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Effect of Surface Rolling on Fatigue Behavior of a Pearlitic Ductile Cast Iron

O. Maluf, M.T. Milan, and D. Spinelli

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Surface rolling is a mechanical treatment usually used in parts fabricated with steel and ductile cast iron, specifically in stress concentration regions, to improve fatigue properties. This process hardens and introduces compressive residual stresses to the surface of the material through the application of controlled strains, thus provoking a reduction of resulting tensile stress at its surface under cyclic loading. This work deals with the effect of surface rolling on high cycle fatigue behavior of a pearlitic ductile cast iron used in crankshafts by the automotive industry. Rotating bending fatigue tests were performed in both smooth and notched specimens, the latter either with or without a surface rolling treatment. Compressive residual stresses and heavy plastic deformation imposed on the surface grains due to cold work made difficult the nucleation and propagation of the crack at the rolled surface of the notch. As a consequence, surface-rolled notch testpieces presented a higher endurance limit (478 MPa) than both smooth (299 MPa) and notched (166 MPa) testpieces did. The surface rolling apparatus developed for this work proved to be very efficient and simple, providing good control of parameters involved in the process (i.e., rolling load, frequency, and number of revolutions).

Keywords ductile cast iron, fatigue, plastic deformation, residual stress, surface rolling

1. Introduction

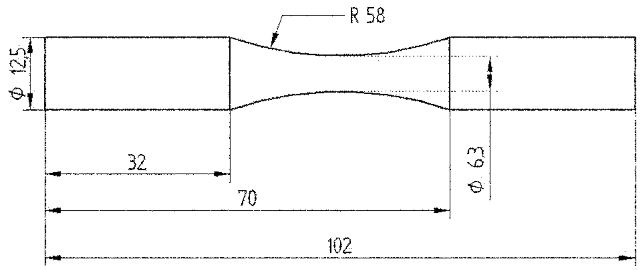
Ductile cast iron is produced through the addition of a metallic alloy containing Fe-Si-Mg to a base cast iron to produce nodular graphite, instead of flake graphite as is found in grey cast irons.[1] This process allows the manufacturing of materials with improved mechanical strength and ductility, which are extensively used in the fabrication of mechanical parts such as crankshafts. Strength and ductility are dependent on the matrix microstructure.[2] Depending on the chemical composition and heat treating, the matrix can be either ferritic, pearlitic, ferritic-pearlitic, bainitic, martensitic, or austenitic.[3] Size and distribution of the graphite nodules in the matrix are also important to the mechanical properties.[4]

The fatigue strength of a cast part depends not only on the microstructure and chemical composition, but also on the surface finishing and geometry of the part. Dimension gradients and notches are stress concentrators, which are prone to fatigue crack nucleation, and if they cannot be avoided in the design of part, they must undergo special treatments.[5] The introduction of carefully controlled compressive residual stresses using processes, such as shot peening, surface rolling, fastener hole cold working, and surface heat treating, is one potential means of increasing resistance to fatigue due to the reduction of the resulting tensile stress at the surface.[5,6] Additionally, de los Rios et al. found that besides compressive residual stresses, short-crack propagation rates in peened parts are much lower than unpeened ones because the resistance to plastic deformation at the crack tip is much higher due to the heavy work hardening imposed to the near surface grains.[7]

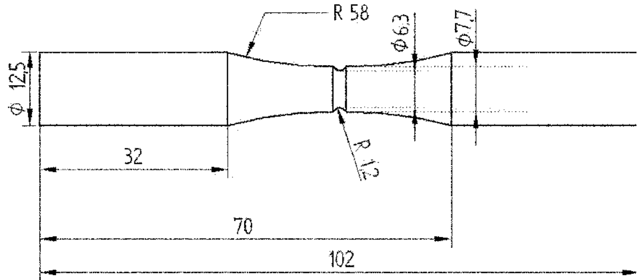
Surface rolling is a process extensively used in the manufacture of ductile cast iron crankshafts, specifically in regions containing stress raisers with the main aim to enhance fatigue strength.[5] Several researchers observed a significant increase in both fatigue strength limit and stage II fatigue crack propagation resistance in cast irons and steels.[1,8-10] This work had two main purposes. The first objective was to study the effect of surface rolling on the high cycle fatigue properties of pearlitic ductile cast iron containing chemical composition and microstructure as specified by the automotive industry, to contribute to the fatigue knowledge base of surface modified components designed for automotive applications. The second objective was to develop a simple and easily adapted apparatus capable of reproducing accurately large-scale industrial surface rolling procedures in the laboratory. Rotating bending fatigue

O. Maluf, M.T. Milan, and **D. Spinelli,** University of Sao Paolo, Engineering School of São Carlos, Department of Materials, Aeronautics and Automotive Engineering, Sao Paolo, 13566-590, Brazil. Contact e-mail: dspinell@sc.usp.br.

Nomenclature	
a	Peterson's material parameter
e	elongation
$E.L.$	endurance limit for 4×10^6 cycles for failure
K_f	fatigue notch factor
K_t	monotonic stress concentration factor
N_f	number of cycles for failure
r	notch root radius
R	stress ratio
S_{max}	maximum applied stress
$\Delta S/2$	applied stress amplitude
$\sigma_{0.2\%}$	0.2% offset yield stress
UTS	ultimate tensile strength



(a)



(b)

Fig. 1 Testpiece geometries and dimensions: **(a)** smooth testpiece, **(b)** notched testpiece; all dimensions are in millimeters.

Table 1 Average Chemical Composition

Elements	Weight %
C	3.56
Si	2.36
Mn	0.45
Cr	0.016
Cu	0.46
P	0.046
S	0.010
Mg	0.050

tests were performed in both smooth and notched specimens, the latter either with or without a surface-rolling treatment. Geometry of the notches and applied surface rolling load were similar to those used in the manufacturing process of automotive crankshafts.

2. Experimental Procedure

Table 1 presents the average chemical composition of the cast iron. The results are within the nominal values given by the GMW10 standard class N700-2.[11] Additionally, according to ASTM A536, the material is classified as 100-70-03 class material.[12]

Bending rotating fatigue tests were performed according to ASTM E468[13] in both smooth and notched specimens, the latter either with or without a surface rolling treatment. All tests were performed at room temperature. The as-cast specimens were subjected to a frequency of 92 Hz, at stress ratio $R = -1$. In this work, the endurance limit was defined at 4×10^6 cycles for failure. Run out was assumed for testpieces whose lives exceeded 10^7 cycles. The number of stress levels and the number of testpieces tested at each stress level were determined according to ASTM E739[14] to obtain a replication between 75% and 88%. Testpieces were manufactured according to ASTM E466.[15] Geometry and dimensions of the testpieces are presented in Fig. 1.

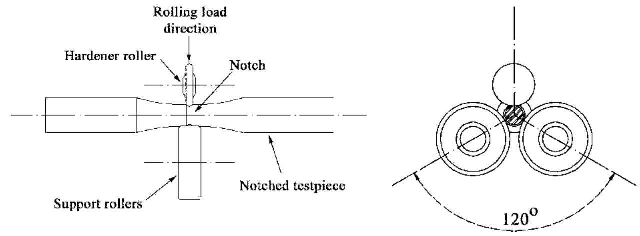


Fig. 2 Schematic representation of the surface rolling apparatus

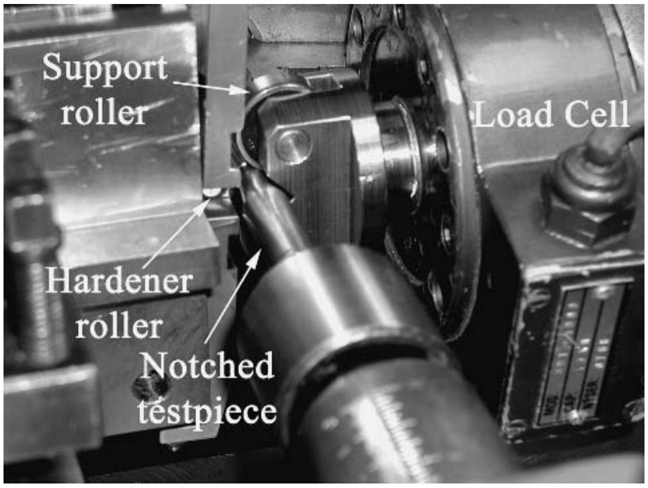
The apparatus used for surface rolling the notches consists basically of 3 rollers disposed at 120° in relation to the testpiece axis, as seen in Fig. 2. The rolling load was applied by a hardener roller, which had a diameter of 15 mm, a thickness of 5 mm, and a curvature radius of 1.3 mm. The other support rollers consisted of a 26 mm diameter sphere. The hardener roller was fixed to an apparatus used for surface rolling of crankshafts, which was adapted for this work (Fig. 3). The apparatus was fixed to the tool post of a lathe and the load was applied through the movement of the tool post perpendicularly to the testpiece axis, which had both ends fixed to the lathe. Load was measured by a 10 kN load cell attached to the support rollers, which were fixed to the base of the lathe. Load readings were acquired by a TRANSDUTEC-TMDE (São Carlos, Brazil) model digital reader. Testpiece notches were surface rolled under an applied load of 2.39 kN at a frequency of 50 rpm for 250 revolutions.

3. Results and Discussion

Table 2 presents average hardness and tensile results of 10 testpieces of the ductile cast iron. The results of bending rotating fatigue tests on smooth, notched, and surface-rolled notch testpieces are compared in Fig. 4, which also shows the best fit S-N equations obtained for each type of testpiece. The endurance limits for smooth, notched, and surface-rolled notch testpieces were 299, 166, and 478 MPa, respectively. The endurance limits were calculated from the best-fit S-N equations, where N_f was taken as 4×10^6 cycles for failure.

Pearlite (84.8% in area) and ferrite (15.2% in area) presented average Vickers microhardness values of 329 and 167 H_V, respectively. Using these values, it was possible to calculate the matrix equivalent microhardness (MEM) using a simple rule of mixtures, obtaining a value of 304 H_V. According to Janowak et al., there is a correlation between MEM and the endurance limit of smooth testpieces.[16] For the ductile cast iron of the present work, the predicted endurance limit according to this model is 310 MPa, which is in good agreement with the experimental result of 299 MPa.

The ratio between the endurance limits of smooth and notched testpieces is defined as the fatigue notch factor K_f.[17] In the present work, K_f yields a value of 1.80. According to Peterson, K_f can be estimated using the following empirical equation[18]:



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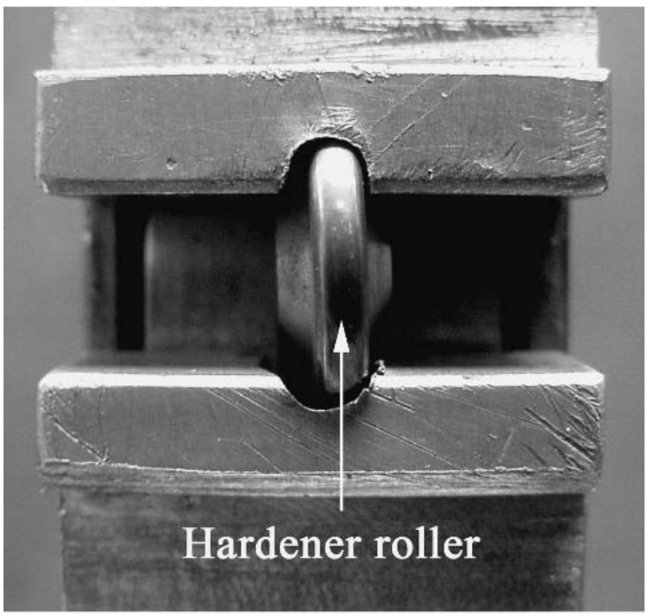

(b)

Fig. 3 **(a)** Detail showing the testpiece fixed to the lathe, the support rollers, the load cell, and the support to which the hardener roller is attached; **(b)** detail of the hardener roller

Table 2 Mechanical Properties of the Ductile Cast Iron

UTS (MPa)	$\sigma_{0,2\%}$ (MPa)	e (%)	HBS
762	465	4	239

$$K_f = 1 + \frac{K_t - 1}{\left(1 + \frac{a}{r}\right)} \qquad \text{(Eq 1)}$$

where K_t is the monotonic stress intensity factor, r is the notch root radius (in inches), and a is given by the following expression:

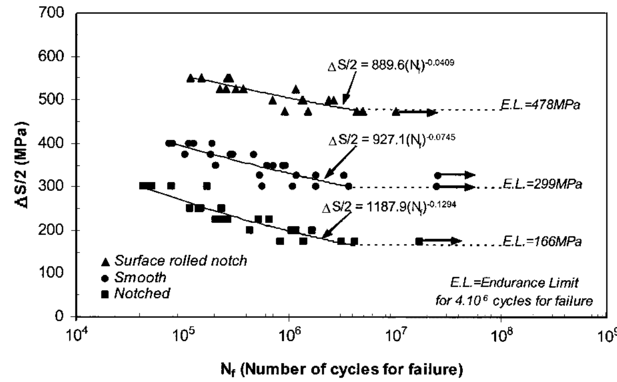

Fig. 4 Stress amplitude against number of cycles for failure of smooth, notched, and surface-rolled notch testpieces

$$a = \left[\frac{300}{S_u(\text{ksi})}\right]^{1.8} \times 10^{-3} \text{ in.} \qquad \text{(Eq 2)}$$

For the testpiece geometry of the present work, $K_t = 1.63$. Using Eq 1, one obtains an estimated $K_f = 1.56$. This value is lower than the K_f value obtained experimentally (1.80). One of the reasons for such discrepancy is perhaps due to the fact that Peterson's model was obtained for ferrous wrought materials.

The reduction of approximately 44% in the fatigue limit of notched testpieces compared with smooth testpieces clearly shows the harmful effect caused by the presence of a notch. On the other hand, when the notch was surface rolled, the fatigue limit was higher than both notched and smooth testpieces. The improvement in fatigue properties is in principle attributed mainly to the compressive residual stresses introduced on the surface of the material, which decreases and shifts the peak tensile stresses to a few tenths of mm below the surface. X-ray diffraction (XRD) measurements indicated a compressive residual stress on the surface of the rolled notch of −530 MPa. As a consequence, both fatigue crack nucleation and propagation are delayed, increasing the fatigue limit. However, it is important to observe that if the compressive residual stress value is superimposed to the endurance limit of the notched testpieces, the expected endurance limit of the surface rolled notch testpieces would be approximately 696 MPa. This value is higher than the actual value obtained (478 MPa), suggesting that a partial residual stress relaxation occurred during the cyclic loading. These results indicate that the surface rolling was successfully applied to the testpieces. The surface rolling apparatus developed for the present work proved to be very efficient and capable of controlling the main variables involved in the process, i.e., rolling load, frequency, and number of revolutions.

Figure 5(a) depicts the typical bullseye structure found in the ductile cast iron. Image analysis showed that the microstructure contained more than 80% of graphite nodules, classified as type I and II, according to ASTM A247.[4] Figure 5(b) shows a longitudinal section of a surface rolled notch testpiece, where the flattened bull eye structures are observed as a result of the plastic deformation caused by the mechanical treatment. It is well known that microstructurally short-crack propagation rates are affected by material properties such as barrier strength, interbarrier spacing, and resistance to plastic defor-

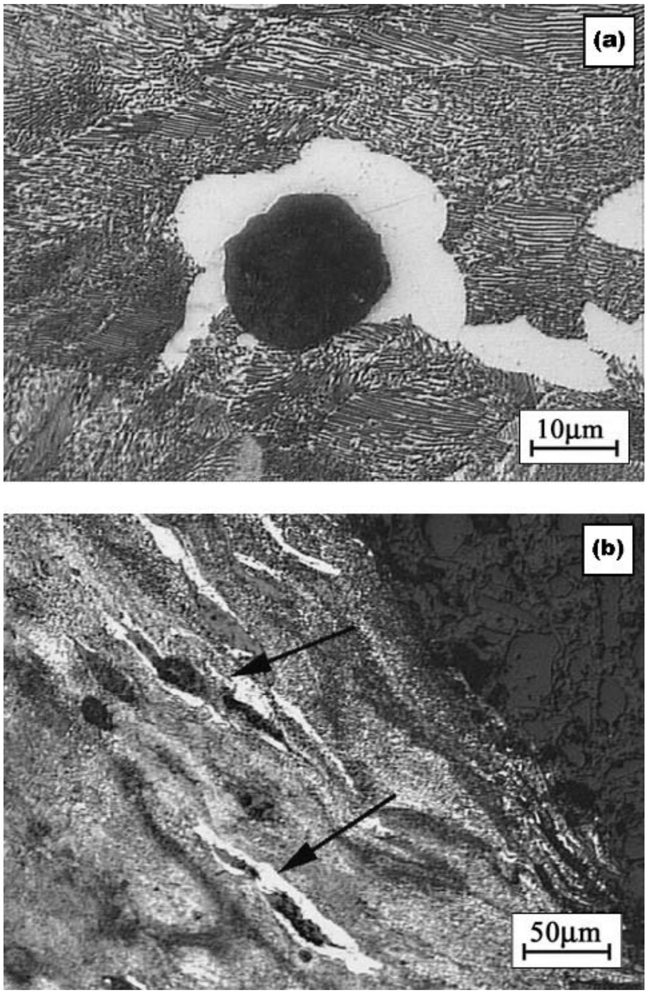

Fig. 5 **(a)** Bullseye structure in a pearlitic matrix of ductile cast iron; **(b)** longitudinal section of surface rolled region showing deformed bull eye structures (indicated by the arrows)

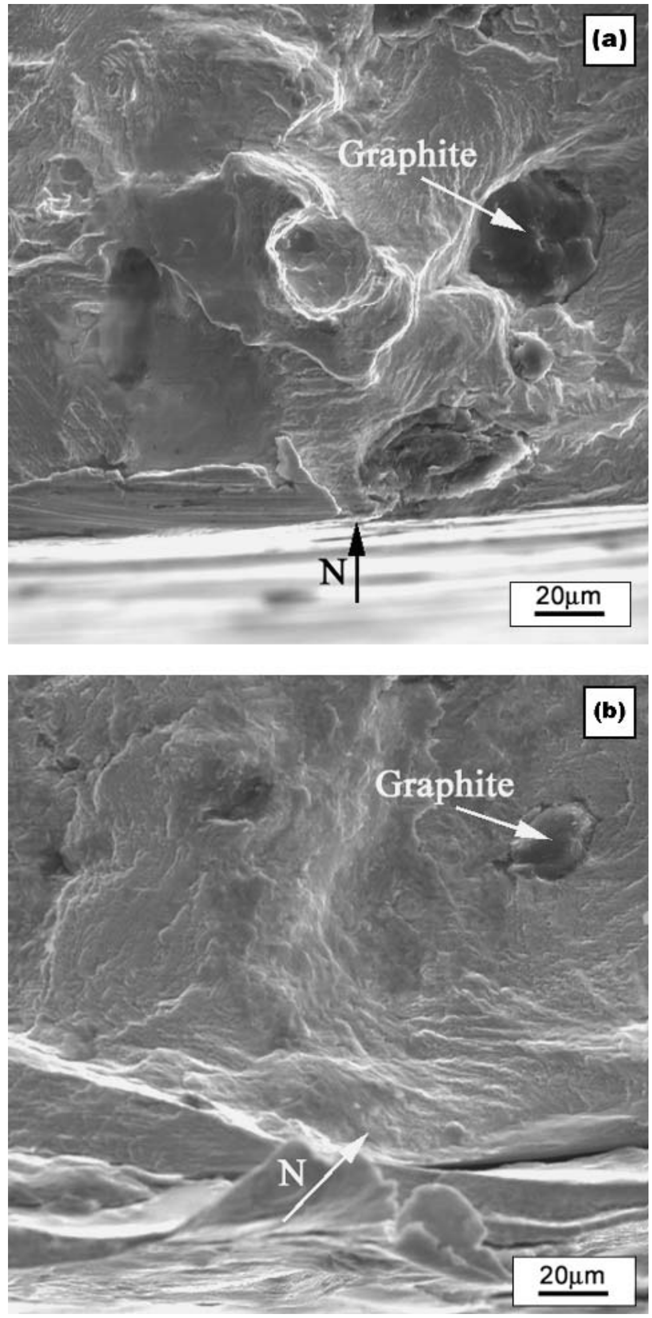

Fig. 6 Possible nucleation sites (N): **(a)** smooth testpiece, **(b)** surface-rolled notch testpiece in which a subsurface crack nucleation is observed

mation at the crack tip.[19,20] In surface-rolled parts, besides the compressive residual stresses, plastic deformation imposed to the near-surface grains will have other effects: a reduction of interbarrier spacing (grain boundaries are closer to each other), heavy distortion of grains, and heavy work-hardening. Therefore, it seems reasonable to assume that these factors can potentially contribute to increasing the fatigue limit of surface rolled parts due to an increase of short crack propagation resistance.

Fatigue fractographs of a smooth testpiece (S_{max} = 325 MPa, N_f = 1 164 400 cycles) and a surface-rolled notch testpiece (S_{max} = 500 MPa, N_f = 2 319 900 cycles) are presented in Fig. 6(a) and 6(b), respectively. The arrows indicate the possible sites of fatigue crack nucleation and stable fatigue crack propagation. It is possible to observe in Fig. 6(b) that subsurface nucleation occurred in the surface rolled notch testpiece. Such a trend was also found in previous work on shot-peened stainless steel.[7] This is presumably a consequence of the shift of peak tensile stresses to subsurface regions due to the compressive residual stresses introduced by the cold work process. Additionally, since subsurface regions are less plastically deformed, crack nucleation and short-crack propagation are likely to occur more easily in this region, avoiding the highly distorted surface grains.

4. Conclusions

The fatigue limit of notched testpieces of the ductile cast iron of the present work is approximately 44% smaller than the fatigue limit of smooth testpieces.

When the notch was surface rolled, the fatigue limit increased by approximately 60% compared with smooth testpieces and by 188% compared with notched testpieces. This is mainly attributed to the surface compressive residual stresses and heavy plastic deformation imposed to the near surface grains.

Subsurface crack nucleation is expected to occur in surface-rolled notch testpieces tested near the fatigue limit. This is probably due to the decrease and shift of tensile residual stresses to subsurface regions. Moreover, the plastically deformed grains near the surface are likely to contribute to a greater resistance to short-crack propagation in this region.

The surface rolling apparatus developed for this work proved to be very efficient and simple, providing a good control of parameters involved in the process (i.e., rolling load, frequency and number of revolutions).

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