

Fatigue Behavior of Cast Iron Including Mean Stress Effects

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ABSTRACT

With improvements in casting technology, cast iron can be an alternative to steel in some applications due to its similar strength. One objective of this study was to analyze cast iron data obtained from the literature and evaluate predictive correlations between its tensile, microstructural, and fatigue properties. Reasonably good correlation of tensile strength and yield strength were found with hardness. However, fatigue strength could not be correlated with hardness or tensile properties. Another objective of this study was to evaluate tensile and compressive mean stress effects on fatigue behavior of 120-90-02 ductile cast iron experimentally, as well as analytically by using predictive models. Mean stress levels were chosen such that R ratios in load-controlled tests were -7 , -3 , -1 , 0 , $1/3$, 0.5 , and 0.75 . Modified Goodman, Smith-Watson-Topper, FKM and the Fatemi-Socie mean stress parameters were used to account for the mean stress effect on fatigue life. Constant life diagrams were also constructed to evaluate predictive capabilities of these mean stress models for applications in design.

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INTRODUCTION

Cast iron tends to be more economical to manufacture than steel, but its microstructure is riddled with internal defects. Ductile iron, a widely used material, contains small graphite particles that are spherical in nature which develop during the casting process. The graphite is surrounded by either a pearlite or a ferrite microstructure depending on the heat treatment. Typical applications for ductile iron are in high wear environments such as automotive parts, machine components, gears, shafts, and other parts [1]. These parts are typically subjected to cyclic loading.

The mechanical properties of ductile iron with a ferrite microstructure are near those of steel [1]. The modulus of elasticity for ductile iron is near 172 GPa. The compressive strength of nodular iron is higher than its tensile strength, but the difference is small compared to grey iron [2].

Many mechanical designs undergo cyclic loading where the loading is not symmetric. Typically, compressive mean stress is beneficial for fatigue life, while tensile mean stress is detrimental [3]. Understanding the effects of mean stress on material fatigue behavior is, therefore, important for design of cast iron parts.

In this paper a literature review pertaining to the fatigue of cast iron including the effect of mean stress is presented. Attempts were made to correlate tensile and fatigue strengths with hardness and nodule diameter using data obtained from literature. Results of mean stress fatigue tests on smooth ductile iron specimens conducted in this study are then presented. Several mean stress models are used to account for mean stress effect on fatigue strength.

BRIEF LITERATURE REVIEW OF CAST IRON INCLUDING MEAN STRESS EFFECT

Germann et al. [4] studied the fatigue behavior and lifetime calculations of EN-GJL-250 (lamellar graphite), EN-GJS-600 (nodular graphite), and EN-GJV-400 (compacted graphite) cast irons. They used a physically based life prediction method which calculates $S-N$ curves by generalizing Morrow and Basquin equations to characterize the fatigue behavior. Salman et al. [5] studied the effects of various austempering temperatures on the fatigue properties of ductile iron. Fully-reversed strain-control testing was performed on austempered ductile irons (ADIs) of various austempering temperatures and the endurance limit was found to range between 300 MPa and 350 MPa. It was also found that the hardness of the ADI decreases with the increase of austempering temperature, while the cycles to failure increased.

Petrenec et al. [6] studied fatigue crack initiation on austempered ductile iron under fully-reversed strain-controlled testing at temperatures of 23 °C and -45 °C. It was observed that the material cyclically hardened due to martensitic transformation of unstable retained austenite caused by cyclic strain near graphite nodules at low temperatures. Softening effects were observed at both temperatures due to crack initiation near graphite nodules and plastic strain localization into slip bands. The main damage mechanism was the coalescence of short cracks which initiated early from graphite nodules around 5% of life into long cracks. The stress concentration factor of the graphite nodules also increased due to the effect of low temperature. Numerical simulations performed through FEA showed that nodules located near the surface had a higher damaging effect compared to internal particles.

Čanžar et al. [7] used four types of nodular cast irons to study the effect of the microstructure on fatigue behavior. Tests were performed under axial strain control. It was found that larger more irregularly shaped nodules promoted higher crack growth rates and smaller values of the critical stress intensity factor, compared to irons containing a higher frequency of smaller more regularly shaped nodules. Yamabe and Kobayashi [8] studied the influence the casting surface had on the fatigue strength of three cast irons which were cast in sand molds and then shot blasted. Using statistics of extremes to determine the maximum defect size, the lower bound fatigue limit could be estimated. Murakami's method was modified by considering not only the defect size, but also the surface roughness. They suggested that the fatigue limit could be determined through nondestructive inspection which incorporates the surface roughness and nodule diameter.

Tayanç et al. [9] studied the effects of different matrix structures using rotating bending fatigue tests on austempered ductile iron. An increase in fatigue strength with heat treatment temperatures between 230 °C and 330 °C was reported, but there was a decrease in fatigue strength when the temperature range of heat treatment was between 330 °C and 430 °C. The specimens containing a martensitic matrix had the lowest fatigue strength. Collini et al. [10] studied how the microstructure affected the mechanical and fatigue properties of identical pearlitic grey cast irons from three different foundries. Experiments showed a high degree of scatter of *S-N* data among the three different foundries. It was found that as the structure of the eutectic cells becomes finer and as phosphorus decreases, the fatigue strength increases. The graphite, as well as the casting process and expertise of the foundry also influenced the properties of the iron.

The fatigue behavior of spheroidal graphite cast iron containing vanadium carbides in a martensitic microstructure was investigated by Tokaji et al. [11]. From the experimental tests it was determined that a fully martensitic structure resulted in higher fatigue strength. The fatigue limit increased with an increase of Vickers hardness, but decreased above a hardness of 650. Most fatigue cracks initiated from casting defects. It was stated that estimation of the fatigue strength by Murakami's method is suitable for as-cast materials. For heat-treated materials, as the hardness increased, the predicted fatigue limit was higher than the experimental limit and this difference became greater as the hardness increased.

Fatigue limit based on casting size and various austempering temperatures in the high cycle fatigue regime was investigated by Lin and Wei [12]. As the casting size increased, the nodule count and nodularity decreased, but the nodule size increased, which reduced the fatigue limit. Although the fatigue limit was found to decrease linearly as the mean nodule diameter increased, a unique relationship did not exist because the fatigue strengths were significantly different at both austempering temperatures.

The influence of the matrix on an alloyed ductile iron was investigated under rotating bending fatigue tests. Similar to [12], Toktaş et al. [13] reported that fatigue strength is not proportional to tensile strength and hardness, but rather to impact toughness and nodule diameter. A correlation between the fatigue ratio and matrix structure was not found, as the fatigue ratio varied from 0.222 to 0.354. Fatigue cracks were found to initiate at the nodule/matrix interface due to a weak interface bond and the fact that the nodules have a very low Young's modulus.

Tanaka et al. [14] investigated the fatigue limit of spheroidal graphite cast iron using plate specimens in fully-reversed bending. It was found that fatigue strength linearly decreased with an increase of the maximum and mean nodule diameters for irons with the same matrix structure. However, if the iron was annealed, the fatigue limit became less sensitive to nodule size. Fatigue limit of matrices which were harder or were quenched and tempered had a greater dependence on the nodule size. It was also found that the relationship between fatigue strength and tensile strength depends on nodule size. Increase in matrix hardness was observed during cyclic loading.

Kogoh et al. [15] evaluated fatigue strength and ultimate strength of smooth spheroidal graphite cast iron specimens under axial load at elevated temperatures. Different heat treatments did not have significant effects on the fatigue limit at elevated testing temperatures. For the cases of room temperature, 300 °C, and 500 °C the annealed material had the highest ratio of fatigue strength normalized by the tensile strength, followed by the as-cast, normalized, and bainitized materials.

Nodular cast iron specimens which were as-cast, shot-blast (having the as-cast surface finish), and fine-ground were studied by Konečná et al. [16]. Based on fatigue tests results, the fine ground specimens had the best fatigue performance and as-cast specimens had the worst fatigue performance. The shot-blast specimens were in-between the fine-ground and as-cast. Zammit et al. [17] determined the optimal shot peen for austenitized and austempered Cu-Ni ductile iron. Through testing, it was determined that an Almen intensity rating greater than 0.4 reduced the fatigue life. The surface hardness also decreased from the edge to the interior from 535 Hv to 370 Hv. The fatigue strength, however, increased from 250 MPa for a polished specimen to 390 MPa for the shot peened specimen. Shot peening also delayed crack growth and shifted the initiation to subsurface.

Ochi et al. [18] studied fracture morphology and fatigue properties of a ferrite-pearlite and pearlite ductile cast iron. The specimens were shot peened and subjected to rotating bending. It was observed that in the long-life regime the ferrite-pearlite matrix structure exhibited a two-step *S-N* curve beyond 10⁷ cycles, whereas the pearlitic matrix

did not behave in the two-step manner. It was determined that the two-step phenomenon occurs due to the location of the fracture origin. Typically at longer fatigue life fractures occurred internally. It was also observed that surface or near surface defects were more detrimental to the fatigue life, as compared to internal defects.

Failure analysis of a crankshaft used in a truck was performed by Asi [19]. The carbon content was found to affect the fatigue and impact strengths, as it affects the size and number of graphite nodules. Smaller nodules with a higher count increased the fatigue strength [20]. The crack path was strongly influenced by non-spheroidal graphite, which also produced a rough fracture surface composed of brittle cleavage facets, indicating low material toughness.

Šamec et al. [21] studied low-cycle fatigue of ductile cast iron ENGJS-500-7 which is used for railway brake discs. Testing was performed at room temperature, 300 °C and 400 °C under axial strain-controlled conditions. At room temperature a slight hardening was noticed near the end of the fatigue life. At the elevated temperatures hardening was more pronounced at 300 °C, while the initial hardening observed at 400 °C transitioned to softening near the end of the fatigue life. Fatigue life was shown to decrease with increasing temperature.

Fash and Socie [22] studied fatigue behavior and mean stress effects in grey cast iron under constant amplitude load-controlled and strain-controlled tests. Cyclic stability was not observed in either strain control or load control. In strain control a continual decrease in the tensile load was noticed, while the compression load remained constant. Strain was monitored in load control and it was observed that both compressive and tensile strains increased with the tensile strain increasing at a faster rate compared to the compressive strain. They also performed a variety of strain-controlled tests with varying strain amplitude and mean strain and reported that the Smith-Watson-Topper (SWT) equation provided good correlation of the data.

Lin and Pai [23] investigated low cycle strain-controlled fatigue behavior of austempered ductile iron subjected to various strain ratios. The material was austempered at 300 °C and 360 °C and both materials had shorter fatigue lives as the strain ratio increased due to the presence of a mean tensile stress. When the testing conditions were fully-reversed, a compressive mean stress developed and no stable hysteresis response was observed, regardless of the strain ratio. Austempering at 300 °C provided a material with a higher fatigue resistance compared to austempering at 360 °C, but the strengthening effect was lost at R ratios of 0 and 0.5 and the latter material had a better fatigue performance. It was mentioned that austenite in the matrix attributed to a lower fatigue strength for low cycle fatigue behavior. Life predictions were made using Morrow and SWT equations.

Fatigue properties of various ductile iron matrices alloyed with up to 0.11 wt% of Ti were investigated under tension-tension loading at $R = 0.1$ [24]. An increase of fatigue resistance was reported to be caused by an increase in material strength for ferritic and pearlite microstructures. The fatigue limit as well as tensile strength increased with nodularity. It was reported in [12, 25, 26] that no simple correlation between fatigue strength and ultimate strength existed. However, Luo et al. [24] showed that the fatigue limit can be

correlated with the ultimate strength, because the ratio of fatigue limit to tensile strength remained constant when graphite nodularity was high. Fatigue failures tended to occur from surface defects at high stress levels, but from internal defects at lower stress levels. The critical maximum stress level at which crack initiation transitions from surface to subsurface was determined to be $0.76S_u$. A bilinear S - N behavior was observed.

CORRELATIONS OF CAST IRON MECHANICAL PROPERTIES

Correlations among cast iron data extracted from literature [4, 9, 11, 12, 13, 17, 18, 20, 26, 27, 28, 29, 30, 31, 32, 33, 34] were attempted to predict tensile and fatigue strengths. Literature studies suggest that the most controlling microstructural feature on material behavior of cast iron is the nodule size. Therefore, data in the correlations are distinguished by nodule size.

Evaluation of the tensile and yield strengths was performed by grouping the average nodule size in groups of 10 μm . It was found that that tensile and yield strengths are dependent on material hardness, rather than the nodule size. A linear fit was obtained by using all applicable data from literature up to a hardness of 450 Hv. Correlations of S_u and S_y with hardness are shown in Figures 1(a) and 1(b) where $R^2 = 0.815$ and $R^2 = 0.913$, respectively.

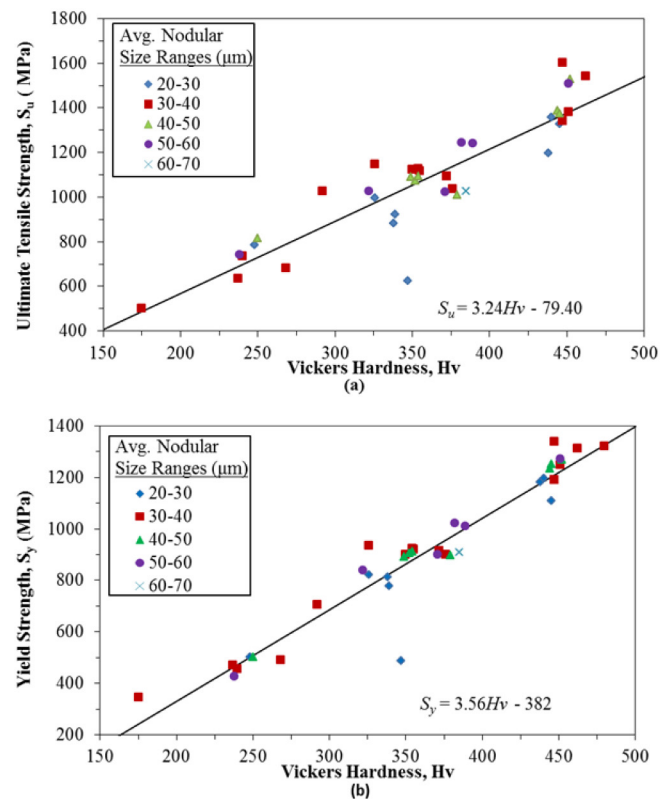


Figure 1. Correlations of (a) tensile strength and (b) yield strength as a linear function of Vickers hardness with cast iron data obtained from literature grouped by average nodule size.

Attempts to correlate fatigue strength with hardness and tensile strength were also made with data categorized by nodule sizes. Figures 2(a) and 2(b) show the fatigue limit as a function of hardness and