Modeling of Repeated Rolling Contact on Rough Surface: Surface Topographical Change

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Abstract. An finite element analysis (FEA) of a repeated rolling contact over an elastic-plastic deforming rough surface is performed. The surface topographical change is calculated to determine the running-in phase to the steady-state rolling contact situation. A rigid hemisphere is repeatedly rolled over a rough flat aluminum surface and the effect of the contact load and the number of overrollings is studied. It is found that the change in surface topography due to the repeated rolling contact results in smoothening of the rough surface due to the flattening of the highest asperities. The result shows that the running-in of the repeated rolling contact takes place within the first few overrollings.

Introduction

The study of the rolling contact problem has special interest in the field of mechanical engineering and computational mechanics due to its application for mechanical elements under rolling contact motion, such as rotary machine components, bearings and rollers. Investigations on the rolling contact problem have been conducted by many researchers, e.g. analytical by Kalker \cite{1}, with a semi-analytical model (SAM) Nelia et al. \cite{2}, numerically Bhargava et al. \cite{3} and Jiang et al. \cite{4} and a numerical and experimental study by Popescu et al. \cite{5}. However, there are only a few publications \cite{1-5} discussing the repeated rolling contact situation dealing with a real rough surface and considering elastic-plastic deformation. Most of the repeated rolling models available in literature are devoted to rolling bodies over a flat surface and are focused on rolling contact fatigue, contact pressure, residual stress and plastic strain.

The running-in phase is a transient phase, where the surface topographical change between two fresh and unworn surfaces which are in contact, vary considerably in time. During this phase the surface characteristics of the components are adjusted, in general the higher asperities are truncated, the coefficient of friction strongly decreases, the center line average roughness ($R_a$) decreases and average contact area increases \cite{6}. Therefore, investigation the change in micro geometry of the surface is an important factor in determining the life of mechanical components.

Jamari \cite{7} introduced an analytical model to be able to predict the asperity change due to (local) elastic-plastic deformation during the running-in phase of rolling contacts. He proposed a deterministic contact model \cite{8} based on the elastic-plastic ellipsoid contact model \cite{9} to predict the plastic deformation of the asperities and change in surface topography. A good agreement was found with the performed experiments \cite{7}. However, with the availability of user-friendly, commercial FEA software packages, the application of FEA is quite effective for an alternative solution to reduce the experimental investigation. This paper studies finite element analysis (FEA) of a repeated rolling contact on an elastic-plastic deforming rough surface with respect to the surface topographical change of the rough surface.
Methodology

**Finite Element Model.** Finite element modeling in the present work is performed with a commercial FEA software package, ABAQUS 6.11 [10]. A rigid hemisphere is rolled over a rough surface (Fig.1a) to observe the surface topographical change and the elastic-plastic deformation due to repeated overrolling. A rigid ball, with \( R = 5 \) mm, is rolled over a rough aluminum surface with elastic-perfectly plastic material behavior. The present model uses a real rough surface obtained from Jamari’s experiment [7]. The mechanical properties of the aluminum in these simulations: elastic modulus \( (E) \), yield strength \( (\sigma_Y) \) and Poisson’s ratio \( (\nu) \) are 75.2 GPa, 85.72 MPa and 0.34 respectively.

Figure 1(b) depicts the mesh details of the rough surface using 24281 Tetrahedron elements [10]. For increasing the calculation accuracy of the parameters studied, a refined mesh, with an element length of 8.8 \( \mu \)m, is applied along the rolling path of contact. A coarser mesh is applied to the part of rough surface with further distance from the rolling path to reduce the simulation time.

![Figure 1](image.png)

**Figure 1.** (a) The schematic illustration of the rolling contact simulation of a rigid hemisphere on a rough flat surface and (b) the mesh generated representing the rough surface.

**Modeling procedures.** The present simulation is developed from the previous studies using a two-dimensional model for the artificial rough surface [11-12]. The modeling procedure of the present simulation is conducted as follows: (i) the ball is pressed on the rough surface with a normal force; (ii) the ball is rolled along the rolling path while maintaining the contact load as depicted in Fig. 1(b); (iii) the ball is unloaded after reaching the end of the track. Three normal forces \( (F_N) \) are used to simulate the severity of the contact, namely 0.05 N, 0.5 N and 5 N. The rolling contact simulation is repeated three times. Free rolling is assumed in these simulations and friction is neglected. The plastic deformation of the asperities as well as the surface topographical change is calculated after the contact is unloaded.

Results and Discussions

**Effect of Contact Load.** In Figs. 2 (a-c), the surface topographical changes of the rough surface along the rolling path are depicted for \( F_N = 0.05 \) N, 0.5 N and 5 N. The change of the surface topography in these figures is given after each overrolling. The dash line indicates the original surface topography whereas the solid line indicates the deformed surface topography due to the rolling contact. The number of overrollings is indicated as \( n \). In Fig. 2(a) where a contact load of 0.05 N was applied, the final surface topography does not alter after the three overrollings. It indicates that the asperities A, B and C mainly deform elastically. In Fig 2(b), a modest change of the surface topography occurs on asperity C (the highest asperity) whereas on the two previous asperities (asperity A and B) no change of the surface topography takes place. A significant change of the surface topography is shown in Fig 2(c) and depicts that plastic deformation is observed for the three asperities (asperity A, B and C). The highest truncation is received for asperity C.
Figure 2. Surface topographical change on the rough surface during repeated rolling contacts for (a) $F_N = 0.05$ N, (b) $F_N = 0.5$ N and (c) $F_N = 5$ N.

Figure 3. The change of the asperities height (asperity A, B and C) during repeated rolling contact for $F_N = 5$ N.

Effect of Repeated Contact. The discussion of the effect of repeated contact is focused on Fig 2(c) for $F_N = 5$ N. It can be seen that most of the plastic deformation takes place during the first rolling cycle and followed by some additional plastic deformation due to the second and third overrolling. Figure 3 shows the change of the height of the asperities during the three overrollings. Based on the results found one may conclude that the steady-state plastic deformation is reached and the transition of the running-in phase to the steady-state phase of the rolling contact occurs within two to three cycles. This conclusion is in good agreement with the experiments and model of Jamari [7]. Figure 4 shows the surface topographical change and plastic deformation and of aluminum rough surface during repeated moving contact [7]. Figure 4(a) depicts a high plastic deformation for $n = 1$ and Fig 4(b) depicts the steady-state plastic deformation where a negligible change in surface topography is found for $n = 3, 4$ and 5.
Figure 4. Surface topographical change and plastic deformation of aluminum surface for (a) \( n = 1 \) and (b) \( n = 3, 4, \) and 5.

Summary

In this work, the repeated rolling contact of a rigid ball over a 3-D rough surface is simulated using finite element analysis. The simulations were performed for several contact loads, (i.e. 0.05 N, 0.5 N and 5 N) for investigating the changes in surface topography of the rough surface. The rough surface is mainly deformed elastically and resulted in a negligible topographical change of the rough surface for \( F_N = 0.05 \) N and 0.5 N. For \( F_N = 5 \) N, a significant change in surface topography due to repeated overrolling along the rolling path is observed. The observation shows that the steady-state plastic deformation of rolling contacts takes place within the first few cycles.

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