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A REVIEW OF THE MECHANICAL PROPERTIES OF NODULAR CAST IRON WITH SPECIAL REFERENCE TO FATIGUE

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ABSTRACT

The mechanical properties of nodular cast iron are reviewed. Effects of alloying, heat treatment, and surface rolling techniques are summarized with reference to long life fatigue strength of this material. Mechanical behavior of this cast iron is shown to be more similar to steel than to gray cast iron. Evidence is presented that graphite nodules act as mechanical stress raisers and that fatigue cracks initiate at these sites. The idea that nodular cast iron can be treated as a notched or flawed steel is advanced. It is suggested that a quantitative relationship between nodule size and fatigue resistance be determined.

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NOMENCLATURE

BHN	Brinell Hardness Number
CE	Carbon Equivalent (wt. %)
E	Elastic Modulus
E'	Cyclic Elastic Modulus
G	Shear Modulus
K'	Cyclic Strength Coefficient
K_{IC}	Plane Strain Fracture Toughness
K_t	Theoretical Stress Concentration Factor
N or N_f	Number of Cycles to Failure
n'	Cyclic Strain Hardening Exponent
R_c	Rockwell Hardness (C Scale)
S	Nominal Applied Stress Amplitude
S_u	Ultimate Tensile Stress
TC	Total Carbon (wt. %)
ϵ	True Strain
ϵ_d	True Diametral Strain
$\frac{\Delta\epsilon}{2}$	Cyclic Strain Amplitude
μ	Poisson's Ratio
σ	True Stress
σ_a	Cyclic Stress Amplitude
σ_{ys}	Yield Strength (0.2% offset)
σ'_{ys}	Cyclic Yield Strength (0.2% offset)

INTRODUCTION

Nodular cast iron, commonly referred to as ductile iron, spherulitic graphite iron, spheroidal graphite iron, or SG iron combines the processing advantages of cast iron (i. e., good castability, machinability, and wear resistance), and the mechanical advantages of steel (i. e., high strength, toughness, ductility, and hardenability). It consists of graphite particles in spheroidal form dispersed in a metallic matrix. This graphite shape and the mechanisms of its formation have been the subject of many investigations (1-14) in recent years. With an existing world market currently exceeding four million product tons per year, much research has been devoted to improving the mechanical properties of this material.

This literature review was initiated to summarize representative work on the fatigue behavior of nodular iron and to give direction to future investigations in this area. It is shown that the behavior of nodular iron is more similar to steel than to gray iron, and it is therefore reasonable to approach this material as a flawed or notched steel. Further, it is shown that development of a quantitative relationship between nodule size (i. e., notch or flaw size) and fatigue resistance is an important step toward understanding the fatigue behavior of this cast iron.

TENSILE PROPERTIES OF NODULAR CAST IRON

The tensile properties of nodular* irons are, for the most part, well understood. These irons can be produced in a wide range of properties, due to their excellent response to heat treatment. When graphite particles are present in nodular form, the bulk properties of the cast iron are largely determined by the properties of the steel matrix. The level of combined carbon in the matrix can be controlled from essentially zero to over one percent by alloying additions and heat treatment, thus allowing the metallurgist to obtain the matrix most suitable for a specific application. The matrix can exist in the form of ferrite, pearlite, martensite, bainite, or combinations of these. Heat treatments employed to obtain the desired matrix structure are annealing, normalizing, quenching and tempering, austempering, and induction or flame hardening.

Classification and Specification

Specification numbers of nodular irons indicate the minimum tensile properties of that particular grade. For example, a 60-40-15 grade indicates minimum properties of 60 ksi ultimate tensile strength, 40 ksi yield strength (0.2% offset), and 15% elongation (2-inch gage length). The principal types of nodular cast irons are listed in Table 1 (18) along with their characteristics and some typical applications.

A summary of nodular cast iron specifications is presented in Table 2 (15). Included in this table are the specifications and properties of austenitic (high nickel alloy) nodular irons, which are utilized where emphasis must be placed on resistance to heat, corrosion, and wear. Table 3 (15) presents a summary of foreign specifications for nodular iron.

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*Unless otherwise stated, the nodular irons referred to are spheroidized by a magnesium process. Other techniques are discussed in Refs. 15, 16, and 17.

Stress-Strain Properties

Nodular graphite cast irons, unlike gray irons, exhibit an essentially linear portion to the stress-strain curve for tension (4, 19, 20), compression (20), torsion (20), and biaxial (19) testing conditions. This is true because the nodular graphite particles, unlike graphite flakes in gray iron, exert a minimal disturbance on the continuity of the matrix. The stress-strain curve for this material does not exhibit a flat top yield region as observed for a low carbon steel; rather, the curve is continuous at all stress levels. Yield strength specifications are generally made in terms of a specific offset (usually 0.2%). Table 4 (20) presents typical tension, compression, and torsion data for five grades of nodular iron. Although stress-strain properties in compression do not differ greatly from those in tension, the "proportional limit" and yield strength are slightly higher in compression. Poisson's ratio for this material is very close to that of steel, but is slightly lower in tension due to the opening of nodule sites in the direction of loading. Gilbert (21) has shown that in tension the longitudinal plastic strain is slightly greater than twice the lateral plastic strain, reflecting the occurrence of a permanent volume change. When nodular iron is stressed into the plastic region, an assumption of constant volume is therefore questionable.

Hardness

The tensile properties of nodular irons are directly related to the hardness of the casting. Brinell hardness number (BHN) is the most common means of expressing the hardness of this material, and is a reliable indicator of tensile properties if graphite is 90% of nodule types I and II*, and the composition is within the range for good nodular iron castings, shown in Fig. 1 (22). Figure 2

*ASTM classification of graphite nodule forms.

presents a comparison between the tensile strength and Brinell hardness of wrought and cast steel (23), nodular iron (18, 22), and gray iron (24). This comparison indicates the similarity of nodular iron and steel as opposed to gray cast iron. Also noteworthy is the result obtained when a correction is made for net matrix cross-sectional area (dotted lines, Fig. 2). Nodular iron is, in effect, a flawed or notched steel with respect to tensile strength.

Effect of Composition on Microstructure

Composition and cooling rate exert a significant influence on the as-cast microstructure of nodular irons. These variables influence the mechanical behavior of this material by affecting the mode of solidification (thus determining graphite morphology) and matrix structure (which is subject to change by subsequent heat treatment). Table 5 (15) summarizes the effects of various elements on the microstructure of cast irons. A more detailed summary is presented in Ref. 15.

FATIGUE PROPERTIES OF NODULAR CAST IRON

In recent years much work has been devoted to understanding and improving the fatigue properties of nodular cast iron. Table 6 presents a summary of representative work published on the fatigue properties of this increasingly important engineering material. The majority of the literature dealing with the determination and improvement of fatigue properties approaches the problem from two basic standpoints: 1) variation of composition, and 2) variation of heat treatment. More recently, however, increased emphasis has been placed on the role of the graphite nodule as a mechanical stress raiser.

Alloying Effects

Gilbert and Palmer (25) have demonstrated the effects of silicon content on fatigue and other mechanical properties of nodular cast irons. They show that increased silicon content up to 4% improves the long life fatigue strength* of ferritic nodular iron, but has a minor effect on the fatigue strength of pearlitic iron. Endurance ratios** of both ferritic and pearlitic (as-cast) irons decrease with an increase in tensile strength as do the endurance ratios of heat treated irons. The relationship of fatigue properties to silicon content is summarized in Fig. 3.

An excellent experimental study was conducted by Haverstraw (26) to evaluate: 1) the effect of alloy content, and 2) the effect of heat treatment on the fatigue properties of nodular cast iron. The results of the latter are reviewed

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*Long life fatigue strength is defined as the stress at which the S-N curve becomes essentially horizontal (generally 10^6 to 10^8 cycles).

**Endurance ratio is defined as the ratio of the long life fatigue strength to the ultimate tensile strength.

in the following section on heat treatment. Table 7 summarizes the properties of seven ductile irons cast with various levels of phosphorous, silicon, and nickel content. The compositions of each of these irons are given in the accompanying table. Rotating bending, S-N results show that some improvement in fatigue strength can be realized by alloying; however, it is clear that within the ranges investigated fatigue resistance is not enhanced substantially.

Grant (27) has shown that hyper-eutectic (> 4.3% CE) cerium-treated nodular irons exhibit higher fatigue strengths than hypo-eutectic (< 4.3% CE) magnesium treated irons. These results, shown in Table 8, indicate the influence of quantity as well as shape of the graphite on fatigue resistance.

Watmough (27) investigated the feasibility of substituting alloyed ductile cast irons for acicular (bainitic) flake graphite irons for some specific fatigue applications. He reported S-N data obtained in rotating bending for seven heats of alloyed ductile iron of various matrix structure and reported obtainable long life fatigue strengths in the range from 29.5 to 34.6 ksi (compared to 20.5 ksi for the acicular flake graphite iron in question). These results agree with Haverstraw (25) in that alloying does not generally result in large increases in fatigue strength.

The tensile and fatigue properties of nickel-molybdenum bainitic ductile iron were investigated by Schelleng (28). He demonstrated a marked improvement in fatigue strength by alloying a nominal ductile iron with varied amounts of nickel and molybdenum. The long life fatigue strength of this bainitic ductile iron, determined in rotating bending, was 52 ksi as compared to 40-45 ksi exhibited by a normal pearlitic ductile iron. Long life fatigue strength levels greater than 50 ksi can normally only be approached by nodular irons with quenched and tempered martensitic structures, and only slight to moderate increases in fatigue resistance are obtainable through suitable alloying techniques.

Heat Treatment Effects

Although the monotonic properties of as-cast nodular irons can be appreciably improved by appropriate heat treatments, it has been shown (26, 27, 30, 31) that long life fatigue strength is by no means proportionally improved. This is demonstrated by endurance ratios listed for as-cast and heat treated irons in Table 9 (18).

Gilbert and Palmer (31) have shown that normalizing does not appreciably affect the fatigue properties of pearlitic nodular irons (Table 9). The same investigators (30) have shown that irons hardened by quenching and tempering exhibit an increase in fatigue strength (Table 9), but found these specimens to be more sensitive to geometric notches than specimens in the as-cast condition. A study of heat treatment techniques was also undertaken by Saxton (32) to improve the fatigue resistance of high hardness (R_c57), high strength (200 ksi) nodular irons, but it was shown that 40 ksi was the highest obtainable long life fatigue strength level for the two iron compositions investigated.

Table 10 summarizes Haverstraw's (26) results on the effect of heat treatment on the fatigue resistance of a commercial and an experimental base nodular iron. Ferritic, pearlitic, tempered low carbon martensitic, and ferritic-martensitic matrix structures were obtained by utilization of special heat treatments. Results on the ferritic structure were comparable to results reported in the literature. Although Haverstraw reported what he felt to be rather high results for the pearlitic structure investigated, Gilbert and Palmer (30) have also reported comparable and slightly greater long life fatigue strengths for normalized pearlitic irons. The low carbon martensitic structure showed the best fatigue strength of the irons investigated (52 ksi), but the ferritic-martensitic structure displayed the higher endurance ratio (0.47).

A low cycle fatigue investigation by Tucker (33) presents the cyclic stress-strain properties (34) of a nodular iron quenched and tempered to 250 BHN. The cyclic stress-strain curve for this heat treated iron, shown in Fig. 4, is defined as the locus of tips of the stable hysteresis loops at different, completely reversed, constant strain amplitudes (34). Monotonic and cyclic stress-strain properties of this material are summarized in Table 11. For this particular iron, the cyclic strain amplitude, $\frac{\Delta\epsilon}{2}$, can be described mathematically as a function of the cyclic stress amplitude, σ_a:

$$\frac{\Delta\epsilon}{2} = \frac{\sigma_a}{20,500} + \left(\frac{\sigma_a}{189}\right)^{7.14} \quad (1)$$

where σ_a is in ksi.

Tucker's data indicated that this material cyclically softens (see Fig. 4). Radon, et al. (35) demonstrated the occurrence of cyclic strain hardening for a nodular iron with a predominantly pearlitic matrix. They conducted completely reversed strain controlled axial fatigue tests at room temperature and 450°C. Results of this investigation are presented in Figs. 5-6. It should be noted that although the authors report diametral strain, the validity of which is somewhat dubious* with reference to flawed materials, they do suggest a correction for this measurement.

Felgar (36) investigated the fatigue properties of nodular cast iron at 900°F. He reported fatigue limits for pulsating (0 to maximum tension) loads and for completely reversed axial loading. These results are indicated in Table 12.

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*For flawed materials, a constant volume assumption for plastic strain is questionable; Gilbert (21) has shown that in tension, permanent volume changes are induced when nodular irons are stressed into the plastic region.

Surface Rolling Effects

Gilbert and Palmer (37) have shown that the fatigue limit of 45^{o} V-notched nodular cast iron specimens can be improved 140% for a pearlitic nodular iron, and 190% for a ferritic nodular iron by surface rolling at an optimum pressure. The results of this investigation not only indicate that the long life fatigue strength can be increased, but that fatigue strength at shorter lives can also be increased. This indicates that a rolled service part will be more tolerant to occasional overstress.

Zemskov, et al. (38) also shows that the long life fatigue strength of nodular irons can be improved by surface rolling. Although rolling pressures much higher than those suggested by Gilbert and Palmer (37) were employed, they report increases of 14% in the fatigue strength of as-cast pearlitic iron, and increases of over 36% for the same iron in the fully annealed condition. Surface rolling effects are also reported for alloyed nodular iron. It was found that, as for unalloyed irons, surface rolling had a more pronounced effect on lower strength irons.* Long life fatigue strengths of irons alloyed with Cr, Mo and W were increased 28% to 35%, while irons alloyed with Ni-Cr exhibited only 13% to 16% increases.

Role of Graphite in Fatigue

Perhaps the most significant work relating fatigue properties of cast irons to graphite morphology was undertaken by Ikawa and Ohira (39). The fatigue properties of cast irons were investigated with reference to plastic deformation of the metallic matrix, crack formation and propagation, and the notch effects of graphite particles. The investigators present test results for cast irons of varied metallic matrices and graphite morphologies ranging from a flake graphite cast

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*In comparison, it is interesting to note that surface rolling is generally considered to have a more pronounced effect on the fatigue resistance of high strength rather than low strength steels.

iron to a 100% nodular iron. Figure 7 shows rotating bending S-N data for the different levels of nodularity given in the accompanying table. These results show that fatigue strength is markedly affected by the degree of nodularity, shown quantitatively in Fig. 8. This result indicates the significance of nodularity control in present-day foundry practices. It is also reasonable to expect that nodule size can have a significant effect on fatigue strength, possibly similar to the effect of graphite length on the fatigue strength of gray irons, shown in Fig. 9. Ikawa and Ohira also present a relationship between endurance ratio and the ultimate tensile strength of the iron. This relationship, shown in Fig. 10, is apparently in contradiction with the results of Haverstraw (26), Gilbert and Palmer (30), and Grant (26), shown in Figs. 11, 3 and 12, respectively, indicating that additional parameters (hardness, nodule size, etc.) are probably involved in this relationship.

In studying the effect of the graphite nodule as a mechanical stress raiser, Ikawa and Ohira concluded that graphite sites can be treated as notches. They calculated stress concentration factors for various graphite forms and found a K_t value of 2.5 for a 100% nodular iron. Taira, et al. (40, 41) have shown that crack initiation takes place in the matrix material adjacent to graphite nodules, and this is attributed to the stress raising effect of the graphite particles. Thum and Ude (42) have suggested that it is reasonable to regard cast iron as a steel with graphite particle inclusions or stress raisers, and that the graphite acts as a void or internal notch. A French investigation (43) suggests that fatigue cracks originate from nodule sites, and Pohl and Holzwarth (44) also suggest this method of crack initiation from their metallographic investigations.

Masuko (45) has shown that an optimized ferrite "bullseye" structure around the graphite nodules (notches) of an as-cast pearlitic iron results in improved fatigue properties. Similar results have been reported on the optimization of plane strain fracture toughness (K_{IC}) values for flake graphite irons (46). This effect can be envisioned as providing a material at the notch root which is more capable of accommodating plastic deformation, (i. e., undergoing cold work hardening), thereby, retarding the crack initiation phase.

SUMMARY AND SUGGESTIONS FOR FUTURE INVESTIGATION

The mechanical properties of nodular cast iron have been reviewed. Investigators have reported improvements in the long life fatigue strength of this material through various alloying, heat treatment, and surface rolling techniques; these results have been summarized. It has also been shown, however, that the fatigue resistance of nodular iron is significantly affected by graphite size, shape, and distribution.

The mechanical behavior of this cast iron has been shown to be more similar to steel than to gray cast iron. Evidence has been presented that graphite nodule sites act as mechanical stress raisers and that fatigue cracks initiate at these sites. It is therefore reasonable to treat nodular iron as a flawed or notched steel.

Today, it is common foundry practice to control nodularity; nodule count is also controlled in some operations. Nodule count reflects a mean or average nodule size, whereas in fatigue the largest inclusions (nodules) give rise to the largest stress concentrations. It follows that the crack initiation phase of fatigue failure is a function of nodule size as well as the other parameters discussed. It is, therefore, important to quantitatively determine the notch effect of various nodule sizes in ductile iron.

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TABLE 1

PRINCIPAL TYPES OF NODULAR CAST IRON (18)

Type	BHN	Characteristics	Application
60-40-15	140-190	Fully ferritic matrix; maximum ductility and low transition temperature.	Navy shipboard and uses requiring shock resistance.
60-45-10	140-200	Essentially ferritic matrix; excellent machinability and good ductility.	Pressure castings, valve and pump bodies, shock resisting parts.
80-60-03	200-270	Essentially pearlitic matrix, high strength as-cast; responds readily to flame or induction hardening.	Heavy duty machinery, gears, dies, rolls for wear resistance and strength.
100-70-03	240-300	Uniformly fine pearlitic matrix, normalized and tempered or alloyed; excellent combination of strength, wear resistance and ductility.	
			Pinions, gears, crankshafts, cams, guides, track rollers.
120-90-02	270-350	Tempered martensitic matrix; may be alloyed to provide hardenability; maximum strength and wear resistance.	

TABLE 2

SPECIFICATIONS AND PROPERTIES OF DUCTILE (NODULAR) IRON CASTINGS (15)

Specification No.	Class or Grade	Min Tensile Strength, Psi	Min Yield Strength, Psi	Min Elongation in 2 In., %	Heat Treatment	Other Requirements	Typical Applications
ASTM A536-65T	60-40-18	60,000	40,000	18	(a)	Chemical composition is subordinate to mechanical properties; however, the content of any chemical element may be specified by mutual agreement.	Pressure castings, valve and pump bodies.
	65-45-12	65,000	45,000	12	—		Machinery castings subject to shock and fatigue loading.
	80-55-06	80,000	55,000	6.0	—		Crankshafts, gears and rollers.
	100-70-03	100,000	70,000	3.0	(b)		High strength gears, automotive and machine components.
	120-90-02	120,000	90,000	2.0	(c)		Pinions, gears, rollers and slides.
SAE J434a	D-4018	60,000	40,000	18	(a)	Typical hardness range: Bhn 137-187	Motor vehicles, agricultural equipment and general machinery purposes.
	D-4512	65,000	45,000	12	—	Bhn 149-207	
	D-5506	80,000	55,000	6.0	—	Bhn 179-255	
	D-7003	100,000	70,000	3.0	(b)	Bhn 229-285	
	DQ & T	—	—	—	(c)	By agreement	

Specification No.	Class or Grade	Min Tensile Strength, Psi	Min Yield Strength, Psi	Min Elongation in 2 In., %	Heat Treatment	Composition, %: T.C.	Si	P	S	C.E.	Typical Applications
ASTM A395-61 ASME SA395	60-45-15	60,000	45,000	15	(a)	3.0 min	2.75 max	0.08 max	—	—	Valves and fittings for steam and chemical plant equipment; steam dryers.
ASTM A476-62T	80-60-03	80,000	60,000	3.0	(d)	3.0 min	3.0 max	0.08 max	0.05 max	3.8 to 4.5 T.C. + 0.3 (Si+P)	Paper mill dryer rolls (up to 450 F)

Specification No.	Class or Grade	Min Tensile Strength, Psi	Min Yield Strength, Psi	Min Elongation in 2 In., %	Heat Treatment	Other Requirements	Typical Applications
MIL-I-11466 (Ordnance)	1 2 3 4 5 6	same as: SAE J 434a				Unless otherwise specified, one metallographic test shall be made for each lot. Graphite shall appear essentially in nodular form.	Military equipment.

Specification No.	Class or Grade	Min Tensile Strength, Psi	Min Yield Strength, Psi	Min Elongation in 2 In., %	Heat Treatment		T.C.	Si	Mn	P	Ni	Cr	Hardness, Bhn	Typical Applications
ASTM A439-62	D-2	58,000	30,000	8.0	—	Min	—	1.50	0.70	—	18.00	1.75	139	Austenitic castings. Resistance to heat, corrosion and wear. Used for other special purposes, such as low thermal expansivity.
						Max	3.00	3.00	1.25	0.08	22.00	2.75	202	
	D-2B	58,000	30,000	7.0	—	Min	—	1.50	0.70	—	18.00	2.75	148	
						Max	3.00	3.00	1.25	0.08	22.00	4.00	211	
	D-2C	58,000	28,000	20	—	Min	—	1.00	1.80	—	21.00	—	121	
						Max	2.90	3.00	2.40	0.08	24.00	0.50	171	
	D-3	55,000	30,000	6.0	—	Min	—	1.00	—	—	28.00	2.50	139	
						Max	2.60	2.80	1.00	0.08	32.00	3.50	202	
	D-3A	55,000	30,000	10	—	Min	—	1.00	—	—	28.00	1.00	131	
						Max	2.60	2.80	1.00	0.08	32.00	1.50	193	
	D-4	60,000	—	—	—	Min	—	5.00	—	—	28.00	4.50	202	
						Max	2.60	6.00	1.00	0.08	32.00	5.50	273	
	D-5	55,000	30,000	20	—	Min	—	1.00	—	—	34.00	—	131	
						Max	2.40	2.80	1.00	0.08	36.00	0.10	185	
	D-5B	55,000	30,000	6.0	—	Min	—	1.00	—	—	34.00	2.00	139	
						Max	2.40	2.80	1.00	0.08	36.00	3.00	193	
MIL-I-24137 (Ships)	A	60,000	45,000	15	(e)	Min	3.00	—	—	—	C.E.			Shipboard electric equipment, engine blocks, pumps, compressors, gears, valves, clamps, and hydraulic equipment.
						Max	—	2.50	—	0.08	4.3			
	B	55,000	30,000	7.0	(f)	Min	2.40	1.80	0.80	—	18.00	1.70	—	Austenitic castings. Resistant to heat, corrosion and shock.
						Max	3.00	3.20	1.50	0.20	22.00	2.40	190	
	C	50,000	25,000	20	(f)	Min	2.70	2.00	1.90	—	20.00	—	—	Nonmagnetic. Shipboard use and propellers.
						Max	3.10	3.00	2.50	0.15	23.00	0.50	175	
MIL-I-22243	10 ft-lb min Charpy-V notch	55,000	37,000	20	(a)	Max	—	2.20	—	0.05	Ti 0.05	—	175	Where maximum notch toughness is needed.
ASTM A445-63T API 604-63	60-45-15	60,000	45,000	15	(a)	Min	3.00	—	—	—	—	—	149	Ferritic castings for valves, flanges, pipe fittings and other piping components.
						Max	—	2.50	—	0.08	—	—	201	

(a) Ferritized by annealing; (b) normalized; (c) quenched and tempered; (d) used in as-cast condition, hardness Bhn 201 min; (e) ferritized by annealing, hardness Bhn 190 max; (f) stress relief, 1200 F (carbide solution at 1750 F if necessary).

Source: Gray and Ductile Iron Founders' Society Inc., Cleveland

TABLE 3

FOREIGN NODULAR IRON SPECIFICATIONS (15)

German Types of Nodular Iron

Type	Tensile Strength kg/mm^2	Tensile Strength ksi	Yield Strength kg/mm^2	Yield Strength ksi	Elongation %	BHN
GGG 38	38-45	55- 64	25-32	36-45	17-30	140-180
GGG 42	42-50	60- 71	28-38	40-54	12-28	150-200
GGG 50	50-60	71- 85	35-45	50-64	7-20	170-240
GGG 60	60-70	85- 99	42-55	60-78	2-12	210-300
GGG 70	70-90	99-128	50-65	71-93	2-10	230-320
Austenitic	38-50	55- 71	20-28	28-40	10-40	140-200

British Types of Nodular Iron (B.S. 2789)

Type	Tensile Strength L tons/in^2	Tensile Strength ksi	Elongation %	Charpy V-Notch RT ft. -lb.
SNG 24/17	24	53.8	17	10
SNG 27/12	27	60.5	12	
SNG 32/7	32	71.7	7	
SNG 37/2	37	82.8	2	
SNG 42/2	42	94.0	2	
SNG 47/2	47	105.0	2	

TABLE 4

STRESS-STRAIN PROPERTIES DETERMINED IN TENSION, COMPRESSION, AND TORSION (20)

Type	60-40-18	65-45-12	80-60-03	100-70-03	120-90-02
Hardness (BHN)	167	167	192	235	331
Tension					
Tensile Strength (ksi)	66.9	67.3	81.1	118.6	141.3
Yield Strength (ksi)	47.7	48.2	52.5	98.2	125.3
Elongation (%)	15.0	15.0	11.2	4.5	1.5
Poisson's Ratio	0.29	0.29	0.31	0.28	0.28
Modulus (10^3 ksi)	24.5	24.4	24.5	23.5	23.8
Compression					
Yield Strength (ksi)	52.0	52.5	56.0	87.5	133.5
Poisson's Ratio	0.26	0.31	0.31	0.27	0.27
Modulus (10^3 ksi)	23.8	23.6	23.9	22.7	23.8
Torsion					
Shear Strength (ksi)	68.5	68.9	73.1	87.3	126.9
0.0375% Yield Strength (ksi)	28.3	30.0	28.0	47.3	71.3
Modulus* (10^3 ksi)	9.1	9.3	9.0	8.7	9.2

*Note that the value reported is slightly lower than that calculated from $G = \frac{E}{2(1+\mu)}$.

TABLE 5

SUMMARY OF THE ELEMENT FUNCTIONS IN CAST IRON (15)

Element	Limit for Ferritic Grade	Limit for Pearlitic Grade	Function	Remarks
		Common Elements		
Carbon	3.00-4.00%	3.00-4.00%	Constituent of the spheroids	Excess causes flotation
Silicon	1.80-3.00%	1.80-2.75%	Graphitizer, ferritizer	Erases pearlite as-cast
Phosphorus	0.035% max.	0.05% max.	Embrittles structure	Pearlite stabilizer
Sulphur	0.015% max.	0.015% max.	Combines with magnesium	Sulphur removal is essential
Manganese	0.20% max.	0.70% max.	Pearlite former	Excess will promote carbides
Magnesium	Sufficient to assure spheroidal graphite - 0.06% max.		The spheroidizer	Excess will promote carbides
		Alloying Elements		
Nickel	Low as possible for as-cast	To specification	Strengthener, employed for hardenability	Pearlite former in as-cast
Molybdenum	0.03% max.	To specification	For hardenability	Promotes intercellular carbides
Copper	0.03% max.	To specification	Strength, hardness	Potent pearlite stabilizer
		Special Purpose Elements		
Cerium/RE	About 0.002% max.	About 0.002% max.	Counteracts subversives	Can produce carbides
				Use only when necessary
Calcium	Insoluble in iron	Insoluble in iron	Inoculates	Reduces cell size--excess can cause carbides
Tellurium	0.02% max.	0.02% max.	To minimize pinholes	Subversive to spheroids
		Flake Graphite Promoting Elements		
Lead	0.002% max.	0.002% max.	Flake graphite former	Most potent subversive element
Titanium	0.07% max., 0.03% max. as-cast	0.07% max.	Flake graphite former	Deteriorates spheroids
Aluminum	0.05% max.	0.05% max.	Flake graphite former	Aggravates hydrogen pinholes
Antimony	0.004% max.	0.004% max.	Limits "Free" magnesium	Lack of Mg. occasions flake
Bismuth	0.002% max.	0.002% max.	Flake graphite former	Flake graphite plus pearlite
Zirconium	0.1% max.	0.1% max.	Flake graphite former	Deteriorates spheroids
		Carbide and Pearlite Formers		
Chromium	0.04% max.	0.10% max.	Very potent carbide former	Retards anneal
Boron	0.002% max.	0.002% max.	Forms very stable borocarbide	Carbide resists anneal
Tin	0.01% max.	0.05% max.	Potent pearlite former	No carbides are formed
Arsenic	0.02% max.	0.05% max.	Pearlite former	Embrittler
Vanadium	0.04% max.	0.05% max.	Forms stable carbides	Retards anneal
		Gaseous Elements		
Oxygen	About 0.003%	About 0.003%	Combines with Mg.	Reduces available Mg.
Hydrogen	About 0.0003%	About 0.0003%	Very potent carbide former	Pinhole former
Nitrogen	About 0.009%	About 0.009%	Pearlite former	Has limited solubility

TABLE 6

REPRESENTATIVE WORKS ON FATIGUE OF NODULAR IRON

Investigator(s) (Year) (Ref. No.)	Material	Test	Fatigue Property Reported	Remarks
Tucker (1971) (33)	Quenched & tempered to 250 BHN	Axial, completely reversed	Cyclic stress-strain properties	Strain control, determination of cyclic σ - ϵ curve, cyclic softening
Schelleng (1969) (29)	Bainitic matrix	Rot. bend.	Fatigue strength	Treats size effect, matrix variation
DeLeiris & Mencarelli (1968) (43)	Ferritic & pearlitic or martensitic*	Torsional and axial	Fatigue strength	Axial, zero to max. load, torsional, completely reversed
Ikawa & Ohira (1967) (39)	As-cast, heat treated matrices	Rot. bend.	Fatigue strength	Effects of nodularity, graphite size, notch effect
Radon, et al. (1966) (35)	Pearlitic matrix	Axial, completely reversed	Cyclic stress-strain response	Stress & strain control, low cycle, cyclic hardening, also austenitic nod. iron results
Haverstraw (1966) (26)	Varied comp. & heat treat.	Rot. bend.	Fatigue strength	Effects of 3 elements & various heat treatments on fatigue strength
Watmough (1966) (28)	Alloyed & heat treated	Rot. bend.	Fatigue strength	Effects of alloying
Zemskov, et al. (1964) (38)		Rot. bend.	Fatigue strength	Surface rolling and alloying
Saxton (1962) (32)	Heat treated matrix	Cantilever bending	Fatigue strength	Influence of heat treatments
Felgar (1959) (36)		Pulsating axial & completely reversed axial	Fatigue strength	900°F

*Judging from tensile strength

TABLE 6 (contd.)

Investigator(s) (Year) (Ref. No.)	Material	Test	Fatigue Property Reported	Remarks
Gilbert & Palmer (1957) (31)	Pearlitic matrix	Rot. bend.	Fatigue strength	Effects of normalizing
Gilbert & Palmer (1955) (30)	Martensitic matrix	Rot. bend.	Fatigue strength	Effects of quenching & tempering
Gilbert & Palmer (1953) (25)	Ferritic & as-cast pearlitic matrix	Rot. bend.	Fatigue strength	Effects of silicon content
Majors (1952) (49)	Ferritic & as-cast pearlitic matrices	Rot. bend.	Fatigue strength	Effect of cyclic frequency, section size
Eagan (1951) (48)	As-cast & ferritic matrices	Rot. bend.	Fatigue strength	Section size effect
Newmark, et al. (1951) (47)		Axial compression	Fatigue strength	No failure reported*
Grant (1950) (27)	Ferritic, as-cast pearlitic matrices	Rot. bend.	Fatigue strength	Magnesium & cerium treated irons

*No failure reported . . . $N > 2.2 \times 10^6$, $S_{max} = 67,000$ psi

TABLE 7

EFFECT OF ALLOY CONTENT ON FATIGUE PROPERTIES OF NODULAR IRON (26)

Identification	Tensile Strength, ksi	Yield Strength, ksi	Elongation %	Hardness BHN	Fatigue Strength, ksi	Endurance Ratio
EB	113.6	61.5	7.7	223	45.8	0.40
HiNi	125.6	80.6	4.7	229	43.2	0.34
MNi	123.2	70.5	6.3	240	47.2	0.38
HiSi	122.0	71.8	7.1	212	45.8	0.38
LoSi	123.1	67.9	7.1	223	43.2	0.35
HiP	119.3	71.5	5.9	223	48.2	0.40
LoP	122.4	67.9	8.8	233	48.8	0.40

Composition*

Identification	% C	% Si	% P	% Ni
EB	3.60	2.50	0.030	
HiNi	3.68	2.46	0.015	1.85
MNi	3.64	2.50	0.017	0.88
HiSi	3.66	2.84	0.038	
LoSi	3.69	2.10	0.038	
HiP	3.63	2.37	0.084	
LoP	3.56	2.30	0.008	

*Approx. 0.30% Mn, 0.015% S for all heats

TABLE 8

FATIGUE PROPERTIES OF CERIUM AND MAGNESIUM NODULAR IRONS (26)

	Tensile Strength, ksi	Fatigue Strength, ksi	Endurance Ratio
Cerium			
NOD 67	54.0	26.9	0.50
V 980	57.0	33.6	0.59
W 7, W 16	69.5	39.2	0.59
V 895	79.3	35.8	0.46
W 3	86.0	41.5	0.48
W 105	91.7	44.8	0.49
Magnesium			
NOD 517 (as-cast)	95.6	35.8	0.38
NOD 517 (annealed)	62.7	29.1	0.46
NOD 518 (as-cast)	103.0	40.0	0.39
NOD 518 (annealed)	67.7	29.1	0.43

TABLE 9

FATIGUE RESULTS ON HEAT TREATED NODULAR IRONS (18)

Property	As-cast	Q & T (a)	Q & T (b)	As-cast	Normalized (c)
BHN	255	295	350	267	325
S_u, ksi	96.3	134.5	149.3	95.6	151.0
Elongation, %	3.0	4.0	1.5	2.0	4.0
Fatigue Strength, ksi	40.3	49.3	49.3	43.7	49.3
Endurance Ratio	0.42	0.37	0.33	0.46	0.33

(a) Oil Quenched from 900°C, Tempered 2 hours at 600°C

(b) Oil Quenched from 900°C, Tempered 2 hours at 550°C

(c) Normalized from 900°C

TABLE 10

EFFECTS OF VARIOUS HEAT TREATMENTS ON THE PROPERTIES OF NODULAR IRON (26)

Identification	Tensile Strength, ksi	Yield Strength, ksi	Elongation %	Hardness BHN	Fatigue Strength, ksi	Endurance Ratio
CBA	72.1	51.0	32.0	131	33.8	0.47
EBA	62.2	41.2	27.1	106	29.8	0.48
CBN	146.6	101.0	4.4	262	48.8	0.33
EBN	113.6	61.5	7.7	223	45.8	0.40
CLCM 95	176.5	152.5	3.6	321	45.8	0.27
CLCM 11	136.9	101.2	7.0	230	42.8	0.31
CLCM 12	86.8	63.3	13.5	148	38.2	0.44
ELCM 95	182.0	156.5	2.7	322	51.8	0.28
ELCM 11	125.7	103.8	5.9	241	46.8	0.37
ELCM 12	86.7	63.5	9.7	132	36.8	0.42
CFM 95	168.1	152.1	2.0	310	43.2	0.26
CFM 11	120.0	101.9	6.7	223	44.2	0.37
CFM 12	83.0	63.2	11.3	162	45.2	0.54
EFM 95	160.1	145.0	2.4	282	42.2	0.26
EFM 11	113.4	55.6	7.9	202	41.2	0.36
EFM 12	89.5	49.5	10.4	142	41.8	0.47

Identification

- E - Experimental
- C - Commercial
- N - Normalized
- A - Annealed
- LCM - Low Carbon Martensite
- FM - Ferrite-Martensite
- 95 - Tempered 1 hr. at 950°F
- 11 - Tempered 1 hr. at 1100°F
- 12 - Tempered 1 hr. at 1200°F

TABLE 11

PROPERTIES OF NODULAR IRON QUENCHED AND TEMPERED TO 250 BHN (33)

Property	Value
E	23,000 ksi
E'	20,500 ksi
σ_{ys}	91.0 ksi
σ'_{ys}	77.0 ksi
n'	0.14
k'	189 ksi

TABLE 12

FATIGUE DATA FOR NODULAR IRON AT 900°F (36)

Maximum Stress ksi	Number of Cycles, Millions	Result
	Pulsating Axial Fatigue	
20.0	15.6	No Failure
25.0	10.0	No Failure
30.0	10.3	Failed
35.0	6.0	Failed in Threads
38.0	12.6	No Failure
	Completely Reversed Axial Fatigue	
25.0	0.025	Failed
22.5	10.1	No Failure
25.0	2.9	Failed
22.5	12.0	No Failure
25.0	6.2	Failed

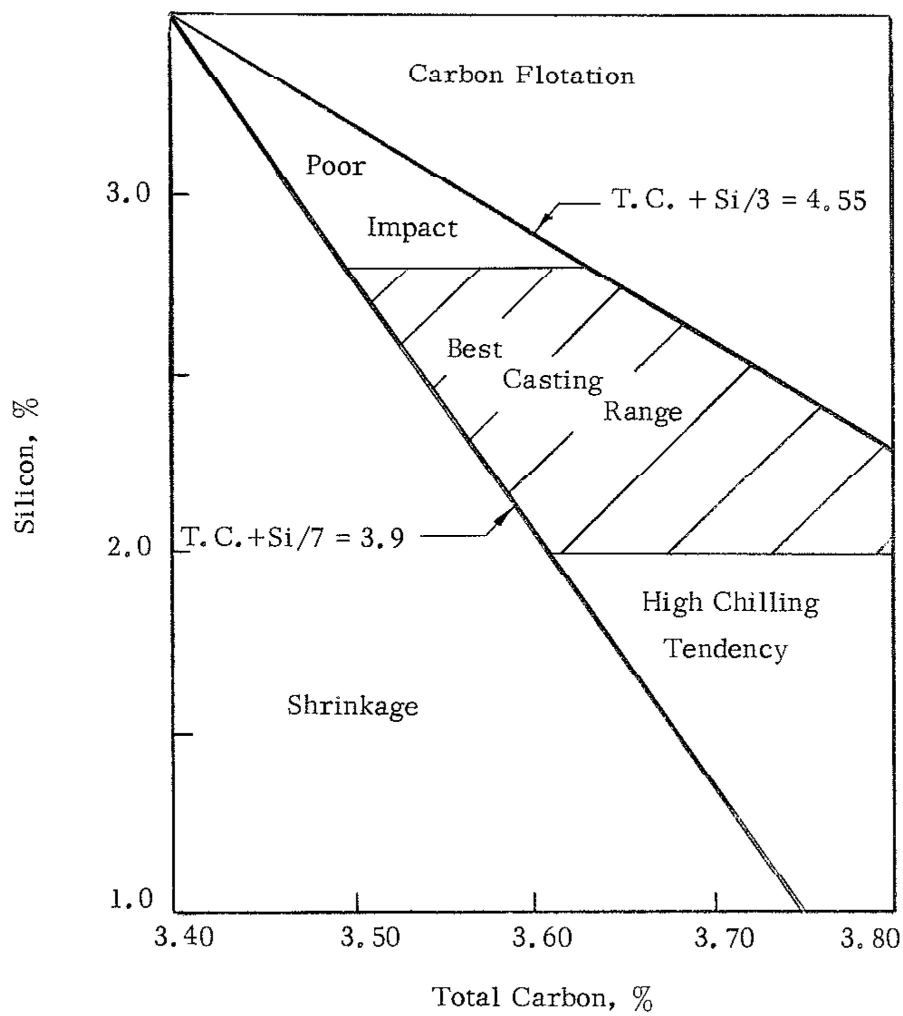


Fig. 1 Optimum Casting Range for Nodular Iron (22)

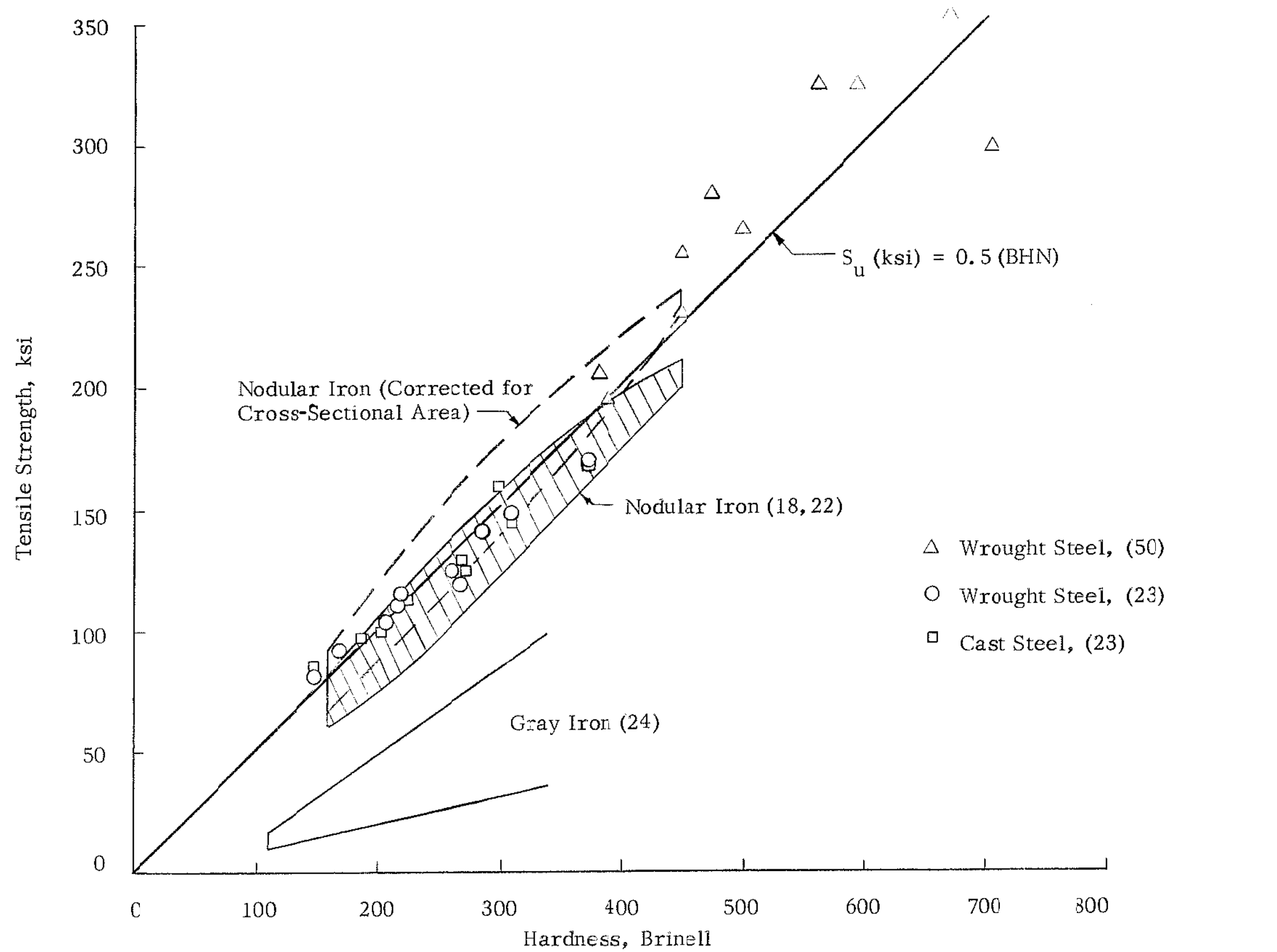
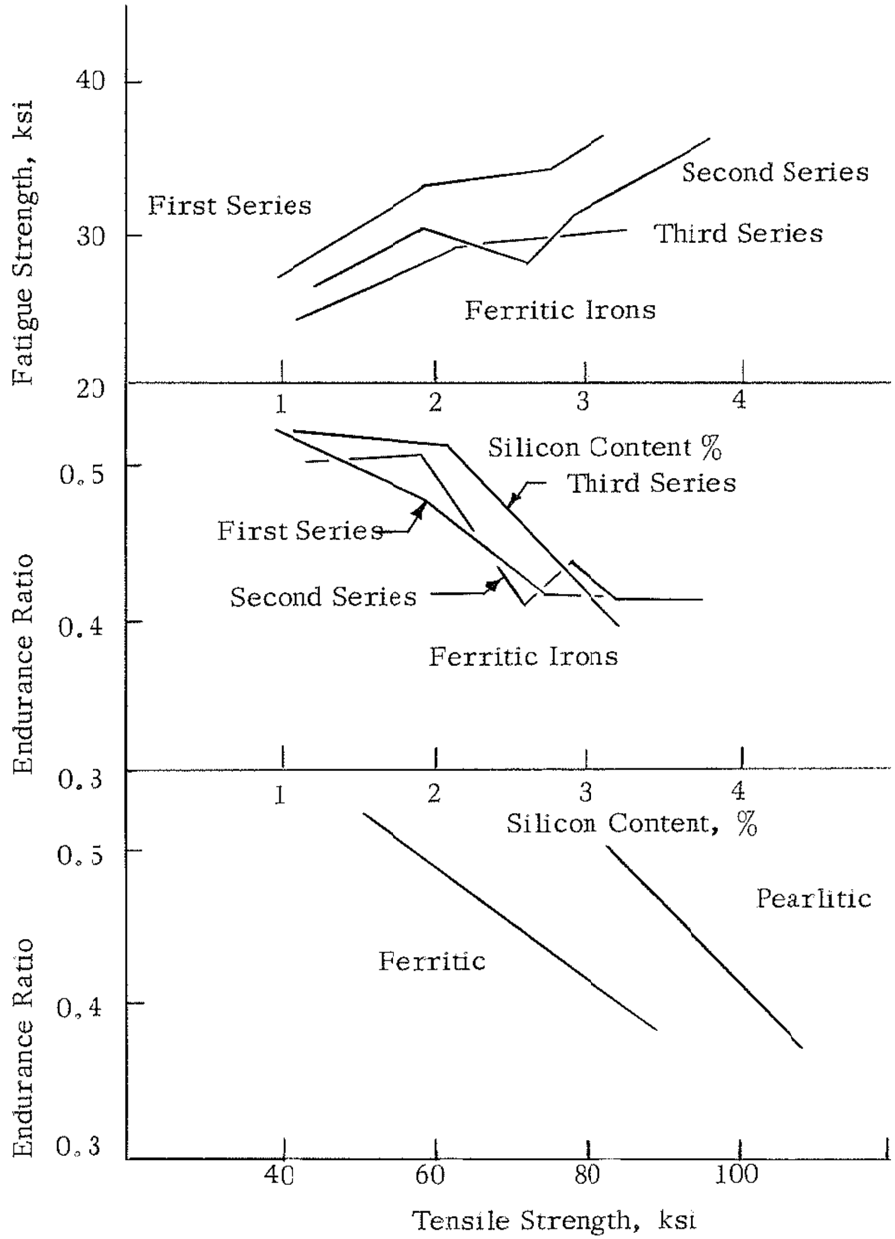


Fig. 2 Tensile Strength vs. Hardness for Wrought and Cast Steel, Gray Iron, and Nodular Iron (18, 22, 23, 24, 50)



Composition %

T.C.	Si	Mn	S	P	Ni	Mg	Ce
Heat Treated: First Series							
2.90	0.96	0.17	0.019	<0.05	2.82	0.044	
2.78	1.92	0.21	0.013	<0.05	3.14	0.086	
2.84	2.75	0.21	0.010	<0.05	3.29	0.106	
2.98	3.06	0.23	0.014	<0.05	3.24	0.081	
Heat Treated: Second Series							
3.29	1.19	0.26	0.032	0.058	0.54	0.048	0.021
3.15	1.87	0.31	0.029	0.065	0.64	0.071	0.026
3.18	2.62	0.32	0.030	0.055	1.02	0.059	0.027
3.22	2.89	0.32	0.033	0.058	1.10	0.062	0.025
3.00	3.21	0.30	0.030	0.053	0.94	0.055	0.021
3.19	3.77	0.31	0.025	0.057	1.31	0.077	0.046
Heat Treated: Third Series							
3.53	1.03	0.31	0.008	0.023	0.55	0.045	
3.21	2.08	0.34	0.014	0.023	0.59	0.050	
3.37	3.23	0.45	0.010	0.011	0.89	0.100	
As-cast: First Series							
2.87	2.00	0.24	0.018	<0.05	3.22	0.066	
2.58	2.69	0.22	0.013	<0.05	3.26	0.150	
2.75	3.12	0.23	0.013	<0.05	3.37	0.110	
As-cast: Second Series							
3.14	1.80	0.28	0.031	0.072	0.62	0.048	0.028
3.23	2.47	0.28	0.026	0.055	1.26	0.130	0.033
3.22	2.82	0.32	0.027	0.054	1.02	0.066	0.021
3.10	3.20	0.31	0.029	0.055	1.05	0.063	0.020
3.22	3.91	0.31	0.025	0.057	1.28	0.084	0.042

Fig. 3 Relationship between Silicon Content and Fatigue Strength for Nodular Iron (25)

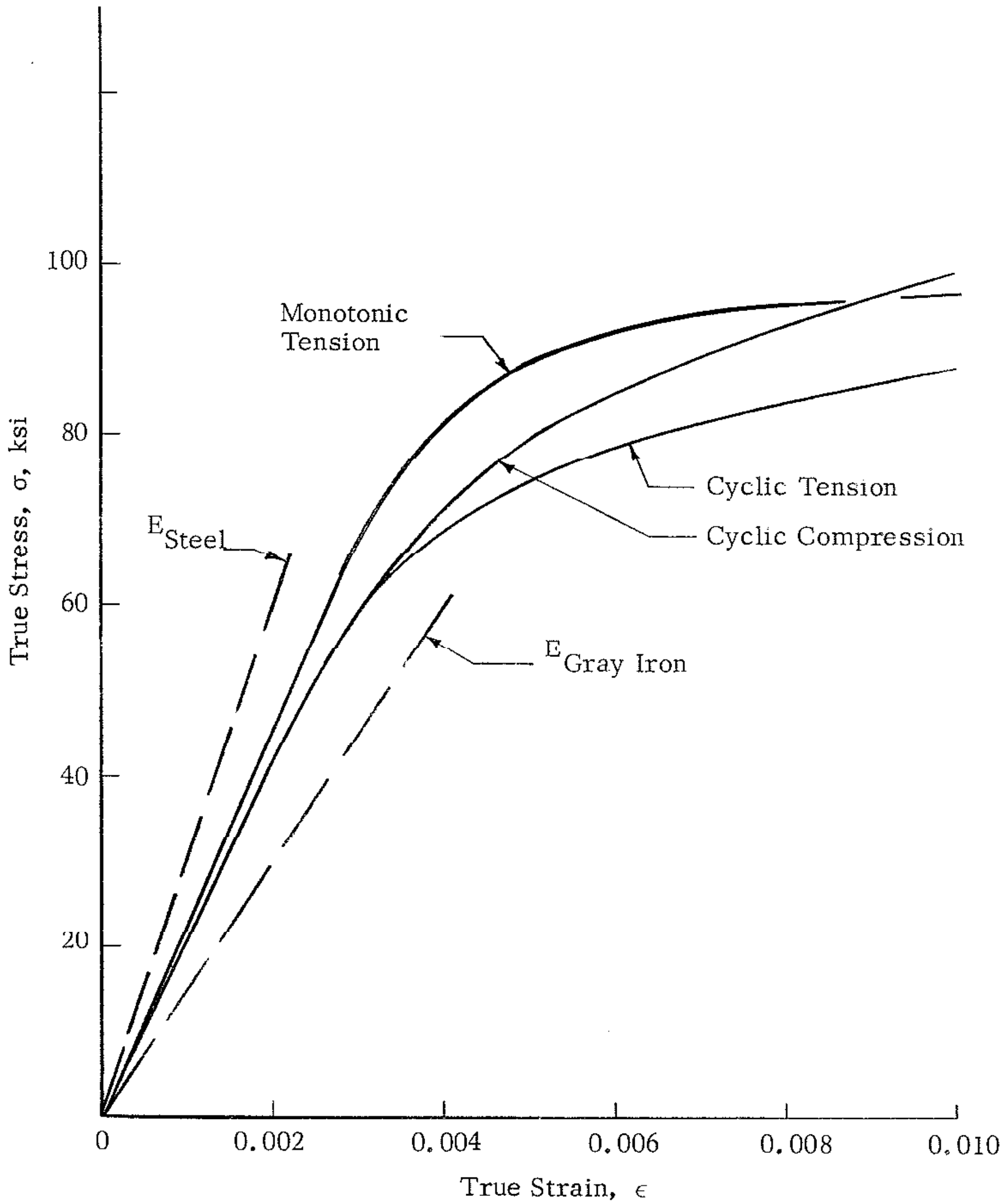


Fig. 4 Monotonic and Cyclic Stress-Strain Curves for Nodular Iron Quenched and Tempered to 250 BHN (33)

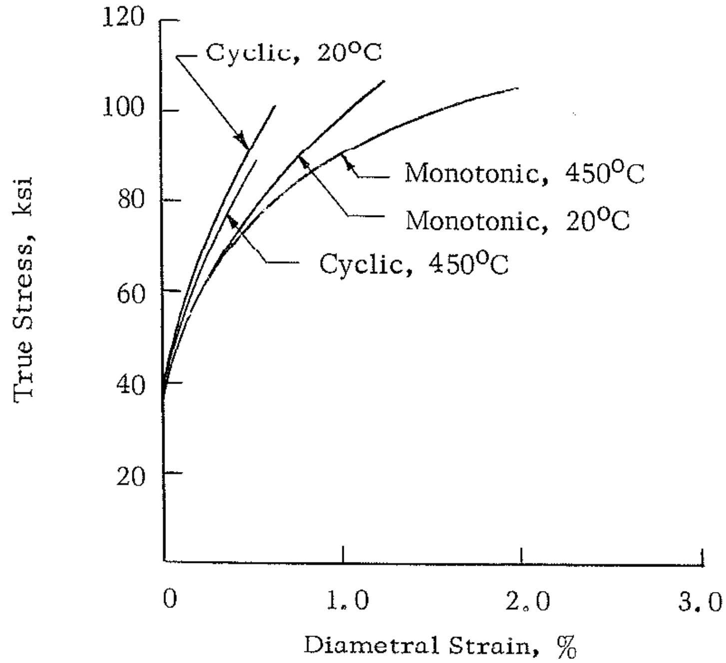


Fig. 5 Monotonic and Cyclic Stress-Strain Curves for Nodular Iron at Room Temperature and 450°C (35)

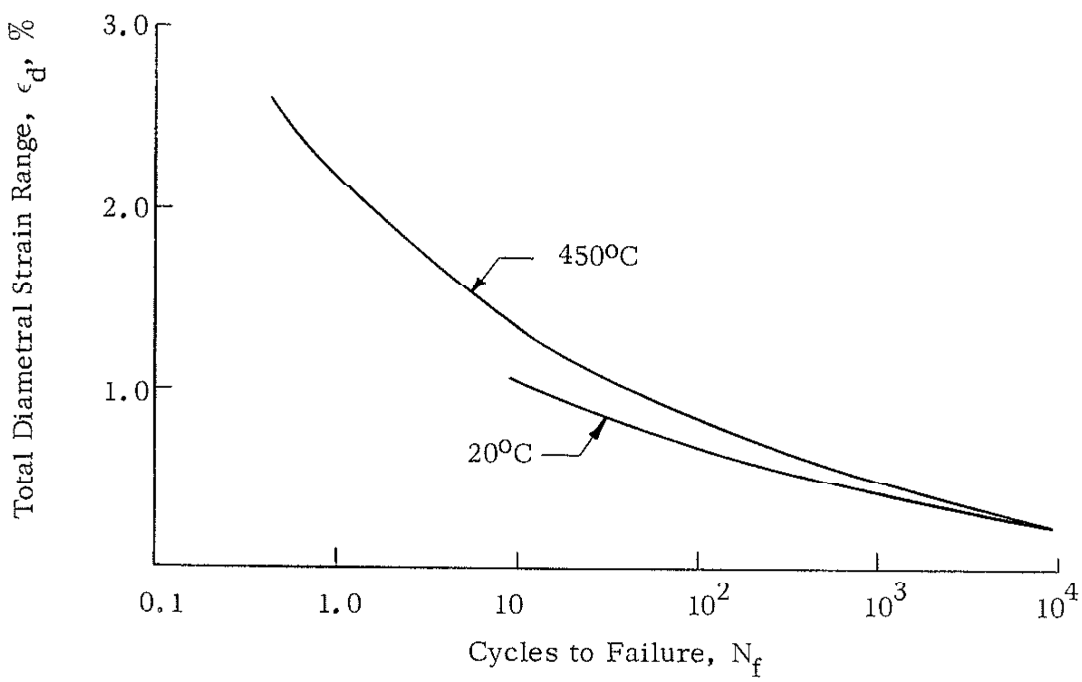
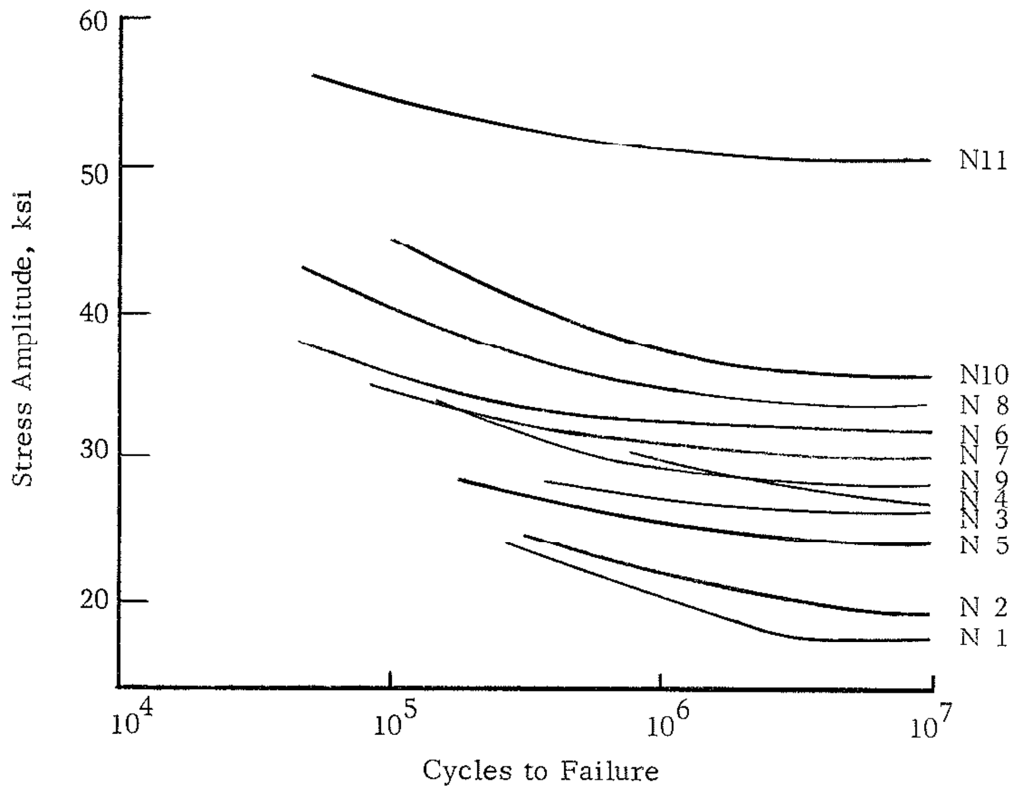


Fig. 6 Strain Range-Life Curves for Nodular Iron at Room Temperature and 450°C (35)



Chemical Compositions and Microstructures of Spheroidal Graphite Iron

Iron	C%	Si%	Mn%	P%	S%	Cr%	Microstructure	
N 1	3.66	1.88	1.16	0.136	0.009	0.041	VI 5/6 (15%) + ID 6/7 (60%) + III 6 (25%)	P90
N 2	3.66	1.88	1.16	0.136	0.009	0.041	VI 5/6 (20%) + IA 6 (15%) + III 4/5 (65%)	P90
N 3	3.66	1.88	1.16	0.136	0.009	0.041	VI 6 (40%) + III 5 (60%)	P90
N 4	3.66	1.88	1.16	0.136	0.009	0.041	VI 5/6 (55%) + III 4 (45%)	P85
N 5	3.66	1.88	1.16	0.136	0.009	0.041	VI 4/5 (60%) + III 4 (40%)	P90
N 6	2.99	3.40	1.13	0.136	0.009	0.041	VI 4/5 (70%) + Me (30%)	P30
N 7	3.16	3.52	1.13	0.136	0.009	0.041	VI 4/5 (80%) + Me (20%)	P30
N 8	3.16	3.52	1.13	0.136	0.009	0.041	VI 4/5 (80%) + Me (20%)	P40
N 9	3.66	1.88	1.16	0.136	0.009	0.041	VI 5/6 (85%) + III 5 (15%)	P90
N10	3.16	3.52	1.13	0.136	0.009	0.041	VI 5/6 (90%) + Me (10%)	P60
N11	3.45	3.89	0.65	0.130	0.006	0.180	VI 6 (100%)	P80

Me: Meshlike Graphite

Fig. 7 S-N Curves of Irons of Varied Microstructure (39)

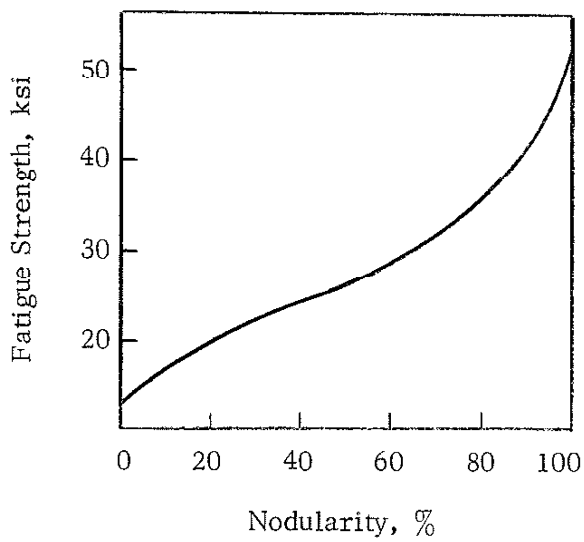


Fig. 8 Effect of Nodularity on Fatigue Strength (39)

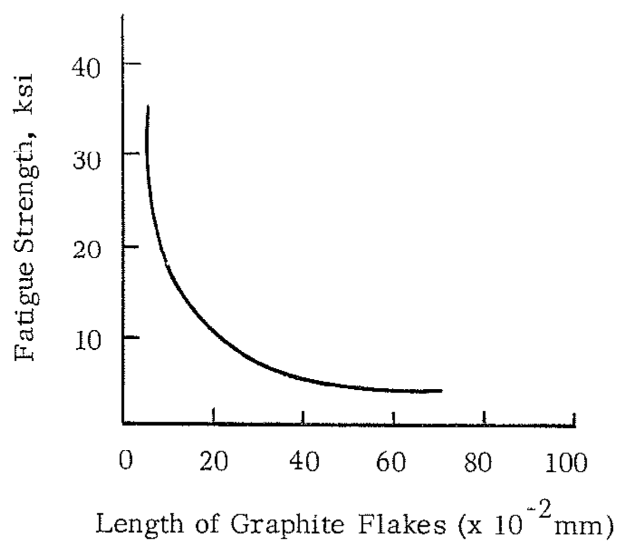


Fig. 9 Effect of Flake Graphite Length on Fatigue Strength (39)

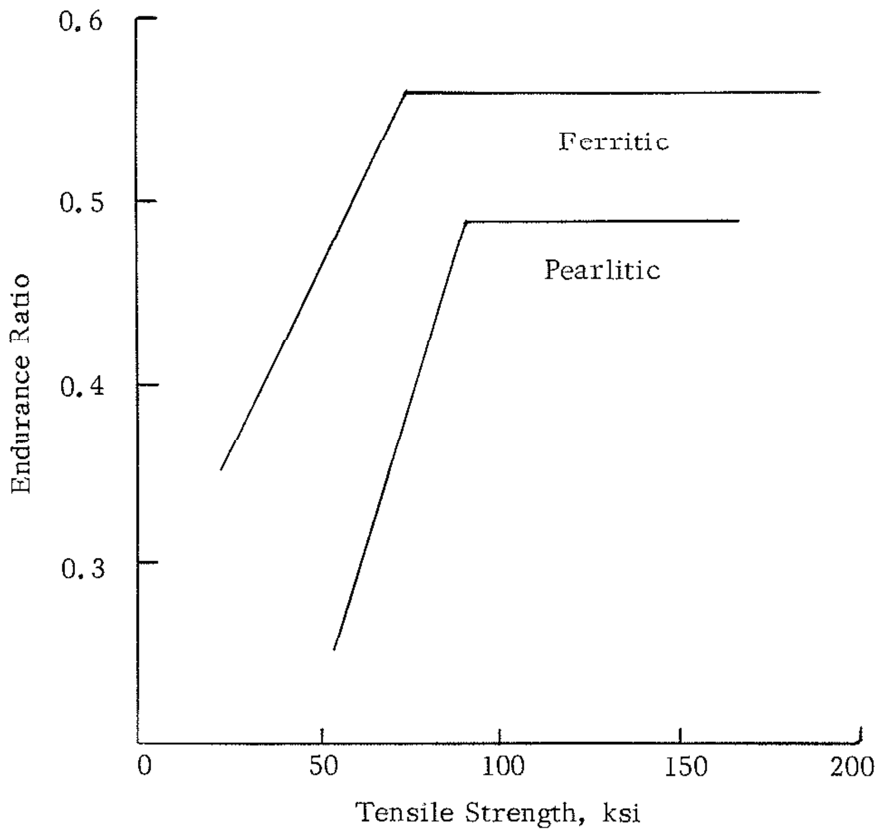


Fig. 10 Endurance Ratio-Tensile Strength Relationship for Cast Irons (39)

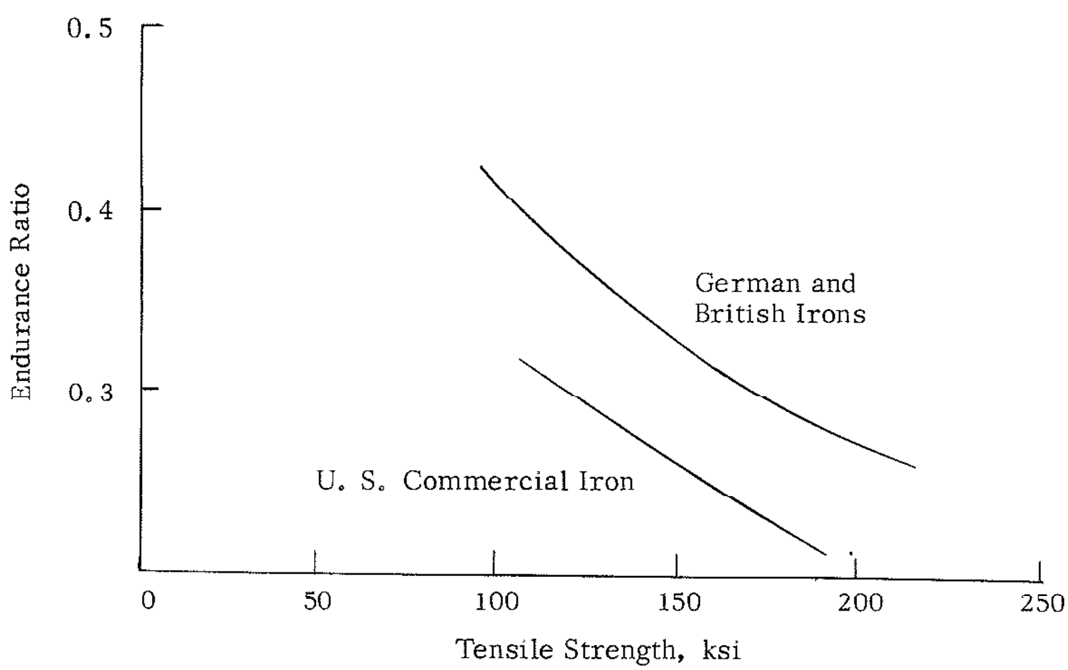


Fig. 11 Endurance Ratio-Tensile Strength Relationship (26)

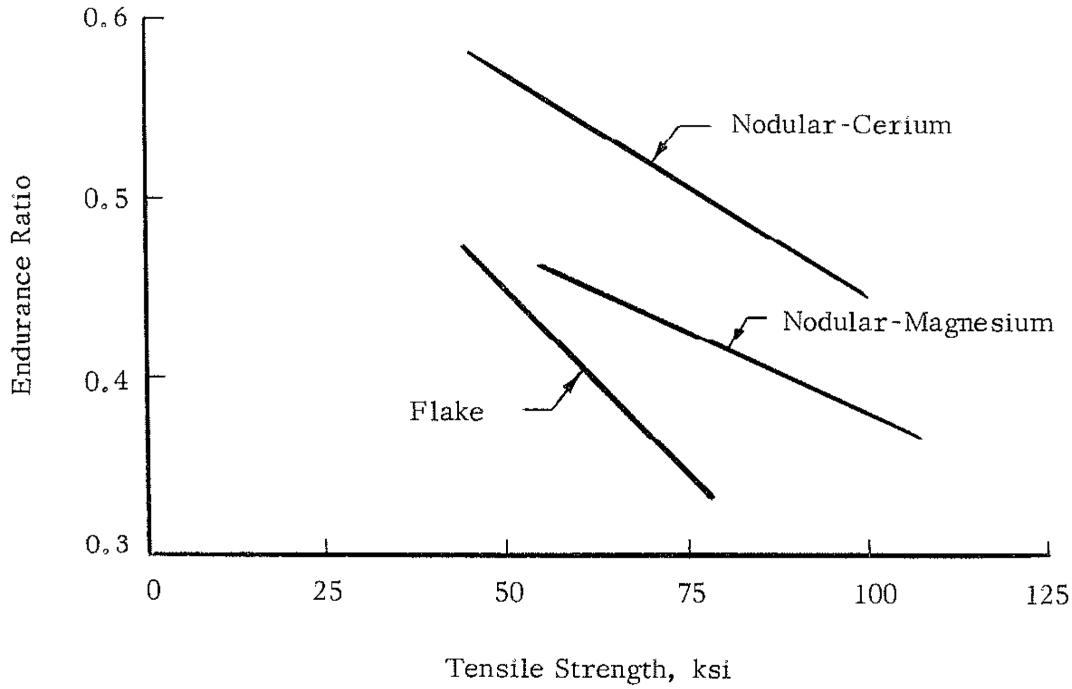


Fig. 12 Endurance Ratio-Tensile Strength Relationship (49)