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Parameterized characterization for rotating-bending fatigue strength of high-strength metal components

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Abstract

Most of the fatigue failure of components in aero-structures occurs on its surface or in subsurface layer. In order to promote the fatigue strength of material or component, more and more attention is paid on surface treatment technology. For better evaluating the quality of the surface, optimizing the surface process technique and selecting the process parameters, a quantitative characterization method and a relating mathematical model are necessary. By studying the influence of the parameters of the surface modification layer on the fatigue properties of metal components, a parameterized characterization method for rotating-bending fatigue strength of high-strength metal component is proposed and a quantitative mathematical model is obtained. The validation of the model is verified in terms of rotating-bending fatigue testing for M50NiL samples. This model can be used not only to evaluate the fatigue strength of metal components but also to provide some reference on surface treatment.

Keywords: fatigue; surface modification layer; parameterized characterization; evaluating model

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1. Introduction

The fatigue performance of materials has drawn a great attention in the design of structures, since failure due to cyclic loading accounts for at least half of all mechanical failures [1,2]. It is well-known that the surfaces of structures are the most susceptible regions to fatigue failure, and fatigue cracks are generally initiated at the surface [3]. To enhance fatigue life of structure, surface treatments is widely adopted to strengthen the material at the surface layers. Meanwhile, the creation of residual compressive stresses at the surface will also hinder fatigue crack initiation.

The reason of improvement in fatigue strength is explained by combination of strengthening and imparted compressive residual stress after surface treatment. The improvement in fatigue strength or life resulting from surface treatment cannot be attributed to the maximum compressive residual stress only, but also to its distribution [4,5]. The magnitude and distribution of residual stress in the section as well as local strength determine position of fatigue crack origin. Up to now, evaluation of the fatigue performance of a component or structure is still an important area of interest to the design engineer [6-8]. Especially a simple expression for characterizing the fatigue strength of a component or structure is necessary in fatigue design and in selection of its suitable surface treatment parameters.

By studying the influence of the parameters of the surface modification layer on the fatigue properties of metal components, a parameterized characterization method for rotating-bending fatigue strength of high-strength metal component is proposed and a quantitative mathematical model is obtained. The validation of the model is verified in terms of rotating-bending fatigue testing of M50NiL samples.

2. The Relationship Between Fatigue Strength and Hardness

It is found from experiments that the fatigue strengths of materials increase with their hardness. Roessle et al proposed the following proportional expression between the fatigue strengths and Brinell hardness of steels [9].

$$\sigma_f = 1.43HB \tag{1}$$

Recently, the fatigue strength and hardness of several kinds of high-strength steels using for aviation structure were studied by experiments. The testing results as well as those from literature [9] and [10] are shown in Fig 1. In terms of least squares linear fit method, the quantitative relation between the fatigue strength and Vickers hardness of these steels is also obtained as the following expression.

$$\sigma_f = 1.41HV + 31.7 \tag{2}$$

The second constant term is only 3~10% of the first term in the right hand of the above equation, hence the expression can be simplified in the same proportional form like Eq. 1.

$$\sigma_f = 1.41HV \tag{3}$$

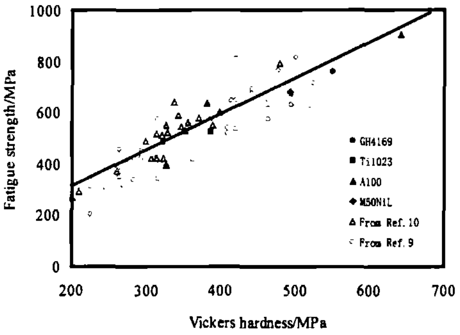


Fig. 1. Relation between the fatigue strengths and Vickers harnesses of high-strength steels

3. The Distribution of the Fatigue Strength in Surface Modification Layer

3.1. The distribution of the fatigue strength without residual stress

In the surface modification layer of a component after surface treatment, the hardness appears gradient change with the depth increase. Hence the local fatigue strength in surface modification layer also changes gradually with the depth increase. For convenience, it is temporarily assumed that the residual stress doesn't exist in the surface modification layer.

For any point in subsurface of a component without surface stress concentration as well as without inclusion of other particles, if the depth is denoted as t, the corresponding Vickers hardness is $HV(t)$, then the local fatigue strength is easily given in Eq.4 according to Eq. 3.

$$\sigma_f(t) = \frac{\sigma_{f0} \cdot HV(t)}{HV_0} \tag{4}$$

where σ_{f0} and HV_0 are the fatigue strength and Vickers hardness of the matrix respectively.

3.2. The distribution of the fatigue strength with residual stress

As indicated in Reference [1] and [3], the improvement in fatigue strength is explained by combination of strengthening and imparted compressive residual stress after surface treatment. The compressive residual stress is also changed with the depth increase. Additionally, the compressive residual stress may significantly decrease after dozens or hundreds cycles of loading. Regarding the decreasing effect of the compressive residual stress, an attenuation coefficient α is introduced, which is a function of the cycle number and material parameters. In practice, the value of α is usually taken as 0.5~0.8 according to different materials. Then, the fatigue strength at depth t with compressive residual stress can be rewritten as

$$\sigma_f(t)=\frac{\sigma_{f0}\cdot HV(t)}{HV_0}-\alpha\cdot\sigma_r(t) \tag{5}$$

in which $\sigma_r(t)$ denotes the value of compressive residual stress at depth t. Apparently the compressive residual stress takes a negative value.

Eq. 5 only describes the fatigue strength distribution of a component, but it does not give the real fatigue strength of the component. The characterization of the fatigue strength of a component will be discussed in the following section.

4. Characterization of the Fatigue Strength of a Component

For a component after case hardening (carburizing and nitriding), if the depth from surface is denoted as t, the distribution of the hardness $HV(t)$ and compressive residual stress $\sigma_r(t)$ can be schematically drawn in Fig. 2, the corresponding distribution of the fatigue strength $\sigma_f(t)$ can be easily obtained by Eq. 2 and shown in Fig. 3. It is explained that the fatigue failure occurs while the working stress excesses the fatigue strength of a component. The fatigue crack initiates at the point on which the working stress reaches the fatigue strength of a component firstly. For a component enduring rotating-bending load, the working stress is shown in Fig. 3, which the slope of its tangent line is marked as k. It is should be noted that the tangent line is still drawn in straight line style, though the hardness is really of a distribution state nearby the surface. This can be proved by numerical simulation that the distribution of the working stress changes little comparing with a straight line.

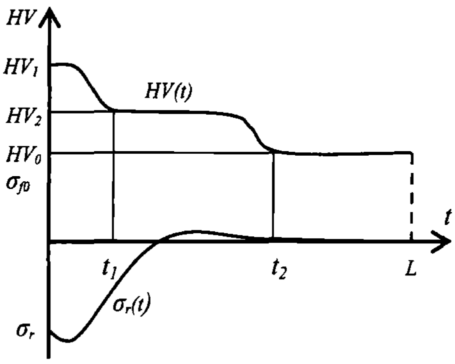


Fig. 2. Distribution of the hardness and compressive residual stress

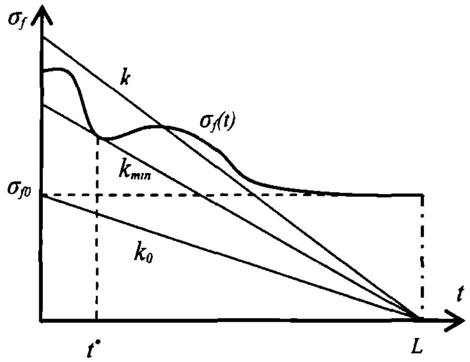


Fig. 3. Distribution of the fatigue strengths

One can note from Fig. 3 that the fatigue failure occurs while the working stress line intersects with the fatigue strength distribution curve. Without intersection between the two curves, the fatigue failure will not occur. Obviously, the fatigue strength of the component can be determined by the line with minimum slope in all the lines intersecting with the fatigue strength distribution curve, which the slope of the tangent line is marked as k_{min} in Fig. 3. The horizontal coordinate of the only intersection point t^* means the depth of the fatigue crack origin core. The fatigue strength of point t^* is $\sigma_f(t^*)$. If the two quantities are obtained, the relating fatigue strength of the component can be given.

To determine the key point t^*, one can get its coordinate value by solving the extreme value. The absolute value of the straight line slope describing the working stress is written as

$$k=\frac{\sigma_f(t)}{L-t} \tag{6}$$

where L denotes the characterizing size of the component, such as the radius of a fatigue sample.

Let the derivative of the right hand of Eq. 6 be zero, one obtain the following formula.

$$\sigma'_f(t)\cdot(L-t)+\sigma_f(t)=0 \tag{7}$$

Combining with Eq. 5, Eq. 7 is rewritten as

$$[\sigma_{f0}\cdot HV'(t)-\alpha\cdot\sigma'_r(t)\cdot HV_0]\cdot(L-t)+[\sigma_{f0}\cdot HV(t)-\alpha\cdot\sigma_r(t)\cdot HV_0]=0 \tag{8}$$

The solution of the above equation is the depth t^* of the origin point of the fatigue crack. Then the relating fatigue strength of the point t^* is obtained by Eq. 5. The fatigue strength of the component can also be given below.

$$\sigma_f=k_{\min}\cdot L=\sigma_f(t^*)\cdot\frac{L}{(L-t^*)} \tag{9}$$

Just like the stress concentration coefficient, we introduce a fatigue strength coefficient K_{ut} to characterize the fatigue property of a component with a surface modification layer. It is the ratio of the two fatigue strengths of a component after and before case hardening.

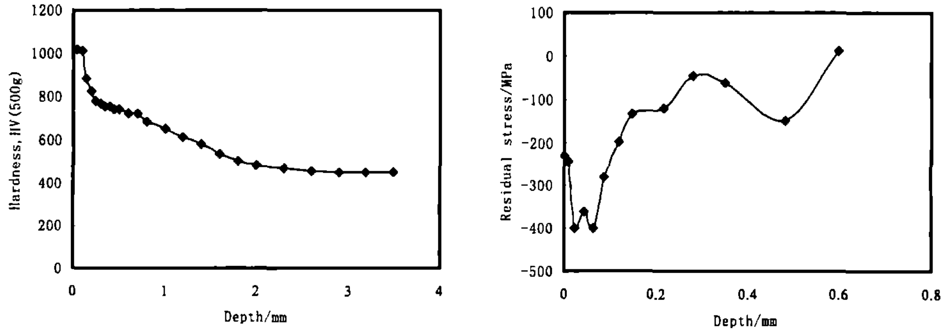
$$K_{ut}=\frac{\sigma_f}{\sigma_{f0}}=\frac{k_{\min}}{k_0} \tag{10}$$

in which $k_0=\sigma_{f0}/L$ denotes the straight line slope of the working stress determined by the fatigue strength of the component without surface modification layer.

Eq. 9 indicates that the greater the K_{ut}, the higher the fatigue strength. It can be used to assess the effect of the surface treatment.

5. Validation of the Characterization Method

Experimental results show that the fatigue strength of a sample is enhanced after case hardening, and the fatigue crack will not initiate at surface of the sample but in subsurface layer. To verify the above characterization method, rotating-bending fatigue testing was conducted by selecting M50NiL samples after case hardening (both carburizing and nitriding). The diameter of the effective working section of the sample is 7.5 mm and the fatigue strength of the M50NiL samples before case hardening is 682MPa. The typical distribution of hardness and compressive residual stress along with depth from surface are shown in Figs. 4 (a) and (b), respectively.



(a) (b)

Fig. 4. (a) distribution of hardness; (b) distribution compressive residual stress

The distribution of the fatigue strength for the typical sample can be obtained by Eq. 5 and shown in Fig. 5. The distribution of the working stress of minimum rotating-bending load possible to cause fatigue failure is also drawn in Fig. 5. It is noted that there are two possible points for fatigue crack initiation. one's depth is 330 μm and the other 650 μm. The fatigue strength of the typical sample acquired from Fig. 5 or from Eq. 9 is 1260 MPa.

By a number of groups of testing, experimental results show that the average fatigue strength of such a kind of M50NiL samples is 1186 MPa. The fracture cross-sections of samples after fatigue failure are checked by SEM and the results indicate that most of the fatigue cracks indeed initiate at about 200~340 mm depth. Obviously, the predicted result by the proposed model and that from testing is coincident. According to Eq. 10, the fatigue strength coefficient K_m of the typical M50NiL sample is 1.74. This means that the fatigue strength is enhanced 1.74 times after case hardening compared with that before case hardening.

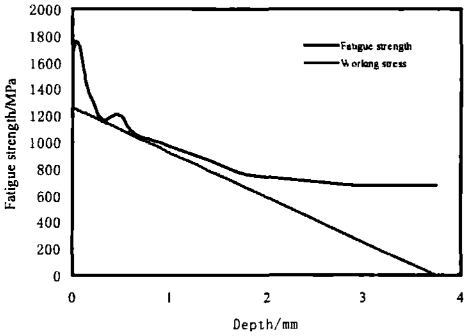


Fig. 5. Determination of the fatigue strength

6. Conclusion

The main parameters influencing the fatigue properties of metal components in the surface modification layer were studied. The magnitude and distribution of residual stress in the section as well as local strength determine the position of fatigue crack origin. A simple parameterized characterization method for rotating-bending fatigue strength of high-strength metal component is proposed, and a quantitative mathematical model is obtained. The proposed model is verified in terms of rotating-bending fatigue testing for M50NiL samples. The error of the result from the proposed model compared with experimental result is only 6.2%.

Acknowledgements

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