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INFLUENCE OF NONMETALLIC INCLUSIONS IN FATIGUE LIFE OF A METALLIC STRUCTURE

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Fatigue cracks leading to failure initiate at surface and subsurface oxide inclusions. The effects of small defects and nonmetallic inclusions are essentially the small crack problem. A small crack can be thought of as a crack with a size on the order of the microstructure. The factors that should be considered in resolving the effects of inclusions on fatigue strength are inclusion shape, adhesion of inclusions to the matrix, elastic constants of inclusions and matrix, inclusion size.

1. FATIGUE MATERIALS IN PRESENCE OF DEFECTS AND INCLUSIONS

It has been said that 90% of fracture accidents are caused by fatigue. Some well known and classical examples of fracture failures include:

- Mechanical, aeronautical or marine (fracture of train wheels, axles and rails, fracture of Liberty ships during and after World War II, fracture of airplanes such as Comet airlines, Japan Air Line Boeing 747, fatigue fractures in the Grumman buses in New York; fracture of the Glomar Java sea boat, 1984, fatigue crack that triggered the sudden loss of the upper cockpit in the Air Aloha plane, 1988) etc.
- Civil engineering (fracture of bridge girders-Silver Bridge in Ohio, fracture of Statfjord A platform concrete off-shore structure, cracks in nuclear reactor piping systems, fracture found in dams etc.).

Investigation indicates that almost 100% of these fractures start from the sites of stress concentrations at structural discontinuities such as holes, notches, shoulders, cracks, defects and scratches.

Stresses at structural discontinuities are higher than at other places on structures because of stress concentration. Flaws, cracks, voids can all act as crack nucleation sites, especially at the surface. Therefore, smooth surfaces increase the time to nucleation; notches, stress risers decrease fatigue life. Dislocation activity (slip) can also nucleate fatigue cracks.

The phenomenon of decrease in fatigue strength, due to stress concentration is called the "notch effect" and it has not always been understood correctly in spite of numerous studies over years.

In the fatigue design of machine components and structures which are intended to be used for an indefinitely long life, which is in design for high cycle fatigue, the nominal stress is usually set to a much lower level than the yield stress. However, even in such cases the stress at stress concentrations sometimes exceeds the yield stress and accordingly local plastic strain is induced.

Plastic strain in such cases is smaller than the elastic strain which preceded it and materials are assumed to behave elastically. Thus, the shape effect due to the shape size of structures is evaluated in such cases using elastic stress analysis.

Notches having a geometrically similar shape have the same value of stress concentration factor regardless of the difference in size.

Most fatigue cracks initiate at the sites of stress concentrations. However, the maximum stress at the stress concentration is not the only factor controlling the crack initiation condition.

This phenomenon has been studied as the problem of the "fatigue notch effect".

2. STRESS CONCENTRATION AT A CRACK

Unlike holes and notches, a crack has a sharp tip whose radius ρ is zero. The definition of a crack, in elastic analysis, is the limiting shape of an extremely slender ellipse. As an extremely slender elliptical hole is reduced towards the limiting shape, then the stress concentration ahead of the elliptical hole that is at the tip of the crack becomes unbounded regardless of the length of the crack. The stresses in the vicinity of a crack tip have a singularity of $r^{-1/2}$, where *r* is the distance from crack tip (fig. 1, equations 1).

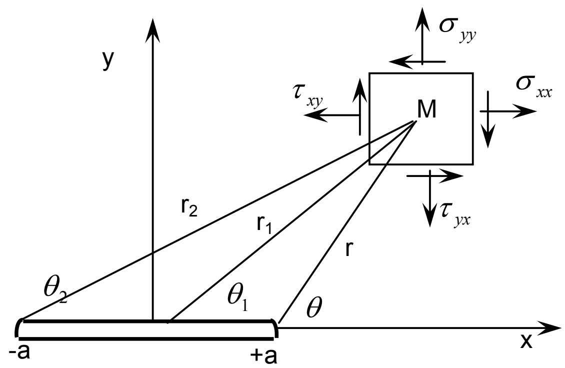

Fig.1

$$\sigma_{xx} = \frac{1}{\sqrt{2\pi r}}\left\{\left[K_I \cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)\right]-\left[K_{II}\sin\frac{\theta}{2}\left(2+\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right)\right]\right\};$$

$$\sigma_{yy} = \frac{1}{\sqrt{2\pi r}}\left\{\left[K_I \cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)\right]+\left[K_{II}\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right]\right\}; \qquad (1)$$

$$\tau_{xy} = \frac{1}{\sqrt{2\pi r}}\left\{\left[K_I \cos\frac{\theta}{2}\sin\frac{\theta}{2}\cos\frac{3\theta}{2}\right]+\left[K_{II}\cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)\right]\right\}.$$

The stress intensity factor K, is defined as the parameter describing the intensity of the singular stress field in the vicinity of a crack tip.

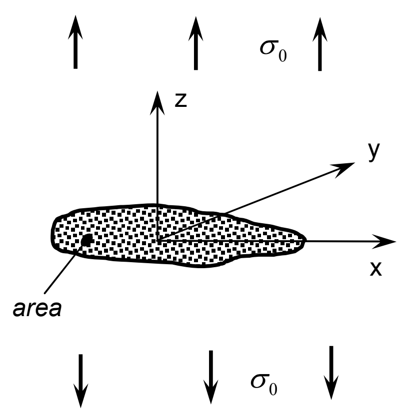

Fig. 2

Figure 2 shows an internal crack on the x–y plane of an infinite solid which is under a uniform remote tensile stress, σ_0, in the z–direction. If the area of this crack is denoted by "*area*", then the maximum value of the stress intensity factor along its crack is given approximately by:

$$K_{1\max} = 0.5\sigma_0\sqrt{\pi\sqrt{area}} \quad (2)$$

3. RATING INDEX OF NONMETALLIC INCLUSIONS

There are numerous factors which have been assumed to influence the fatigue strength. Existing conclusions, each derived from a limited number of experiments are contradictory. No reliable quantitative method has been established for evaluation of the effects of nonmetallic inclusions. The solution to the relationship between small defects and small cracks may be thought of as an example of a fracture mechanics application.

In fact, the effects of small defects and nonmetallic inclusions are essentially the small crack problem which can be solved in a unified form from the viewpoint of small crack fracture mechanics.

Atkinson introduced inclusion rating index chart for Fairley inclusion counting method which take into account the number, sizes and stress concentration factors of nonmetallic inclusions (fig. 3).

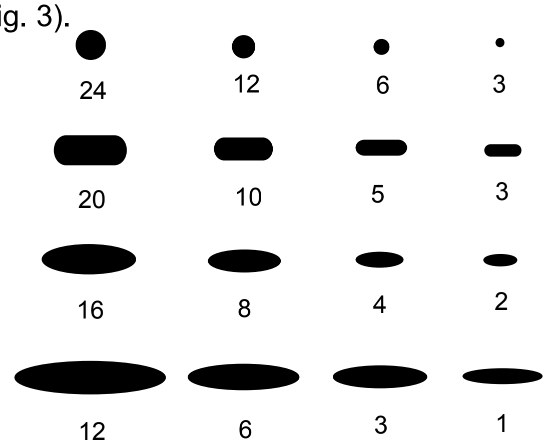

Fig. 3

4. INFLUENCE OF NONMETALLIC INCLUSIONS RELATED TO THE DIRECTION AND MODE OF LOADING AND MATYRIX

The same inclusions can have different effects on fatigue strength depending on the direction of loading. These results indicate that the shape and size of an inclusion are the important factors. Different influences of inclusions appear, depending on whether a loading produces a tensile stress in the longitudinal direction, or in transverse direction.

Existing overviews on inclusions usually point out the following factors that should be considered in resolving the effects of inclusions on fatigue strength.

Figure 4 shows a replot of Sumita et al.'s experimental data on the effect of nonmetallic inclusions on steels having various matrix structures [2].

For *Hv<400* the vacuum-remelted steel (V) which is assumed to contain very small amounts of nonmetallic inclusions, has almost identical fatigue strengths in the longitudinal (rolling) direction (VL). In contrast, for *Hv>400*, the open melted steel (A) shows definite differences in fatigue strength for longitudinal (AL) and transverse (AT) directions.

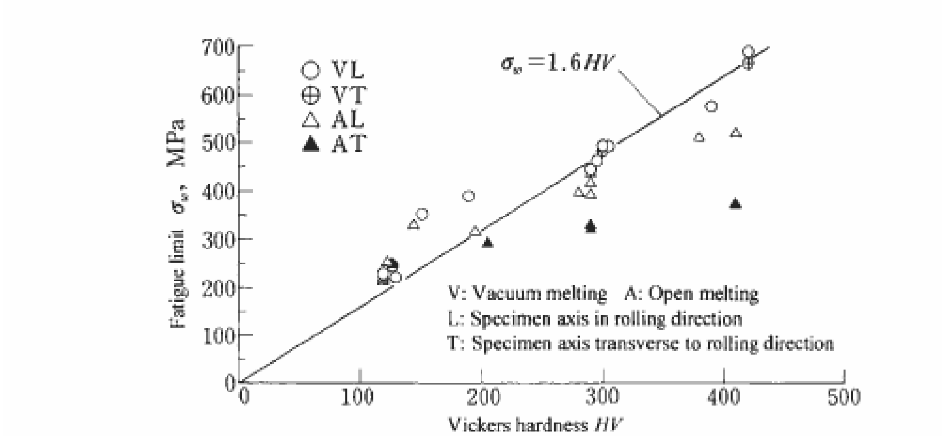

Fig. 4

As the fatigue strength of VL and AL is similar, values of fatigue strength, σ_w, for both can be predicted from hardness *Hv* by using the empirical Eq. 3.

$$\sigma_{w0} \cong 0.5\sigma_U, \quad \sigma_{w0} \cong 1.6Hv \pm 0.1Hv \tag{3}$$

where σ_U is ultimate tensile strength, *Hv*- Vickers hardness, in kgf/mm^2, σ_{w0} in MPa.

Elongated inclusions (type A) have little influence on fatigue strength of a specimen with its axis in the L direction, and much influence on a specimen with its axes in T direction. Anyway, nonmetallic inclusions have various shapes and some of their shapes are altered by plastic deformation.

The influence of inclusions is not as detrimental in torsional fatigue as it is in rotating bending and in tension-compression fatigue.

5. SIZE AND LOCATION OF INCLUSIONS AND FATIGUE STRENGTH

Some researchers showed that only oxide inclusions more than 30 µm in diameter should be counted when evaluating the fatigue life of ball bearings (fig. 5). It is also observed that the effect of inclusions of the same size could vary depending on where they were situated in the cross–section of a specimen. Inclusions smaller than a threshold size did not affect the fatigue strength of a material. In some investigations it was found that inclusions did not influence the fatigue the fatigue strength of high strength steels.

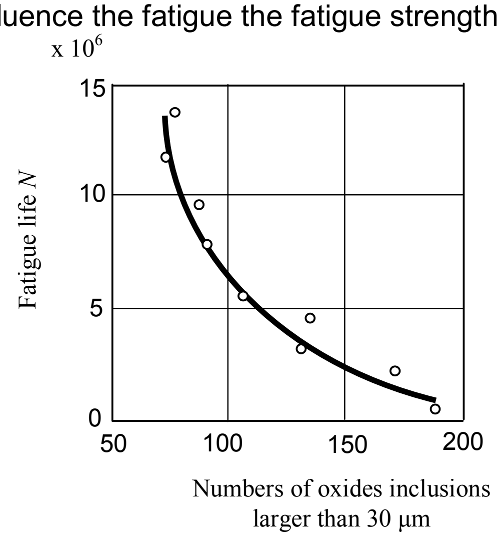

Fig. 5

5. OTHER ASPECTS OF INCLUSIONS' INFLUENCE ON METAL FATIGUE

In order to establish a solid foundation for fatigue modeling, it is necessary to understand where fatigue cracks initiate and what kind of stresses (tensile, compressive, shear stresses) cause their initiation and propagation.

Many researchers (Murakami, Nishioka, Watanabe etc.) have found that the major parameters of nonmetallic inclusions affecting contact fatigue are inclusions shape and size, adhesion of inclusions to matrix, elastic constants of matrix and inclusion.

They have stated that in the conducted tests all fatigues failures are initiated at subsurface inclusions. Moyer et al. (1988) have found that fatigue initiated near subsurface nonmetallic inclusions is associated with long bearing life.

In other paper, Toyoda et al. (1990) have reported that due to improved fatigue strength or gear surfaces, subsurface nonmetallic inclusions tend to cause fatigue failures of shot-penned carburized gears. They have proposed that an empirical equation for fatigue life should involve Vickers hardness of material at a crack initiation site, the projected area of inclusions onto the plane perpendicular to tensile stress and the residual stress.

Murakami et al. have suggested a predictive method for estimating fatigue failure which is based on Vickers hardness of material and the maximum size of nonmetallic inclusions. One of the main assumptions is that an inclusion occupying a certain region can be replaced by a crack with the same area in the plane perpendicular to the maximum tensile stress.

It has been found that oxides generate tensile stresses in the surrounding matrix. Incidentally, sulfide inclusions have rarely been observed to affect fatigue life of high strength steels. Thus, this data helps to explain why oxide nonmetallic inclusions are more harmful than sulfide inclusions.

The Timken Company research has demonstrated that fatigue life of bearings is limited by the length of large inclusions, stringers, which are clusters of individual oxide particles that exist in steels.

Toyoda et al. (1990) have found that fatigue strengthening of carburized steels can be achieved by reducing their oxygen content which decreases the size of oxides.

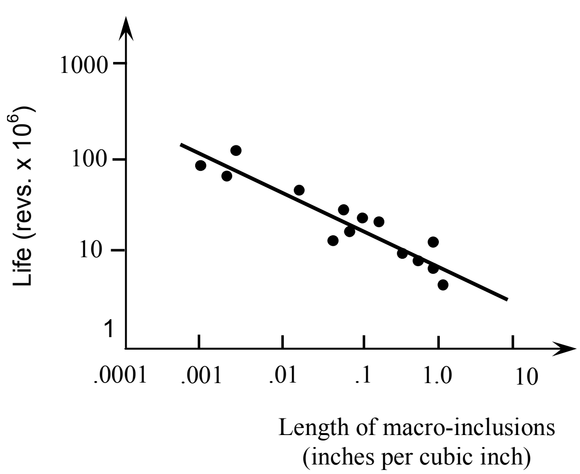

Fig. 6

Stover and Kolarik (1987) have determined a power correlation between bearing fatigue life and ultrasonically measured steel cleanliness, represented in figure 6 [6].

Steel cleanliness, characterized by nonmetallic inclusion rating, strongly depends on the steelmaking practice and determines steel fatigue resistance.

At the same time, it should be known that fatigue properties do not depend on the overall steel cleanliness. Hard brittle oxide inclusions and titanium carbonitrides may induce the formation of butterflies under fatigue contact conditions. These inclusions have often been found to be the origin of fatigue fracture in rotating beam specimen.

6. CONCLUSIONS

In majority of studies, it has been shown that fatigue cracks leading to failure initiate at surface and subsurface oxide inclusions.

The effects of small defects and nonmetallic inclusions are essentially the small crack problem and this problem can only be solved in a unified form from the viewpoint of small crack fracture mechanics.

Existing overviews on inclusions usually point out the following factors that should be considered in resolving the effects of inclusions on fatigue strength:

- Inclusion shape;
- Adhesion of inclusions to the matrix;
- Elastic constants of inclusions and matrix;
- Inclusion size.

All these factors are related to stress concentration factors and to the stress distribution around inclusions.

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