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Correlation between surface fatigue and microstructural defects of cemented carbides

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Abstract

The main aim of the present theoretical work is to determine numerical dependence between the geometrical parameter of maximum area of structural defect $\sqrt{\text{area}_{\text{max}}}$ (proposed by Y. Murakami, 1983) and surface fatigue of cemented carbides. The proposed relations allow making predictions of surface fatigue properties of cemented carbides (WC-Co hardmetals—with 10 wt% Co and 15 wt% Co binder; TiC-based cermets—with 32 wt% Fe/8 wt% Ni and 16 wt% Fe/14 wt% Ni binder) in conditions of sliding, rolling contact and impact cycling loading.

Pores are considered being equivalent to small defects. Three comparative defects conditions are distinguished: surface pores, pores just below free surface and interior pores. The Vickers hardness of the binder (as mainly responsible for the fracture mechanism of hardmetals and cermets, due to porosity) is presumed to be the basis of such an assumption.

The estimate of this prediction has been done by analyzing the pore sizes using the statistics of extremes. The lower limit of fatigue strength and surface fatigue life can be correctly predicted by estimating the maximum occurring pore size in a critical material volume.

Keywords: Cermets; Hardmetals; Surface fatigue; Murakami model

1. Introduction

Surface cracks and defects, which are most likely to be found in many structures in service such as pressure vessels, pipeline systems, off-shore structures and aircraft components, have been recognized as a major origin of potential failure for such components. The study of fatigue crack propagation from such defects has been an important subject during recent decades.

Powder metallurgy materials such as hardmetals and cermets are most widely used as tool materials in machining and forming applications. These materials are best known for their excellent strength-wear resistance combination. Wear resistant cemented carbides tend to contain inward and superficial natural structural defects, pores, non-metallic inclusions or inhomogenities, etc. Their existence is crucial for most mechanical properties and material selection, and unfortunately cannot be totally excluded by current technologies.

Based on the experimental fact that the crack shape of propagating surface cracks in a plate under cyclic tension, bending or combined loading is approximately semi-elliptical, a theoretical model with two degrees of freedom is proposed for prediction of the fatigue crack growth [1,2]. This model permits to conjecture the size and location of the surface and subsurface cracks that occur during cyclic loading.

Present work is based on these assumptions and aimed at linking the geometrical parameter of maximum area of structural defect $\sqrt{\text{area}_{\text{max}}}$ (proposed by Y. Murakami, 1983) [3], and surface fatigue parameters for cemented carbides. Hertzian contact theory and Palmqvist model for indentation surface cracks were applied for numerical evaluation of subsurface crack location (depth) and number of impact cycles to failure (N_{f}, fatigue life).

The proposed equations are hypothetical and have not been proved experimentally so far, but are based on the previously published studies on steels, ceramic materials and glasses [4–7].

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2. Theoretical backgrounds

Contact between two solid bodies under cyclic stressing and rolling with impacts is described with Hertzian theory of fracture mechanics. This method can be used for evaluations of surface residual stress levels in brittle materials like WC-Co and TiC-Fe/Ni also. This gave an idea to combine Hertzian contact approach with the Palmqvist indentation theory. As a result we obtained a computational technique for surface crack geometry evaluation and surface fatigue life prediction for heterogeneous materials, containing hard phases (WC, TiC).

The Murakami approach for microstructure analysis with a proposed geometrical parameter of maximum area of structural defect $\sqrt{\text{area}_{\max}}$ and extreme value statistics were incorporated to make the prediction more precise and correct. This method can be used for prediction of fracture toughness also. No additional fatigue or other tests are required.

2.1. Fracture by Hertzian contact (indentation)

The problems of contact between two non-conforming bodies with circular shape (rolling bearings, gears, wheel-on-rail, etc.) were first solved by Hertz and generally referred to as Hertzian contacts [8]. One of the uses of Hertzian indentation is to determine number and sizes of surface flaws. Here we consider the surface with large number of small cracks then the stress field around contact area (in our case indentation) will encompass a large number of ring cracks, outside the contact path, of radius d ,see Fig. 1. Then d can be found as [5]

$$d=\left(\frac{3PR}{4E^*}\right)^{1/3}, \tag{1}$$

where P is the load on the indenter, R the indenter radius and E^* is the equivalent Young's modulus.

As we know ν_1, ν_2 and E_1, E_2 are the Poisson's and Young's moduli for the indenter and substrate, respectively, then E^* can be determine from

$$\frac{1}{E^*}=\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}. \tag{2}$$

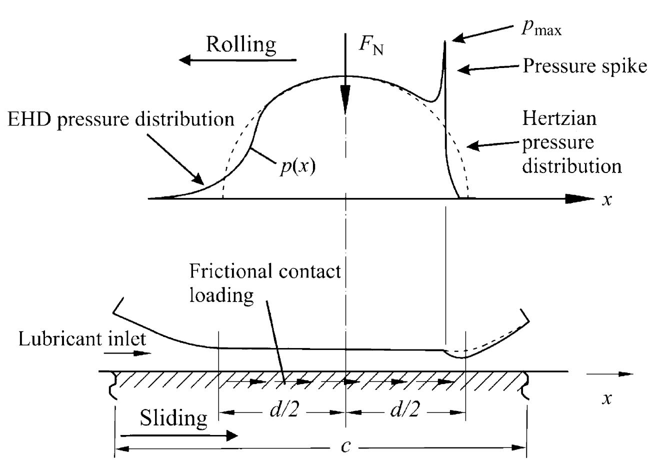

Fig. 1. EHD contact pressure distribution [9,10].

Then the maximum pressure under the contact $p_{\max}$ is [5]

$$p_{\max}=\frac{3P}{2\pi d^2}=\left(\frac{3}{2\pi}\right)(P)^{1/3}\left(\frac{4E^*}{3R}\right)^{2/3}. \tag{3}$$

On the other hand, the mean contact pressure p_{mean} during the impact of an indenter in the Hertzian region [8] is equal to

$$p_{\text{mean}}=\frac{F_N}{\pi c^2}, \tag{4}$$

where F_N is the maximum normal force and c is the maximal scar that corresponds to the elastic and plastic deformation ($c=c_{el}+c_{pl}$) [6].

This is the normal condition for mechanical elements (gears, bearings) when the contacting surfaces are separated by a thin lubricant film (Elastohydrodynamic lubrication:EHD or EHL).

2.2. Fatigue life prediction

Fatigue limit was defined by Murakami as the threshold stress for crack propagation and not the critical stress for crack initiation [3].

This leads to the fact that cracks/defects are present in the microstructure of the hardmetals or cermets. Several relationships are available for prediction of the lower bound of scatter of fatigue limit (σ_f) and fracture toughness (K_{Ic}) which are based on the Vickers hardness (H_V) and maximum inclusion area (geometrical parameter of maximum area of structural defect $\sqrt{\text{area}_{\max}}$) and uniform tensile/compressive stress (σ_0) values:

$$\sigma_f=1.43\frac{H_V+120}{\left(\sqrt{\text{area}}\right)^{1/6}}, \qquad \Delta K_{th}=1.43(H_V+120)\left(\sqrt{\text{area}}\right)^{1/3},$$

$$K_{Ic}=0.5\sigma_0\sqrt{\pi\sqrt{\text{area}}}. \tag{5}$$

These equations are proposed for surface defects. For other defects, just below surface and interior defect, the coefficient 1.43 must be replaced by 1.41 and 1.56 correspondently [3].

Then for surface defects with previously evaluated Murakami parameter $\sqrt{\text{area}_{\max}}$ (defect size) [3] and fatigue limit lower bound (σ_f) values [11,12]. It is possible to find the total accumulated energy E_i in the material as a function of the number of impact cycles, calculated from

$$E_i=3\sigma_f\pi R^3\left[\frac{2}{3}-\left(\frac{c}{R}\right)^2\sqrt{1-\left(\frac{c}{R}\right)^2}+\frac{2}{3}\left(1-\frac{c}{R}\right)^2\right], \tag{6}$$

The strain energy release rate (G) for the propagation of the crack with given parameters to the controlled dimensions can be found from

$$K_{Ic}=\sqrt{\frac{E\times G}{1-\nu^2}}. \tag{7}$$

Finally, the surface fatigue life N_{fs} (number of impact cycles to failure) can be predicted by extracting the strain energy release rate G from the total accumulated energy E_i, while the fracture