

Elastic-Plastic Indentation and Flat Plate Rolling under Plane Strain Conditions

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ABSTRACT

In this paper, residual stresses due to single indentation and rolling on a finite plate at very high rolling loads are investigated by two-dimensional plane strain finite element analyses using ABAQUS. In the finite element analyses, the roller is modeled as rigid and has frictionless contact with the finite plate. The plate material is modeled as an elastic-plastic power-law strain hardening material with a non-linear kinematic hardening rule for loading and unloading. For indentation and rolling at high rolling loads with extensive plastic deformation, the computational results show that the contact pressure distributions are quite different and they are also significantly different from the elastic Hertzian pressure distribution. The computational results for the rolling case show a significantly higher longitudinal compressive residual stress and a lower out-of-plane compressive residual stress along the contact surface when compared to those for the single indentation case. The results suggest that the effects of rolling must be accounted for when two-dimensional finite element analyses of crankshaft sections are used to investigate the residual stresses due to fillet rolling of the crankshafts under prescribed loading conditions.

INTRODUCTION

For automotive crankshafts, fatigue damages are initiated near the fillets due to stress concentration. The fillet rolling process has been used for years to introduce compressive residual stresses near crankshaft fillets and, consequently, to improve fatigue strengths of crankshafts [1,2,3]. During the rolling process, the material near the roller is loaded into plastic range. Once the rolling load is removed, compressive residual stresses are induced. The residual stresses can significantly affect the fatigue lives of the crankshafts under high cycle fatigue loading conditions. Therefore,

understanding the residual stresses near crankshaft fillets are important. Previously, researchers estimated the residual stresses near crankshaft fillets either using two-dimensional or three-dimensional finite element analyses [2, 3, 4, 5, 6, 7, 8]. Chien et al. [4] conducted two-dimensional elastic-plastic finite element analyses of crankshaft fillet rolling to estimate the residual stresses. They also investigated the behavior of crack initiation and growth near crankshaft fillets with consideration of residual stresses based on linear elastic fracture mechanics. Chien et al. [4] used the rolling depth of crankshaft fillets after the unloading of the roller as the calibration parameter in their two-dimensional finite element analyses. The rolling depth was determined by the fillet surface profiles obtained from the shadowgraphs taken before and after the fillet rolling process. Spiteri et al. [2] examined the bending fatigue limit of crankshaft sections with consideration of residual stresses based on the results of three-dimensional finite element analyses. Most of the previous analyses for the fatigue behavior of crankshaft sections are based on the residual stresses from single indentation of rollers. Spiteri et al. [2] showed the subsurface axial stress distributions due to single indentation and rolling of a disk based on plane strain finite element analyses. However, the effects of single indentation and rolling on the circumferential and out-of-plane stress components have not been explained in details.

Numerous studies were conducted to understand the stress distributions and deformation patterns near rolling contact surfaces. Researchers mainly conducted indentation and rolling contact analyses to examine the stress-strain histories near the contact surfaces. Some of the previous elastic-plastic analyses were on the indentation of elastic-plastic half spaces using rigid spheres. Mesarovic and Fleck [9] conducted finite element analyses of the normal indentation of an elastic-plastic half-space by a rigid sphere. Indentation maps were

constructed with axes of contact radius a (normalized by the indenter radius R) and the yield strain of the half-space. Kral et al. [10] investigated the elastic-plastic contact problem of a rigid sphere indentation of a homogeneous half-space using finite element analyses. The rigid sphere with a radius of 1.5 mm was modeled by contact elements. The results for the contact pressure, surface and subsurface stresses, initiation and growth of the plastic zone, and yielding of the half-space during unloading were presented. The results for the indentations with loads up to 300 times the load necessary for the initial yield were obtained on materials with different elastic and plastic properties. It was shown that the resulting pressure distributions are significantly different from the Hertzian pressure distribution. Komvopoulos [11] analyzed the plane-strain indentation of a layered half-space by a rigid cylinder using contact elements instead of an assumed distribution of the surface tractions or the displacements on the contact surface. It was shown that the pressure distribution is considerably different from the Hertzian pressure distribution, particularly for stiff and relatively thick layers and/or under large plastic deformation.

Several previous elastic-plastic analyses of rolling were based on translating a Hertzian [12, 13, 14, 15, 16] or modified Hertzian pressure distribution [17,18] across the surface of an elastic-plastic half space. Merwin and Johnson [12] analyzed the plane-strain rolling of a rigid cylinder on a half-space. Bhargava et al. [17,18] conducted finite element analyses to investigate the plane-strain problem of a cylinder rolling on a semi-infinite body, both for single and multiple passes. They assumed elastic-plastic linear kinematic hardening material behavior and represented the cylinder by a translating Hertzian or modified Hertzian pressure distribution for a maximum p_0/k ratio of 5, where p_0 is the maximum Hertzian pressure and k is the shear yield stress of the material (see Merwin and Johnson [12] and Bhargava et al. [17] for the bounds of characteristic deformation regimes). Yu et al. [15,16] presented an analytical method for elastic-plastic rolling contact and shakedown, and demonstrated its application to obtain steady-state solutions for two- and three-dimensional repeated rolling contact problems. They used a moving Hertzian pressure distribution to simulate the rolling process for a maximum p_0/k ratio of 6. Chen et al. [19] presented a three-dimensional numerical model for simulating the repeated rolling or sliding contact of a rigid sphere over an elastic-plastic half-space for a p_0/k ratio of 5.2. Jiang and Sehitoglu [20] analyzed the residual stresses for the line rolling contact problems utilizing an analytical approach in conjunction with a new plasticity model for p_0/k ratios ranging from 5 to 9. Jiang et al. [21] also conducted three-dimensional elastic-plastic rolling analyses incorporating elastic and plastic shakedown concepts for a p_0/k ratio of 6. For both cases, a prescribed Hertzian pressure distribution was traversed over the surface to simulate the loading history experienced by a wheel and rail.

Most researchers used the moving Hertzian pressure distribution to represent the contact pressure for rolling with p_0/k ratios ranging from 5 to 9. Bijak-Zochowski and Marek [22] used elastic rollers with spring contact elements for rolling simulations. They modeled the process of a cylinder running on the strip by finite element analyses, using a program SEGLA developed by the authors. Their work gives good insight on the residual stress distribution in the strip due to rolling. However, the results were obtained for a relatively large wheel radius ($R = 457$ mm) and the normal force corresponding to the average loads values of the train wheel on the track, giving a p_0/k ratio of 4. For the crankshaft rolling, the roller radius is much smaller and the rolling load is high, with a p_0/k ratio of about 22.

This investigation is aimed to quantify the differences between the residual stresses distributions due to single indentation and rolling with very large contact pressure. The rolling model and its boundary conditions are selected for this study to identify whether the results of the finite element analyses for single indentation of crankshaft sections conducted by previous researchers are sufficient to represent the residual stresses distribution for further strength/fatigue analyses by comparing the longitudinal stresses in the rolling direction and the out-of-plane stresses. While a three-dimensional finite element analysis is more appropriate to calculate the residual stresses due to rolling, a two-dimensional model is useful for the initial design iterations.

In this paper, a crankshaft fillet rolling process along the circumference of the main journal is idealized by a two-dimensional flat plate plane strain rolling model with appropriate boundary conditions. The roller is assumed to be rigid and the contact between the roller and the plate is frictionless. The roller load per unit width for the two-dimensional model is computed from the corresponding three-dimensional finite element analysis for single indentation. The plate material is modeled as an elastic-plastic power-law strain hardening material with the non-linear kinematic hardening rule of ABAQUS [23] for loading and unloading. For rolling, a single pass rolling is simulated. The plastic zone development and the residual stress distributions on the plate upper surface and in the subsurface under the roller center induced by the single indentation and the rolling are then compared. Finally, some conclusions based on the results of this investigation will be made.

MODELING PROCEDURES

Figure 1 shows a schematic of a two-dimensional model of a flat plate rolling process. The roller is assumed to be rigid and the contact between the roller and the plate is frictionless. Figure 1 shows the phases of the rolling simulation. Initially, the roller is sitting on the starting position of the flat plate. Then the roller is moved down with a given load. The roller is then moved horizontally to the right by applying both the

translation and rotation. After traveling the full rolling length, the roller is moved up and the rolling is completed.

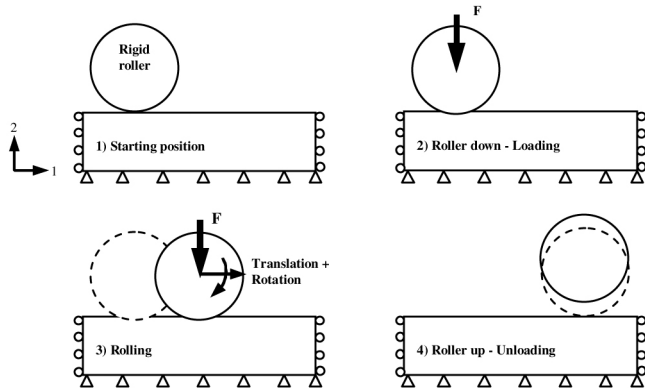


Figure 1. A schematic of a two-dimensional model of a flat plate rolling process. The roller is assumed to be rigid and the contact between the roller and the plate is frictionless.

The finite element analyses were performed using the commercial finite element code ABAQUS. Figure 2(a) shows a two-dimensional finite element model of a rigid cylinder rolling on a finite flat plate. The Cartesian coordinate system is also shown in the figure. Two-dimensional plane strain 4-noded CPE4R elements of size 0.4 mm by 0.4 mm are used in this model. The selection of the sizes of the finite elements to simulate single indentation and rolling follows the guidelines that are established in Ali and Pan [24] and will not be reported here. The diameter of the rigid cylinder (roller) is 14 mm. The bottom of the plate is fixed, and the displacements on both end surfaces AB and CD of the plate in the x direction are constrained. The length of the plate is 300 mm with the rolling start point on the upper surface at $x = 62$ mm and the rolling end point at $x = 216.264$ mm to eliminate possible end effects. One goal of this investigation is to examine the residual stresses in crankshafts after fillet rolling. The total rolling length 154.264 mm and the plate thickness 24.552 mm are corresponding to the circumferential length and the radius of the main journal of a crankshaft of interest, respectively. The primary roller is modeled as a rigid body. The tensile stress-strain curve of the plate material is shown in Figure 2(b). The nonlinear kinematic hardening rule of the ABAQUS is assumed based on the tensile stress-strain curve shown in Figure 2(b).

The nonlinear kinematic hardening rule in ABAQUS is based on the Mises yield function. For the unloading/reloading process, the yield function can be expressed as

$$f(\sigma_{ij} - \alpha_{ij}, \sigma^0) = \left[\frac{3}{2} (\sigma'_{ij} - \alpha'_{ij}) (\sigma'_{ij} - \alpha'_{ij}) \right]^{\frac{1}{2}} - \sigma^0 = 0 \quad (1)$$

where σ_{ij} is the stress tensor, σ'_{ij} is the deviatoric stress tensor, α_{ij} represents the center of the yield surface, α'_{ij} is the deviatoric part of α_{ij} , and σ^0 represents the size of the yield surface. Here, σ'_{ij} and α'_{ij} are defined, respectively, as

$$\sigma'_{ij} = \sigma_{ij} - \frac{1}{3} \sigma_{kk} \delta_{ij} \quad (1a)$$

$$\alpha'_{ij} = \alpha_{ij} - \frac{1}{3} \alpha_{kk} \delta_{ij} \quad (1b)$$

where δ_{ij} is the kronecker delta.

The associated plastic flow is expressed as

$$\dot{\epsilon}_{ij}^p = \dot{\bar{\epsilon}}^p \frac{\partial f(\sigma_{ij} - \alpha_{ij}, \sigma^0)}{\partial \sigma_{ij}} \quad (2)$$

where $\dot{\epsilon}_{ij}^p$ represents the plastic strain rate tensor and $\dot{\bar{\epsilon}}^p$ is the equivalent plastic strain rate defined as

$$\dot{\bar{\epsilon}}^p = \left(\frac{2}{3} \dot{\epsilon}_{ij}^p \dot{\epsilon}_{ij}^p \right)^{\frac{1}{2}} \quad (2a)$$

In ABAQUS, the nonlinear kinematic hardening rule is defined to be an additive combination of a purely kinematic term of the Ziegler linear hardening law and a relaxation term which introduces the nonlinearity. The evolution of α_{ij} is expressed as

$$\dot{\alpha}_{ij} = \frac{C}{\sigma_0} \dot{\bar{\epsilon}}^p (\sigma_{ij} - \alpha_{ij}) - \gamma \dot{\bar{\epsilon}}^p \alpha_{ij} \quad (3)$$

where σ_0 is constant and represents the size of the initial yield surface, α_{ij} represents the center of the yield surface, $\dot{\bar{\epsilon}}^p$ is again the equivalent plastic strain rate, and C and γ are material parameters that must be calibrated from cyclic test data. Here, C is the initial kinematic hardening modulus and γ determines the rate at which the kinematic hardening modulus decreases with increasing plastic deformation. When C and γ are zero, the model reduces to the isotropic hardening rule. When γ is zero, the Ziegler linear hardening law is recovered. Note here that, for the nonlinear kinematic hardening rule of ABAQUS, the option of "HALF CYCLE"

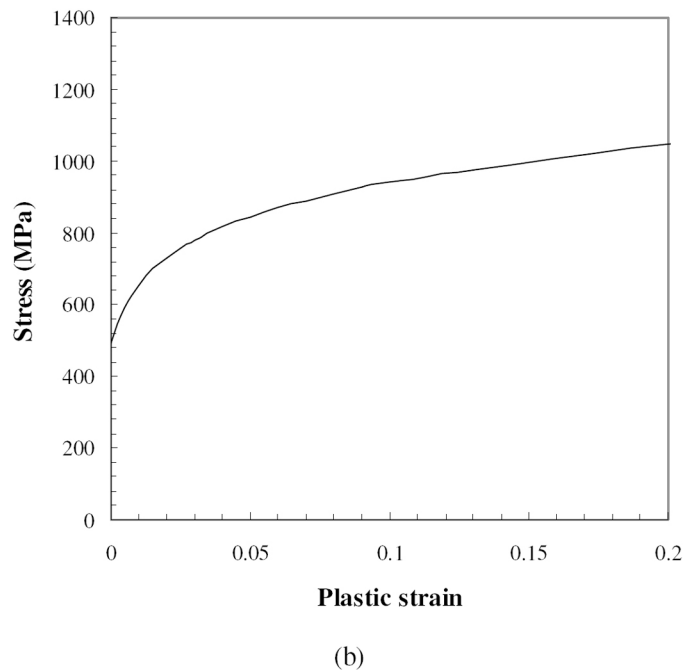
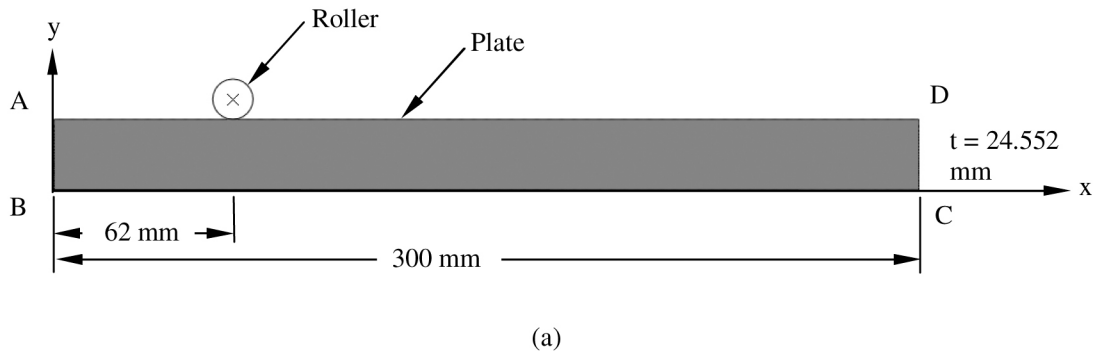


Figure 2. (a) A two-dimensional finite element model of a rigid cylinder rolling on a finite flat plate and (b) the tensile stress-strain curve of the plate material used in the finite element analyses.

for data type was adopted in order to use the cyclic stress-strain curve of the material as the input stress-strain data [23].

A mesh refinement study was conducted for simulation of the rigid cylinder indenting on the finite plate. The mesh size of 0.4 mm (Mesh-1) and 0.1 mm (Mesh-2) were used in this study. The results based on Mesh-1 and Mesh-2 were compared. The results showed that the subsurface stresses based on both meshes were in good agreement except those of the contact surface. Thus Mesh-1 was used for the subsequent rolling simulation for saving computational time.

The rolling process of interest involves 12 rotations of a crankshaft in a rolling machine. Figure 3(a) shows the actual rolling load history for the crankshaft fillet rolling where the load is increased linearly up to the full rolling load for the first 3 rotations of the crankshaft. The load is then kept as a constant level for the next 6 rotations. Finally, the load is decreased linearly to zero for the final 3 rotations. However,

in this investigation, only one pass of the rolling load is applied as shown in Figure 3(b). The full rolling load for the crankshaft fillet rolling is assumed to be 5700 N applied to the primary roller with the direction that is 34° inclined from the vertical direction. The details of the geometric arrangement of the primary and secondary rollers and crankshafts can be found in [3]. The details to convert the 5700 N load for the crankshaft fillet rolling to the line load for plane strain plate rolling are outlined in Appendix A. After the conversion, a line load 3847.0 (N/mm) was used in the plane strain plate rolling model as the roller load for single indentation and rolling.