The influence of notches on fatigue of heat treated sintered steel

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Abstract

Using sintered steels in ever more demanding applications require thorough understanding of the material behavior to be able to make reliable, optimal designs. One of the most common failure mechanisms of components in service is fatigue. Thus, reliable models for predicting fatigue strength is important, and one of the factors that need to be accounted for is stress concentrations.

In this paper plane bending fatigue of a diffusion bonded alloy, Distaloy AQ, is investigated. Heat treated specimens with different notch sizes are tested, and the results evaluated using models based on critical distance, stress gradients, highly stressed volume and fracture mechanics. It was found that all models worked well but the models based on stress gradients and critical distance gave the lowest scatter compared to experimental data, whereas critical distance gave the highest scatter. The fracture mechanics model gave intermediate scatter, but used one less fitting parameter.

Introduction

Using sintered steels in ever more demanding applications require thorough understanding of the material behavior to be able to make reliable, optimal designs. One of the most common failure mechanisms of components in service is fatigue. Thus, reliable models for predicting fatigue strength are important. Most components will contain notches, and accurately accounting for stress concentrations is important.

Modern tools, such as finite element calculations, make it easy to make stress calculations and accurately determine the peak stresses in critical areas of a component. However, using the maximum local stress amplitude, σ_{max}, to determine fatigue strength tends to give overly conservative results. This is called the notch effect, and to make full use of the material it needs to be accounted for in the fatigue evaluation. Different methods to evaluate the strength of structures exist, and the purpose of this paper is to test some of them on a sintered steel. It is also desirable that the methods are suitable for using with finite element calculations.

A set of methods that are well suited to combine with finite element calculations are based on the theory of critical distance, see for instance [1] for a discussion on these models. One possibility is to define the effective stress at a given distance, d_P, from the surface:

$$\sigma_{eff} = \sigma\left(d_P\right) \le \sigma_{w,cd} \qquad (1)$$

This is usually referred to as a point method. The stress at d_P should be below the critical value $\sigma_{w,cd}$.

Instead of using stresses at a distance from the surface, the relative stress gradient, χ, can also be applied. Some design codes such as FKM Guidelines [2] used this approach. The model can be written:

$$\sigma_{eff} = \frac{\sigma_{max}}{k_\chi} \le \sigma_{w,gr} \qquad (2)$$

$$k_\chi = 1 + \alpha\chi^{\beta(\chi)} \qquad (3)$$

$$\chi = \frac{-1}{\sigma_{max}} \frac{d\sigma}{dx}\bigg|_{x=0} \tag{4}$$

where α is a material parameter, and the critical value of the effective stress is $\sigma_{w,gr}$. The exponent β is taken as a function of χ according to [2], α is treated as a constant.

The notch effect can be seen as a result of a smaller volume of the material being stresses around a notch. A recent model, cf. for instance [3], for fatigue in PM explicitly uses the stressed volume as a parameter. By using the Weibull distribution, essentially a weakest link theory, the strength of the material is expressed as:

$$\sigma_w = \sigma_{ref} \cdot \left(\frac{V}{V_{ref}} \right)^{\frac{-1}{n}} \geq \sigma_{max} \tag{5}$$

where index “ref” refers to a reference stress and volume and n is the Weibull exponent. The volume V can be taken as the volume, V_{90}, with stresses at least 90% of the peak stress. This choice is somewhat arbitrary, but the 90% value seems to work well, and is also adopted here.

In a couple of earlier papers, [4]-[5], it has been demonstrated how fatigue of sintered steel can be analyzed using a fracture mechanics approach. The basic assumption of the model is that fatigue cracks initiate at the largest pore in the stressed volume. An extreme value statistics method is used to estimate the size of the largest pore, A, leading to the equation:

$$A = \lambda + \delta \left[\ln \frac{V}{V_0} - \ln\left(-\ln P\right) \right] \tag{6}$$

where λ and δ are parameters describing the distribution of the largest pore and P is the probability of failure. This approach automatically incorporates the highly stressed volume since the pore distribution will depend on the size of the scanned volume. The parameter V_0 is the size of the volume used to determine λ and δ. Also here the highly stressed volume V is taken as V_{90}.

From the size of the largest pore the fatigue strength can be calculated with fracture mechanics:

$$\sigma_w = \frac{\Delta K_{th}}{C \cdot A^{\frac{1}{4}}} \geq \sigma_{max} \tag{7}$$

where ΔK_{th} is the threshold value for fatigue crack growth and C a geometry dependent parameter, found from handbooks, for a corner crack C=1.36. The size of the defects is expressed in terms of crack area, A, rather than crack length, in line with the Murakami approach [6], and a convenient way of expressing defect size. The exponent ¼ comes from linear elastic fracture mechanics, which is applicable for hardened materials, cf. [4] and [5]. Combining these equations yield an expression that gives the fatigue strength as a function of the stressed volume, incorporating the volume effect in a natural way.

In this paper the notch effect in a hardened sintered steel, Distaloy AQ is investigated. Fatigue testing was performed on test bars with different stress concentrations and the different models presented above are tested.

Material and fatigue testing

The material used in this study is a diffusion alloyed powder from Höganäs AB - Distaloy AQ (Fe/0.5Ni/0.5Mo) + 0.6C + 0.6LubeE. The powder was compacted to test bars with a density of 7.05 g/cm^3, all bars 5 mm thick. To test the notch effect test bars in four different geometries were used, cf. Figure 1, with notches ranging from 0.25 to 3 mm. Sintering was done at 1120°C for 30 min. Finally the bars were neutral hardened, quenched in oil, and tempered (200°C for 60 min), resulting in a martensitic structure with some Ni-rich austenite, see Figure 2.

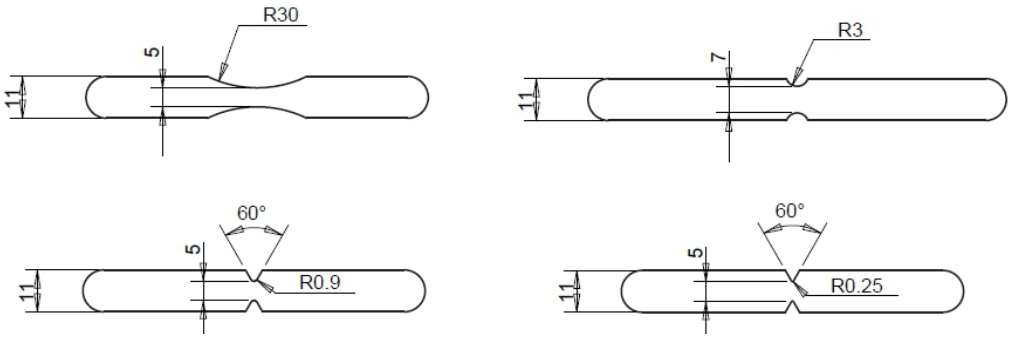


Figure 1. Test bars, a. FS, b. FSN-3, c. FSN-0.9 and d. FSN-0.25, thickness 5 mm.

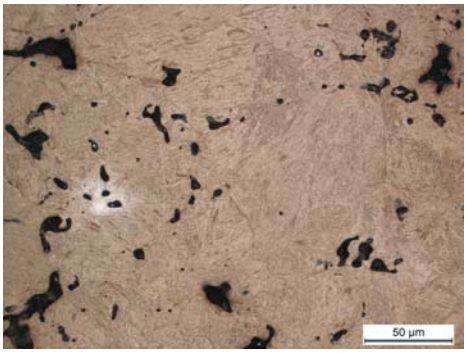


Figure 2. Microstructure, martensite with some Ni-rich austenite.

The porosity was analyzed according to the procedure described in [5] and a Gumbel distribution fitted to the data. The distribution function for volume V is, in line with equation (6) given by:

$$F_V(x) = \left[F_{V_0}(x)\right]^{\frac{V}{V_0}} = \exp\left[-\frac{V}{V_0}\exp\left(-\frac{x-\lambda}{\delta}\right)\right] \qquad (8)$$

where V_0 is the scanned volume, and λ and δ parameters in the distribution. The resulting distribution is presented in Figure 3 and the corresponding parameters are given in Table 1, note that the distribution function was rewritten to yield a straight line in the diagram. As can be seen the model fits the measured porosity distribution well.

Fatigue testing was done in plane bending under fully reversed load (R=-1). The staircase method was used to determine the endurance limit, σ_w, at two million cycles. The resulting average stress amplitudes are presented in Table 1. The values are given as maximum notch stresses. The standard un-notched plane bending endurance limit at two million cycles was found to be 424 MPa, which is in the upper range of what can be expected for a hardened PM steel. From the experiments it's clear that there is a notch effect, since the peak stress in the notch increases as the notch gets sharper.

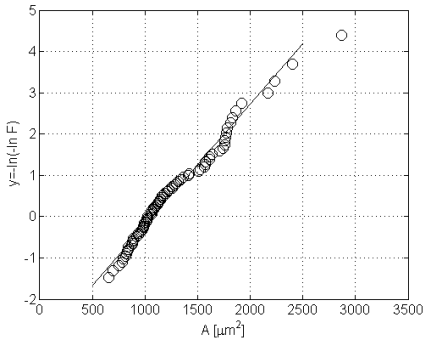


Figure 3. Measured porosity distributions and fitted Gumbel distributions.

Table 1. Gumbel parameters and endurance limit at two million cycles.

Gumbel parameters			σ_w [MPa]			
V_0 [mm^3]	λ [µm^2]	δ [µm^2]	***FS***	***FSN-3***	***FSN-0.9***	***FSN-0.25***
0.0098	1070	342	424	474	534	558

Finite element calculations

Finite element calculations were performed on the test bar geometries to determine the stress fields in the critical section. Calculations were done in 3D, applying a bending moment to one size, fixing the other side in space. The resulting stress fields are shown in Figure 4 and Figure 5 give the normalized stresses as a function of distance from the surface. From the calculations stress concentration factors, K_t, stress gradient, χ, and V_{90} could be determined. The results are given in Table 2, some of the V_{90} values were obtained from [3]

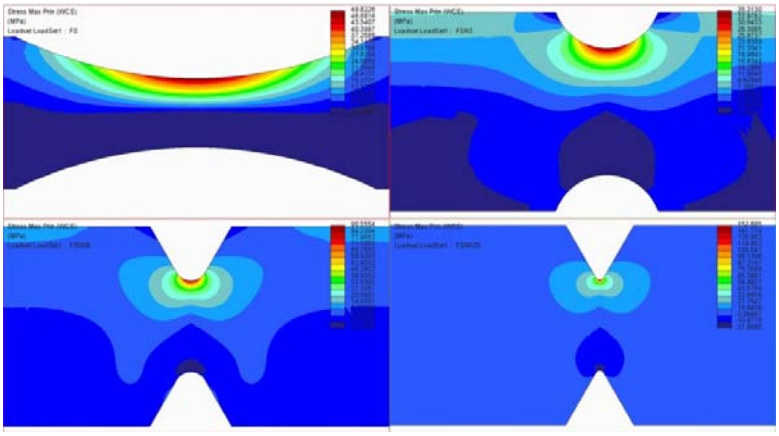


Figure 4. Maximum principal stresses around the notches, a. FS, b. FSN-3, c. FSN-0.9 and d. FSN-0.25.

Table 2. Parameters describing the stresses in the test bars.

Geometry	K_t	χ [mm^{-1}]	V_{90} [mm^3]
FS	1.04	0.461	7.748 [3]
FSN-0.25	3.15	4.67	0.014 [3]
FSN-0.9	1.88	1.91	0.1395 [3]
FSN-3	1.44	0.838	0.938

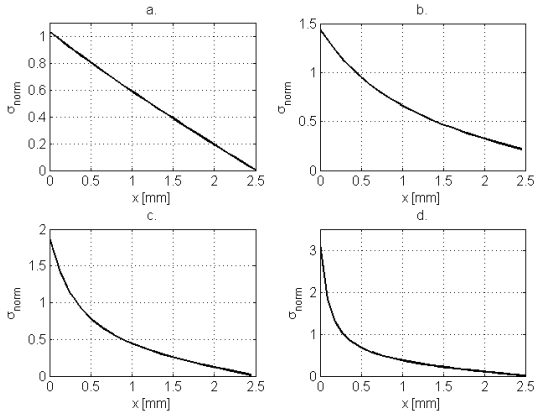


Figure 5. Normalized stresses in the test bars as a function of distance from the surface, a. FS, b. FSN-3, c. FSN-0.9 and d. FSN-0.25.

Evaluation of models for fatigue of notched specimens

To test the different models for fatigue of notched specimens, the measured fatigue limits were used to estimate the parameters in each model. The estimated parameters were then put back into the models and the predicted endurance limits calculated and compared to the measured values. Table 3 contains a summary of the fitted parameters. The parameters were found by a least squares fit to the measured data, all four data points were used in the regression.

Table 3. Model parameters fitted to experimental data.

Model	Critical distance	Gradient method	Volume method	Fracture mechanics
Parameters	$\sigma_{w,cd}$=442 MPa d_P=0.0478 mm	$\sigma_{w,gr}$=316 MPa α=0.524	σ_{ref}=468 MPa V_{ref}=1 mm^3 (selected) n=23.3	ΔK_{th}=4.60 MPa$\sqrt{m}$

Figure 6a shows the results from fatigue testing as a function of the highly stressed volume, the estimated values based on the parameters in Table 3 are also included. Figure 6 shows the estimated values from the different models versus the experimental data. The ±5% scatter bands have also been drawn in the figure. Most of the data points fall within the ±5% scatter, except a one point based on critical distance. The gradient and volume methods generally yield quite similar results and are also the ones closest to the experiments. The fracture mechanics approach yield slightly higher deviations from the experiments and critical distance give the highest deviation.

Discussion

All of the investigated models are able to replicate the notch effect in a similar way and with limited scatter. The gradient and volume methods gave predictions closest to the experimental data, whereas, the critical distance approach gave somewhat higher deviations. This is somewhat surprising given that it's similar to especially the gradient method. The reason for this deviation is unclear, and it can be noted that in [7] it was found that the method of critical distance was very suitable for sintered steels.

An important aspects of the models is the number of parameters needed. The models, except the fracture mechanics approach, all require two parameters to be estimated from fatigue testing, implying at least two geometries need to be tested. The fracture mechanics model only need the threshold stress intensity factor, but also require a separate analysis of the porosity to calculate the parameters in the distribution function. Since fatigue testing is more time consuming, and expensive, than a porosity investigation this is an attractive property since only standard un-notched fatigue test is required to estimate ΔK_{th}. The results can also be extrapolated to another density by only making a new porosity analysis, which is not possible with the other models. It should, however, be noted that the fracture mechanics model is currently limited to hardened materials where linear fracture

mechanics can be applied. A potential extension of the model to also softer structures could be to apply a nonlinear fracture mechanics model.

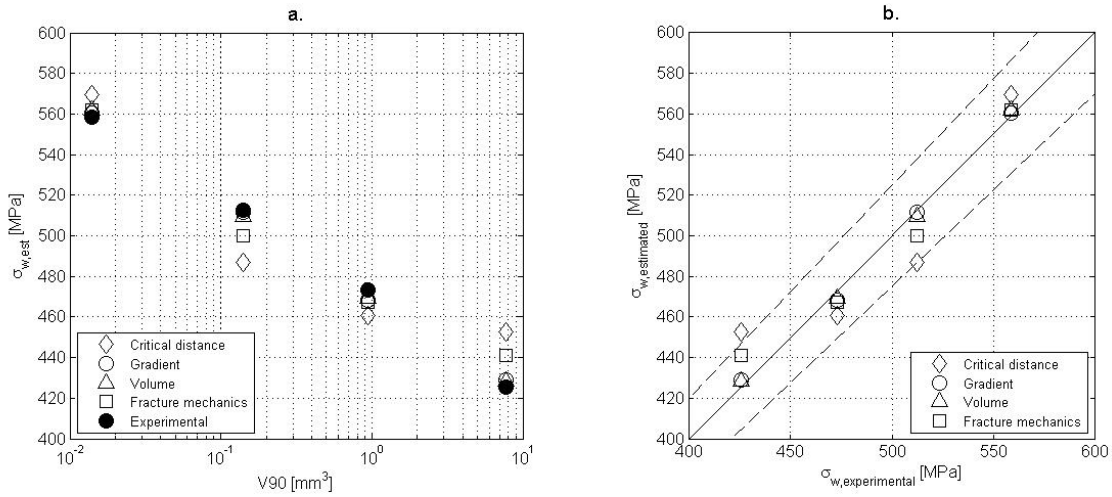


Figure 6. a. Estimated and measured fatigue strength as a function of V_{90} and b. Experimental versus estimated fatigue strength with ±5% scatter bands.

In the end the goal of a model of the notch effect in fatigue is to yield accurate estimate of the fatigue strength of a component. In the paper the parameters were estimated using all available experimental data which means that the predicted fatigue values center with experimental data both above and below. An interesting continuation of the investigation would be to use a small set of fatigue data from test bars to estimate the parameters in the models and use the results to predict the strength of an actual component and to test the component.

Conclusions

All the tested models were able to estimate the notch effect in a PM steel with a reasonably small scatter. The gradient and volume methods gave the estimates closest to the experimental data, whereas the theory of critical distances gave somewhat higher scatter than the other models. The fracture mechanics approach used one less fitting parameters than the other models, but still gave a small scatter.

References

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