FATIGUE OF HEAT TREATED PM STEELS – A FRACTURE MECHANICS APPROACH

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***Abstract*— Fatigue is one of the most common failure mechanism for components subjected to mechanical load. Therefore it is of key importance to have reliable models to describe the fatigue strength of materials and components. This paper describes how a fracture mechanics based model can be used to take both density and notch effects into account. First the porosity is described using extreme value statistics, and then the largest pores linked to the fatigue strength by linear fracture mechanics. It is demonstrated how this concept can be used to estimate the fatigue strength for test bars with different densities and stress concentrations, requiring only a minimum of fatigue testing.**

Keywords – fatigue, fracture mechanics, sintered components

I. INTRODUCTION

Fatigue is one of the most common failure mechanism for components subjected to mechanical load. Therefore it is of key importance to have reliable models to describe the fatigue strength of materials and components. This is important both to make reliable designs, but also to make use of the full potential of the material. An overly conservative design is bad not only from a cost and performance point of view, but also for the environment since the resources are not optimally used.

The fatigue strength of a material can often be related to defects, such as inclusions, in the micro structure [1]. For PM steels the porosity is a natural part of the material, but the pores are nevertheless weak points in the structure. Previous investigations, for instance [2]-[4], have linked the fatigue strength of these materials to the pore structure. Often this effect is only indirectly accounted for by taking fatigue strength to be a function of density. However by directly incorporating the porosity into the fatigue model not only the influence of density can be accounted for, but also for instance the internal microstructuralnotch effect. This also leads to a better understanding of how fatigue in PM materials work.

In this paper a model for fatigue strength of PM steels is developed by linking the porosity to the fatigue strength of the material using a fracture mechanics approach. It is then demonstrated experimentally how the model can be used to understand both the influence of porosity and stress concentrations on the fatigue strength.

II. FATIGUE MODEL

The fatigue model is divided into two parts; the first part describing the pore structure of the material and the second the linking the porosity to the fatigue strength. It is well known that fatigue cracks start at the largest defect in the highly stressed volume of the material. In the PM case the largest defect is typically the largest pore. Thus, a model not describing the average porosity, but the largest pores needs to be developed.

Extreme value statistics is a useful tool to describe rare events. Instead of trying to analyze the tail of the total porosity distribution to determine the size of the largest pore a new statistical distribution is developed only describing the largest pores in the material. There are several extreme value distributions that are possible, but in this paper the Gumbel distribution is selected. The Gumbel distribution appears when taking the maximum of a number of stochastic variables with an exponentially decreasing tail and is often used to describe the largest defects in a material [1]. It has also been used in a number of previous publications to describe the largest pore in PM steels [3]-[6]. The main motivation for using it in this paper is that it provides convenient expressions to work with and gives good correlation with the measured porosity distributions as will be shown below.

Applying the Gumbel distribution the largest pore area A in a certain volume V can be calculated from:

$$A = \lambda + \delta \left[\ln \frac{V}{V_0} - \ln\left(-\ln F\right) \right] \quad (1)$$

λ, δ and V_0 are parameters found by analyzing the porosity. Different failure probabilities can be analyzed by selecting values for F, for the median F=0.5.

The next step is to link the largest pore to the fatigue strength, which is done by a fracture mechanics approach assuming that the local stress concentration around a pore is sufficiently sharp to treat is as crack like. If the material is linear elastic, or the plasticity is confined to a volume sufficiently close to the crack tip, the load on the pore can be described using the stress intensity factor, KI, from linear elastic fracture mechanics (LEFM). The endurance limit, σ_w, can then be linked to the pore area through:

$$\sigma_w = \frac{\Delta K_{th}}{1.36 \cdot A^{\frac{1}{4}}} \quad (2)$$

where ΔK_{th} is the threshold stress intensity factor for fatigue crack growth. The factor 1.36 comes from the observation that fatigue cracks typically start in corners for PM fatigue test bars.

Since most components are subjected to non constant stress fields the highly stressed volume must be defined. An often used measure is the V_{90}-concept, which is the volume of the material subjected to at least 90% of the maximum stress in the component, [7]. This concept has been used for a number of different investigations, for instance [8] and [9], and seems to work well also for PM steels. Therefore the largest pore in equation (1) is calculated for $V=V_{90}$.

III. Experimental investigation and fatigue testing

To test the fatigue model an experimental investigation was made on test bars with different stress concentrations compacted to three different densities. The material used in the study is a diffusion alloyed powder from Höganäs AB, Distaloy® AQ (Fe/0.5%Ni/0.5%Mo) + 0.6%C + 0.6%LubeE. Test bars were compacted to densities of 6.90 g/cm^3, 7.05 g/cm^3 and 7.20 g/cm^3, sintered at 1120°C for 30 min in a 90/10 N_2/H_2 atmosphere. After sintering the test bars were hardened at 860°C for 20 min, quenched in oil and finally tempered at 200°C for 60 min in air. This resulted in a martensitic structure, with some Ni-rich austenite.

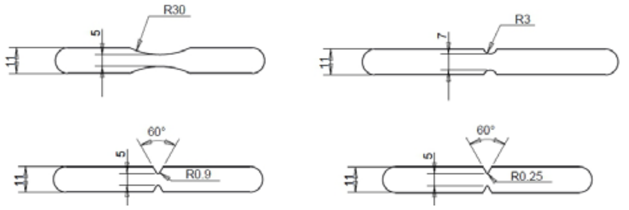

Fig. 1. Overview of test bars.

Fig. 1 shows an overview of the test bar geometries used for the investigation, all test bars are 5 mm thick. As is seen in the figure the notch radii in the test bars range from 0.25 mm to 30 mm, giving different stress concentrations and V_{90} values.

To determine the parameters in the Gumbel distribution as described above a metallographic investigation was made. A cross section through the middle of the notch was made and investigated using light optic microscopy linked with image analysis. The method to calculate the distribution parameters follows the procedure described in [1].

Fig. 2 shows the measured larges pores along with the least squares estimates of the distribution parameters. For each density 80 subsections with A_0=0.278 mm2 were measured. As can be seen in the figure the Gumbel distribution fits the experimental data well, which motivates the use of this model. At the large end tail of the distribution it can be seen that there are some points deviating from the curve. This phenomenon was investigated numerically in [4] and it was shown that even under ideal conditions that type of outliers are expected. Therefore they are not used in the parameter estimation either.

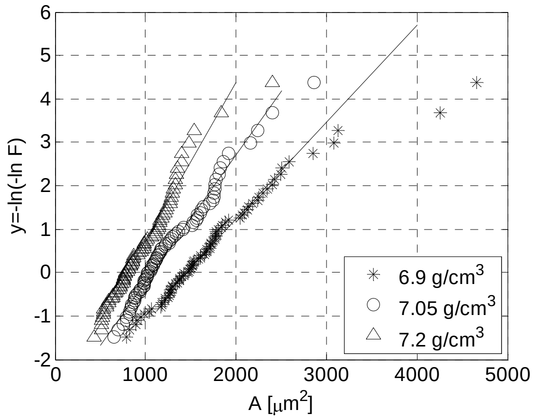

Fig. 2. Gumbel distributions for largest pores.

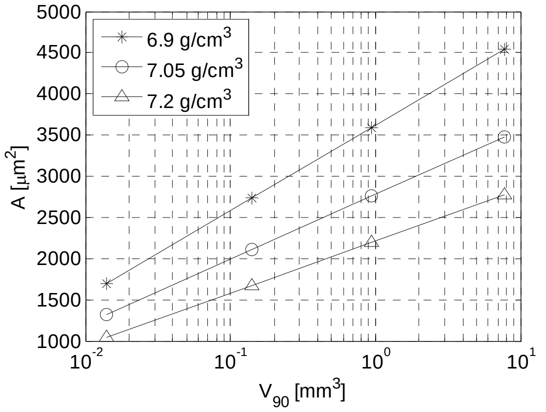

Fig. 3. Estimated values of largest pore area as a function of V90 and density.

Fig. 3 shows the median values (F=0.5) of the estimated largest pore size for the different densities and highly stressed volumes. From the figure it can be seen that when density decreases or the highly stressed volume increases the size of the largest pore will increase.

Fatigue testing was done in displacement controlled plane bending, using the staircase method to evaluate the endurance limit, σ_w, at two million cycles and alternating load, i.e. R=-1. Each series consisted of between 20 and 25 test bars. In the following the fatigue strengths are presented as the median values of the stress amplitude. The stress is defined as the peak notch stress, calculated as the nominal stress multiplied with the stress concentration factor K_t.

Fig. 4 shows the correlation between the endurance limits of the material and the largest pore from the porosity model. From the figure it can be seen that there is a strong correlation. By combining the fatigue strength versus pore size data with the fracture mechanics model in equation (2) the fatigue threshold value can be estimated to ΔK_{th}=4.50 MPa√m. This value is consistent with what is expected for martensitic steels. The solid line in Fig. 4 shows the resulting correlation between the experiments and equation (2). As is seen in the figure the data fits well with the model. Most data points are within 4% of the estimate according to the fatigue model, and the maximum deviation, just below 8%.

Since fatigue testing normally is both time consuming and expensive it is advantageous to keep the testing at a minimum. Therefore it's also interesting to see how well the strength can be estimated using only one fatigue experiment. Therefore the threshold value is also estimated using only the un-notched test results for ρ=7.05 g/cm^3. The result is ΔK_{th}=4.41 MPa√m, shown as a dashed line in Fig. 4. This value differs only 2% from the value obtained when all data points were combined, and the maximum deviation from the experimental data is 6%.

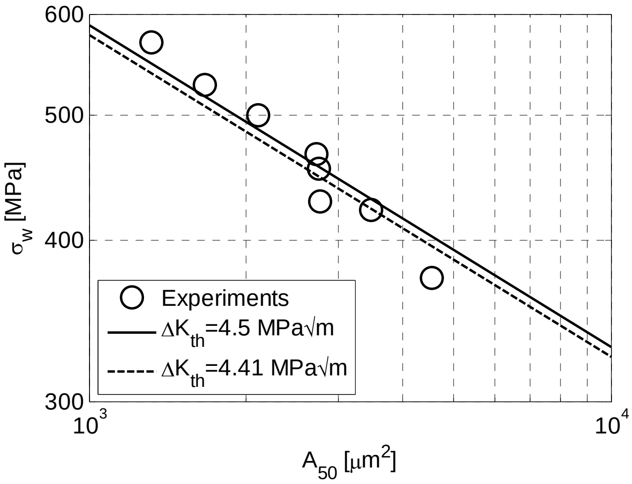

Fig. 4. Correlation between endurance limit and largest pore size.

IV. Discussion

The suggested model fits well with the experimental data, and is able to combine the effects from both density and stress concentrations on the fatigue strength of PM steels. The density effect is explained by the fact that for a lower density the largest pores will be bigger than for a lower density. Correspondingly a sharp stress gradient leads to a smaller highly stressed volume and thus a smaller expected largest pore and higher fatigue strength. Also, the estimated threshold value of ΔKth=4.50 MPa√m is within what can be expected of a martensitic material [10]. Using this value all experimental points fall within 8% of the estimated values.

There are several advantages to this approach. First of all it gives a direct link between fatigue strength and porosity, rather than indirectly through density. The higher relative strength of a material with high density can be clearly explained by the expected size of the largest pores rather than adding an empirical factor adjusting the strength values with density.

Another advantage is that the fatigue part of the model only includes one parameter, ΔK_{th}, that needs to be estimated from fatigue testing. Thus this testing can be kept to a minimum, which is beneficial both from a cost and time perspective. For instance, when only one data point was used to calculate the threshold value the difference from the value obtained from a least squares regression with all values was only 2%. And it was possible to correlate all the experimental values from different densities and stress concentrations within 6% with this one parameter, which is less than the 8% from the least squares estimate.

What is needed instead of fatigue testing is a model describing the porosity in the material. The approach here is based on extreme value statistics to describe the largest expected pore in a certain volume. For this model there are three parameters that need to be determined through metallographic investigation of the pore structure. But this is less time consuming than fatigue testing.

Using linear fracture mechanics is motivated by the fact that the hardness of the martensitic micro structure gives a very small plastic zone in front of the crack tip. Using a similar approach for softer materials are of course also of interest, but here the limitations of LEFM needs to be further investigated. Also the V90 concept could potentially be developed, an alternative method would for instance be to use a random defect concept where the interactions between defects and stresses in different parts of the component are taken into account. [10] presents one approach to the random defect problem that could potentially also be adopted to PM steels.

V. Conclusions

It was found that a model linking the fatigue strength of a PM steel to an extreme value description of the material is able to estimate the fatigue behavior of a range of stress concentrations and densities. The largest pores are well described by a Gumbel distribution that can be obtained through metallographic investigation of the material. A linear elastic fracture mechanics approach can then be used to link the size of the largest pores for a given geometry and density to the fatigue strength through a threshold value for crack growth. The model provides a physical interpretation of the included parameters and only one parameter needs to be determined from fatigue testing

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