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Improving Fatigue Life of Ductile Cast Iron via Surface Enhancement

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ABSTRACT

Ductile cast irons can be used in a variety of applications from statically loaded structural supports to various dynamically loaded components. Ductile cast iron can be substituted for steel and can be utilized at a cost savings due to its ability to be easily cast and machined. Ductile cast iron applications could be further broadened if the fatigue properties were further enhanced. Shot peening has been widely used to increase fatigue performance by imparting a layer of compressive residual stress. Deeper and higher magnitude compression, such as that obtained by Low Plasticity Burnishing (LPB), could further improve performance and reduce the occurrence of premature failure. During this investigation, high cycle fatigue (HCF) tests were conducted on 80-55-06 ductile cast iron. The fatigue performance was evaluated for ground, shot peened, and LPB processed samples. Testing was conducted with surface damage and in active corrosion fatigue (CF). Residual stress measurements were obtained as a function of depth. Surface roughness readings were also collected. Results indicated an increase in the fatigue performance for undamaged samples that were shot peened or LPB processed compared to the ground condition. When subjected to damage such as CF alone or CF in combination with a surface notch, the LPB samples had the highest fatigue lives. LPB processing was successful in extending the fatigue performance over shot peening or grinding and can be used to significantly enhance the fatigue properties of ductile cast iron components.

Keywords: High Cycle Fatigue, Corrosion Fatigue, Damage Tolerance, Residual Stress, Surface Treatment, Low Plasticity Burnishing, Shot Peening, Ductile Cast Iron

INTRODUCTION

Ductile cast iron is often utilized as a substitute for steel in many component applications. It has comparable properties to steel while offering a cost savings over producing finished parts from steel castings, forgings, or weldments. Further enhancing the fatigue properties of ductile cast iron could broaden the applicability of the alloy as a substitutional material [1-6].

A layer of surface compression has long been recognized to enhance the fatigue strength of metallic components [7-10]. Shot peening is one of the most widely used surface treatments for imparting residual stress. Other surface treatments including Low Plasticity Burnishing (LPB) [11], laser shock peening [12], and ultrasonic peening [13] can produce deeper compression with less cold working of the surface than shot peening. Reduced cold working improves the thermal and mechanical stability of the beneficial compression [14]. Studies have also demonstrated that reduced cold working reduces the likelihood and rate of corrosion [15-18].

Low Plasticity Burnishing has been shown to provide a deep surface layer of high magnitude compression in aluminum, titanium, nickel alloys, and steels which serves to mitigate fatigue damage mechanisms including foreign object damage (FOD) [19-21], fretting [22,23], and corrosion fatigue (CF) [24-27]. The LPB process is performed on conventional CNC machine tools and robots at costs and speeds comparable to conventional machining.

The current study investigates the use of compressive residual stress imparted by grinding, shot peening, or LPB processing to mechanically suppress localized stress concentrations and to improve the fatigue performance of ductile cast iron. During the course of the investigation the residual stress and surface roughness were also determined.

EXPERIMENTAL TECHNIQUE

Material

Ductile cast iron bar stock, specifically Dura-Bar 80-55-06 continuously cast, was used for this study. Dura-Bar 80-55-06 is a medium strength as-cast grade material with a UTS and yield comparable to AISI 1040 steel. The bar stock, certifiably conforming to ASTM A-536, had a nominal diameter of 1.75 in. The chemistry and mechanical properties were verified by an independent testing laboratory and are listed in the tables below.

CHEMISTRY							
Element (Weight Percent)							
Al	B	C	Cr	Cu	Mn	Mo	Ni
0.014	0.001	3.72	0.028	0.051	0.23	<0.038	<0.03
P	S	Si	Sn	Ti	V	Fe	
0.015	0.007	2.34	0.026	<0.02	<0.01	Bal	

Table I: Material Chemistry

MECHANICAL PROPERTIES	
Yield Strength (ksi)	UTS (ksi)
62.0	101.1
Elongation (%)	Reduction of Area (%)
10.7	10.6

Table II: Material Mechanical Properties

Specimen Processing

High cycle fatigue (HCF) test specimens were machined from the bar stock. The test specimen geometry was chosen to produce fatigue failures from the gage section even in cases where the residual compression was high. Nominal test specimen dimensions were 0.38 x 1.25 x 8 in. Each test specimen was machined such that the mid-plane of the bar stock became the test surface during fatigue testing. All specimens were low stress ground prior to any surface treatment.

Specimens were tested without any damage in baseline (ground), shot peened (SP), and LPB conditions. The shot peening was performed to an Almen intensity of 9A and a coverage of 150% with CCW14 steel shot using a conventional air blast peening system equipped with a rotating table. The LPB processing was performed at Surface Enhancement Technologies (SET) using conventional CNC vertical milling centers and proprietary LPB processing parameters. An example of an LPB processed fatigue specimen is shown in Figure 1. The ends of the samples shown in the figure were shot peened in order to prevent premature failures from the mounting grip ends.

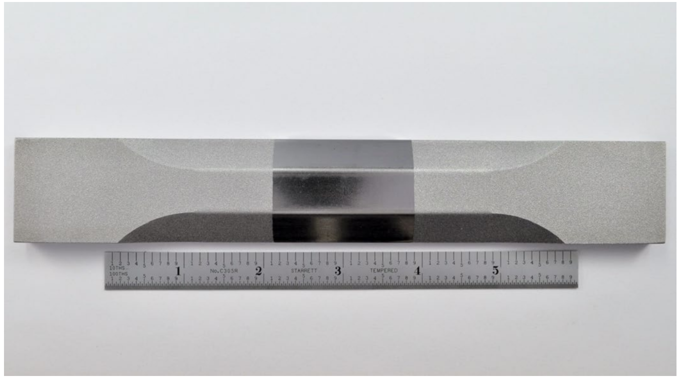

Figure 1: LPB Processed HCF Specimen

Specimens were tested with a notch to simulate mechanical damage or corrosion pitting. The notch was either 0.010 in. or 0.020 in deep. Notches were introduced using electrical discharge machining (EDM). EDM provides a highly reproducible flaw with residual tension and cracks in the recast layer at the bottom of the notch. Photographs of a notch taken through a microscope at low and high magnifications are shown in Figure 2.

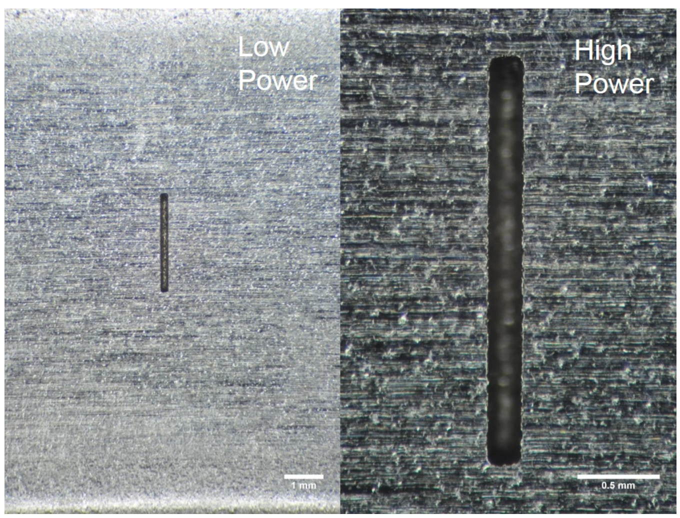

Figure 2: Mid-Gage EDM Notch in HCF Ground Specimen

Several sets of high cycle fatigue tests were performed in active corrosion fatigue (CF) using a 3.5% NaCl solution. Active corrosion exposure was achieved by attaching a pad saturated in the salt solution to the gage region. The saturated pad was sealed in order to keep the gage region moist during the duration of the fatigue test. An example of a LPB processed sample with a 0.020 in. deep notch tested in CF is shown in Figure 3.

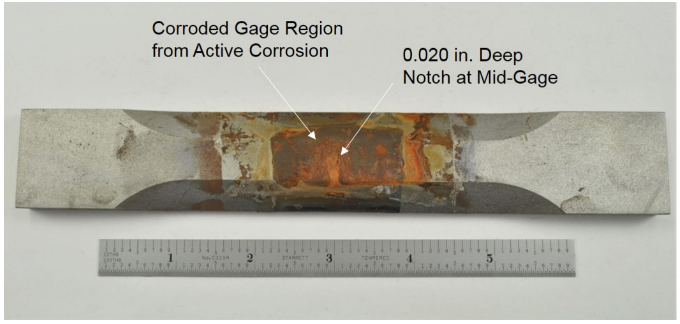

Figure 3: Actively Corroded LPB Processed HCF Specimen After Testing to Run-Out

High Cycle Fatigue

High cycle fatigue tests were performed under constant amplitude loading on a Sonntag SF-1U fatigue machine. A photograph of the 4-point bend fatigue test setup is shown in Figure 4.

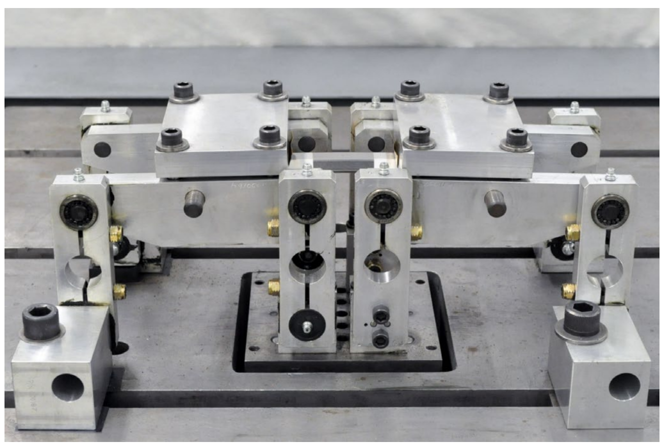

Figure 4: High Cycle Fatigue Four Point Bending Test Fixture

Fatigue testing was conducted at an ambient temperature of approximately 72 °F and at a frequency of 30 Hz. The stress ratio, R, was 0.1. Tests were conducted to the event of component fracture or until a "run-out" life of 10 x 10^6 cycles was attained. All partially fractured components were broken open to permit direct observation of fracture surface details.

Fatigue tests were performed on specimen groups that were ground, shot peened, or LPB processed. Several sets of samples were tested at comparable stress levels using surface damage alone or in combinations that included active 3.5% NaCl salt solution in corrosion fatigue.

Fractography

Following fatigue testing, each specimen was examined optically to identify the location of the fatigue origin within the gage region. Pictures were taken using a digital camera through a Nikon microscope to show typical examples of the failure locations for each specimen group.

Residual Stress

Surface and subsurface residual stress measurements were made by x-ray diffraction at Lambda Research using specialized diffractometers built for residual stress measurement. Measurements were performed in the longitudinal direction using a sine-squared-psi technique, employing the diffraction of chromium K-alpha radiation from the (211) planes of the ductile cast iron [28-31].

Material was removed electrolytically for subsurface measurement in order to minimize possible alteration of the subsurface residual stress distribution as a result of material removal. All data obtained as a function of depth were corrected for the effects of the penetration of the radiation employed for residual stress measurement into the subsurface stress gradient [32] and for stress relaxation caused by layer removal [33]. The value of the x-ray elastic constants required to calculate the macroscopic residual stress from the strain normal to the (211) planes was determined in accordance with ASTM E1426. The magnitude of any systematic errors was monitored per ASTM specification E915.

Surface Roughness

The surface roughness of the gage region of an LPB processed specimen was compared to the gage regions of both ground and shot peened specimens. The surface roughness values were obtained using a Mitutoyo SJ-201 Surface Roughness Tester. The surface roughness, Ra, was calculated over a 0.3 in evaluation length in the transverse direction (parallel to LPB lay) and over a 0.5 in evaluation length in the longitudinal direction (perpendicular to the LPB lay). All reported values are the average of three measurements. The tester was verified using a 116 µin standard.

RESULTS AND DISCUSSION

High Cycle Fatigue

Fatigue testing results are presented graphically as S-N plots in Figures 5 and 6. Figure 5 shows the HCF results for Baseline (Ground), Shot Peened (SP) and Low Plasticity Burnished (LPB) specimen groups tested with no damage. Figure 6 shows the specimen groups tested with a 0.020 in. deep notch. The data are shown in a semi-log plot of maximum stress in units of ksi (10^3 psi) and MPa vs. cycles to failure. Arrows on data points indicate a run-out condition of 10^7 cycles.

Figure 7 contains a bar plot summarizing the data from Figures 5 and 6. The fatigue limit for all six conditions is shown as a percentage of the baseline fatigue limit (at 10 million cycles). Fatigue limit is defined as the limiting value of stress at which failure occurs as the cycles to failure (N_f) approach run-out.

The LPB processed fatigue limit was slightly higher than the nominal 90 ksi of the shot peened specimens. The ground specimen fatigue limit was about 20 ksi lower than the fatigue limits of the LPB and shot peened specimens. In the absence of damage, the fatigue limit of ground ductile iron could be improved by about 25% with the application of shot peening or LPB processing.

Fatigue limits of the specimen groups with 0.020 in. deep notches dropped to 25 ksi for the ground, 30 ksi for the shot peened and 60 ksi for the LPB condition compared to the fatigue limits of the non-damaged groups. The LPB specimen group had nominally twice the fatigue limit of the ground or shot peened specimen groups when subjected to 0.020 in. deep surface damage. LPB processing effectively restored the fatigue limit of specimens damaged to 0.020 in. to within nominally 80% of the undamaged ground value.

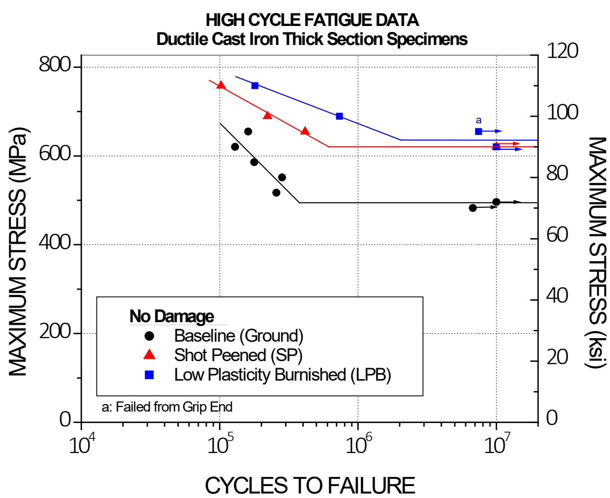

Figure 5: High Cycle Fatigue Results of Ductile Cast Iron Specimens With No Damage

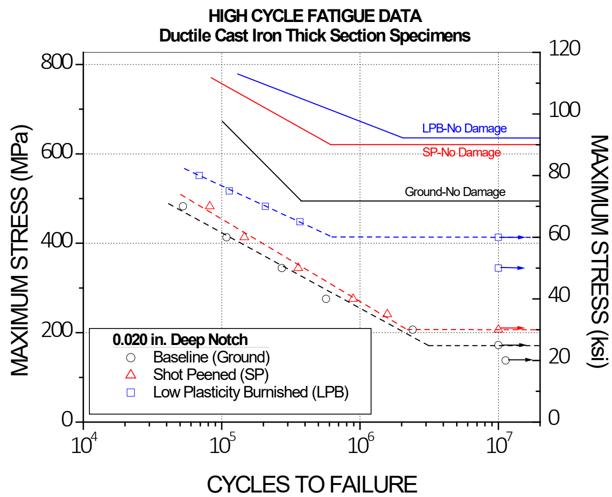

Figure 6: High Cycle Fatigue Results of Ductile Cast Iron Specimens with 0.020 in. Deep Notches

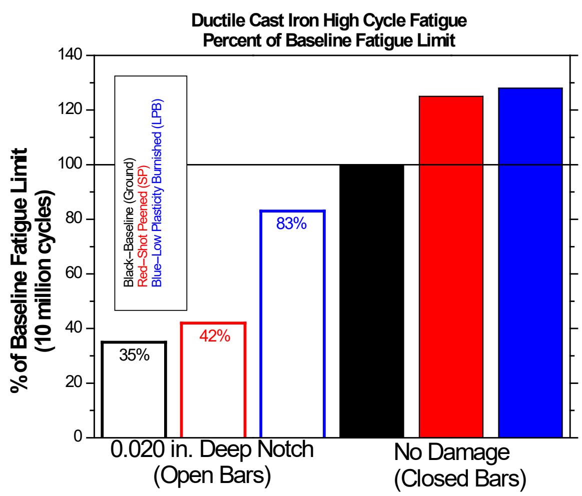

Figure 7: High Cycle Fatigue Results of Ductile Cast Iron Specimens Plotted as a Percentage of the Baseline Fatigue Limit

Figure 8 shows results for specimens tested with 0.010 in. damage + CF and 0.020 in. damage + CF. Data for specimens tested at 50 ksi are shown in Figure 9. A similar bar plot for specimen groups tested at 70 ksi is shown in Figure 10.

Specimens tested at 50 ksi and 70 ksi had a debit in fatigue life as a result of corrosion fatigue. LPB processed samples maintained the highest fatigue life while the ground samples had the lowest. All LPB processed samples tested with 0.020 in. deep notches at 50 ksi ran out to 10 million cycles, exhibiting greater than 10 times the fatigue life than both the ground and shot peened specimens. LPB processed samples tested with 0.010 in. deep notches at 70 ksi ran out to 10 million cycles for the notched condition and failed in about 8 million cycles for the notched + CF condition. All conditions of the ground and shot peened samples failed in less than 150,000 cycles at the 70 ksi stress level. Corrosion fatigue generally had less influence on fatigue life than the notch damage.

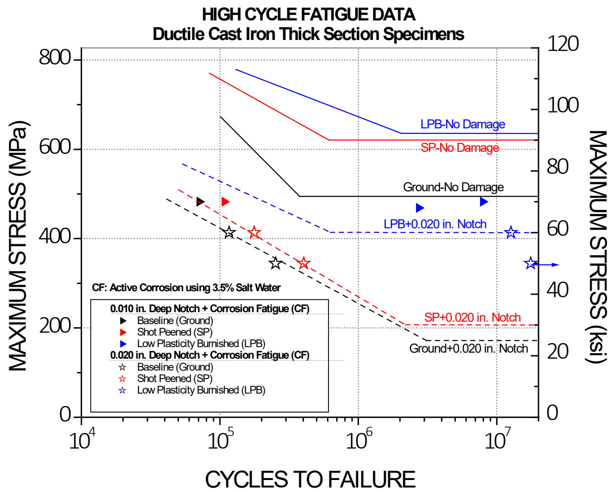

Figure 8: High Cycle Fatigue Results of Ductile Cast Iron Specimens With 0.010 in. and 0.020 in. Deep Notches and Corrosion Fatigue (CF)

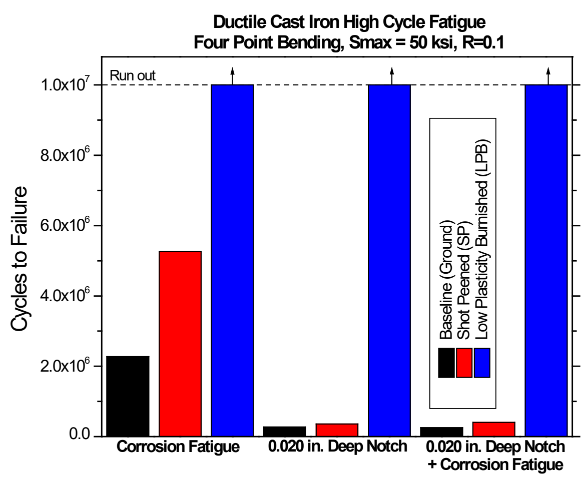

Figure 9: High Cycle Fatigue Results at Smax= 50 ksi

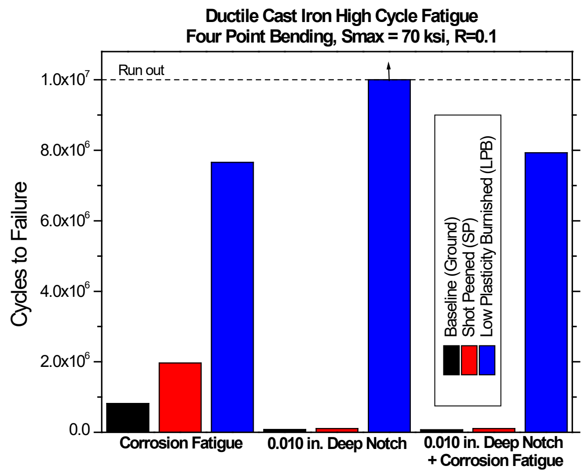

Figure 10: High Cycle Fatigue Results at Smax= 70 ksi

Fractography

Typical fracture faces for each tested sample group are shown in Figures 11 through 15. An example of the undamaged specimen group is shown in Figure 11. Figure 12 shows an example of a fracture face of the specimens that were notched to 0.020 in. Fracture faces for samples tested in CF with and without notches are shown in Figures 13 and 14, respectively. An example of a fracture face of a CF specimen that did not fail from the notch is shown in Figure 15.

Samples with no damage failed within the gage from single surface initiations. With the exception of a few LPB samples tested in CF, samples with notch damage primarily failed from the notch. Samples tested in CF only generally failed from one dominant initiation with some additional minor surface initiations within the gage region.

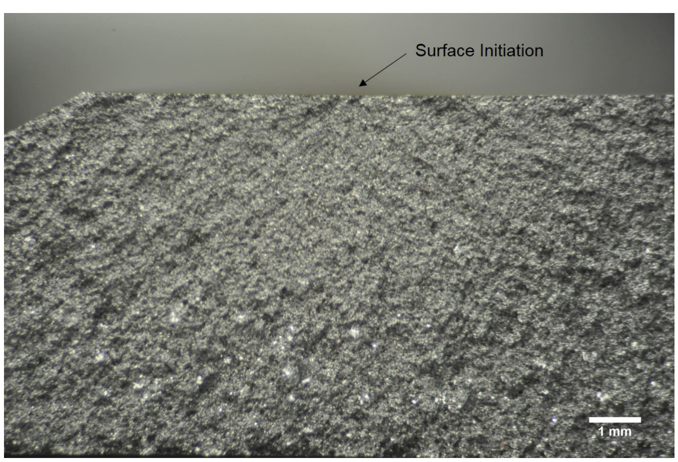

Figure 11: Fracture Face of a Baseline (Ground) Specimen

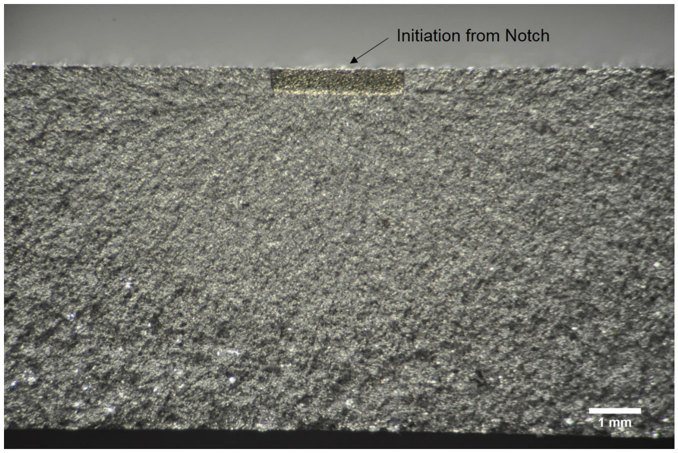

Figure 12: Fracture Face of a Shot Peened Specimen With a 0.020 in. Deep Notch

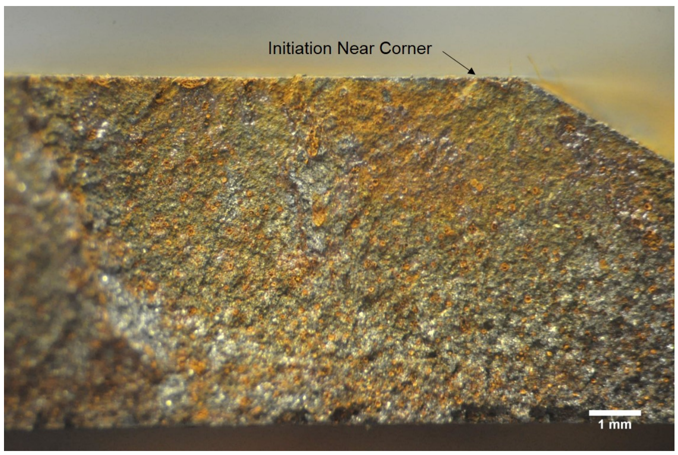

Figure 13: Fracture Face of a LPB Specimen Ran in CF

Figure 14: Fracture Face of a Shot Peened Specimen With a 0.020 in. Deep Notch Ran in CF

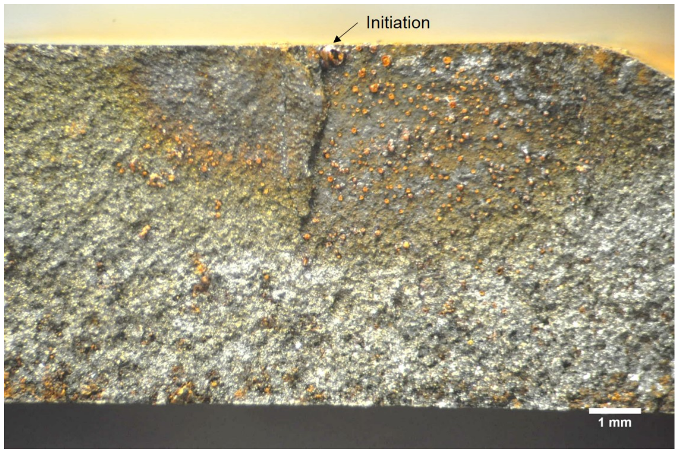

Figure 15: Fracture Face of an LPB Specimen With a 0.010 in. Deep Notch Ran in CF

Residual Stress

The longitudinal residual stress distributions measured as functions of depth are shown graphically in Figure 16. Compressive stresses are shown as negative values, tensile as positive, in units of ksi (10^3 psi) and MPa (10^6 N/m^2).

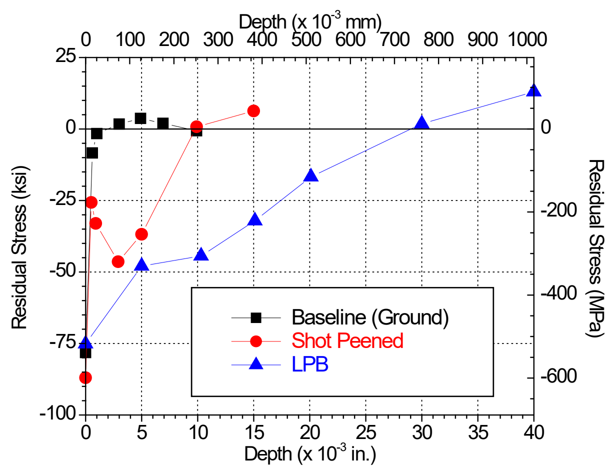

Figure 16: Residual Stress Distributions for Ground, Shot Peened, and LPB Processed HCF Test Specimens

Residual stress was most compressive at the surface for all conditions. Depth of compression was approximately 0.002, 0.010, and 0.03 in. for the ground, SP, and LPB conditions, respectively. Maximum compressive magnitudes are similar for the three conditions. Residual stress results support the fatigue findings. Compression that extends deeper than the damage provides a benefit. Deeper compression afforded by LPB is able to reach below both the corrosion damage and simulated 0.020 in. damage to provide the highest fatigue benefits.

Surface Roughness

The results of the Ra surface roughness measurements for the ground, shot peened, and LPB processed gage regions are shown in Figure 17.

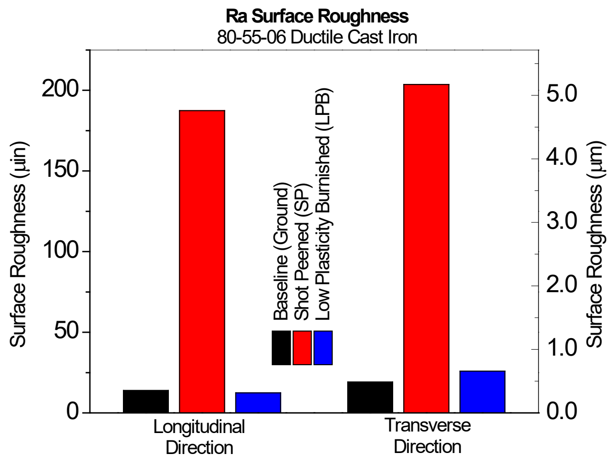

Figure 17: Surface Roughness of Ground, Shot Peened, and LPB Processed Surfaces

Surface roughness was comparable in the directions along and transverse to the loading axis for all three respective processes. The shot peening process left a much rougher surface than either the LPB or grinding process. LPB provided surface roughness similar to finish grinding with optimal fatigue properties.

CONCLUSIONS

High cycle fatigue performance of 80-55-06 ductile cast iron is consistent with the subsurface residual stress distributions produced by the finish treatments studied. For both the ground and shot peened condition the compression is less than 0.01 in., and damage on that order or deeper produces a significant fatigue debit reducing the fatigue strength to less than 50% of the baseline. The 0.030 in. depth of LPB compression retards initiation and growth from either shallower damage or active corrosion providing a fatigue strength nearly equal to that of the ground undamaged condition. LPB mitigates the corrosion effects during cyclic loading, effectively restoring the fatigue limit typically lost in corrosion fatigue. Proper introduction of deep compression into ductile cast iron components via surface treatments such as LPB can greatly improve damage tolerance and fatigue performance in corrosive and non-corrosive environments.

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