

Stress-Strain Relations for Nodular Cast Irons with Different Graphite Volume Fractions under Tension and Compression

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ABSTRACT

In this paper, the results of finite element analyses for nodular cast irons with different volume fractions of graphite particles based on an axisymmetric unit cell model under uniaxial compression and tension are presented. The experimental compressive stress-strain data for a nodular cast iron with the volume fraction of graphite particles of 4.5% are available for use as the baseline material data. The elastic-plastic stress-strain relation for the matrix of the cast iron is estimated based on the experimental compressive stress-strain curve of the cast iron with the rule of mixture. The elastic-plastic stress-strain relation for graphite particles is obtained from the literature. The compressive stress-strain curve for the cast iron based on the axisymmetric unit cell model with the use of the von Mises yield function was then obtained computationally and compared well with the compressive stress-strain relation obtained from the experiment. Different unit cell models with different graphite volume fractions were then developed. The computational stress-strain relations under tension and compression were then obtained for different graphite volume fractions. The different tensile and compressive curves for different graphite volume fractions are used to obtain the pressure sensitivity parameters of the Drucker-Prager yield function for nodular cast irons for simulations of fillet rolling process of crankshafts.

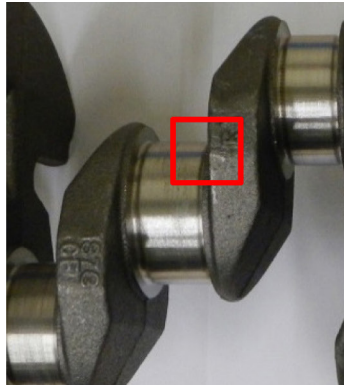
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1. INTRODUCTION

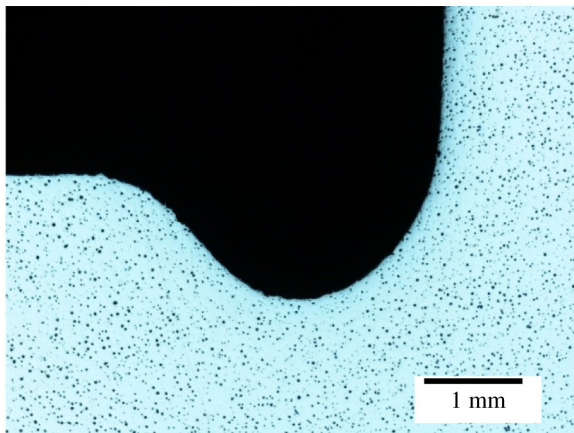
For automotive crankshafts, fatigue damages are usually initiated near the fillets due to stress concentration. The fillet rolling process has been used for years to introduce compressive residual stresses near the crankshaft fillets in order to improve the fatigue strengths of crankshafts. Accurate predictions of the residual stress distributions after fillet rolling are very important to determine the fatigue failure processes and the fatigue limits of crankshaft sections in the design stage. Cast irons are very popular for automotive crankshafts compared to steel for relatively lower material and manufacturing costs. It is well known that the tensile and compressive yield behaviors of cast irons are different due to the existence of graphite particles. Simulating crankshaft fillet rolling process with acceptable accuracy requires appropriate material models that should include the effects of the pressure sensitive yielding. The different yielding behaviors under tension and compression can be modeled by a phenomenological pressure-sensitive yield function.

The yield functions to describe pressure-sensitive yielding behavior usually involve the hydrostatic stress and the second invariant of the deviatoric stress [1, 2, 3, 4]. However, with the associated flow rule, the pressure-sensitive yield functions usually lead to the plastic dilatancy which is at least an order of magnitude larger than that observed in experiments. Therefore, non-associated flow rules based on pressure-sensitive yield functions were adopted to properly model the plastic behaviors of pressure-sensitive materials under monotonic loading conditions [5, 6, 7]. Choi [8] proposed an anisotropic hardening rule with a conventional and a non-conventional non-associated flow rules in order to take away the large ratcheting effects of the Drucker-Prager yield function with the associated flow rule. Choi and Pan [9] adopted the anisotropic hardening rule of Choi [8] based on the Drucker-Prager yield function with the non-conventional non-associated flow rule to investigate the stress distributions near the fillet of a crankshaft section under fillet rolling and subsequent bending. The computational results showed that as the pressure sensitivity increases, the maximum tensile stress at the fillet surface

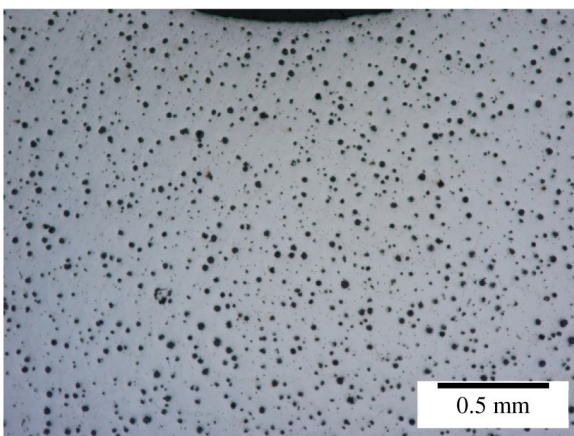
increases and the size of the tensile stress region increases after the release of roller and under subsequent bending. The anisotropic hardening rule of Choi [8] with the conventional non-associated flow rule is adopted in Sung et al. [10] to characterize the pressure-sensitive cyclic plastic behavior of the cast iron crankshaft section during the fillet rolling process since the current commercial finite element codes do not provide a cyclic plasticity model for pressure-sensitive materials such as cast irons under cyclic loading conditions.



(a)



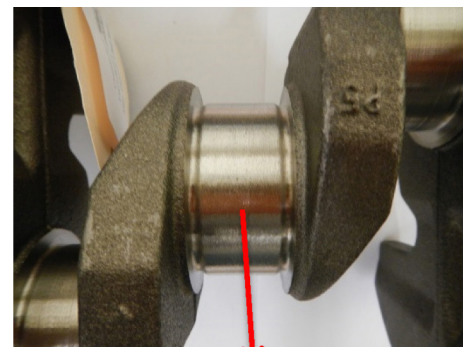
(b)



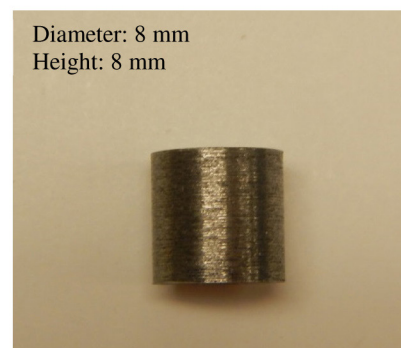
(c)

Figure 1. (a) An unrolled cast iron crankshaft section and the location of the cast iron sample near the fillet for examination, (b) a micrograph of the cross section near the fillet, and (c) a close-up view of the microstructure near the fillet.

For accurate stress distribution by these advanced material models [9,10] based on the Drucker-Prager yield criterion, the pressure sensitivity parameter are needed to account for the graphite volume fraction of cast irons. This study is aimed to examine the relationship between the pressure sensitivity parameter and the graphite volume fraction under different strain levels using computational models. In this paper, the stress-strain curve of a cast iron at large compression strains are obtained from unrolled crankshafts as the baseline material data for establishment of computational models. The elastic-plastic stress-strain relation for the matrix of the cast iron is estimated based on the experimental compressive stress-strain curve of the cast iron with the rule of mixture. The elastic-plastic compressive stress-strain relation for graphite particles is obtained from the literature. The compressive stress-strain curve for the cast iron based on the axisymmetric unit cell model is then obtained computationally and compared with the experimental results. Different unit cell models with different graphite volume fractions were then developed and the computational stress-strain relations under tension and compression were then obtained to understand the relation between the volume fraction of graphite particles in cast irons and the corresponding different tensile and compression stress-strain curves in terms of the pressure sensitivity parameter of the Drucker-Prager yield function. Finally, some conclusions based on the results of these investigations are made.



(a)



(b)

Figure 2. (a) A crankshaft section and the location where small compression specimens were cut, and (b) a cylindrical cast iron compression specimen with a diameter of 8 mm and a height of 8 mm before the compression test.

2. EXPERIMENT

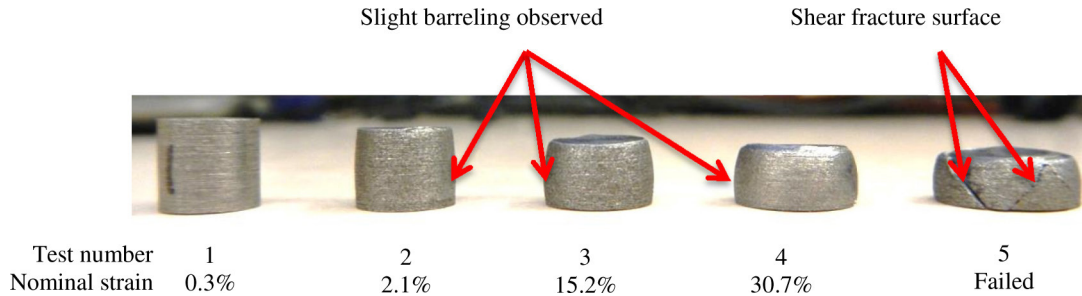


Figure 3. Five cylindrical specimens tested to different compressive nominal strains.

Small samples of the cast iron near the fillets of crankshafts before rolling were obtained to examine the microstructure of the cast iron near the fillets. Figure 1(a) shows an unrolled crankshaft section of a cast iron crankshaft and the location of the cast iron sample near the fillet for examination. Figures 1(b) and 1(c) show a micrograph of the cross section near the fillet and a close-up view of the microstructure near the fillet, respectively. Next, compression tests to large plastic strain were carried out to obtain the compression stress and plastic strain relation and the deformation patterns of graphite particles under compression. Figure 2(a) shows a crankshaft section and the location where small compression specimens were cut with the compression direction parallel to the crankshaft journal axis. Figure 2(b) shows a cylindrical cast iron compression specimen with a diameter of 8 mm and a height of 8 mm before the compression test. It should be noted that for specimens with a larger aspect ratio of height to diameter, such as the aspect ratio of 2, uneven deformation and buckling occurred during compression tests. Hence, small specimens with the aspect ratio of 1.0 were made for compression tests in this study.

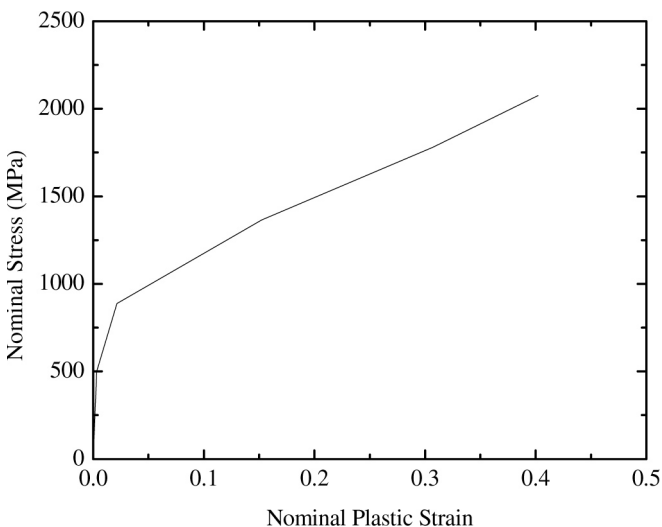


Figure 4. Nominal stress-plastic strain curve for the cast iron.

Table 1. Power law fitted parameters K and n for the elastic-plastic true stress-true strain curves for the graphite obtained from [11]

K	n
905	0.6174

Figure 3 shows five cylindrical specimens tested to different compressive nominal strains. At higher compression strains, slight barreling of specimens was observed. The compression specimens failed in shear fracture when the nominal strains were above the nominal compression strain of 30.7%. Figure 4 shows the nominal stress-plastic strain curve for the cast iron. The plastic strains are measured directly from the tested specimens. The modulus of elasticity and the compressive yield stress were measured and estimated as 181 GPa and 500 MPa, respectively, based on the data obtained from an extensometer attached to the two plates that were used to compress the specimens. The commercial specification of the modulus of elasticity and the compressive yield stress for this cast iron is 176 GPa and 489 MPa, respectively. The measurements agree quite well with the specifications. The elastic-plastic compressive true stress-true strain curve for graphite was obtained from [11]. The modulus of elasticity and the compressive yield stress for the graphite are 8.9 GPa and 30 MPa, respectively [11]. A power law relation is used to extend the compression true stress-true strain curve obtained from [11] to larger true strains. The fitted power law relation is expressed as

$$\sigma = K\epsilon^n \quad (1)$$

Here, σ represent the true stress, ϵ represent the true strain, and K and n represent the fitted material parameters. The fitted power law parameters K and n are listed in Table 1. Figure 5 shows the elastic-plastic compressive true stress-true strain curve for the graphite to very large true strains.

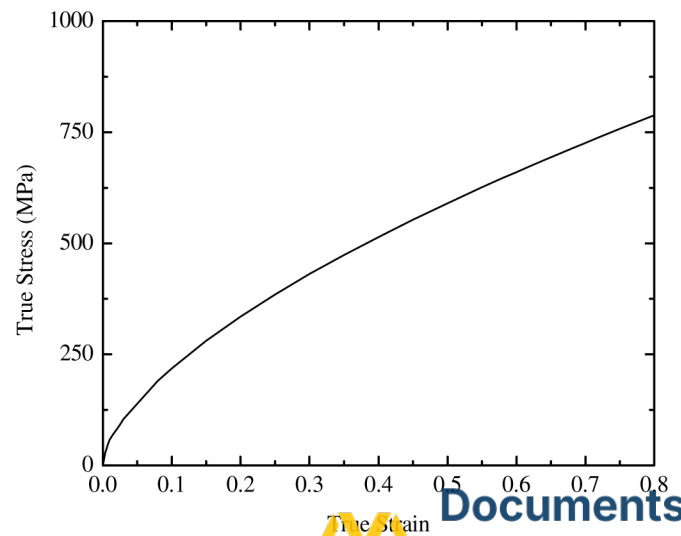


Figure 5. Compressive true stress-true strain curve for the graphite.