes from the first load cycle till failure. Even during HCF where the maximum applied (macro) stress does not exceed the yield stress, the damage takes place through localized plastic deformation. The stage before the crack initiation can be divided into various sub-stages such as (i) initial hardening (or softening) due to the changes in the dislocation density; (ii) evolution of dislocation structure (morphology); (iii) strain localization through the formation of persistent slip bands (PSB); and (iv) evolution of surface relief [1,3,12,15,20,23].

Magnetic parameters derived from hysteresis loop and Barkhausen emission signals are strongly affected by the changes in the microstructure since the dimensions of the magnetic domains and the domain walls are comparable with the dimensions of such microstructural features as grain boundary, grains, precipitates, dislocation cell walls, dislocation cells, cracks, etc. Both, the domain wall movement and domain nucleation, are affected by the microstructural features [21]. It is because of this, magnetic techniques for the characterization of microstructure and residual stress, based on hysteresis loop parameters and/or magnetic Barkhausen effect (MBE) signals have attracted many investigators over the last several decades [21,22].

Fatigue cracks almost always start from the surface and proceed inwards. Making use of the surface specific fatigue damage phenomena, technique such as the one based on laser scattering has been proposed [3]. We believe if a magnetic technique is to be successful, it should specifically monitor the changes in the surface characteristics (physical and microstructural). Many of the work reported in the literature on magnetic techniques for fatigue damage characterization have considered the magnetic hysteresis loop parameters, which essentially relate to the bulk magnetic properties [4,8,9,15,24]. When the reported literature on HCF damage assessment by MBE signal analysis is surveyed we find that there is no systematic attempt to correlate the damage progression and the MBE parameters. Most of the reports pertain to the development and discussion on the probe design, instrumentation and methodology [10,11,13,19], and no information on the structural changes, which require detailed investigation by transmission electron microscopy (TEM). When the microstructural changes have been reported [12], the emphasis has rather been on the detailing of the microstructural changes than the correlation of the microstructural features with the MBE parameters. Even in the cases of investigations on hysteresis loop parameters with fatigue damage, information on microstructural data are scarce. In Ref. [8] scanning electron microscopy has been used to have an idea of the surface relief phenomenon, which occurs later in fatigue life. In Ref. [15], TEM micrographs have been shown only for the virgin materials and for a specimen after a small number of fatigue cycles. It is therefore found that there is a need for a detailed analysis of the microstructural changes that take place during the whole range of fatigue life, and how these changes can be correlated with the MBE parameters. This work is an attempt in this direction.

2. Experimental

The measurements were carried out in two different sets of steel specimens having yield strength of 230 and 430 MPa, respectively. The nominal chemical compositions in wt% of both the steels are given in Table 1. The average grain size of the specimen was 16 μm and was determined through image analysis.

<table>
<thead>
<tr>
<th>Sample</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set I</td>
<td>0.16</td>
<td>–</td>
<td>0.6</td>
<td>0.035</td>
<td>0.035</td>
<td>0.07</td>
<td>Balance</td>
</tr>
<tr>
<td>Set II</td>
<td>0.15</td>
<td>0.185</td>
<td>0.463</td>
<td>0.0121</td>
<td>0.0234</td>
<td>0.04</td>
<td>Balance</td>
</tr>
</tbody>
</table>

The first set was prepared at National Metallurgical Laboratory, Jamshedpur and was fatigue tested in a high cycle fatigue test machine (model 100HFP5100, RK Amsler, Germany) at room temperature with load ratio of $R = -1$ and at a frequency of 84 Hz. The applied constant stress amplitude was 150 MPa. The test specimens were machined from the same strip of steel. The shape and dimension of the test specimen is shown in Fig. 1. Prior to fatigue test, the specimens were annealed at 700 °C for 30 min in an inert atmosphere. Different percentages of damage (20, 40, 60, 80%, etc.) w.r.t. the total fatigue life were introduced to the specimens and was calculated using the equation

\[
\text{% of damage} = \frac{N}{N_f} \times 100\% \tag{1}
\]

Fig. 1. The shape and dimension of the test specimen of first set.
where \( N \), number of fatigue cycles performed in a specimen; \( N_f \), average number of fatigue cycles at failure.

The second set was prepared at Kaiserslautern, Germany using ck15 (a C-steel with \( C = 0.15 \) wt%) sample loaded in a 100 kN servo hydraulic machine at a stress amplitude of 260 MPa and frequency of 10 Hz. The average fatigue life (\( N_f \)) of this set of specimens was established using three different specimens. Then five specimens were prepared having different percentage of damage after being unloaded at 120 (1%), 350 (2.5%), 1000 (7%), 3500 (25%) and 10,000 (71%) cycles for magnetic measurement and microstructural characterization.

For MBE, measurements were carried out at IZFP, Saarbruecken, Germany. For MBE measurement, the test specimens were magnetized at a frequency of 3 Hz using a U-shaped yoke (Fig. 3). For the first set, the MBE signal was picked up using a surface probe with a ferrite core as well as an encircling coil as shown in Fig. 2, whereas for second set where the specimens were round hour-glass type, only the encircling coil was used. The surface probe was used to compare the results with those obtained by encircling coil, because the latter is not suitable from an industrial application point of view. The magnetic field was measured placing the Hall probe at the center of the specimen. Fatigue modifies the surface, which in turn affects the magnetization level of the material. The use of Hall probe helped to maintain a constant applied field for all the specimens with different percentage of damage. After amplification, the MBE signal was filtered in the range of 1–100 kHz and then fed to the data acquisition card. This frequency range was chosen after it was established by using various frequency bands that this was the frequency range where the maximum signal intensities were obtained.

The software developed using LABVIEW was employed to obtain the Barkhausen emission amplitude (\( M \)) vs. magnetic field (\( H \)) profile. The maximum amplitude of Barkhausen emission (\( M_{\text{max}} \)) was measured from the \( M-H \) profile and plotted with respect to the percentage of fatigue damage.

To establish the MBE as a non-destructive technique for the remaining life prediction of cyclically loaded structure, online monitoring was also performed in three specimens having 0.16 wt% of carbon with the same loading condition as used for the first set. The MBE measurements were carried out on virgin as well as fatigued specimen after each interruption using a surface probe.

For microstructural characterization, transmission electron microscopy (TEM) was performed in annealed and fatigued specimens using Philips CM200 at 200 kV. The specimens for TEM were prepared from pieces of 0.4 mm thickness cut by EDM from the gauge length region. Mechanical polishing was done from one major surface down across the cross-section. When the thickness was about 0.1 mm, further thinning was carried out by ‘twin jet’ electro-polishing. By this, it was ensured (as much as practically possible) that the examination layer for TEM pertained to the surface layer of the specimens.

3. Results and discussion

The TEM of virgin and specimens with 1, 2.5, 7, 25 and 71% of fatigue damage from second set are shown in Fig. 4. As can be seen from these micrographs, the specimen contains dense dislocation tangles at the virgin state (Fig. 4a). Dislocation cell structure formation starts early during the fatigue damage (Fig. 4b). The dislocations rearrangements then took place and formed well-defined cell structures (Fig. 4b–e). On further fatiguing, a band-like structure was formed (Fig. 4f). Similar TEM results were obtained for other set of specimens also. In order to interpret the MBE results, it is therefore needed to consider that only at the very initial stage, the magnetic domain walls had to interact with dislocation tangles. Soon after, it is the dislocation cell walls and the cells, which were interacting with the magnetic domain walls.
The variation of $M_{\text{max}}$ with percentage of fatigue damage for first and second sets is shown in Fig. 5. It was observed that initially $M_{\text{max}}$ increases till 40% of damage and then decreases. Fig. 6 shows the variation of MBE peak voltage with fatigue cycles for three specimens during online monitoring. Though all the three specimens have broken at different number of cycles the nature of variation of $M_{\text{max}}$ with percentage of fatigue damage was found to follow the same trend for all the specimens, which is depicted in Fig. 7. One common trend in the results from all the specimens is that initially there is an increase in $M_{\text{max}}$ followed by a decrease. The extent of the fatigue damage at which this change in the trend takes place, however, is different. From the results of tests in all the specimens, which were taken to failure, a sharp increase in $M_{\text{max}}$ was observed near the failure stage.

The process of fatigue damage evolution is strongly affected by individual microstructure of the loaded specimen. The MBE signal is associated with the irreversible motion of the domain wall across the pinning sites. The peak voltage ($V$) of MBE signal depends on the velocity of domain wall ($v$), number of defects or microstructural features ($n$) and the time of flight between the defects ($\tau$) as per the following equation

$$V \approx \frac{nv}{\tau}$$  \hspace{1cm} (2)

It has been estimated that the MBE voltage increases with an increase in $v$ and $n$ and decrease in $\tau$ [14,25].
Though the equation is simple, its manifestation in the generation of MBE signals is complex. The same type of microstructural feature (for example dislocations, secondary precipitates) may act as pinning points or as damping points when a magnetic domain wall moves. If the first phenomenon is operative, ‘$n$’ will increase, increasing the value of ‘$V$’. On the other hand, if the second phenomenon is operative, then it will affect ‘$v$’ as well as $\tau$ thereby affecting the value of $V$ in a complex manner. Size of the microstructural features is one of the important criteria. For precipitates, it has been predicted [26] and verified that the size should be similar as the domain wall width [27]. For iron, the domain wall width has been reported to be about 1 $\mu$m [26]. However, there are reports that the size of the precipitates should be much more than the domain wall width to have Barkhausen emission [28,29]. Noting the reported width of the domain wall and extending the discussion to dislocation, it can be argued that, initially when the dislocations are in a dispersed morphology (like in the virgin state of the material in the present case), they will dampen the movement of the domain walls rather than pin them. In such a case, both the $n$ and $v$ being low, the $V$ will be low. As the dislocation clustering take place in the form of cells, the values of $n$ and ‘$\tau$’ will be affected. The values of $n$ will increase since more and more dislocation sites will start acting as strong pinning points. The value of $\tau$ will be reduced since the distance from one pinning point to another is now lower. The value of $V$ will now increase.

The decrease in the $M_{\text{max}}$ values beyond certain extents of fatigue damage was found to be associated with a reduction in the dislocation cell structure. Here intense localization of strain and the formation of PSBs take place. The reduction in the $M_{\text{max}}$ ($V$) values is attributed to the less number of domain walls being able to move because of stronger pinning. The reduction may also come due to presence of compressive stress at the tip of the notch like features (intrusion and extrusion) as explained below:

The localization of cyclic strain in a specific volume is called PSB. The localization of cyclic plastic strain in the PSBs results in the formation of notch-like intrusions and the high stress concentration at the tip of the intrusions causes crack nucleation. Hence with the formation of PSBs, localized stress concentrations took place near the crack tip initiation. At the same time, the model of Essmann et al. [30] showed that the layer of dislocations are deposited at the PSB–matrix interfaces and these interface dislocation dipole layer sets up a residual internal compressive stress in the PSB. The MBE is strongly influenced by the stress condition of the material. The presence of residual compressive stress at the PSBs is considered to cause the MBE amplitude reduction and minimum with the formation of notch like defect, intrusions, which strongly affect the redistribution of local stress on the surface of the material. This result shows that prior to crack nucleation the peak amplitude of MBE will be reduced to minimum. Beyond this stage, as the crack initiates, the stress relaxation takes place, which in turn increases the amplitude of MBE. As explained above the knee in the variation of $M_{\text{max}}$ corresponds to the formation of intrusion leading to the crack nucleation.
4. Conclusion

The work has showed that changes in the dislocation density and morphology during the progression of high cycle fatigue damage in a low carbon steel, influence the amplitude of magnetic Barkhausen emission ($M_{\text{max}}$) considerably. From the results the following conclusions can be drawn:

1. The fatigue process characterized in terms of $M_{\text{max}}$ could be divided into three stages. In the first stage the MBE peak voltage increases due to the rearrangements of dislocations and formation of cell structures. The second stage is characterized by the decrease of MBE peak voltage accompanied by a reduction in the dislocation cell size and increased dislocation density, and due to the formation of slip bands. In the third stage the MBE peak voltage again increases till failure because of the initiation and growth of macro-cracks. The knee point transition between the second and the third stage is attributed to the formation of notch-like intrusions, which acting as the source of crack initiation.

2. This information could be used as a guideline to monitor the fatigue damage of in-service components by MBE technique.

Acknowledgements

The authors wish to thank Prof. S.P. Meherotra, Director, National Metallurgical Laboratory, India for giving his permission to publish the work. This work is the part of Indo-German collaborative work under CSIR–FhG program. The authors are also acknowledged Mr Klaus Szielas, Dpl. Ing, IZFP and Mr Nebel, Dpl. Ing., Kaiserslautern, Germany for their technical help.

References