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Pressure Ratings and Design Guidelines for Continuous Cast Ductile Iron in Hydraulic Applications

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ABSTRACT:

The methods for determining pressure ratings in components within a hydraulic circuit are defined by NFPA standard T2.6.1, R1-1991. This standard requires 2 separate tests: A burst test to determine the ultimate allowable stress and an impulse test to validate the fatigue strength of a component under cyclical loading.

In this study, the pressure rating for continuously cast ductile iron bar stock was determined using the guidelines established in T2.6.1 utilizing test manifold blocks consisting of two drilled ports, one under hydraulic pressure and the other open to the atmosphere.

This report contains the results of the pressure rating validation and plotting of the fatigue data for 1045 plain carbon hot rolled steel and ASTM A536 grade 65-45-12 continuous cast ductile iron.

INTRODUCTION:

Ductile iron is widely used in hydraulic components including manifolds, piston pump bodies, pistons, glands, spools and valves. It is an attractive alternative over carbon steel especially when fabrication of the parts involves cutting, turning, milling and drilling. The presence of graphite nodules in the microstructure creates free machining properties leading to longer tool life and faster machining.

Mechanical properties of the standard ASTM A536 ductile iron grades are similar to plain carbon steel grades having a similar matrix structure. However, the graphite nodules influence the elongation in the plastic range by comparison to steels having the same tensile and yield strength (Ref. Table 1).

Table 1: Mechanical Properties, Ductile Iron and Steel

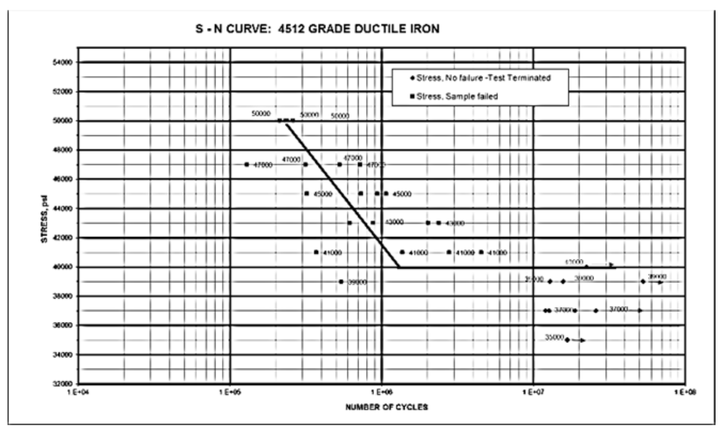
Mechanical Property Comparisons: 1045 Steel (typical) vs. 65-45-12 Ductile Iron		
	65-45-12 Ductile Iron	**AISI 1045 HR Steel**
Tensile Strength (psi)	65,000	81,900
Yield Strength (psi)	45,000	45,000
Elongation (%)	12	16
Hardness, Avg. BHN	180	163
Modulus of Elasticity	27,000	29,000
Poisson's Ratio	0.275	0.290

Because of the lower elongation, ductile iron is classified as being more brittle than steel and as a result there is a misconception that ductile iron has lower fatigue properties as well. However, under normal operation the side walls in a hydraulic manifold will operate in the elastic range, below the yield strength, and elongation should not be the determining factor in the allowable pressures within a hydraulic system.

In previous studies (Ref. Fig. 1), continuous cast ductile iron bar stock having good nodularity and nodule count with a matrix of at least 75% ferrite has been shown to have fatigue strengths over 40ksi, very close to the minimum yield strength of the material.

This created the argument that ductile iron fatigue data should be a consideration in determining allowable hoop stresses in a hydraulic manifold.

Figure 1: SN Plot 65-45-12 Ductile Iron rotating beam test



Mechanical properties along with fatigue limits show that ductile iron is similar to 1045 carbon steel. However, a literature search showed that there is very little information available on the pressure ratings for ductile iron in hydraulic manifold applications. Even less is available to compare ductile iron properties to carbon steel.

The authors feel that because of the lack of information available on the rated pressure of ductile iron there is a tendency to use 1045 carbon steel in high pressure hydraulic systems.

Given the fact that ductile iron can be machined faster than steel, provide longer tool life with minimal deburring and is 10% lighter, there is a need to develop pressure rating and design data for ductile iron so that it can be used in high pressure hydraulic systems.

This report provides a comparison of ultimate burst strength and fatigue limits between 65-45-12 continuous cast ductile iron and 1045 carbon steel. The aim of this work is to define a pressure rating for continuous cast ductile iron ASTM A536, grade 65-45-12 and to draw a comparison between ductile iron and 1045 steel.

The data provides a useful tool to the design engineer in determining minimum wall thickness requirements for a given port diameter of a manifold operating at or below the rated pressure.

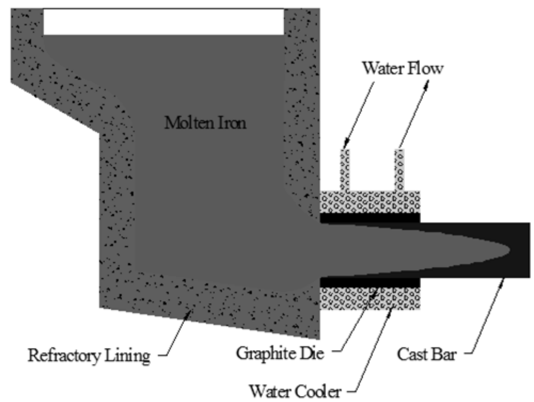
BACKGROUND:

CONTINUOUS CASTING PROCESS:

The continuous casting process for making ductile iron bar stock involves a bar machine crucible with a water cooled graphite die mounted on the front of the machine at the bottom of the vessel. Molten iron flows into the die and a thin solidified skin is formed that takes the shape of the bar. As the bar is cast through the die in a series of strokes, the solidified rim becomes just thick enough to hold the shape of the bar as it exits the cooling jacket (Ref. Fig. 2).

The molten iron core is superheated to approximately 400°F over the liquidus and reheats the rapidly chilled outer skin to a temperature approximately 50 degrees under the solidus. As it is cast down the production line, the entire bar solidifies and cools in still air.

Figure 2: Cross Section of Bar Machine Crucible



During the casting process, the level of molten iron in the bar machine drops to a predetermined level and fresh inoculated iron is added to the crucible in pre-established intervals.

The fluctuation of iron occurs in the widest part of the crucible at the top so the effect on the head pressure during casting is negligible. There are three primary advantages of the continuous casting process:

1. The bar machine crucible is designed so that slag, dross and impurities that could cause casting defects float to the top of the bath, well away from the entrance to the graphite die. Only very clean iron is allowed to enter the die, free from the impurities that could degrade the microstructure and mechanical properties of the bar.

2. The head pressure in the bar machine crucible is constantly feeding iron into the solidifying bar and essentially acts as a huge riser preventing shrinkage and providing very good surface finishes in the machined part.

3. As the bar comes out of the die, it is reheated to a temperature of approximately 1950°F and allowed to solidify and cool in still air. The reheating and subsequent ambient cooling eliminate any chill carbides that formed in the rapidly solidified rim. The result is a homogenized structure throughout the cross section with very consistent machinability.

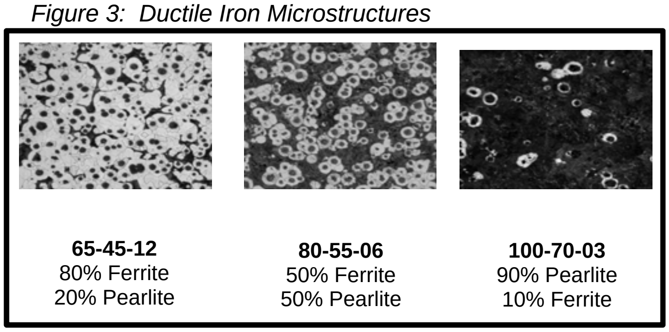
A wide range of round and rectangular bar stock can be produced using the continuous casting process in sizes up to 20" diameter rounds and 16" x 24" cross section rectangles.

DUCTILE IRON GRADES:

There are 5 standard ductile iron grades within the scope of ASTM A536. Each grade is defined by the minimum required tensile and yield strengths and elongation. Three of the grades are commonly produced in the as cast condition and the other two usually require heat treating – either a full anneal to increase elongation or quench and temper to increase tensile and yield strengths.

The 3 as cast grades, 65-45-12, 80-55-06 and 100-70-03, vary in the matrix structure pearlite composition which influences hardness and tensile strength, per the microstructures shown in Figure 3:

Figure 3: Ductile Iron Microstructures



65-45-12 ductile iron is the most commonly used grade for the production of hydraulic manifolds and other components because it offers a good combination of machinability, along with strength and fatigue properties that are similar to plain carbon steel.

For the purpose of this investigation, continuously cast ASTM A536 grade 65-45-12 rectangle stock was used exclusively in all of the ductile iron investigation and all test materials were selected from standard production inventory at random, so as to represent typical production material. All of the specimens were machined using production tooling under normal machining practices to represent a typical production facility.

MANIFOLD DESIGN CONSIDERATIONS:

Stress failures in a hydraulic manifold can occur in either of the three modes:

1. Hoop stresses: The pressure exerted on the wall of a chamber under internal pressure.

2. Radial Stresses: Adjacent pressure ports each under its own hydraulic pressure.

3. Axial Stresses: The longitudinal stresses exerted on blind holes, bolts and flanges.

Consideration of all three types of stresses is important in the proper design of a high pressure hydraulic system. For the purpose of this study, only hoop stresses are being considered to determine the pressure rating and fatigue limits of the material being tested.

In the design of a manifold under constant pressure, there are 3 variables to consider: the pressure rating of the material being used, the size of the port under pressure, and the wall thickness where the burst failure is most likely to occur. The test manifolds had port diameters of 0.5", 1.0" and 2.0" with wall thicknesses between 0.025" and 0.600". Pressures for the burst tests were increased gradually until failure occurred. The pressures used in the impulse studies were not varied during the test.

STRESS CALCULATIONS:

The hoop stress exerted on the manifold wall can be calculated by either of the 2 formulas:

Barlow:

$$Hoop\ Stress\ (psi) = \frac{(Max.\,Bore\ Pressure\ (psi))(Radius\ of\ Bore(in.))}{Wall\ Thickness\ (in.)}$$

Thick-Walled Pressure Vessel:

$$Hoop\ Stress\ (psi) = \frac{(O.D.^2 + I.D.^2)}{(O.D.^2 - I.D.^2)}(Bore\ Pressure\ (psi))$$

Stress calculations in thin walled applications using both formulas are similar when the wall thickness is less than 0.250", but as wall thickness increases, the stress calculated using the thick walled formula is higher.

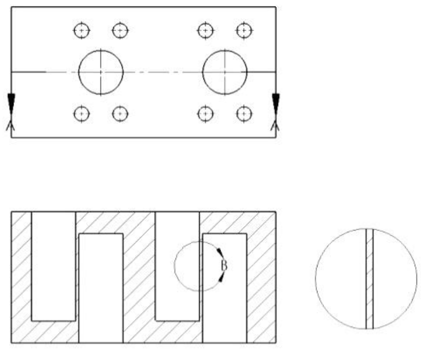
The thick-walled pressure vessel formula is used in all calculated stress data in this report.

TEST MANIFOLD BLOCK DESIGN:

Test block sizes were milled rectangles, 6.5" x 4.0" x 3.5", oriented with the test ports drilled longitudinally into the center of the 3.5" face along the 6.5" length. Each block had 4 ports, 2 that are drilled from the top surface and subject to the test pressure, and two that would be drilled from the opposite face parallel to the pressure port with a specified wall thickness targeted to be the failure point separating the drilled holes.

The two sets of drilled holes were separated by a heavy wall section so that the test pressure in either port did not affect the integrity of the adjacent test ports (Ref. Fig. 4).

Figure 4: Manifold Test Block Design



TEST LAB AND PROCEDURES:

Three independent parties were involved in this study: Dura-Bar, a producer of continuous cast iron bar stock, Daman Products Company, a hydraulic manifold producer, and the Fluid Power Institute of the Milwaukee School of Engineering.

All of the testing procedures, as well as the execution of the actual testing, were established and performed under the supervision of the Director of the Fluid Power Institute and the FPI staff, including teaching staff and research assistants. Details of the entire study are available in the form of Technical Reports published by the Fluid Power Institute.

This report summarizes the findings from each of the 4 milestones that comprised the entire study: Burst Testing First Round, Impulse Testing First Round, Burst Testing Second Round, and Impulse Testing Second Round.

First round burst and impulse testing were used to establish pressure ratings in accordance with NFPA T 2.6.1 and second round testing was used to develop the SN fatigue curve for both materials.

BURST TESTING – FIRST ROUND:

OBJECTIVE:

Increase pressure in the test port until failure occurs in the side wall to determine maximum hoop stress.

PROCEDURE:

The manifold blocks were plumbed for burst testing in a dead-head configuration. Pressure measurements were taken using a GP50 pressure transducer. Maximum pressure was recorded with a Newton Process Meter.

Water pressure was applied to the internal cavity until failure occurred, as indicated by a sudden loss of internal cavity pressure (the ability of the chamber to hold pressure). All testing was done at room temperature, approximately 68°F.

Test manifold blocks had 0.5", 1.0" and 2.0" bore diameters with varying wall thicknesses according to Table 2:

Table 2: Bore Diameter and Wall Thickness configuration for Burst Test, First Round

Bore Diameter (in)	Wall Thickness (in)
0.5	0.05
	0.10
	0.20
1.0	0.10
	0.20
	0.40
2.0	0.15
	0.30
	0.60

Two separate pressure tests were conducted on each configuration.

Note: Pressure ports were fitted with SAE code 62 flanges and grade 8 bolts. Anti-seize lubricant was applied to the bolts and torqued to bolt manufacture specifications. All O-rings were buna with 90 durometer hardness.

RESULTS:

The maximum pressure obtained in the chamber up to failure is tabulated below in Tables 3, 4 and 5. In the majority of cases, failure was due to axial stresses exerted on the bolts causing elongation in the elastic state leading to O-ring failure (the bolts did not appear to be permanently deformed or damaged).

Table 3: 0.50" Bore Diameter Burst Test

0.50" Bore Diameter

	Trial 1		Trial 2	
1045 Steel				
Wall Thickness (in.)	Maximum Pressure (psi)	Failure Type	Maximum Pressure (psi)	Failure Type
0.05	40,063	O-ring	41,427	O-ring
0.10	41,381	O-ring	N/A	N/A
0.20	40,722	O-ring	N/A	N/A
65-45-12 Ductile Iron				
0.05	40,025	Burst	N/A	N/A
0.10	40,953	O-ring	N/A	N/A
0.20	42,599	O-ring	N/A	N/A

For the second trial, a harder nylon o-ring was tried on the steel specimen to find out if o-ring failures could be prevented. No further testing was performed once it became evident that hoop stress failure would not occur.

Table 4: 1.00" Bore Diameter Burst Test

1.00" Bore Diameter

	Trial 1		Trial 2	
1045 Steel				
Wall Thickness (in.)	Maximum Pressure (psi)	Failure Type	Maximum Pressure (psi)	Failure Type
0.10	36,300	O-ring	N/A	N/A
0.20	36,788	O-ring	N/A	N/A
0.40	34,824	O-ring	N/A	N/A
65-45-12 Ductile Iron				
0.10	35,496	O-ring	N/A	N/A
0.20	35,552	O-ring	N/A	N/A
0.40	35,283	O-ring	N/A	N/A

Only one trial was performed once it became evident that hoop stress failures in the side wall would not occur.

Table 5: 2.00" Bore Diameter Burst Test

2.00" Bore Diameter

	Trial 1		Trial 2	
1045 Steel				
Wall Thickness (in.)	Maximum Pressure (psi)	Failure Type	Maximum Pressure (psi)	Failure Type
0.15	33,427	O-ring	37,226	O-ring
0.30	30,220	O-ring	36,607	O-ring
0.60	32,511	O-ring	N/A	Thread Failure
65-45-12 Ductile Iron				
0.15	27,017	Burst	N/A	N/A
0.30	33,551	O-ring	38,123	O-ring
0.60	36,715	O-ring	36,284	O-ring

RESULTS DISCUSSION:

In all cases, with the exception of two ductile iron blocks, the failures resulted from o-ring leakage rather than hoop stress failures. Using the results above, it was determined that larger bores with thinner walls needed to be studied to determine the ultimate allowable burst stress that could be applied to either the 1045 or 65-45-12 ductile iron test blocks.

Note: 2 ductile iron test blocks failed having calculated wall stresses of 221,957 194,564 psi on the 1.0" and 2.0" bores, respectively. However the data obtained in the second round of testing was found to be more repeatable, the first round tests were not used in the plotting of data on the SN curves.

BURST TESTING – SECOND ROUND:

OBJECTIVE:

Continue to determine the hoop stress limit in test ports under internal water pressure applied to various bore diameters and wall thicknesses.

PROCEDURE:

All procedures described previously were the same, with the exception of bore diameters and wall thicknesses. The test blocks having 0.50" bore diameters were eliminated and the wall thicknesses were reduced to a 0.075" maximum.

Sixteen specimens were tested, all resulting in hoop stress failures with the corresponding data shown in Table 6.

Table 6: Burst Testing, Second Round Test Block Configuration, Burst Pressures and Calculated Hoop Stresses

Bore Diameter (in.)	Wall Thickness (in.)	Burst Pressure (psi)		Calculated Applied Hoop Stress (psi)	
		Trial 1	Trial 2	Trial 1	Trial 2
1045 Steel					
1	0.025	11,788	14,734	241,798	302,227
	0.050	22,357	22,274	235,281	234,407
2	0.050	17,624	17,589	361,507	360,789
	0.075	22,887	22,305	317,017	308,956
65-45-12 Ductile Iron					
1	0.025	11,696	12,190	239,911	250,044
	0.050	21,090	22,597	221,947	237,807
2	0.050	11,890	11,549	243,890	236,895
	0.075	15,223	16,435	210,860	227,648

RESULTS DISCUSSION:

For the second round of burst testing, failures occurred where desired, in the midpoint of the bore at the thin-walled section of the parallel test ports. Using the thick-walled stress calculation, the wall stress to failure is determined for each material and tabulated in Table 6.

As expected, 1045 steel failed at a higher burst pressure than ductile iron which coincides with steel having a higher ultimate tensile strength.

The average calculated hoop stress to failure for each material can be plotted on the SN curve as the failure point for one cycle:

295,000 psi for 1045 Steel

234,000 psi for 65-45-12 Ductile Iron

IMPULSE TESTING FIRST ROUND:

OBJECTIVE:

Obtain pressure rating for 1045 steel and 65-45-12 ductile iron.

PROCEDURE:

Test manifolds had bore diameters of 0.50", 1.00" and 2.00" with wall thicknesses ranging between 0.050" to 0.400", and were plumbed into a dead head hydraulic circuit. Testing was performed on 3 sets of 9 block configurations for each material for a total of 54 manifolds in the circuit.

The assembly was tested at a pressure of 8,000 psi using 120°F Benz-Oil petroleum based ISO VG 46 hydraulic oil at one impulse per second until failure or until 1,000,000 cycles was reached.

RESULTS:

No failures occurred in any of the 54 test blocks after 1,000,000 cycles. The test pressure was held constant at 8,000 psi and the calculated wall stress would be the same for each material having the same bore diameter and wall thickness. The configurations and calculated wall stress is in Table 7.

Table 7: Impulse Testing, First Round, Manifold Test Block Design and Calculated Hoop Stress

Impulse Testing:
Manifold Design, 1045 and 65-45-12 Ductile Iron

Bore Size (in)	Wall Thickness (in)	Test Pressure (psi)	Cycles	Calculated Wall Stress (psi)
0.5	0.05	8000	1M	44,364
	0.10			24,667
	0.20			15,143
1.0	0.10	8000	1M	44,364
	0.20			24,667
	0.40			15,143
2.0	0.15	8000	1M	57,612
	0.30			31,188
	0.60			18,256

RESULTS DISCUSSION:

Pressure Rating Determination:

In the NFPA Standard T2.6.1, Table 1 – Coefficient of Variation for different metals lists a K_o value for low carbon steel of 0.08 and all grades of iron of 0.14. (Note that this K_o value does not take into account the differences between continuous cast and sand cast irons.)

Table 2 of the NFPA Standard lists the variability factors as a function of level of confidence, number of samples tested and variation coefficient.

For the 1045 steel, the variability factor is 1.12 to obtain a 90% confidence level with 3 samples tested. Ductile iron has a 1.23 variability factor with the same parameters.

Pressure rating determination based on these test results is:

$$\frac{8000psi}{1.12} = 7143psi \text{ for 1045 steel}$$

$$\frac{8000psi}{1.23} = 6504psi \text{ for 65-45-12 ductile iron}$$

Infinite Life Stress Calculation:

Calculated wall stresses in Table 7 range from 15,143 psi minimum to 57,612 psi maximum. Since there were no failures in any of the test blocks, infinite life wall stress can be plotted on the SN curve as 57,612 psi.

IMPULSE TESTING SECOND ROUND:

OBJECTIVE:

Obtain data points for number of cycles to failure between 1 and 1 million at various calculated wall stresses to complete SN fatigue curve.

PROCEDURE:

Test procedure was similar to that conducted in the first round of impulse testing, except that the manifold bore diameters were increased and the wall thicknesses decreased to give a more aggressive design, higher wall stresses and hoop stress failures for a limited number of cycles.

All testing was conducted above the rated 8,000 psi pressure for each material, and set at 8,500 psi to help ensure failures of the wall before 1 million cycles.

Table 8: Test Specimen Configuration:

Steel and Ductile Iron Test Block Designs

Bore Dia. (in.)	Wall Thickness (in.)	Test Pressure (psi)	Calculated Wall Stress (psi)
1	0.025	8500	174,354
	0.050	8500	89,452
2	0.050	8500	174,354
	0.075	8500	117,737

Note that the applied calculated wall stress for the 1.0” bore, 0.025” configuration is identical to the 2.0” bore having 0.050” wall thickness.

RESULTS:

Hoop stress failures occurred on each of the test blocks at cycles ranging from approximately 400 up to 175,000.

Complete tabulation of the results is in Table 9:

Table 9: Impulse Testing, Second Round. Manifold Design, Cycles to Failure and Calculated Hoop Stress

Bore (in)	Wall Thickness (in)	Cycles to Failure	Wall Stress (psi)
1045 Steel			
1	0.025	1	
		3,635	
		9,498	
Average Cycles to Failure		**4,378**	**174,354**
1	0.050	13,932	
		39,021	
		61,694	
Average Cycles to Failure		**38,216**	**89,452**
2	0.050	7,085	
		7,085	
		7,085	
Average Cycles to Failure		**7,085**	**174,354**
2	0.075	49,565	
		62,760	
		68,250	
Average Cycles to Failure		**60,192**	**117,737**
65-45-12 Ductile Iron			
1	0.025	2,005	
		2,012	
		2,337	
Average Cycles to Failure		**2,118**	**174,354**
1	0.050	74,440	
		74,440	
		74,440	
Average Cycles to Failure		**74,440**	**89,452**
2	0.050	100	
		390	
		620	
Average Cycles to Failure		**370**	**174,354**
2	0.075	16,585	
		19,890	
		22,838	
Average Cycles to Failure		**19,771**	**117,737**

RESULTS DISCUSSION:

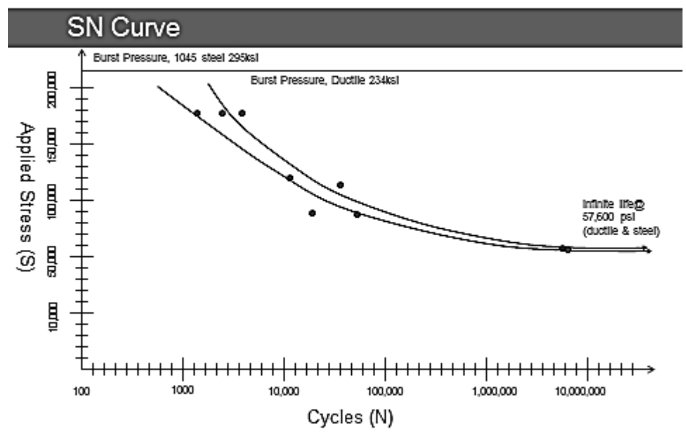
The data matched expectations; the number of cycles to failure increased with decreasing calculated wall stress.

Plotting of the data gives a qualitative picture of the SN Curve showing the single point wall stress values as a horizontal line with infinite life determined by the testing conducted in the Impulse Testing First Round experiment.

What is important to note is that although there is variability in the data, especially in the area of low cycle fatigue testing of less than 100,000 cycles, the true maximum wall stress to infinite life appears to be between 89,452 and 57,612 psi (Ref. Fig. 5).

Future work may be conducted to complete the data points for cycles between 100,000 and 1 million.

Figure 5: SN Plot, 1045 Steel and 65-45-12 Ductile Iron



SUMMARY AND CONCLUSION:

The data collected in this study provides useful information about the ability of continuous cast ductile iron to be used interchangeably with 1045 carbon steel for hydraulic manifold applications up to and including the rated pressure of 6,500 psi.

The data also shows that although the ultimate tensile strength of 1045 steel is higher than 65-45-12 ductile iron, the yield strength and fatigue properties are similar and there is virtually no difference in material properties when a part is subjected to high cycle impulse pressures.

It is important to note that the mechanical properties in a ductile iron component are influenced by the casting design, graphite morphology, matrix structure and the casting process.

The data collected in this report pertains to a high quality ductile iron, continuously cast to strict internal process specifications and the pressure ratings, burst data, impulse test data and fatigue curves do not necessarily apply to all commercially produced ductile irons.

Dura-Bar is an ISO 9001 registered firm and holds processing certifications from the Ductile Iron Society and the American Bureau of Shipping, and is a member of the National Fluid Power Association.

ACKNOWLEDGMENTS:

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