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The effect of hardness distribution by carburizing on the elastic–plastic contact performance

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ABSTRACT

This paper aims to investigate the effect of the hardness distribution by carburizing on the contact behaviors. A developed elastic–plastic contact model based on a semi-analytical method is used. The effect of hardness on elastic–plastic contact behaviors is considered by means of the linear hardness-yielding strength relationship. Different hardness distributions are considered to simulate the possible results obtained in heat treatment. The results show that the hardness distribution and carburizing time/case depth have different influence on the plastic strain under different loads and roughness, while its influence on the maximum contact pressure and contact area ratio is very limited.

1. Introduction

Surface heat treatment is a technology to change the surface hardness of metal by heating and cooling on the surface. It has been used widely in the industrial production. As one of common surface heat treatments, carburizing is a process which increases the hardness by increasing the carbon content in the neighbor of the function surface of steel elements. Suh et al. pointed out that [1] after being carburized, the work pieces have a harder surface on a ductile core. The hard surface enables the elements have a good wear resistance; furthermore, the compressive stress generated in the hardened surface layer will enhance fatigue resistance. Tsujikawa et al. [2] investigated the effect of molybdenum in hardening on low-temperature plasma carburized layer of austenitic stainless steel; they found that the higher hardness of plasma carburized AISI316 steel results from the higher amount of supersaturated carbons. Adachi et al. [3] also investigated the low-temperature plasma carburizing; they found that the Vickers hardness of the carburized spray coating can be up to 1000 HV. The low-temperature plasma carburizing enables the sprayed coatings to have the higher wear resistance and slightly lower corrosion resistance.

The carburized case depth is an important index to estimate the carburizing process. Genel et al. [4] and Asi et al. [5] pointed out that carburization can improve the fatigue life of mechanical components. However, Preston [6] pointed out that the improvement in fatigue strength due to the case depth is limited, because the larger case depth will reduce the residual compressive stress which is important to restrain the crack ignition and growth at the surface. Genel and Demirkol [4] also concluded that the case depth should not exceed the limiting value, if the risk of easy crack initiation and growth was considered. That is to say, the case depth cannot be too deep or shallow; so it is necessary to find out an appropriate case depth in practical engineering. Cahoon et al. [7] and Pavlina et al. [8] gave the relationship between the hardness value and yield strength through curve-fitting based on a lot of experimental measurements, and most researches showed that they are in approximately linear relationship.

Most researches on this topic were conducted based on experiment, which is time-consuming and expensive. If the relationship between yielding strength and hardness is obtained, it can also be investigated by means of numerical calculation based on deliberate elastic–plastic contact model. During the past decades, great progress has been made on the modeling of contact problem. Basically, there are mainly two kinds of models, the statistical model and the deterministic model. The statistical model is mainly concentrated on the statistical parameters; however, the interactions between the asperities are always ignored. A lot of researchers conducted significant works on the statistical model, such as the Greenwood et al. [9], Chang et al. [10] and Zhao et al. [11]. The deterministic model can fully consider the interaction between the asperities, such as the finite element analysis (FEA) and semi-analytical method (SAM). Kucharski et al. [12] gave the empirical relationship between the contact load and the contact area for the rough surface based on FEA. Liu et al. [13] analyzed the elastic–plastic line-contact problems for rough

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Nomenclature

a	Hertzian contact radius
b	Coefficient, equal to $\frac{\ln[(H_{\max}-H_{\text{material}}+t)/t]}{d}$
d	case depth
E	Young's modulus
g, $\mathbf{g}$	surface gaps
$\mathbf{h}$	geometrical interference
$\mathbf{h}_0$	initial body separation
H	hardness
H_{material}	the hardness value of substrate material
$H_{\max}$	the hardness value of surface
$\mathbf{k}$	influence coefficient relating the pressure to the surface displacement
m	Meyer's hardness coefficient
p, $\mathbf{p}$	contact pressure
p_H	maximum Hertzian contact pressure
R	radius of ball
t	coefficient to obtain different hardness distributions
u^e, $\mathbf{u}_e$	elastic deformation
u^p, $\mathbf{u}_p$	surface residual displacement
W	applied load
x, y	coordinates
z	the coordinate along the depth
$\boldsymbol{\delta}$	the approach between two rigid surfaces
$\boldsymbol{\varepsilon}^p$	plastic strains
ν	Poisson's ratio
$\boldsymbol{\sigma}^0$	applied stress
$\boldsymbol{\sigma}^p$	residual stress
σ_y	yield strength

surfaces; the contact pressure, contact area, and average gap of real rough surfaces under the elastic, elastic-perfectly plastic, and the elastic–plastic contact conditions were numerically investigated in their study. Kogut et al. [14], Jackson et al. [15] used the ANSYS™ to solve the elastic–plastic contact problem of a sphere and a rigid flat. The relationship between the interference and contact area and pressure were simulated in order to use in other applications.

In recent years, with the development of computer technology, the SAM has attracted researchers' attention in solving the contact problem, due to its efficiency and robustness. The presence of discrete convolution–Fast Fourier transform (DC–FFT) by Liu et al. [16] greatly speeds up the calculation involved in contact problem, such as elastic deformation [17], stress distribution, etc. For the elastic contact, Polonsky et al. [18] developed an efficient conjugate gradient method (CGM) based approach, which has a good convergence for arbitrary rough surface. For the plastic contact, Chiu [19,20] firstly derived the closed-form solution to the problem in infinite space and half-space with an initial uniform strain, which was the base of later related works. However, its practical use in contact problem appeared until the work by Jacq et al. [21], who gave the analytical expressions for stress calculation based on the initial work of Chiu. In the later years, some significant works for the elastic–plastic contact problem based on the SAM have been conducted by Jacq te al. [21], Boucly et al. [22], Nélias et al. [23,24], Chen et al. [25,26], Wang et al. [27,29], Kim et al. [28] and Zhang et al. [30]. In order to apply the SAM to the contact problem effectively and accurately, recently, Liu et al. [31,32] derived the analytical influence coefficients relating the unit eigenstrain to the eigenstress and displacement in the half-space.

In most elastic–plastic contact analysis, the effect of hardness on contact performance was not considered; however, hardness significantly affects the yielding strength of material, and for the carburization or other surface heat treatment, the hardness always changes with the depth, which will change the yielding strength resulting in change of contact behaviors. Besides, for engineering application, engineers wish to know reasonable hardness distribution for specific application, as modern techniques can adjust hardness distribution during the process of heat treatment. In this paper, different hardness distributions along the depth are considered and its effect on the yielding strength is considered based on the relationship proposed by Cahoon et al. [7]. A developed SAM model is used to solve the elastic–plastic problem for rough surface with the consideration of hardness. The Fast Fourier transformation (FFT) algorithm is used for high computation efficiency and accuracy. In order to figure out the reasonable hardness distribution through heat treatment, the equivalent plastic strain, maximum contact pressure and contact area ratio are analyzed specially.

2. Hardness simulation

In the present study, the material is assumed to obey the isotropic linear hardening law and be elastic-perfectly plastic. This assumption enables the stress–strain relationship to follow the Hooke's Law in the initial elastic zone; and when the stress reaches the yielding stress, although plastic strain will further increases, the stress is always equal to yield stress. The yield strength and hardness are proven to have an approximately linear relationship [7,8]. Cahoon et al. [7] proposed the following relationship by summarizing experimental results for many materials:

$$\sigma_y = \frac{H}{3}(0.1)^{m-2} \tag{1}$$

where σ_y (kg/mm^2) is the yield strength; H is the Vickers hardness, and unit is kg/mm^2; m is the Meyer's hardness coefficient, and $m-2=0.14$ is used in this paper. In the present model, the relationship (1) is used to obtain the yield strength from hardness. For the carburizing treatment, the hardness is maximal on the surface and gradually decreases with the distance from the surface. Three kinds of hardness distributions are designed against the distance from the surface: concave, linear and convex distributions, which are formulated by the following equations:

concave:

$$\begin{cases} H = H_{\text{material}} + t\exp[b(d-z)] - t & z \le d \\ H = H_{\text{material}} & z > d \end{cases} \tag{2}$$

linear

$$\begin{cases} H = H_{\max} - z * (H_{\max} - H_{\text{material}})/d & z \le d \\ H = H_{\text{material}} & z > d \end{cases} \tag{3}$$

convex:

$$\begin{cases} H = H_{\max} - t\exp(bz) + t & z \le d \\ H = H_{\text{material}} & z > d \end{cases} \tag{4}$$

where $H_{\max}$ is the hardness value at surface; H_{material} is the hardness value of substrate material; d is the case depth; z is the coordinate along the depth; t is the constant coefficients to obtain the different distributions. To guarantee the continuity of the piecewise curves in Eqs. (2) and (4), b is equal to $\frac{\ln[(H_{\max}-H_{\text{material}}+t)/t]}{d}$.

Three kinds of hardness distribution along the depth direction are shown in Fig. 1. The coefficient t is set as 200. The case depth

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