Some Basic Reflections About the Influence of Non-metallic Inclusions on Rolling Contact Fatigue of Bearing Steels

HANS-JÜRGEN BÖHMER  
Material Mechanics, Research and Development Center  
FAG Kugelfischer Georg Schäfer KGaA  
LT-P-W/1, Postfach 1260  
D-8720 Schweinfurt, Germany

ABSTRACT

The detrimental influence of inclusions on rolling contact fatigue behaviour of bearing steel is well known and empirically described. Yet only a few publications exist where the effect of inclusions is investigated analytically. This paper presents a new method to describe the influence of inclusions based on a mechanical analysis.

From this analysis some general effects of inclusions on material stress and behaviour in rolling contact fatigue were concluded. The actual "notch effect" of inclusions is qualitatively independent of their specific properties, even if they are more pliable or stiffer than the matrix. Only the amount of the notch effect is - to a certain extent - dependent on their respective properties. Many discrepancies between classical theory of Hertzian contact and damage analysis of rolling element bearings can be explained by this analysis.

The correct appraise of compressive residual stresses in rolling contact fatigue is strongly bound to the consideration of inclusions. It is shown that compressive residual stresses have the greatest benefit if they are about 15% of the applied Hertzian pressure. Exceeding this value may be detrimental.

KEYWORDS

Bearing steel, non-metallic inclusions, inclusion assessment, residual stress, mechanical behaviour, stress concentration, rolling contact fatigue, endurance limit

NOMENCLATURE

b  half width of the Hertzian contact area in rolling direction
E_m  Youngs modulus of the matrix material
E_i  Youngs modulus of the inclusion
P_0  Hertzian pressure
x  direction parallel to the Hertzian contact area and perpendicular to the rolling direction
y  direction perpendicular to the Hertzian contact area
σ_1  principal stress
σ_2  principal stress
σ_3  principal stress
σ_eq  equivalent stress according to Mises
σ_eq,inc  maximum equivalent stress in the vicinity of an inclusion
σ_x,res  residual stress in x-direction
σ_y,res  residual stress in y-direction
σ_z,res  residual stress in z-direction

INTRODUCTION

The influence of non-metallic inclusions on rolling contact fatigue is well known. Even with the clean steel now available, damage analysis for rolling element bearings has often shown that inclusions had been the crack initiation point. Many publications confirm their important role [1-4] by presenting experimental results and empirical investigations. Yet the amount of analytical research is low [5-10]. To give a basic overview of the behaviour of inclusions the author discussed the influence of inclusions on the stress distribution in the steel matrix [11-13]. Based on the first results achieved from this work, some general effects resulting from the disturbance of the stress state close to inclusions shall be deduced.

Presented at the International Gas Turbine and Aeroengine Congress and Exposition  
Cologne, Germany June 1-4, 1992
THE INFLUENCE OF INCLUSIONS ON STRESS DISTRIBUTION

Inclusions influence the stress distribution in their vicinity due to the differences between the properties of the inclusion and the matrix. This effect has been discussed by previous authors in detail [5-14]. Two separate effects have to be considered. First, due to different thermal expansion coefficients residual stress fields develop around inclusions during cooling if the thermal expansion of the inclusion is lower than that of the matrix [5-7]. Second, the different deformation behavior of the inclusion disturbs the stress flow due to external loads in the vicinity of inclusions [8-14]. This last effect was called the notch effect of inclusions. Fig. 1 demonstrates the results of these effects on the material stresses.

FIG. 1 Material stress in the vicinity of non-metallic inclusions

The upper left part of the figure gives an example of the equivalent stress distribution according to Van Mises which will occur due to residual stresses formed during cooling around a spherical aluminum-oxide-inclusion. The influence of the pure notch effect on equivalent stress distribution is shown at the upper right part. This example refers to the same type of inclusion located close to the surface of a loaded rolling bearing element. After the superposition of the two tensor fields related to both effects, an equivalent stress distribution was calculated and is shown in the lower part of the figure.

The stress field due to residual stresses formed during cooling has a spherical symmetry. Yet subjected to external loads the notch effect of inclusions causes a very complex and inhomogeneous stress field. Thus to describe material stresses in the vicinity of an inclusion and to find the maximum equivalent stress, the whole environment of the inclusion has to be analyzed. Two principal types of inclusions can be distinguished. Stiff types where the Young's modulus of Elasticity of the inclusion \(E_I\) is higher than that of the matrix \(E_M\) and pliable types, with a lower modulus.

In the special case of uniaxial external loading, maximum stressing occurs for stiff inclusions \(E_I/E_M=2.0\) a little bit before and behind the inclusion in the loading direction. For pliable inclusions \(E_I/E_M=0.5\) maximum stressing occurs at the equator, where the loading direction is tangential to the inclusion surface [11-13]. Fig. 2 illustrates this.

FIG. 2 Material stress in the vicinity of non-metallic inclusions due to uniaxial load

THE NOTCH EFFECT OF INCLUSIONS ON ROLLING CONTACT.

In case of rolling contact the stress fields are three dimensional. Due to the extreme inhomogeneous stress state around inclusions it is always possible to find locations in the vicinity of inclusions where the differences between the three principal stresses are higher than they would be in an inclusion free matrix [11-13]. Regarding an inclusion free matrix subjected to Hertzian contact, specifically in the near surface region the two principal stresses with the greatest amount are nearly of the same value. Consequently the equivalent stress in this region is low. If inclusions are present, this equality will no longer exist, resulting in a significant increase in the equivalent stress. This effect is, in general, independent of the type and properties of the inclusion, because it is caused by the inhomogeneity of the stress state around inclusions.

Fig. 3 demonstrates the amount of this effect by comparing the ratio of the maximum equivalent stress \(\sigma_{eq,inc}\) in the vicinity of a stiff inclusion to the equivalent stress \(\sigma_{eq}\) in the inclusion free matrix in dependence of the relation between the principal stresses in the inclusion free material. For example, if the stress state in the inclusion free materi-
the material is uniaxial ($\sigma_2/\sigma_1 = \sigma_3/\sigma_1 = 0$) the presence of the inclusion raises the equivalent stress only about 15%. Yet if $\sigma_2/\sigma_1 = 1.0$ and $\sigma_3/\sigma_1 = 0.6$ in the inclusion free matrix (surface condition in Hertzian contact), the increase due to the inclusion will be about 50%. If all principal stresses in the inclusion free matrix are equal, the equivalent stress is zero, but in the vicinity of an inclusion there will be a remarkable equivalent stress. Thus, in this case the ratio $\sigma_{eq, inc}/\sigma_{eq}$ becomes infinite, the drawing in fig. 3 had to be terminated in this region.

The dependence of the notch effect of inclusions on the multiaxiality of the stress state has an impact on the material stresses due to rolling contact. In rolling contact in an inclusion free material two principal stresses are almost equal in the area close to the rolling element surface [4,17,18]. Thus the notch effect of an inclusion will be very significant there. With increasing depth the multiaxiality of the stress state due to Hertzian contact decreases, consequently the notch effect of inclusions decreases. Fig. 4 demonstrates this. For three possible locations $z/b$ of an spherical aluminum-oxide inclusion, the deviation of the equivalent stress profile (dashed lines) compared to the profile as valid for an ideal inclusion free material (thin lower line) is shown. If all maximum stresses in the vicinity of inclusions at different depths are connected by an enveloping curve (thick upper line), the risk potential of inclusions according to their location will be determined. In the figure the depth $z$ is related to the half width $b$ of the contact area in rolling direction, all stresses are related to the Hertzian pressure $P_0$.

From fig. 4 the following conclusions can be drawn. Due to the randomly distributed presence of inclusions in steel the depth of the maximum material stress is closer to the surface as determined today by the classical theory, which does not take inclusions into account. If inclusions are considered, the maximum equivalent stress is greater. The location of crack initiation is shifted towards the surface. Thus, the endurance limit and time to crack initiation is decreased if inclusions are present.

### RESIDUAL STRESSES

The role of residual stresses in rolling contact has been widely discussed [15-21]. To determine the influence of residual stresses on material stresses in rolling contact on principle a homogeneous residual stress pattern is superposed to the stresses resulting from external load. The residual stress pattern is described in relation to the Hertzian pressure $P_0$. The values of the residual stresses in $x$- and $y$-direction (directions parallel to the contact surface) are set equal and constant. The residual stresses in $z$-direction (perpendicular to the surface) are negligible and set to zero.

Taking into account different amounts of compressive residual stresses fig. 5 to 8 show the risk potential of inclusions depending on their location $y/b$ (rolling direction) and $z/b$ (depth). Similar to the enveloping curve in fig. 4 the shown areas in the fig. 5 to 8 connect the maximum equivalent stresses in the vicinity of inclusions at the respective locations. Without any residual stresses the maximum equivalent stress appears at certain depth below the center of the contact area (fig. 5). With residual stresses the material stresses below the contact area are decreased except in the vicinity of the surface (fig. 6 to 8). Further, an increase in the equivalent stress in a shallow depth shortly before and after the contact area could be found.

If the compressive residual stresses are about 15% of the Hertzian pressure the lowest equivalent stress will be achieved (fig. 6). If the compressive residual stresses exceed this ratio the equivalent stress will increase again. Furthermore, if the movement of the
The presence of non-metallic inclusions influences material behaviour in rolling contact fatigue in two ways. First, the cohesion of the steel matrix is weakened due to the presence of the phase boundaries between the matrix and the inclusions. Second, the stress state around inclusions is influenced in a way that the material stress is significantly increased. This increase results partially from residual stresses formed during cooling due to a lower thermal expansion of the inclusion compared to the matrix. Furthermore the differences in deformation behaviour between inclusions and the matrix causes an internal notch effect. As was shown, this notch effect leads to an increase of the material stress independent of the properties of the inclusions, regardless of whether the inclusions are stiffer or more pliable than the matrix.

The increase in material stress due to inclusions can be expressed as the ratio between the maximum equivalent stress in the vicinity of an inclusion and the equivalent stress at the same point if no inclusion would be present. This ratio is dependent on the multiaxiality of the stress state as it would appear in the inclusion free material. If this stress state is uniaxial, the ratio – it can be called notch factor of the inclusion – is only a marginally greater than one. With increasing multiaxiality this notch factor also increases very significantly.
From these effects some important general influences of inclusions on the material behaviour in rolling contact fatigue can be concluded. The material stress is higher and the maximum stress is closer to the surface than predicted from classical theory. Thus endurance limit, life time and location of failure initiation are strongly influenced by inclusions. These results give an explanation for many discrepancies between failure analysis of bearings and failure prediction according to the classical theory of Hertzian contact.

The correct prediction of the influence of residual stresses significantly depends on the correct assessment of the notch effects of inclusions. According to these reflections compressive residual stresses of about 15% of the applied Hertzian pressure will bring the most benefit in fatigue behaviour till crack initiation. If the amount of compressive residual stress significantly exceeds this value a detrimental effect is predicted.

REFERENCES


