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THE MECHANICAL BEHAVIOR AND FRACTURE OF THIN WALL IRON UNDER QUASI-STATIC AND DYNAMIC LOADING CONDITIONS

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ABSTRACT

The use of cast iron in automotive applications in this era of increasing fuel efficiency requires the ability to cast very thin sections (2-7 mm). The mechanical properties of thin wall ductile iron castings are strongly affected by the thickness of the castings because thinner castings cool at a faster rate. In this study, strength properties were found to decrease as a reciprocal function of thickness. Strain properties were found to increase as a linear function of thickness. Determining quasi-static and dynamic mechanical properties is difficult due to the thin section sizes. Experiments relating mechanical properties with casting thickness will be discussed, including non-standard fatigue tests. Various means of verifying the non-standard tests will also be discussed.

KEYWORDS

ductile iron, mechanical properties, fatigue, thin section castings

INTRODUCTION

Iron-based castings will have some degree of pearlite in the microstructure, depending upon the processing conditions and cooling rate. As the percentage of pearlite increases, the strength increases and ductility decreases. Traditionally, castings have been produced with thick walls (greater than 7 mm), which results in a large percentage of the softer, more ductile ferrite. The mechanical properties of a keel block poured at the same time and from the same heat as a casting have been sufficient to represent the mechanical properties of the casting in general [1]. Mechanical properties are dependent on processing parameters, including the chemical composition, cooling rate, inoculation, solidification rate [1], and many other variables. The high cooling rate of thin-wall ductile iron is reported to result in a decrease in mechanical properties, specifically, ductility and toughness [1]. Thin sections of castings have been shown to have a larger amount of pearlite than thicker sections within the same casting [4], Figure 1. Whereas the keel block is sufficient to represent the properties for thick castings, it may not be for thin castings.

In order to effectively use thin wall castings, design properties pertinent to their processing conditions need to be available. No test methodology exists for thin wall iron, however, so a program is needed to develop the quasi-static and dynamic properties of thin-wall iron. To address this need, a program was undertaken to develop test specimen configurations, test procedures, and sampling recommendations. The results of the quasi-static testing are presented. The results from the quasi-static tests are then used to predict fatigue behavior.

EXPERIMENTAL PROCEDURE

Three heats of ductile cast iron were produced using an open ladle treatment. The final chemistries of the three heats are listed in Table 1. The treated irons were poured into resin-bonded dry sand molds. The irons were post-inoculated using two methods: for heat 6, a lump of 75% foundry grade ferrosilicon was placed in the mold, and for heats 8 and 9, 75% foundry grade ferrosilicon was added to the stream during pouring. The test castings were thin strips (referred to as singles) approximately 25 mm wide by 100 mm long, with a 25 mm x 25 mm x 35 mm runoff and a step plate (referred to as stepblock) consisting of joined strips approximately 25 mm wide by 100 mm long. The nominal thicknesses of the strips were 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, and 6.0 mm. Microstructure of the castings was characterized using image analysis software and an optical microscope [4].

The specimen blanks were machined into flat tensile bars approximately 75 mm long with a 25.4 mm reduced gage section. The width of the test section was approximately 6.35 mm with a thickness that depended on the original cast dimension. A taper of less than 0.1 mm was created from the shoulder to the center of the gage length. Approximately 0.25 mm of the broad surface was removed by grinding, effectively removing the as-cast surface. The tensile samples were tested on a screw-drive universal testing machine at 0.5 mm/min. Details of this testing procedure are published in [1].

From the stress-strain data, monotonic (quasi-static) design properties were calculated [1]. These design properties include reduction in area (%RA), elongation (%elo), true fracture ductility (ε_f), modulus of elasticity (E), yield strength (σ_y), ultimate tensile strength (s_u), true fracture strength (σ_f), strain hardening exponent (n), and strength coefficient (K).

TABLE 1
FINAL COMPOSITION OF TREATED IRONS (wt%)

Element	Heat 6	Heat 8	Heat 9
C*	3.80	3.71	3.76
Si	2.74	2.67	2.67
Mn	0.22	0.20	0.21
Cu	0.15	0.10	0.14

Cr	0.05	0.04	0.04
Mg	0.020	0.021	0.021
S	0.006	0.006	0.009

* calculated (base iron carbon content - 0.13 wt%)

Strain-life curves for eight different thicknesses of ductile cast iron were constructed using the strain-based four-point method [1]. The coordinates of the four points can be constructed from quasi-static properties by the following estimates:

where the first coordinate is the value in cycles to failure, N_f, and the second coordinate is the value of the strain range, $\Delta\varepsilon$. Points P_1 and P_2 define the elastic strain line. Points P_3 and P_4 define the plastic strain line. The sum of the two lines creates the fatigue curve for the alloy. Point P_4 is determined by the intersection of the elastic and plastic curves at the transition fatigue life, N_t, and is estimated to be 10^4.

RESULTS

The mechanical properties were plotted as a function of as-received thickness. Properties that are a measure of strain, such as reduction in area, elongation (Figure 2), and true fracture ductility, were observed to have a linear relationship with the as-received thickness. Properties that are a measure of stress, such as yield strength, ultimate tensile strength (Figure 3), and true fracture strength were observed to have a reciprocal or inverse relationship with the as-received thickness. In addition, the two properties derived from the stress-strain curve, e.g., the strain hardening exponent and the strength coefficient, as well as one property often related to strength, e.g., hardness, were also found to have an inverse relationship with the as-received thickness. Modulus of elasticity was a constant value, independent of the as-received thickness.

Multiple linear regression was used to describe the results obtained from the mechanical testing campaign. The strain properties were evaluated for a fit against the following general model:

where μ is the mean value of reduction in area, elongation, or strain to failure. The model determines if there is a difference between the baseline value and any of the explanatory variables, which in this case is the as-received thickness. The coefficient β_0 is the mean value for the property at a thickness of zero. If the coefficient for thickness, β_1, is found to be statistically significant, then the mechanical property depends on the as-received thickness. The thickness coefficient was found to be significant for all measures of strain.

Properties that appeared to have a reciprocal (inverse) relationship with the as-received thickness were evaluated with a slightly different model:

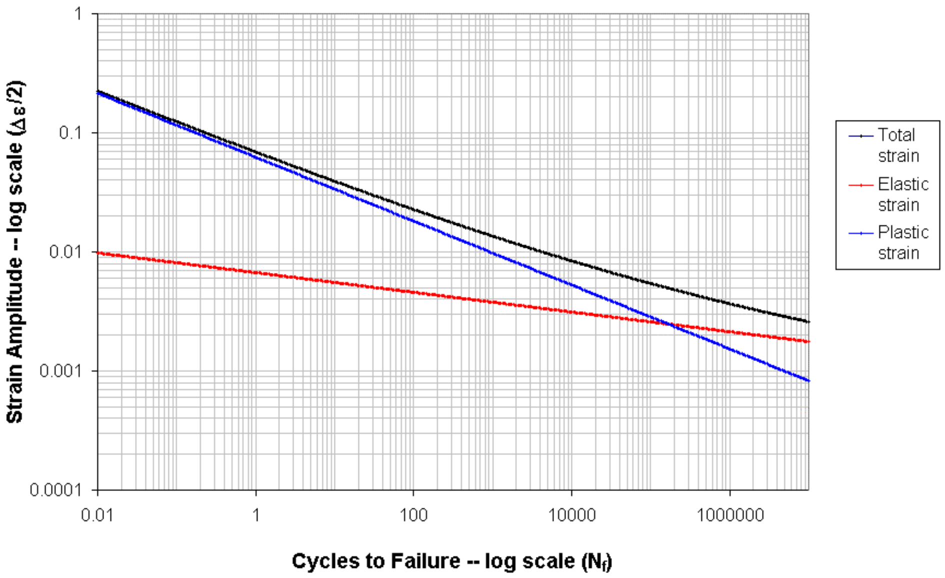
The coefficient β_3 is the mean value for the property at an infinite thickness. The coefficient for the inverse thickness, β_3, was found to be significant for measures of stress, strain hardening exponent, strength coefficient, and hardness. The only property where thickness was not found to be significant was modulus of elasticity, which is a constant value of 158 GPa.

The multiple linear regression equations can also be used to predict the mean value of the property at a given thickness. These results are presented in Table 2.

TABLE 2
MEAN VALUES OF MECHANICAL PROPERTIES

t (mm)	% RA	% elo.	ε_f	σ_y (MPa)	s_u (MPa)	σ_f (MPa)	n*	K* (MPa)	HRG
2.0	1.9	1.6	0.024	485	597	596	0.28	2180	80
2.5	2.4	2.1	0.028	450	558	563	0.24	1770	75
3.0	2.8	2.5	0.033	427	532	541	0.22	1500	72
3.5	3.2	3.0	0.037	411	513	525	0.20	1310	70
4.0	3.7	3.5	0.042	399	499	513	0.19	1170	68
5.0	4.6	4.4	0.051	381	480	497	0.17	960	66
6.0	5.4	5.3	0.060	370	467	486	0.16	830	65
7.0	6.3	6.2	0.069	362	457	478	0.15	730	64

[*] values calculated from yield to 1% strain.



The strain-life curve constructed from these values for a sample 7.0 mm thick is shown in Figure 4.

DISCUSSION

Elongation and other measures of strain followed a linear relationship with respect to the as-received thickness of the ductile iron tensile specimen. Ultimate tensile strength and the other stress-related properties followed an inverse relationship with respect to the as-received specimen thickness. Since cooling rate is a function of the surface area divided by volume (mm^2/mm^3), it follows that the inverse thickness relationship (1/mm) closely approximates cooling rate when trying to explain the behavior of the stress-related properties. The inverse thickness effect is also seen in the pearlite percentages in Figure 1, which had been attributed to cooling rate.

The linear relationship between strain and thickness can be attributed to anomalies within the castings [1]. Any inconsistency in the microstructure or defects in the volume can be expected to alter the mechanical properties to a greater extent than the volume fraction of the inconsistency would suggest. For example, one sand grain may be present within the entire gage length, yet the specimen will break at the location of the sand grain with a lower tensile strength than that of the matrix. This effect was observed in the thin-wall ductile iron test specimens.

Based on the quasi-static results, it is expected that the fatigue properties of thin-wall castings will also differ from those of the bulk due to the combination of cooling rate and microstructural anomalies. Fatigue tests are planned to validate these predictions. A flat specimen with a 25 mm gage length will be used to determine low and high cycle fatigue properties. One of the assumptions of the predicted fatigue curves is that life transitions from plastic strain-controlled to elastic strain-controlled behavior at a lifetime of 10^7 cycles. This assumption, in particular, needs to be verified.

CONCLUSIONS

- Reduction in area, elongation, and true fracture ductility were observed to have a linear relationship with the as-received thickness of thin wall castings. This is attributed to the presence of microstructural anomalies.
- Yield strength, ultimate tensile strength, true fracture strength, strain hardening exponent, strength coefficient, and hardness were observed to have a reciprocal or inverse relationship with the as-received thickness. This is attributed to the faster cooling rate of the thinner sections producing larger amounts of pearlite.
- Thin wall castings have properties that differ from the bulk. Accurate mechanical properties of thin wall cast iron may require testing specimens from the desired thickness. Additional testing is planned to correlate thin wall casting properties with those from keel blocks.
- Fatigue properties can be predicted from the quasi-static mechanical properties. Testing is planned to verify the transition life, as well as the validity of the curves.

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