

Residual Stress Distributions in Rectangular Bars Due to High Rolling Loads

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ABSTRACT

In this paper, residual stress distributions in rectangular bars due to rolling or burnishing at very high rolling or burnishing loads are investigated by roll burnishing experiments and three-dimensional finite element analyses using ABAQUS. First, roll burnishing experiments on rectangular bars at two roller burnishing loads are presented. The results indicate the higher burnishing load induces lower residual stresses and the higher burnishing load does not improve fatigue lives. Next, in the corresponding finite element analyses, the roller is modeled as rigid and the roller rolls on the flat surface of the bar with a low coefficient of friction. The bar material is modeled as an elastic-plastic strain hardening material with a nonlinear kinematic hardening rule for loading and unloading. The computational results showed that a higher rolling load does not necessarily always produce higher compressive residual stresses in the desired regions of the bar and gives better fatigue lives of the bar under bending as indicated from the experimental results. The computational results also showed that the longitudinal residual stresses are sensitive to the initial yield stress and the detailed strain hardening behavior assumed at large strains.

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1. INTRODUCTION

In roller burnishing or deep rolling, a rolling element, which can be a roller or a ball, is pressed and rolled against the surface of a work piece. During the rolling process, the material under the roller is loaded into plastic range. Once the rolling load is removed, compressive residual stresses are induced on or near the surface of the work piece. Rolling improves surface finish and induces compressive residual stress which retards surface or subsurface crack growth of the components under cyclic loading conditions. In this paper the terms "deep rolling" and "roller burnishing" will be used interchangeably even though the terminology "deep rolling" and "roller burnishing" found in the literature may represent different purposes with the former for the purpose of inducing large plastic deformation and then residual stresses in near surface layers in contrast to the later which is usually applied with much lower forces and mostly aims to obtain a better surface quality in terms of roughness [1].

In recent publications on the roller burnishing or deep rolling, researchers were more focused on the need for reliable finite element analyses that can be used to provide a fundamental understanding of the mechanics as well as to understand the effects of various parameters on the residual stresses in work pieces. Wu et al. [2] investigated the variation of the residual stresses through the

thickness of rolled sheets as a function of the size of the roller relative to the thickness of the sheet both experimentally and numerically for cold-rolled α brass sheets. Sartkulvanich et al. [3] conducted finite element analyses of hard roller burnishing to show the effects of the process parameters upon surface finish and residual stress. Their results show that the burnishing pressure has the most influence, where a high burnishing pressure produces less roughness and more compressive residual stress at the surface. Klocke et al. [4, 5, 6] conducted experiments to examine the influences of processing and geometry parameters on the surface layer state after roller burnishing of specimens of IN718 and Ti-6Al-4V. The results of their finite element analyses are in agreement with the residual stress measurements obtained from the experiments. Prabhu et al. [7] investigated the influence of deep cold rolling (DCR) and low plasticity burnishing (LPB) on surface hardness and surface roughness of AISI 4140 steel. Their results showed that by using LPB process the surface hardness has been improved by 167% and by using DCR process, the surface hardness has been improved by 442%. Their study also showed that the force, ball diameter, number of tool passes and initial roughness of the work piece are the most pronounced parameters, which have significant effects on the surface of the work piece during the deep cold rolling and LPB processes.

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 pressure distribution on the contact surface and the stress-strain histories near the contact surfaces for fatigue and durability analyses of gears, bearings and railroad rails at the rolling loads close the elastic and plastic shakedown limits. A brief discussion of these works can be found in Ali and Pan [8]. However, when rolling and burnishing are used in the manufacturing processes to induce residual stress and to improve surface finish, the roller load is relatively high compared to the rolling loads experienced during the service of the rolled components and the number of rolling is also limited. Many elastic-plastic semi-analytical and finite element analyses of rolling were based on translating a Hertzian and modified Hertzian pressure distributions across the surface of an elastic-plastic half space [9, 10, 11, 12, 13]. Jiang and Sehitoglu [14], and Jiang et al. [15] used semi-analytical methods and finite element methods to investigate the cumulative plastic deformation due to rolling and sliding line contact with different cyclic plasticity theories. Yu et al. [16,17] presented a direct finite element method for elastic-plastic rolling contact, and demonstrated its application to obtain steady-state solutions for two-and three-dimensional repeated rolling contact problems. Semi-analytical methods with incorporation of the plastic strains due to contact with efficient contact models and different plasticity models have been developed, for example, see Chaise and Nelias [18].

Most researchers used the moving Hertzian or modified Hertzian pressure distribution to represent the contact pressure for rolling with p_0/k ratios ranging from 5 to 9, where p_0 is the maximum Hertzian pressure and k is the shear yield stress of the material. Bijak-Zochowski and Marek [19] used elastic rollers with spring contact elements for rolling simulations. Ali and Pan [8] investigated the residual stresses distributions due to rolling by a rigid roller on a finite plate under plane strain conditions with very large contact pressure distributions that are relevant to the crankshaft rolling process with the high p_0/k ratio of about 22. The computational results show highly asymmetric contact pressure distributions at high rolling loads. Their computational results suggest that when the rolling loads are high, roller should be modeled to obtain reliable residual stresses on or near the contact surface. Their computational results also indicate that the residual stresses on or near the contact surface also highly depend on the boundary conditions along the boundary of a finite plate.

Recently, roller burnishing experiments were carried out on rectangular bars of gray cast iron. The roller burnishing experiments were carried out by force control at a low roller burnishing load and a high roller burnishing load. The longitudinal residual stress data show that the samples with the low roller burnishing load have the highest compressive residual stresses in the subsurface compared to those of the samples with the high roller burnishing load. The results of fatigue tests indicate that the fatigue lives of the samples with the low roller burnishing load are about 10 times of those of the non-rolled samples. However, the fatigue lives of the samples with the high roll burnishing load are not longer than those of the samples with no roller burnishing.

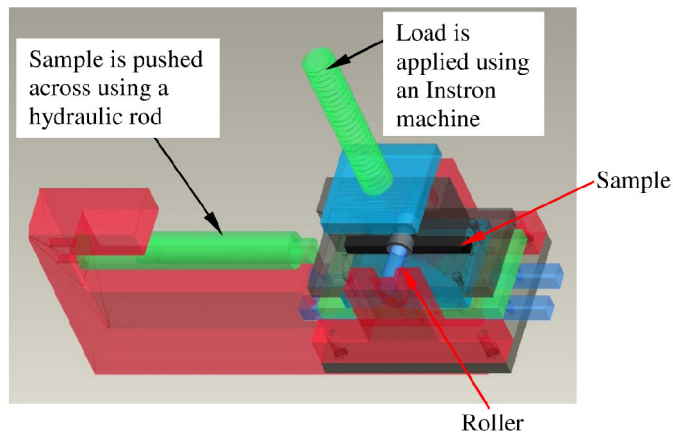
Furthermore, it is important to recognize that compressive residual stresses are largely dependent on the rolling loads, component material and boundary conditions. The current investigation is aimed to quantify the differences between the residual stresses distributions in a finite rectangular bar due to very large contact pressures from two different high rolling loads. The rolling parameters for this investigation include smaller roller radius, high rolling loads (with p_0/k ratio of about 12.5 to 15 with the rigid roller assumption), and finite rectangular bar dimensions. Therefore, a thorough investigation is required to understand the residual stress distributions in rectangular bars due to rolling using three-dimensional finite element analyses.

In this paper, roller burnishing experiments conducted on rectangular bars at two roller burnishing loads are first presented. The microstructures of the cast iron samples after roller burnishing with the two roller loads are then shown. The fatigue lives for various samples under four-point bend fatigue tests are then presented and the failure modes of the failed samples are examined. Also, the longitudinal residual stress measurements along the centerlines of the rolled surfaces in the thickness directions of the bars are presented. Next, finite element models of a three-dimensional rectangular bar are then developed for rolling simulations with the appropriate boundary conditions. The roller is assumed to be rigid and the roller rolls on the flat surface of the bar with a low coefficient of friction. The bar material is modeled as an elastic-plastic strain hardening material with a non-linear kinematic hardening rule of ABAQUS [20] for loading and unloading. Effects of the two rolling loads with variation of the material stress-strain data are investigated. A single pass rolling is simulated. The longitudinal residual stress distributions in the bar along the width and the thickness directions are compared for both rolling loads. Also, the longitudinal residual stress distributions in the vertical direction (thickness) are then compared with the measurement data. Finally, some conclusions based on the results of this investigation will be made.

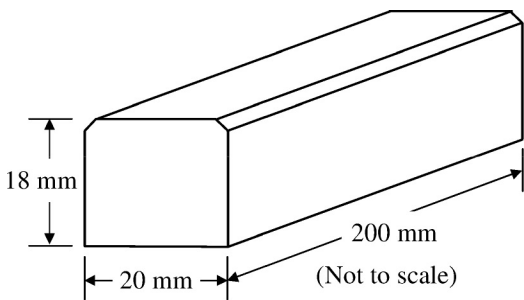
2. EXPERIMENTS

In this paper, the details of the results of finite element analyses for a roll burnishing experiment conducted at Caterpillar are presented. Therefore, a brief review of the roll burnishing experiment is first presented in this section [21]. **Figure 1(a)** shows a schematic of the experimental setup for conducting a burnishing experiment on a rectangular bar of a gray cast iron. **Figure 1(b)** shows a schematic of the gray cast iron bar. The length, width and thickness of the rectangular bar are 200 mm, 20 mm and 18 mm, respectively. The longitudinal edges on the rolling surface of the bar are chamfered (< 0.5 mm). Samples are prepared within a tolerance of ± 5 microns. **Figure 1(c)** shows a front view of the experimental setup with a gray cast iron bar as marked. **Figure 1(d)** shows a closeup view of the roller. The diameter of the steel roller is 25.4 mm. As marked in **Figure 1(a)**, the load is applied to the roller by an Instron testing machine. As indicated in **Figure 1(a)**, the rectangular bar freely sits inside a rectangular slot of the bottom platen that supports the bar. The bottom platen along with the rectangular bar is pushed to the opposite of the rolling direction using a hydraulic rod. The samples were rolled up to 90% or 180 mm of the total bar length of 200 mm. The burnishing/rolling was by force controlled with two rolling loads at a low roll burnishing (LRB) with 60 kN load and a high roll burnishing (HRB) with 90 kN load. The rolling speed is about 9 mm/sec with single pass rolling. The rolling loads used for this

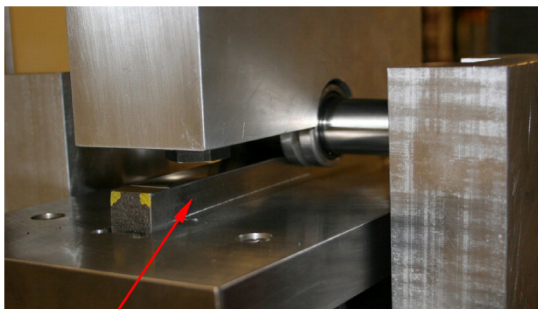
investigation were to obtain given changes of the sample thickness that corresponds to typical dimension changes applied by roller burnishing on large casting components to satisfy the requirements of the surface finish and dimensional tolerance.



a.



b.



Gray cast iron sample

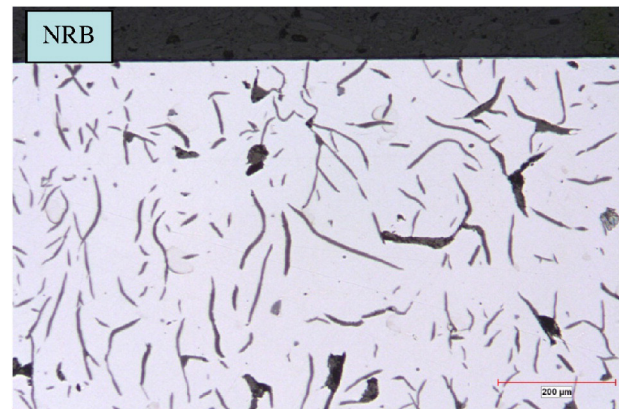
c.



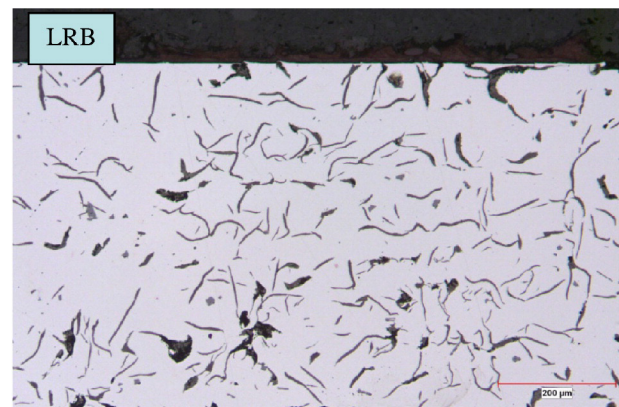
d.

Figure 1. Schematics of (a) the experimental setup for rolling a rectangular bar, (b) a rectangular bar, (c) a front view of the experimental setup, and (d) a close-up view of the roller.

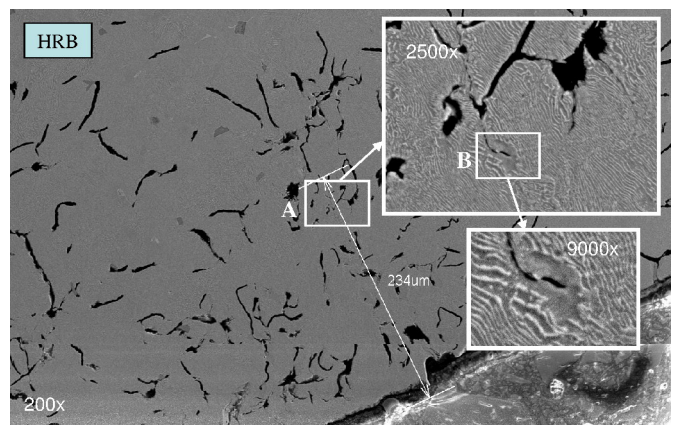
Figures 2(a), 2(b) and 2(c) show SEM images of graphite morphologies and microstructures of NRB (No Roll Burnishing), LRB (Low Roll Burnishing) and HRB (High Roll Burnishing) samples, respectively. At a lower magnification (200x), it appears that HRB load has induced cracks at some of the graphite flake tips as marked by region A in Figure 2(c). However, the images of inserts at higher magnifications and a chemical analysis showed that they are indeed graphite flakes. This confirms that no significant microstructure damage was done due to the HRB load used for roller burnishing in this investigation.



a.



b.



c.

Figure 2. SEM images showing morphologies and microstructures of (a) NRB (No Roll Burnishing), (b) LRB (Low Roll Burnishing) and (c) HRB (High Roll Burnishing) samples.

Figure 3 shows a four-point bending fatigue test setup. Four-point bending fatigue tests were conducted for the following five categories of samples: (i) NRB (No Roll Burnishing), (ii) LRB (Low Roll Burnishing), (iii) HRB (High Roll Burnishing), (iv) LRB samples that were stress relieved at 500 °C for 50 hrs., and v) NRB samples that were stress relieved at 500 °C for 50 hrs. The goal of the fatigue tests was to compare the fatigue lives of about 1 million cycles for 5 categories of samples for a given load for all samples. The samples were continuously monitored and a failure is determined when the black spots started to appear on ZnO paste as an indicator of surface cracks.

Figure 4 shows the fatigue life data obtained from bending tests for 5 categories of samples. The fatigue test results show that the mean life (cycles to failure) for the NRB and HRB samples are nearly the same and is about 0.4 million cycles. On the other hand, the mean life (cycles to failure) for the LRB samples is about 4.3 million cycles. The fatigue test results indicate that the low roll burnishing load (60 kN) improves the fatigue life by almost 10 times than the non-roll burnishing case. However, it appears that the high roll burnishing load does not improve the fatigue life compared to the no roll burnished samples. Moreover, after the residual stress of the LRB samples are relieved, both the “stress relieved LRB” and NRB samples show almost similar mean fatigue life. A set of “stress relieved NRB” samples are also tested and showed almost similar mean lives as those of the NRB samples.

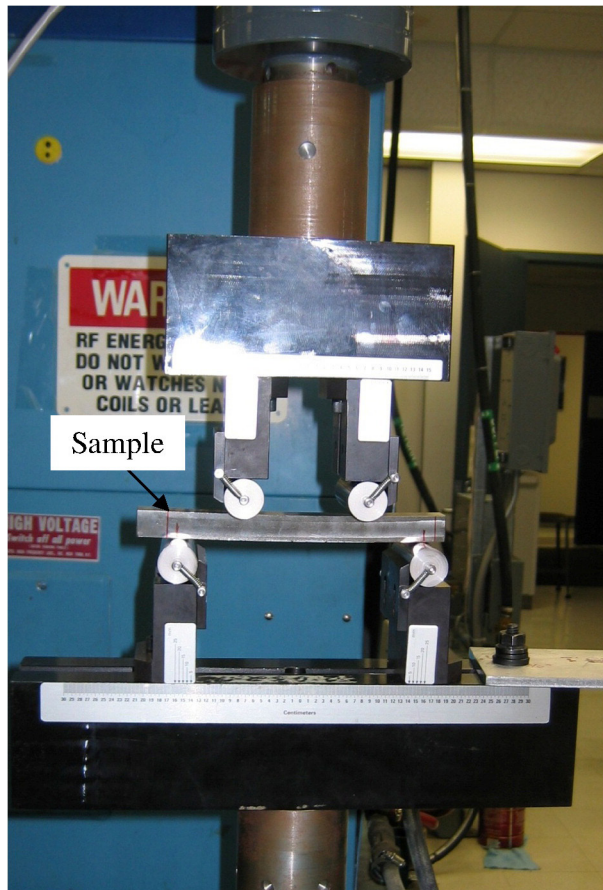


Figure 3. A four-point bending fatigue test setup.

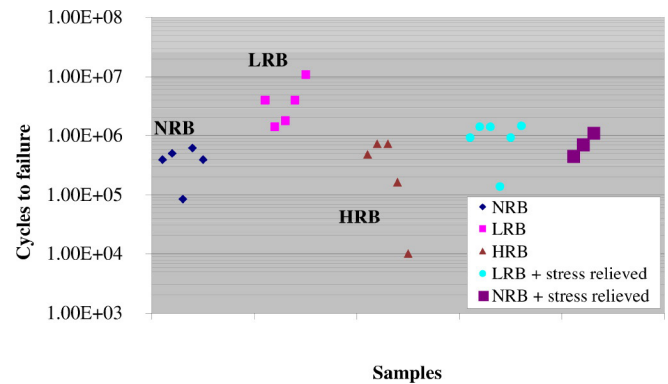
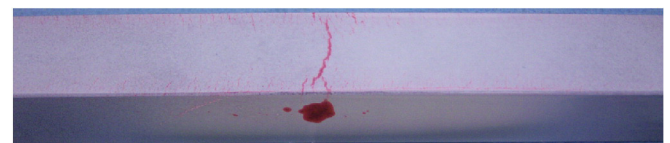


Figure 4. Fatigue life data obtained from bending fatigue tests for 5 categories of samples.

Figures 5(a) and 5(b) show the top surfaces of the roll burnished samples after fatigue tests with applications of ZnO paste and penetrating dye, respectively. All broken or unbroken roller burnished samples showed multiple cracks on the rolled surfaces after fatigue tests. The cracks seemed to have either initiated or have grown noticeably at a location few millimeters away from the edges. This observation is also found to be consistent with the results of three dimensional finite element simulations as will be discussed later. Figure 6 shows the top surface of NRB samples after fatigue tests with applications of ZnO paste and penetrating dye, respectively. All the NRB samples show failure initiation from the chamfered edges and a single dominating crack. Figure 7 shows the top surface of stress-relieved LRB samples after fatigue tests with application of ZnO paste. Unlike the LRB and HRB samples where multiple cracks were observed, the stress-relieved LRB samples have only single dominating crack for each sample similar to that shown in the NRB samples.



a.

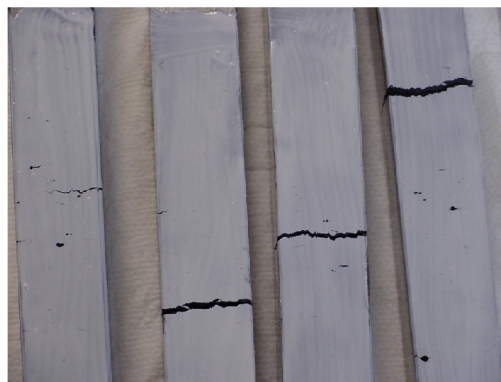


b.

Figure 5. Roll burnished samples after fatigue tests with applications of (a) ZnO paste and (b) penetrating dye.

Figure 8 shows the longitudinal residual stress measurements based on the X-ray diffraction along the centerline of the rolled surface to the subsurface of the bar in the thickness direction for various samples. As shown in the figure, for NRB samples, there was some compressive residual stress on the surface but disappear quickly in the subsurface. The longitudinal residual stress data show that the LRB samples have the highest compressive residual stresses compared to those of the HRB samples in the subsurface. This is consistent with that of the fatigue test results discussed earlier. However, a detailed finite element analysis will follow shortly to further investigate the findings. It is also found that the compressive residual stress increases from the surface to the subsurface at least up to a depth of 250 microns for LRB and HRB samples.

The average thickness changes of the LRB and HRB samples are 45 ± 5 and 95 ± 10 micrometers, respectively. Figure 9 shows the bowing of the bar due to the roller burnishing. In the figure, the bottom surface of the bar was the rolled surface. The bar was held to visualize the bowing for measurement convenience. Depending on the magnitude of a rolling load, plastic deformation occurs on the rolled surface and in the subsurface, and thus causes the bowing of the bar. The bar bowing measured by the displacement for the bottom surface from one end to the other as shown in Figure 9 for a HRB sample. The average bowing displacements of HRB and LRB samples are 2.79 and 2.38 mm, respectively.



a.



b.

Figure 6. NRB samples after fatigue tests with applications of (a) ZnO paste and (b) penetrating dye.



Figure 7. Stress-relieved LRB samples after fatigue tests with applications of ZnO paste.

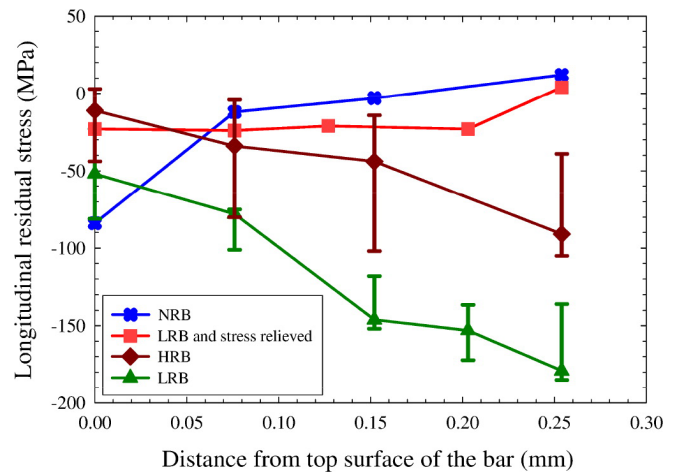


Figure 8. Longitudinal residual stress measurements along the centerline of the rolled surface to the subsurface of the bar in the thickness direction for 4 categories of samples.



Figure 9. Bowing of a bar due to the roll burnishing.

3. MODELING PROCEDURES

Three-dimensional finite element analyses were conducted to investigate the effects of the burnishing loads on the residual stress distributions in these rectangular bars after the burnishing or rolling. Figure 10(a) shows a schematic of the rectangular bar rolling process.

The x-y-z coordinate system is also shown. The roller is assumed to be rigid [22] and the roller rolls on the flat surface of the bar with a coefficient of friction, μ , of 0.01. Initially, the roller is sitting on the starting position of the bar at 10 mm from the left end. Then the roller is moved down with a given load. The roller is then moved horizontally in the rolling (z) direction by applying both a translation and rotation to the roller center. After traveling a rolling length of 180 mm before reaching the front end, the roller is moved up and the rolling is completed. The diameter of the roller is 25.4 mm. The length, width and thickness of the rectangular bar are 200 mm, 20 mm and 18 mm, respectively. The rolling starts on the upper surface from the plane of $z = 10$ mm and the rolling ends at the plane of $z = 190$ mm. Similar to the experiment, two burnishing loads are applied to the roller burnishing simulations: a low roll burnishing (LRB) load of 60 kN and a high roll burnishing (HRB) load of 90 kN. The details of applying the rotation and translation to the roller can be found in Ali and Pan [23].

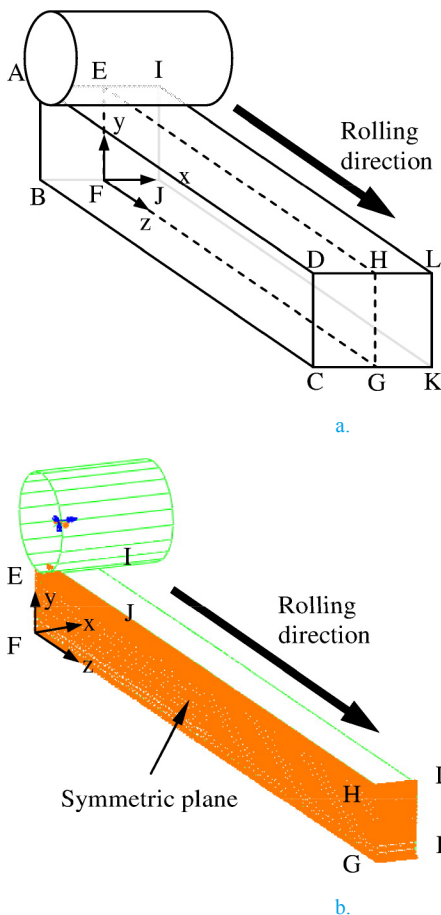


Figure 10. (a) A schematic of a rectangular bar rolling process and (b) a half three-dimensional finite element model of the rectangular bar for rolling simulations.

Figure 10(b) shows a right half three-dimensional finite element model of the rectangular bar for rolling simulations with the appropriate boundary conditions. For the finite element model, the displacement in the x direction of the symmetry plane (EFGH) is set to be zero. The displacement of the bottom surface (FGKJ) is constrained in the y direction and released after the rolling is completed. The displacement of the front face (HGKL) is constrained in the z direction and released after the rolling. The finite element analyses were performed using the commercial finite element code

ABAQUS/standard implicit solver. The Cartesian coordinate system is also shown in the figure. Three-dimensional fully integrated 8-noded (C3D8) elements of size of 0.5 mm by 0.5 mm by 0.5 mm (Mesh-1) were used in this model for a preliminary finite element analysis. Three-dimensional reduced integrated 8-noded (C3D8R) elements were also used. However, the computations using the reduced integrated 8-noded elements converged very slowly and the results were not reported here. In general, the trends of the results based on C3D8 and C3D8R elements are consistent. ABAQUS also provides “selectively reduced” integration for fully integrated lower-order elements where the reduced integration is used for the volume strain and the full integration for the deviatoric strains. As a consequence, the lower-order elements give an acceptable performance for approximately incompressible behavior [20]. As a starting point, the selection of the sizes of the finite elements to simulate rolling follows the guidelines that were reported in Ali and Pan [8]. A detailed mesh refinement study will be discussed later.

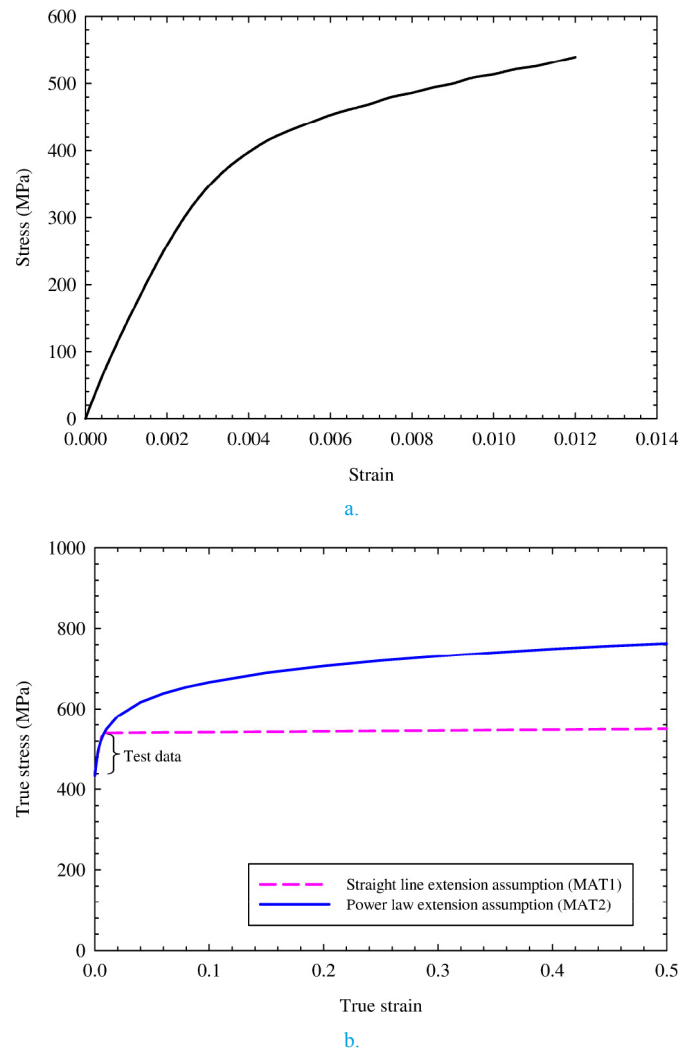


Figure 11. (a) The experimental compressive stress-strain curves for the gray cast iron and (b) the stress-strain curves used in the finite element analyses based on the extensions of the experimental compressive stress-strain curve.

Figure 11(a) shows experimental compressive stress-strain curves for the gray cast iron. Since the material under rolling is subjected to compression, the experimental compressive stress-strain curve is used for the input of the stress-strain curve for the finite element analyses.