Fatigue Notch-Sensitivity of Nodular Cast Iron in Comparison to Steel*

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Synopsis

The Neuber material constant has been determined for nodular iron. It is found from data in literature that this constant is about nine times that of steel of the same strength in a rotating beam specimen with grooves. This implies that the relation between notch-sensitivity of nodular iron $q^{(N)}$ and forged steel $q^{(S)}$ is in accordance with the equation

$$q^{(N)}/q^{(S)} = (1 + \sqrt{A/R})/(1 + 3\sqrt{A/R})$$

where A is the "Neuber constant" for steel and R the notch radius. Consequently the notch-sensitivity is less for nodular iron than for steel, since the above relation is less than one. This would be a natural result when considering the internal stress concentrations in nodular iron arising from the graphite nodules. In view of this fact the fatigue limit will not decrease as much as for steel when a mechanical notch is applied to the specimen. Further on it appears from this study that the net fatigue, i.e. the notched fatigue limit of nodular iron, often is at least comparable to that of steels of the same strength. This is also confirmed by fatigue tests on gears made of both cast and forged carbon steels. The cause of this is discussed. The main reason is probably the capacity of nodular iron to "damp" the peak of stress concentration due to the applied notch.

1. Definitions and Notch-Sensitivity Formulae

The definition generally accepted in the field of fatigue of materials for the notch-sensitivity is

$$q = \frac{K_f - 1}{K_t - 1} \quad (1)$$

where, q : notch-sensitivity index

K_f : fatigue notch factor: σ_e/σ'_e
unnotched fatigue limit/notched fatigue limit

K_t : theoretical stress concentration factor: $\sigma_{\max.}/\sigma_{\text{nom.}}$

The reason for subtracting 1 is to provide a scale for q which goes from zero to unity i.e. from no notch effect to full theoretical effect where K_f is 1 and K_t respectively.

An exhaustive treatment of this topic has been made by Peterson.¹⁾ He has also calculated K_t for numerous cases.²⁾ In this work, which has been used in the present study for determination of K_t , he emphasizes that it might be more correct to replace K_t by another theoretical stress concentration factor K'_t . This factor combines K_t and a biaxial stress factor but the difference is never greater than 15%.

A great number of formulae have been suggested for calculation of the fatigue notch factor K_f . The most commonly used is probably the Neuber relation:

$$K_f = 1 + \frac{K_t - 1}{1 + \sqrt{A/R}} = \frac{K_t + \sqrt{A/R}}{1 + \sqrt{A/R}} \quad (2)$$

where, R : contour radius of notch at minimum section

A : a material constant or the "Neuber constant" representing grain size or an arbitrary "particle" of material.

Combination of Eqs. (1) and (2) gives

$$q = \frac{K_f - 1}{K_t - 1} = \frac{1}{1 + \sqrt{A/R}} \quad (3)$$

This means that q is independent of K_t . It is not always the case for all the formulae suggested in literature. For instance, Heywood³⁾ has proposed two formulae for K_f to overcome limitations of Eq. (2) where R approaches zero and where K_t approaches unity. However, it is also shown that these formulae give about the same values for notches commonly encountered in design.

Figure 1 indicates that there is a relation for nodular iron which is similar to that pointed out in Eq. (3). The graph is valid for ferritic nodular iron with a tensile strength in the range of 57 to 71 thousands of pounds per square inch (40 to 50 kg/mm²); the largest R value refers to reversed bending and the rest to rotating beam specimens with diameters of 0.265 to 0.417 inches (6.7 to 10.6 mm). A variety of other functions will satisfy the same random conditions as Eq. (3).

For example, this yields for the exponential function

$$q = 1 - e^{-kR} \quad (4)$$

where k would be some type of material constant. Probably it will rather confuse the picture than clear it up if another material constant is introduced along with all the others suggested in literature.

Fig. 1. Notch-sensitivity of ferritic nodular iron as a function of notch radius

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II. Methodology

The notch-sensitivity index q varies with the notch radius and also with the type of notch. It is also influenced by the size of the specimen and the type of load. As to the material the grain size predominantly affects q . The notch-sensitivity seems to increase with section size but decrease with grain size. Consequently, q is not a true material constant. In the present investigation an attempt has been made to eliminate these factors as far as possible. Thus the study is based on fatigue data from rotating beam testing. This is, by the way, the only type of loading that has been reported in comparably large numbers for nodular iron. The minimum specimen diameter is the same for notched and unnotched bars and varies from 0.220 to 0.417 inches (5.6 to 10.6 mm) for nodular iron and in the range of 0.125 to 0.625 inches (3.2 to 15.9 mm) for steel. Data from test bars above 0.625 inches are available but excluded for steel. Indicated changes in the specimen size will not significantly affect the result according to Agerman.⁴⁾ V-notches as well as U-notches are included in the data material. To compensate for this use may be made of a notch-flank-angle factor, $\pi/\pi-w$, where w is the flank angle of the notch. This was proposed by Neuber for very sharp notches. However, this factor does not apply for notches of the type ordinarily used in test pieces^{3),5)} and has not been utilized in this investigation. In other words, it has been possible, at least to a reasonable extent, to neutralize the size effect, the type of loading and of the notch.

To make q more defined, grain size has to be taken into account. However, grain size is rarely specified for a material. Unfortunately, this is the case also for yield strength. This material property would otherwise easily be related to grain size according to Petch.⁶⁾ Further on, Schaub⁷⁾ has correlated the yield strength to the fatigue limit of commercial low carbon steels. The endurance limits nevertheless appear to be more closely related to tensile strengths than to other mechanical properties. This might be due to the fact that these other mechanical properties are more unavailable and/or too sensitive to be measured without a wide scatter. Agerman⁴⁾ concludes from numerous rotating beam tests that the fatigue limit is proportional to the tensile strength with surprisingly low deviation. Kuhn and Hardrath⁸⁾ have also explored a noteworthy idea in relating the "Neuber constant," A to the tensile strength of steels. Their idea is here utilized for nodular iron. The method of calculation is reviewed in brief. K_t is calculated for the notch and inserted into Eq. (3) along with experimental values for K_f and R . Now A is related to tensile strength and q determined as a function of R and tensile strength. A comparison of q can then be made between steel and nodular iron at equal R and tensile strength.

When considering two different materials, it is also important, however, to compare the notched fatigue limit when the notches and the tensile strengths are the same. The method for this is as follows:

$$\sigma'_e \equiv \frac{\sigma_e}{K_f} = \frac{C \cdot \sigma_{uts}}{K_f} \dots\dots\dots(5)$$

where, σ_{uts} : ultimate tensile strength
 C : a constant,

and the endurance limits refer to 10^7 cycles. From this it follows, when using the index N and S for nodular iron and steel, that

$$\frac{\sigma'_e{}^{(N)}}{\sigma'_e{}^{(S)}} = \frac{C^{(N)}}{C^{(S)}} \times \frac{K_f{}^{(S)}}{K_f{}^{(N)}} \dots\dots\dots(6)$$

Equal notch endurance limits give

$$\frac{C^{(N)}}{C^{(S)}} \times \frac{K_f{}^{(S)}}{K_f{}^{(N)}} = 1 \dots\dots\dots(7)$$

If one of them is better, e.g. nodular iron, the following is obtained

$$\frac{K_f{}^{(S)}}{K_f{}^{(N)}} = \frac{K_t + \sqrt{A^{(S)}/R}}{K_t + \sqrt{A^{(N)}/R}} \times \frac{1 + \sqrt{A^{(N)}/R}}{1 + \sqrt{A^{(S)}/R}} > \frac{C^{(S)}}{C^{(N)}} \dots\dots(8)$$

This is realized after using Eqs. (2), (6), and (7).

Objections may be raised in considering C as a constant. However, it would be quite acceptable for a rough estimation. For steel one often finds $C^{(S)}=0.5$. As an example, it has been shown⁹⁾ that $C^{(S)}$ mostly lies within the limits of 0.4 and 0.6. A check has been made in order to study the matter thoroughly. Considering only rotate-bending tests^{8),10)} with specimen diameters within, the previously mentioned range, an average very close to 0.5 was obtained for $C^{(S)}$. The fatigue data was based on hot-worked steel, ordinary low-alloyed steels as well as carbon steels (0.2 to 0.7%C) in the tensile strength range of 57 to 143 thousands of pounds per square inch (40 to 100 kg/mm²) after various treatments. Figure 2 indicates the magnitude of $C^{(N)}$. The data is gathered from investigations^{11)-17),27)} where the notch effect has also been examined. In addition, a study¹⁸⁾ is included

Fig. 2. Endurance limit as a function of ultimate tensile strength for nodular iron in rotate-bending tests

in which the internal notch effect of graphite in cast irons has been reviewed. The microstructure was mainly ferritic, ferritic/perlitic, or perlitic. Alloying additives such as nickel, chromium, and copper are involved as they occur frequently. Figure 2 shows that $C^{(N)}$ lies between 0.35 and 0.55. A reasonable statistical value for comparison would be a figure somewhat above 0.4 which means that the empirical average value of p in the equation

$$C^{(S)} = P \cdot C^{(N)} \dots \dots \dots (9)$$

would be close to 1.2 since $C^{(S)}$ was estimated to 0.5.

III. Results

Figure 3 shows the relation between the reciprocal of the square root of the "Neuber constant" for steel⁸⁾ and nodular iron. Defining the data for steel to be more valid for the present study, *i.e.* considering only rotate-bending tests in a limited diameter range and neglecting a few values with a notch sensitivity above 0.90 but also the notch-flank-angle factor as mentioned before, the linear regression line indicated in Fig. 3 was obtained. The regression coefficients are 0.48 and 0.54 for nodular iron and steel respectively. The straight lines in Fig. 3 coincide closely to the relations given in Table 1, from which is obtained:

$$A^{(N)} = 9A^{(S)} \dots \dots \dots (10)$$

The table also reveals the reliability of the calculated fatigue notch factor. The factor is computed by Eq. (2) using the linear relationships according to Fig. 3. The median and the standard deviation in both samples must be regarded as acceptable.

Combination of Eqs. (3) and (10) gives for equal tensile strengths

$$q^{(N)}/q^{(S)} = (1 + \sqrt{A^{(S)}/R})/(1 + 3\sqrt{A^{(S)}/R}) \dots (11)$$

From this relation it follows that nodular iron has a

Fig. 3. Relationship between the Neuber constant A and the ultimate tensile strength for steel according to Kuhn and Hardrath⁸⁾ and for nodular iron

lower notch-sensitivity than steel. It is now important to examine whether the obviously higher unnotched fatigue limit of steel will compensate for this so that its notched fatigue limit will remain on a higher level.

When notched fatigue limit of nodular iron is equal to or higher than that of steel, Eqs. (8), (9), and (10) give

$$\frac{K_t + \sqrt{A^{(S)}/R}}{K_t + 3\sqrt{A^{(S)}/R}} \times \frac{1 + 3\sqrt{A^{(S)}/R}}{1 + \sqrt{A^{(S)}/R}} \geq p \dots \dots \dots (12)$$

This relation can be transformed to

$$K_t \geq \sqrt{A^{(S)}/R} \times \frac{3\zeta - 1}{1 - \zeta} \dots \dots \dots (13)$$

where

$$\zeta = P \times \frac{1 + 1/\sqrt{A^{(S)}/R}}{3 + 1/\sqrt{A^{(S)}/R}} \dots \dots \dots (14)$$

For small values of R , ζ approaches $P/3$ according to Eq. (14), which corresponds to the minimum value of ζ . The maximum value of ζ should however be less than 1, which is necessary to get the inequality as Eq. (13). Using this ζ -limit and $P=1.2$ for Eq. (14) it follows that $\sqrt{A^{(S)}/R} > 1/9$ can be derived, which means that $R < 4$ mm for $\sigma_{uts} = 100$ kg/mm². Successively higher radii limits are achieved at lower tensile strengths.

Setting both sides equal in Eq. (12) will result in an imaginary notched fatigue limit equilibrium between steel and nodular iron visualized in Fig. 4. This yields for various notch radii, stress concentration factors, and tensile strengths. Thus, along the curves steel and nodular iron have the same notch fatigue limit but above the curves nodular iron is better according to Eq. (13). The broken horizontal lines in Fig. 4 for constant ratio of the notch depth, t to notch radius R was determined from the simple Neuber relation $K_t = 1 + 2\sqrt{t/R}$.

It is evident from Fig. 4 that an increased tensile strength decreases the area above the imaginary equilibrium curves which means that steel is getting successively superior. On the other hand, it is obvious from this principle graph that there are a lot of notches at moderate tensile strengths which nodular iron should withstand better.

IV. Discussion

The notched fatigue data on which this investigation

Table 1. The reciprocal of the square root of the "Neuber constant" A and the statistical ratio of calculated and measured fatigue notch factor

	$A^{-1/2}$ (mm ^{-1/2})	K_f (calculated)/ K_f (measured)	
		Median	Standard deviation
Nodular iron	$0.015 \sigma_{uts}$	1.02	0.13
Steel	$0.045 \sigma_{uts}$	1.01	0.05

Fig. 4. Equilibrium relations between steel and nodular iron for notched fatigue

is based cannot be compared directly. Account has to be taken of the variation of the stress concentration factor which is found in literature. This factor varies for nodular iron in the range of 2 to 4.9 and for hot-worked steel from 1.3 to 3.2. Advisably these factors should have varied in a large and equal range to avoid extrapolation. A direct comparison requires a neutralization of this variation so that the notch effect is studied for equivalent conditions. In doing so one first finds that the notch-sensitivity of nodular iron is lower than that of steel. This would be a natural result when considering the internal notches in the nodular iron due to the graphite nodules. Because of this the fatigue notch factor is less than for steel. Further on, however, it appears that the notched fatigue limit of nodular iron is comparable or better than steel over a wide range of conditions. This is shown in Fig. 4. The lack of data for large notch radii and stress concentration factors as well as a somewhat unreliable p -value in Eq. (9) are some of the reasons for considering Fig. 4 as merely indicating a trend. It can nevertheless be concluded that nodular iron has remarkably good notched fatigue properties. This has also been established at tests on gears.^{14),20),21)} In these investigations, the rolling-fatigue strength of nodular iron was better and the root fatigue strength at least comparable to cast and forged carbon steel of the same tensile strength.

The reason for the excellent fatigue properties might be found in the graphite nodules and their stress reducing by the mutual effect of interference. Pohl and Holzwarth²²⁾ discuss the influence of nodule size and distribution for mechanical unnotched specimens. They conclude that the nodule size will not significantly affect the result if the volume fraction of graphite remains constant. An analogous conclusion may be drawn from Kazinczy's²³⁾ study of the metallurgical defect size in cast steel. Considering the nodules as defects of the magnitude of 0.004 to 0.04 inches, this size range will hardly diminish the fatigue limit.

On the contrary, if the interparticle spacing between the graphite nodules is decreased, which for the same volume fraction means smaller nodules, the fatigue limited is expected to increase due to stress reduction in the surface layer. This implies also lower values of flow stress in tensile tests according to Mogford *et al.*²⁴⁾

Ikawa and Ohira¹⁸⁾ have related the fatigue properties of cast irons to the graphite structures for mechanical unnotched specimen. They point out that the slip pattern of the matrix along the cracks in the case of flake graphite is relatively small but in spheroidized graphite or granular graphite iron the plastic deformation of the matrix along the cracks and graphite is very remarkable. Because of this it is concluded that the matrix is hardened to prolong life owing to the understress treatment. Further on, Fortino²⁵⁾ has found that the fatigue limit of crankshafts was increased with the degree of spheroidizing.

In view of these facts it now appears well established that nodular iron has superior fatigue properties to other irons but inferior to forged steel in the unnotched condition. When a mechanical notch is introduced it seems that the nodular iron in many cases is at least comparable to forged steels at moderate tensile strengths. This is remarkable and the explanation may be due to the fact that the nodules probably soften the effect of the mechanical notch. The notched fatigue limit can be still improved by work hardening of the notch as Gilbert and Palmer¹⁷⁾ have shown in laboratory tests. Their results have been confirmed in a Russian investigation on crankshafts.²⁶⁾

The overall size effect of the test specimen was eliminated in this study. There are only a few fatigue data based on large specimen sections published for nodular iron. Using the rotate-bending values from the investigation of Eagan²⁷⁾ and data from two Swedish research laboratories on alternating bending, sections up to 1" and 2.36" respectively have been obtained. These values will all fall within the scatter of size factor shown by Agerman⁴⁾ for forged steel.

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