A CONSERVATIVE APPROACH TO PREDICT THE CONTACT FATIGUE BEHAVIOR OF SINTERED STEELS

A. Molinari, I. Metinöz, I. Cristofolini

Abstract

A conservative approach to predict the Contact Fatigue behavior of porous Powder Metallurgy steels is proposed. It is based on the assumption that the contact fatigue crack nucleation is anticipated by the local plastic deformation of the material, which occurs when the maximum local stress exceeds the yield strength of the matrix. A model to predict contact fatigue crack nucleation has been developed and validated by experiments. A local approach is used, based on the characteristics of the largest pores, which promote fatigue crack nucleation, and on the microhardness of the microstructural constituents where they are localized.

Keywords: contact fatigue, crack nucleation

INTRODUCTION

Contact fatigue is a well known failure mechanism for Powder Metallurgy components subject to cyclic contact stresses. The crack nucleates in the subsurface layers and propagates under the cyclic loading, leading to the production of debris [1-5]. Crack nucleation is anticipated by local plastic deformation; therefore in absence of such a deformation, the fatigue cracks will not nucleate [6]. A conservative approach to predict the contact fatigue resistance may be developed based on this assumption. Such an approach is conservative since it does not consider the eventuality that the nucleated crack does not propagate within the working life of the component in defining safe working conditions.

Plastic deformation occurs when the maximum local stress exceeds the yield strength of the matrix. Both the maximum local stress and the yield strength of the matrix depend on the peculiar characteristics of sintered steels: porosity and the inhomogeneous microstructure resulting from the use of diffusion bonded powders. Pores reduce the fraction of the load bearing section; moreover they and their clusters are the preferred sites for crack initiation in mechanical fatigue [7-9], due to the raise of the local stress, which depends on the pores size and morphology [10]. The same effect may be expected in contact fatigue. Microstructural inhomogeneity results in inhomogeneous distribution of the local strength of the matrix. These two characteristics have to be introduced in the theoretical model: porosity through the fraction of the load bearing section, the microstructural inhomogeneity through the microhardness of the various microstructural constituents.

The present study considers two typical sintered steels widely used for the production of mechanical components: Fe-4Ni-0.5Mo-1.5Cu-0.5C and Fe-1.5Mo-2Cu-0.65C, the former through hardened and the latter sinterhardened. The model was developed by considering both an averaged approach and a local approach, considering the either the mean mechanical properties of those of the microstructural constituents where the larger pores are localized. Lubricated rolling-sliding tests were carried out to validate the model.

Alberto Molinari, Ibrahim Metinöz, Ilaria Cristofolini, Department of Industrial Engineering, University of Trento, Trento, Italy

EXPERIMENTAL

The Model

Plastic deformation occurs when

$$\sigma > \sigma_{y0} \quad (1)$$

where σ is the maximum local stress and σ_{y0} is the yield strength of the matrix.

The maximum local stress is calculated from the maximum shear stress τ_{max} through by equation (2) [11]

$$\sigma = \tau_{max}\beta_k/\Phi \quad (2)$$

where β_k is the notch effect coefficient and Φ is the fraction of load bearing section.

The maximum shear stress τ_{max} is calculated from the Hertzian theory of the elastic contact between cylinders [12, 13], taking into account the effect of porosity on the elastic properties (Young modulus and Poisson coefficient) of the sintered steels.

The notch effect coefficient β_k is calculated by equation (3) [11]:

$$\beta_k = (K_t - 1)\eta + 1 \quad (3)$$

where K_t is the shape coefficient of pores, that is about 3 [11], and η is a coefficient that depends on the microstructure of the matrix and is 0.7 for heat treated steels [11]. The fraction of load bearing section may be calculated from porosity [14-16], from the elastic modulus [17], from the extension of the fractured areas on the fatigue or low temperature impact fracture surfaces [18]. Here, the method proposed in [19] that calculates Φ from the fractional porosity ε and the shape factor of pores f_{circle} through eq. (4), was used:

$$\Phi = [1 - (5.58 - 5.7\, f_{circle})\, \varepsilon]^2 \quad (4)$$

where

$$f_{circle} = 4\pi A/p^2 \quad (5)$$

A and p are the area and the perimeter of the pores, respectively, and are measured by Image Analysis of the metallographic sections. Since fatigue crack nucleates in correspondence of the larger and more irregular pores, only the larger pores corresponding to 10% of the whole of the population were considered.

According to Bell and Sun [20], the matrix yield strength σ_{y0} may be obtained from microhardness μHV using equation (7)

$$\sigma_{y0} = \mu HV/B \quad (6)$$

where B is a constant that in case of heat treated steels is 4.2.

Validation of the model

The model was validated by carrying out contact fatigue tests on two common sintered steels produced using diffusion bonded powders: Fe-4Ni-0.5Mo-1.5Cu-0.5C and Fe-1.5Mo-2Cu-0.65C. The rings for contact fatigue tests (10 mm height, 40 mm external diameter, 16 mm internal diameter) were uniaxially cold compacted and:

- Fe-4Ni-0.5Mo-1.5Cu-0.5C was sintered at 1150°C, through hardened and stress relieved at 200°C;
- Fe-1.5Mo-2Cu-0.65C was sinterhardened at 1150°C and stress relieved at 200°C.

Final density was 7.3 g/cm^3. The production process was carried out on industrial plants.

Lubricated rolling-sliding tests were carried out on an Amsler tribometer at room temperature, against an AISI M2 tool steel (65 HRc) as counterface material. The rotation speed of the sintered and of the counterface disks were 400 rpm and 360 rpm, respectively, which gives rise to a 10% sliding. Lubrication was provided by a chain that conveyed oil in the contact region from a receptacle. Tests were stopped after 10^6 cycles and the presence of contact fatigue cracks was verified by metallographic analysis of the cross sections at the light optical microscope.

Figure 1 shows the results of the tests and of the calculation in case of the heat treated Fe-4Ni-0.5Mo-1.5Cu-0.5C steel at a mean Hertzian pressure P_0 = 0.6 GPa. The fraction of the load bearing section is 0.62.

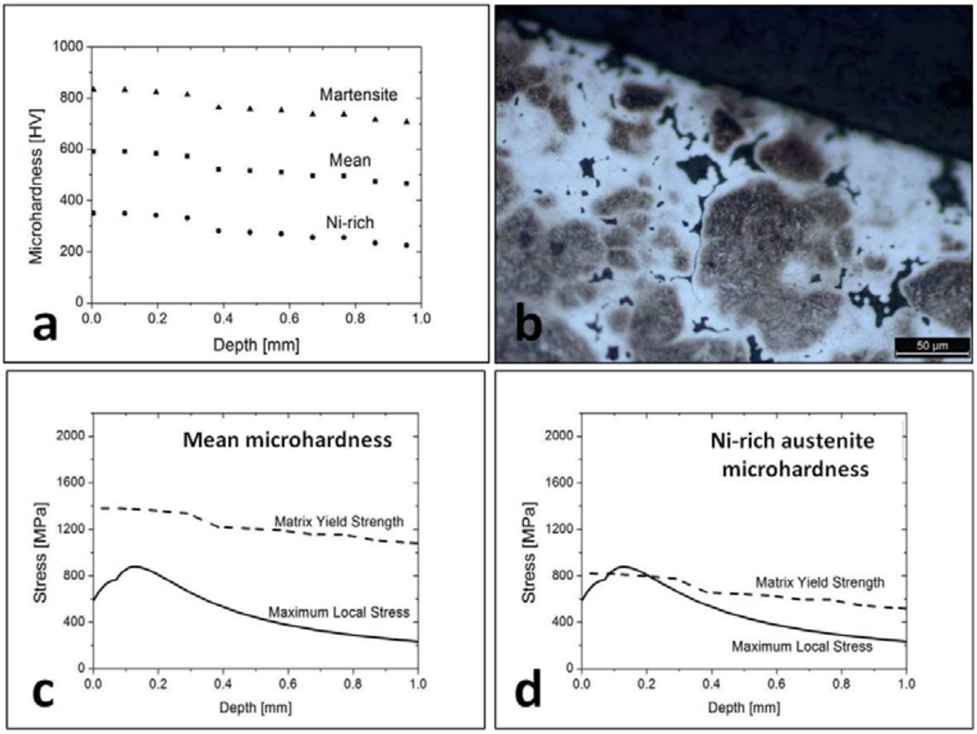

Fig.1. Microhardness profile (a), microstructure of the tested specimen (b), profile of maximum local stress and of matrix yield strength calculated from the mean microhardness (c) and from the microhardness of Ni-austenite (d) for heat treated Fe-4Ni-0.5Mo-1.5Cu-0.5C steel at P_0 = 0.6 GPa.

Since microstructure comprises martensite and Ni-rich austenite, the microhardness profiles relevant to the two constituents and the mean one are shown in Fig.1a. The model does not predict plastic deformation if the matrix yield strength is calculated from the mean microhardness (Fig.1c), but cracks are clearly observed in the ring after the contact fatigue test, as shown in Fig.1b. Since the large pores are surrounded by the Ni-austenite, the matrix yield strength was calculated from its microhardness, and the resulting comparison with the maximum local stress is shown in Fig.1d. Here, yield strength is lower than the maximum local stress at a depth between 0.1 and 0.2 mm, where cracks are actually observed. The model predictions are therefore confirmed by experiments only if the calculation is made with a local approach that considers the microstructural constituents where pores responsible for the crack nucleation are localized as representative of the metallic matrix of the material.

Figure 2 shows the same results as Fig.1 for the sinterhardened Fe-1.5Mo-2Cu-0.65C steel at a mean Hertzian pressure P_0 = 1 GPa. The fraction of the load bearing section is 0.59.

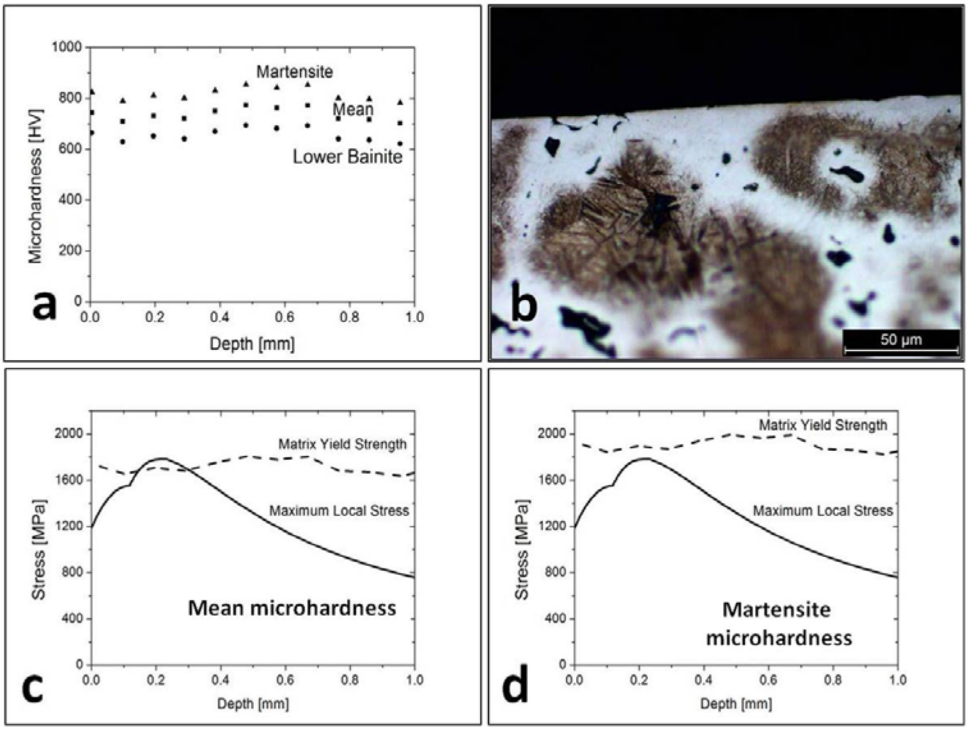

Fig.2. Microhardness profile (a), microstructure of the tested specimen (b), profile of maximum local stress and of matrix yield strength calculated from the mean microhardness (c) and from the microhardness of martensite (d) for sinterhardened Fe-1Mo-2Cu-0.65C steel at P_0 = 1 GPa.

In this case microstructure comprises lower bainite and martensite, the later being significantly harder as shown in Fig.2a. The model based on the mean microhardness (Fig.2c) predicts local plastic deformation, and in turn the nucleation of the contact fatigue crack at a depth between 0.15 and 0.3 mm from the surface. However, no cracks are observed in the tested specimen (Fig.2b). In this material the larger pores are surrounded by martensite (white constituent in the microstructure); therefore the local approach has to consider its microhardness in calculating the matrix yield strength. The resulting prediction is shown in Fig.2d: in the whole of the layer considered the matrix yield strength is higher than the maximum local stress, in agreement with the experimental results.

Using the local approach, the resistance to contact fatigue of the two materials was calculated, obtaining 0.55 GPa and 1.1 GPa for the two materials, respectively. These values were confirmed by experimental tests.

Influence of density

Density influences the contact fatigue behaviour through its effect on:

1. the fraction of the load bearing section, that increases on increasing density;
2. the elastic properties that increase on increasing density, resulting in an increase in the Hertzian stresses and, in turn, in the maximum local stress.

The former effect increases he resistance to contact fatigue while the latter is expected to have a negative influence.

The fraction of the load bearing section and the elastic modulus E of the sinterhardened Fe-1Mo-2Cu-0.65C steel in the density range 6.0-7.3 g/cm^3 are reported in Table 1: fractional porosity was calculated from theoretical density while E was taken from technical publications of the powder producer.

Tab.1. Fractional porosity, fraction of the load bearing section and elastic modulus of sinterhardened Fe-1Mo-2Cu-0.65C steel in the density range 6.0-7.3 g/cm^3.

Density [g/cm^3]	ε	Φ	E [GPa]
6.8	0.115	0.30	125
6.9	0.108	0.32	130
7.0	0.099	0.35	135
7.1	0.088	0.40	140
7.2	0.075	0.45	145
7.3	0.061	0.52	150

The theoretical predictions are reported in Fig.3 at two mean pressures: 0.6 GPa and 1.0 GPa.

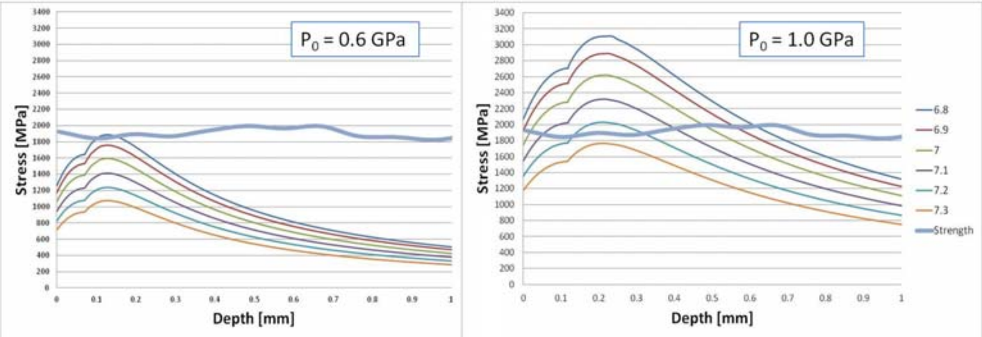

Fig.3. Theoretical prediction of the effect of density on the contact fatigue resistance of the sinterhardened Fe-1Mo-2Cu-0.65C steel at 0.6 GPa and 1.0 GPa mean pressure.

The increase in density increases the resistance to contact fatigue that means that the effect of density on the fraction of the load bearing section prevails on that on the Hertzian stress. This conclusion finds confirmation in the whole of the literature on the subject. Moreover, figures show that in case of a mean pressure of 0.6 GPa, density might be decreased down to 6.9 g/cm^3 without promote the nucleation of the contact fatigue crack. It's interesting the comparison with the other steel considered in the present work: the 7.3 g/cm^3 through hardened Fe-4Ni-0.5Mo-1.5Cu-0.5C steel fails at 0.6 GPa, while the Ni-free sinterhardened Fe-1Mo-2Cu-0.65C steel survives the same mean pressure with a much lower density. This great difference is simply due to the microstructure of the two materials, and in particular to the different condition in terms of localization of the larger pores responsible for the nucleation of the fatigue crack: in a soft constituent in Fe-4Ni-0.5Mo-1.5Cu-0.5C and in the harder constituent in Fe-1Mo-2Cu-0.65C.

At the higher mean pressure, even a slight decrease of density is enough to establish the local conditions favourable to plastic deformation and, in turn, to the nucleation of the contact fatigue crack.

These predictions were verified experimentally, confirming the validity of the theoretical model.

CONCLUSIONS

A conservative approach to predict the contact fatigue behaviour of two different sintered and heat treated steels was proposed, based on the nucleation of the fatigue crack. The nucleation of the fatigue crack is anticipated by the local plastic deformation of the material and may be predicted by comparing the maximum local stress and the yield strength of the matrix. The model was verified with experimental data from contact fatigue tests.

The model predicts fatigue crack nucleation provided that a local approach is used, which considers the larger pores to calculate the fraction of the load bearing section and the mechanical properties of the microstructural constituents where they are localized to calculate the yield strength of the matrix. With such an approach, the great difference between the contact fatigue resistance of a Ni-free and a Ni-alloyed steel, that was experimentally verified, finds a theoretical justification. Indeed the large pores in the Ni alloyed steel are localized in the Ni-rich austenite, which is the softer microstructural constituent, leading to a localized plastic deformation for a lower Hertzian stress than in case of the Ni-free steel. Through the model, the effect of density on the contact fatigue behaviour of the Ni-free steel was theoretically estimated.

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