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On the Notch Strength of Cast Iron

by

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Abstract

In gray cast iron, the strength decrease by notches is much smaller than estimated by elastic formula. In order to clarify the reasons for the low notch sensitivity, different cast irons with various strength grades and notch configurations were investigated at room and liquid nitrogen temperature. The finite element method was used to calculate the stress distribution around the notch considering the non-elastic stress strain behavior of the material.

According to the stress analysis, the low notch sensitivity is caused by two factors, the non-elasticity of cast iron that reduces the maximum working stress to a much lower value than the elastic estimation, and an over stressed region at the notch root where the stress is higher than the tensile strength of the material.

A fracture criterion with an over stressed depth, δ, was established for the strength evaluation of cast iron under a stress gradient. The value of δ is about 3 mm at room temperature and less than 1 mm at liquid nitrogen temperature. These values are related to the metallurgical size of the graphite eutectic cell, and the mechanical conditions of initiation and propagation of cracks in cast iron.

1. Introduction.

One of the strength characteristics of cast iron is its low notch sensitivity. Reports [1),2)] have shown that the decrease in strength due to notches in cast iron is much smaller than that estimated by elastic formula; in extreme cases the effect of notches is hardly seen. This characteristic is difficult to explain since cast iron is considered to be a typical brittle material where the strength drops drastically with notches or cracks.

The low notch sensitivity of cast iron has been attributed[1)] to its peculiar microscopic structure with graphite flakes in the metallic matrix. Although the precise mechanism is not known, it is considered that the graphite flakes act as microscopic notches and cancel out the effect of a macroscopic mechanical notch.

In this report, the notch sensitivity of cast iron in static strength is examined with stress calculations based on stress strain relations determined in macroscopic test specimens. Initially, experiments of notch strength were performed on different cast irons with various strength levels and notch configurations. The notch stress was then analyzed by the finite element method for the non-elastic stress strain behavior of cast iron. A fracture criterion that considers an "over stressed depth", δ, is proposed for flake graphite cast iron. The over stressed depth concept gives a good explanation of the low notch sensitivity and its dependence on notch configuration and temperature.

Department of Mechanical Engineering II.

2. Experiments on notch strength of various cast irons.

Experiments were performed on the notch strength of different cast irons with various notch configurations. One experiment was made on circumferentially notched bars of two flake graphite cast irons (FC20 and FC30) and one nodular cast iron (FCD45) with microstructures as shown in Fig. 1. The test pieces were round bars, 20 mm(FC) and 18 mm(FCD) diameter, lathed from 30 mm diameter cast bar (FC) or 25 mm wide keel blocks (FCD). The notch had root radii from 0.2 to 7 mm, and were finished with #800 emery paper. Specimens were loaded to fracture by a load-cell type testing machine with a crosshead speed of 0.5 mm/min. The notch strength, σ_{nf}, is defined by the maximum load P_m divided by the cross-sectional area of the notch section. Reductions in the cross-sectional area at fracture is negligible in cast iron.

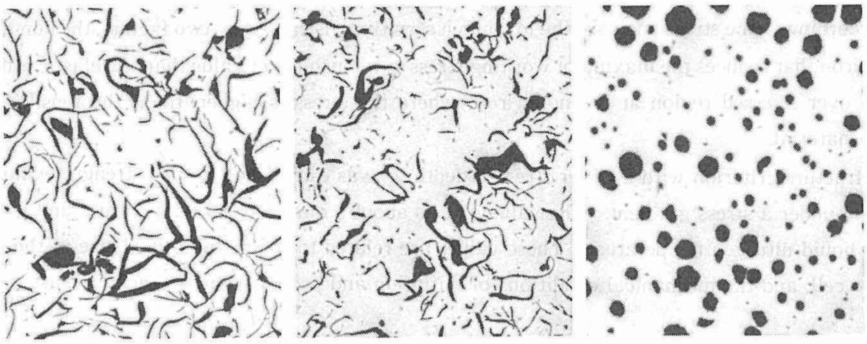
FC20 FC30 FCD45

Fig. 1 Microstructures of test specimens (no-etched). (×50)

Variations in notch strength is expressed by a "Notch Strength Ratio" (NSR), σ_{nf}/σ_f, where σ_f is the tensile strength of the material obtained from a simple tension test of a smooth specimen. Average σ_f values for the three specimens of the cast irons were 220, 318, and 466 MPa for FC20, FC30, and FCD45.

Experimental results are shown in Fig.2, where the ordinate is NSR and the abscissa is a form factor or elastic stress concentration factor of the notch, α_e. Here, α_e indicates only the relative sharpness of the notch, because cast iron becomes non-elastic at loading to fracture.

Fig.2 shows that the strength of different cast irons is influenced differently by different notch cofigurations. For FC20, the strength decreases and is about 85% of the strength of a smooth specimen for a R=3 mm notch. However in the range of very sharp notches, there is no further decrease. For FCD45, the strength for all noches increases by 20~30% (NSR=1.2~1.3). For FC30 the strength is scarcely affected by the notches, and decreases only 5% even for a very sharp notch. For the blunt notches, the strength of FC30 increases by about 10%. The increase in the fracture strength caused by a notch is quite unexpected for cast iron.

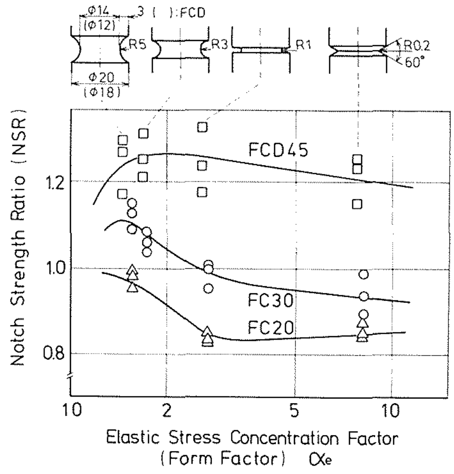

Fig. 2 Effect of notches on the fracture strength of different cast irons.

Fig.3 shows an experiment with edge notched plates with various notch radii. The specimens were flake graphite iron FC25 plates with a tensile strength of 280 MPa, 10 mm thick, 50 mm wide, and the edge notches were of 15 mm depth and 0.15~30 mm radii. The strength clearly decreases with increasing α_e, but flattens out to a value of about 0.7 for very sharp notches. The value is lower than with circumferential notches and there is no strength increase in the blunt notch region.

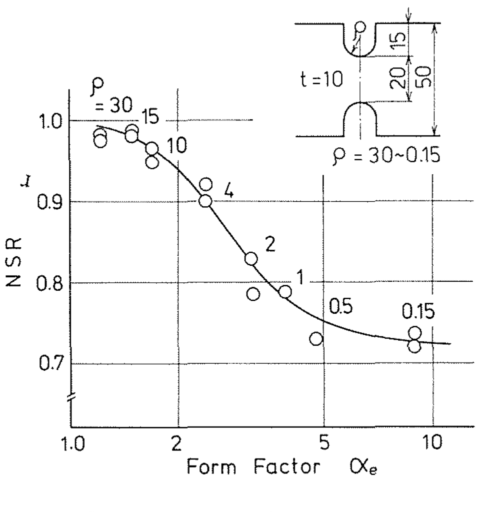

Fig. 3 Strength decrease in edge notched plates.

Fig.4 shows the results of experiments similar to those in Fig.3 at liquid nitrogen temperature (−196°C) on edge notched or holed plates of FC25 iron. The room temperature strength was 245 MPa, and it decreased by about 20% for $\alpha_e = 2\sim2.5$ notches. At liquid nitrogen temperature the strength was 261 MPa for a smooth specimen, 6% higher than at room temperature, but with notches it decreased about 40% for $\alpha_e = 2\sim2.5$ notches. The strength decrease at low temperature was more prominent than at room temperature in all notches investigated.

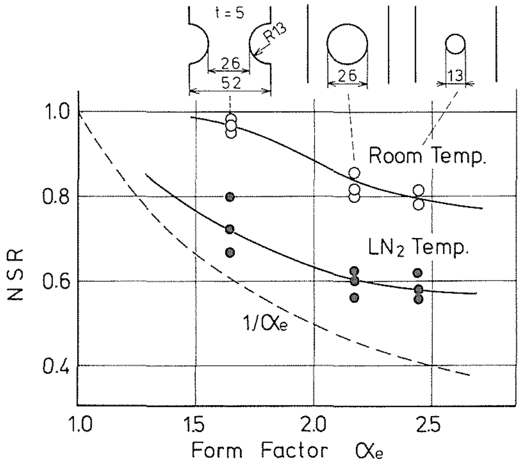

Fig. 4 Notch strength at liquid nitrogen temperature.

The broken curve in Fig.4 is $1/\alpha_e$, the theoretical strength decreases by the notches in elastic material, showing that the results at liquid nitrogen temperature approaches the theoretical value. A similar result was obtained with circumferential notches of FC30; while the strength was hardly affected at room temperatume the specimens showed a remarkable strength decrease at liquid nitrogen temperature.

These changes in cast iron strength with notches can not be explained by the usual notch effect of the machined outer notch, and neither by the internal notch effect of the graphite flakes. Particularly the increases in strength are impossible to understand by simple considerations of the micro notch effect of graphite flakes. The experimental results in which the notch sensitivity of cast iron becomes pronounced at low temperature suggests that low notch sensitivity is not directly caused by the micro notch effect of the graphite flakes, because the micro notch effect would be more pronounced at low temperatures where the matrix becomes very brittle[3] and notch sensitive. In this paper the macroscopic stress distribution around the notch root is discussed as the determining factor in the low notch sensitivity of cast iron.

3. Stress analysis of a notched specimen by the finite element method.

3-1. Method of the stress analysis.

In order to obtain the stress distribution in a notched specimen considering the non-elastic stress strain behavior of cast iron, the finite element method (FEM) together with elasto-plastic theory was applied. At first, the stress strain curve of cast iron was approximated by a mathematical function, $\sigma=C(A+\varepsilon_p)^n$, where σ is the stress, ε_p is the plastic strain obtained by subtracting the elastic strain σ/E from the total strain ε with a constant elastic modulus, E. The factors C, A, and n are material constants determined experimentally. The measured curves in Fig.5 were well approximated by $\sigma=645\cdot(6\text{x}10^{-5}+\varepsilon_p)^{0.189}$, $E=1.1\text{x}10^5$ (MPa) at room temperature and $\sigma=2450\cdot(10^{-4}+\varepsilon_p)^{0.339}$, $E=1.16\text{x}10^5$ (MPa) at liquid nitrogen temperature. In the approximated curves, there is a yield point where the cast iron is assumed to change from elastic to plastic; in cast iron there is no such clear yield point. In the plastic state, strain incremental theory was assumed to be valid and Mises's equivalent stress $\bar{\sigma}$ and equivalent strain $\bar{\varepsilon}_p$ relation was assumed to be constant for the multi-axial stress state. These assumptions are not completely valid for

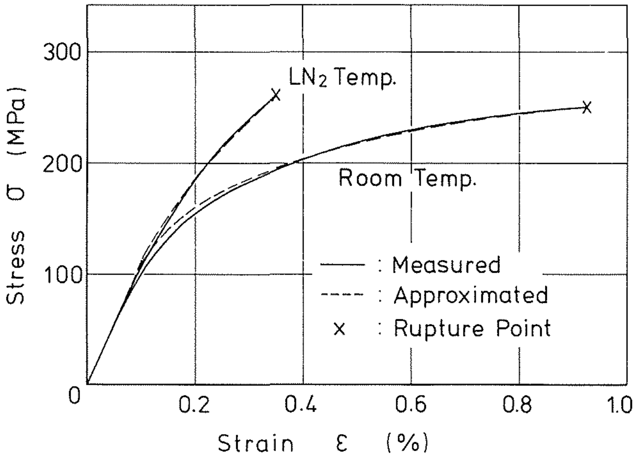

Fig. 5 Stress strain curve of cast iron and its approximation.

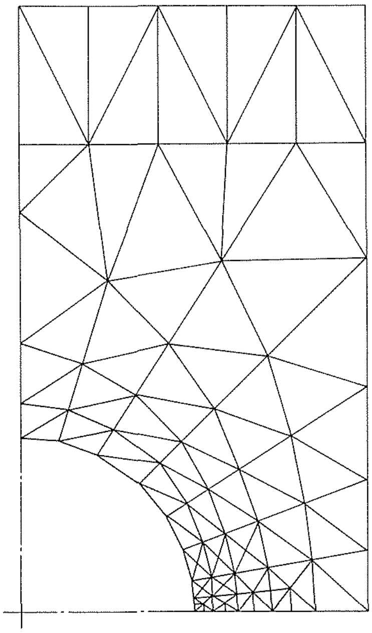

Fig. 6 An example of elements division for the FEM.

cast iron[4,5], but experiments by the strain gauge method showed that errors from these assumptions are small. An example of the element division for FEM is shown in Fig.6. The computations were carried out with a program, EPIC-I, developed by Yamada[6].

3-2 Stress distribution in edge notched plates.

An example of stress distribution at the notch section calculatec by the FEM is shown in Fig.7. The specimen is the semi-circular edge notched plate shown in Fig. 4. In Fig.7, (a) is the stress distribution for average fracture strength (NSR=0.96) at room temperature and (b) is at liquid nitrogen temperature (NSR=0.72). The solid line is the non-elastic stress distribution and the broken line is the corresponding elastic distribution.

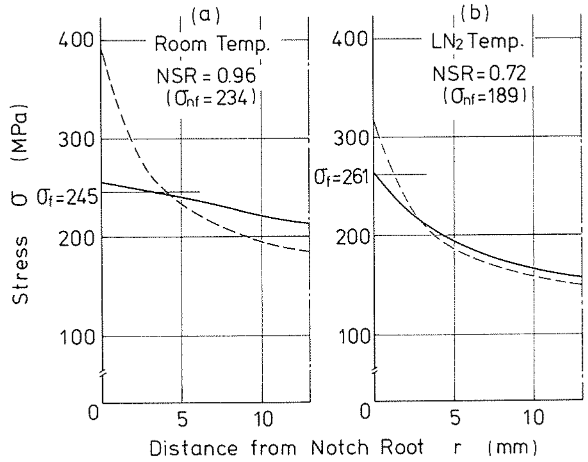

Fig. 7 Stress distribution at the notch section at fracture (semi-circular edge notch, root radius=13 mm).

At room temperature the steep stress concentration at the notch root was relaxed by the non-elastic behavior of the material and the stress distribution became flatter at fracture. For the nominal fracture stress, σ_{nf}, 234 MPa, the maximun stress is about 255 MPa, only 65% of the elastic value 390 MPa. Experiments by strain gauge showed that the non-elastic value was accurate, and that in cast iron the working stress at the notch root is very much lower than estimated from notch configuration and elastic formula. At fracture, the stress concentration factor α decreased to about 1.1 from the elastic value $\alpha_e=1.7$. This may be the main reason for the low notch sensitivity ; by a stress concentration of $\alpha=1.1$, the strength decrease can not be larger than 10%, which is much smaller than the 40% that can be expected from $1/\alpha_e=0.6$. However the measured strength decrease, 4% is even smaller.

Fig.7. also shows that the tensile fracture strength of the material, σ_f, is 245 MPa by a simple tension test, while the maximum working stress at the notch root, 255 MPa, is apparently higher than this value. This indicates that, before fracture, there is a region where the working stress exceeds the tensile strength; the region may be called the "over stressed region". Such a region is also known to exist in the bending of cast iron beams[7]. In Fig.7 the depth of the over stressed region is about 3 mm. In addition to the low stress

concentration, the existence of this over stressed depth may also help to account for the low notch sensitivity.

In Fig.7 (b), the stress calculation was carried out by the same method based on the stress strain curve shown in Fig.5. The curve shows that the iron fractures with an almost linear stress strain relation and a very brittle manner.

At low temperatures, the difference between the elastic and non-elastic stress distribution is smaller than at room temperature, because the stress strain curve deviates less from the elastic relation. The maximum stress at the notch root at fracture, 265 MPa, is about 85% of the elastic value 314 MPa. The stress concentration factor decreased to 1.4 from the elastic value 1.7, but is higher than the 1.1 at room temperature.

At liquid nitrogen temperature, the maximum stress at the notch root nearly coincides with the tensile strength of the material, 261 MPa, and the over stressed depth is very small, and less than 0.2 mm. This means that the notched specimen fractures when the maximum working stress reaches the tensile strength of the material, validating the maximum stress hypothesis. By stress analysis of the other notches in Fig.4, the calculated maximum stress was slightly higher than σ_f, but the over stressed depth was less than 1 mm.

Fig.8 is the over stressed depth, δ, obtained from the experimental results in Fig.4. At room temperature, the value of δ ranges from 2.5 mm to 4 mm, with a nearly constant average value of 3 mm. At liquid nitrogen temperature, δ is less than 1 mm and also nearly constant. As a result, a fracture criterion of notched cast iron can be deduced ; namely the specimen fractures when the stress value at the depth δ mm from the notch root reaches the tensile strength of the material, or the depth of over stressed region reaches the critical value δ.

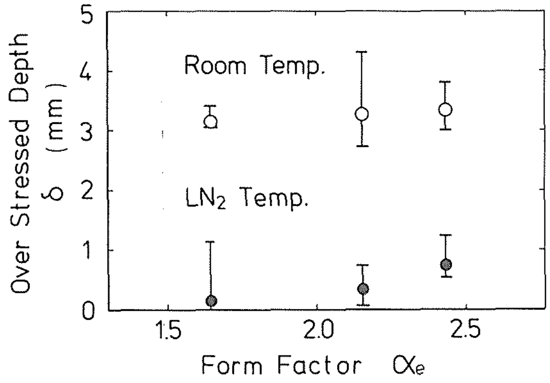

Fig. 8 Over stressed depth in notched plates.

3.3 Stress distribution in circumferentially notched bars.

Fig. 9 is the result of a stress analysis similar to that in Fig. 7 performed on circumferentially notched bars, (a) is at room temperature and (b) at liquid nitrogen temperature. The NSR values are 1.05 and 0.85, showing that the notch increases the strength by 5% at room temperature.

The maximum stress at the notch root exceeds the tensile strength and there exists an over stressed region at both temperatures. The depth is about 3 mm at room temperature and about 0.5 mm at liquid nitrogen temperature. Both coincide well with the values obtained for edge notched and holed plates in the previous section. The effect of tangential stress, σ_θ, and radial stress, σ_r, is neglected because, according to the experiments[8)], the second stress (σ_θ) has little effect on the fracture strength of cast iron in biaxial tension, and the third stress[9)] (σ_r) is very small at the notch root.

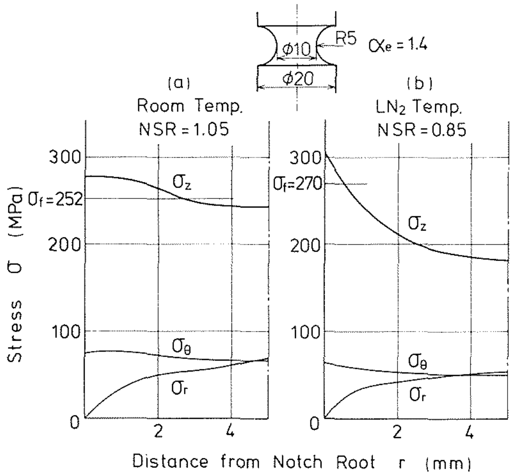

Fig. 9 Stress distribution at fracture (circumferenital notch).

Finally, the low notch sensitivity of flake graphite cast iron and its dependence on temperature can be explained by the following two reasons: The first is the non-elastic stress strain behavior that relaxes the stress concentration and lowers the working stress at the notch root, and the second is the existence of an over stressed depth that enables the test piece to sustain loads where the maximum working stress exceeds the tensile strength of the material. At liquid nitrogen temperature, the stress relaxation effect by the non-elasticity is small and at the same time, the over stressed depth becomes very small, and consequently the cast iron shows high notch sensitivity. The strength increase with blunt notches is also explained by the over stressed region at the notch root, because in round bars, a high stress value far removed from the central axis can sustain a higher load than a low stress around the center. The restricted fracture site in a notched specimen may also work to increase strength since the critical strength may be higher than in a smooth specimen where the strength is determined by the weakest position of the test length.

4. Fracture criterion with the over stressed depth δ.

It may be possible to use δ as a fracture criterion of flake cast iron sinece the over stressed depth was found to be nearly constant, about 3 mm at room temperature and below 1 mm at liquid nitrogen temperature, for both notched plates and circumferentially notched bars. Fig. 10 shows the over stressed depth obtained for notch tests, including Fig.

2, 3, 4, with various materials and notch configurations. The abscissa is $2/\rho$ (ρ is the notch radius) and indicates the elastic stress gradient at the notch root. At room temperature, δ ranges from 1 mm to 5 mm depending on the notch radii ρ. The value of δ decreases with increasing stress gradient and reaches the minimum value, about $1\sim2$ mm, for very large $2/\rho$ or very sharp notches. At liquid nitrogen temperature, δ is almost constant and less than 1 mm independent of the stress gradient and the notch configurations. In practice, a fracture criterion with a constant δ, 3 mm at room temperature and 0.5 mm at liquid nitrogen temperature, is adequate for strength evaluations of notched cast iron.

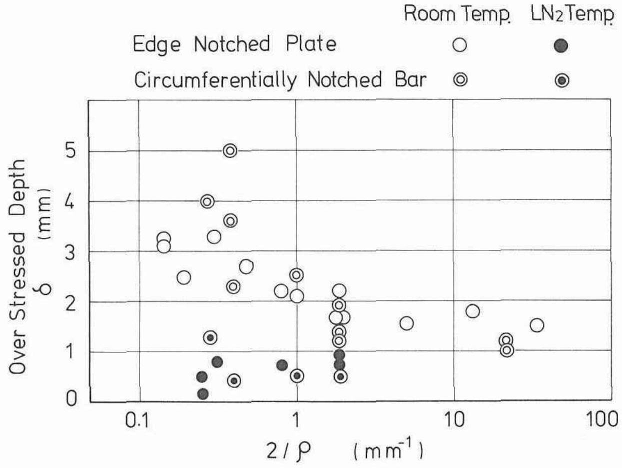

Fig. 10 Over stressed depth δ for various notch configurations.

Concepts similar to the over stressed depth proposed here have been proposed by Neuber[10], Siebel[11], and others for fatigue fracture of steel and other metals. They suggest that the strength of a notched specimen is not governed by the maximum peak stress but by a stress value at a depth, ε_o, below the notch root. The value of ε_o was related to the size of crystal grains or other metallurgical factors and is in the order of 0.1 mm or less. The value of δ for static fracture of cast iron obtained here is much larger.

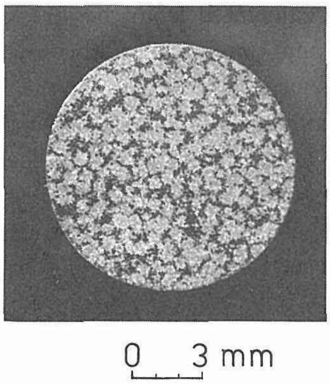

Fig. 11 Graphite eutectic cells in flake graphite cast iron.

In flake graphite cast iron the micro-structural unit, the element like crystal grains, is the graphite eutectic cell (Fig. 11); the cell diameter is 0.4～1 mm in ordinary cast iron. The value of δ at liquid nitrogen temperature nearly coincided with the size of a graphite eutectic cell, and at room temperature it is 3～5 times the cell diameter.

The experimental result that δ depends not only on the stress gradient but also on the test temperature suggests that δ can not be explained by inhomogeneities in the material or metallurgical factors, crystal grains or eutectic cells, because such factors are temperature independent.

The present authors consider that δ in cast iron is related to the mechanism of initiation and propagation of fracture. For crack initiation under a stress gradient, the stress must reach a critical value at least down to the depth of a eutectic cell, because this is the elemental unit of fracture in cast iron. At liquid nitrogen temperature, a crack initiated in this manner would propagate immediately since the material is very brittle. Such behavior can be verified as follows:

The fracture toughness value K_{IC} of cast iron at liquid nitrogen temperature is about 10 $MN/m^{3/2}$.[12] By substituting this value and the tensile strength 200～300 MPa in $K_{IC}=\sigma\sqrt{\pi a}$, the critical crack length, a, under this stress becomes 0.4～0.8 mm. This almost coincides with the cell diameter.

Thus, the smallest value of δ is the initiating and also propagating condition of a fracture and is almost equal to the cell diameter. The larger value of δ at room temperature may be explained by the higher stress value required for propagating the initiated crack as the fracture toughness value is much higher, however there are many problems in applying the fracture mechanics concept to cast iron at room temperature.

5. Stress analysis on nodular cast iron.

In order to examine the reasons for the marked increase in strength by circumferential notches in nodular cast iron, stress analysis was performed. The specimen was a 20 mm diameter bar of pearlitic FCD 60 with a tensile strength of 645 MPa, notch depth 5 mm and notch radii from 1 mm to 7 mm. The strength increase by the notches was such as seen in FCD 45 in Fig. 2, with NSR value from 1.1 to 1.2.

Stress distributions were calculated from the stress strain curve in Fig. 12. Fig. 13 shows the results for 5 and 1 mm notch radii with form factors (α_e) 1.4 and 2.6, and the average measured NSR values were 1.15 and 1.13. In the 5 mm notch, the stress concentration of axial stress σ_z at the notch root completely disappeared and the stress distribution is convex with a higher value at the center of the notched section than at the notch root. The distribution of tangential stress σ_θ and radial stress σ_r is also convex and higher at the center. Furthermore, the value of axial stress, σ_z exceeds the tensile strength of the material throughout the notch section. The whole notch section is over stressed and the δ value can not be determined.

Stress state such as seen in Fig. 13 (a) is known to occur when notched bars of ductile materials yield. The stress distribution is convex and the axial stress is larger than the yield strength of the material obtained by a simple tension test. In ductile material, this phenomenon is considered to be caused by a "plastic constraint effect"[14] by a triaxial stress state induced by the notch. Plastic deformation or yielding of the material is prevented by lateral stresses with an apparent increase in yield stress. For nodular cast iron, the fracture strength can be considered to increase, such as the yield strength of ductile material, from 645 MPa to above 700 MPa by this constraint.

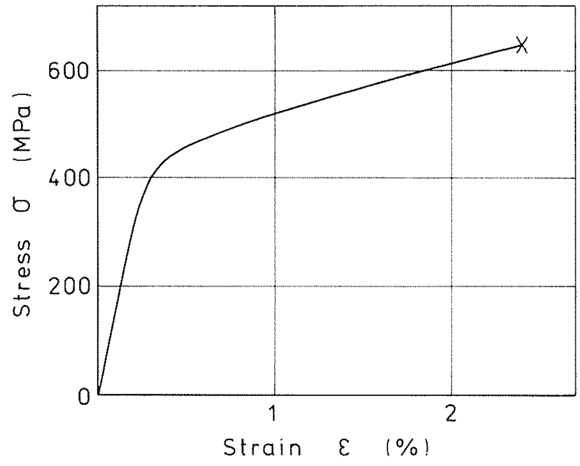

Fig. 12 Stress strain curve of nodular cast iron, FCD60.

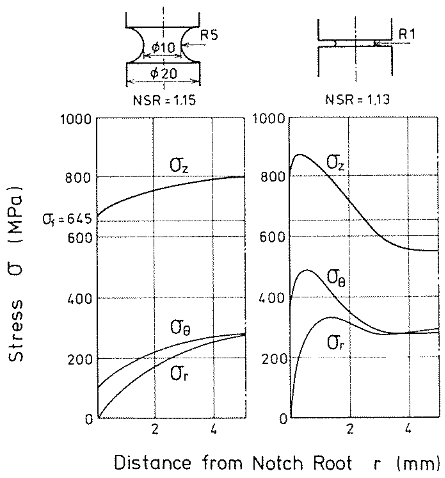

Fig. 13 Stress distribution at fracture in circumferentially notched nodular iron.

In the 1 mm notch (Fig. 13 (b)), stress concentration at the notch root remains and the maximum stress is about 30% higher than the tensile strength. The over stressed depth is determined to be about 2.5 mm. Considering the increase in critical strength by the constraint effect of a triaxial stress, the δ value would be smaller. The value of δ so obtained is considered to be the propagating condition of a ductile crack initiated at the notch root. As a result of microscopic observation of the axial section near the notch, fracture was judged to be initiated at the notch root and propagate inward in the 1 mm radius notch, while in the 5 mm radius notch the fracture was initiated at the central part of the notched section.

6. Conclusion.

Gray cast iron is less strength sensitive to notches than steel and other metals. The low notch sensitivity is mainly attributed to its non-elastic behavior.

The experimentally observed decrease in strength caused by notches is much smaller than calculations by the elastic formula, and depends on material grade, notch configuration, and test temperature. Stress analysis by the FEM applied to the experimental results indicates that the notch strength characteristics in cast iron are mainly caused by two factors, the non-elastic behavior of the stress strain relation and an over stressed region at the notch root. The former reduces the maximum working stress to a value lower than the elastic stress, and the latter enables the iron to sustain a stress higher than the tensile strength of the material under a stress gnadient.

To evalucate notch strength, a fracture criterion was deduced from the stress distribution in the notch and the depth of the over stressed region where the calculated stress is higher than the tensile strength. Fracture of cast iron occurs when the over stressed depth reaches a critical value δ. The value of δ is 1～5 mm at room temperature and depends somewhat on the stress gradient; in practice a δ value of 3 mm can be used. At liquid nitrogen temperature, δ is less than 1 mm and independent of the stress gradient. Here, cast iron is nearly elastic and is highly notch sensitive with a small δ.

In ductile cast iron, the constraint of lateral stress at the notch root must be considered; this increases the strength in addition to the effect by the above two factors.

The smallest value of the over stressed depth δ in flake graphite iron can be related to the size of the graphite eutectic cell which acts as an initial flaw for fractures in cast iron, and the larger value of δ is considered to be the propagating conditions of cracks.

Notch strength of cast iron can be evaluated from a macroscopic stress analysis based on the stress strain curve and the depth of the over stressed region which includes microscopic notch effects of graphite flakes and rupture of the matrix. The method reported here is also applicable over a wide range of strength evaluations[15] under stress gradients in bending or notched tension of other low ductile materials.

References:

1) Nakanishi, F., Okamoto, S., Trans. of the JSME, 17, 61 (1951), 103.
2) Ishibashi, T., Trans. of the JSME, 18, 68 (1952), 87.
3) Noguchi, T., Sugawara, Y., Bulletin of the Faculty of Eng. Hokkaido Univ. 89 (1978), 51.
4) Coffin, L. F. Jr., J. of Applied Mechanics, 17, Sept. (1950), 233.
5) Crosland, B., Proc. Inst. Mech. Engr., 179 (1964-65), 415.
6) Yamada, Y., "Structure Analysis by Computer Series, II-2-A" (Baifukan, Tokyo, 1975).
7) Pinegin, W., VDI-Z 50, 50 (1906), 2029.
8) Cornet, I., Grassi, R. C., J. of Basic Engrg., 83, Mar. (1961), 39.
9) Mair, W.M., J. of Strain Analysis 3, 4 (1968), 254.
10) Neuber, H., "Kerpspannungslehre" (Berlin, 1937), 144.
11) Siebel, E., VDI-Z, 9, 13 (1949), 319.
12) Terada, A., Noguchi, T., Proc. of the JSME (Hokkaido), 812-2 (1981), 33.
13) Bridgeman, P.W., Rev. Mod. Phys., 17 (1945),3.
14) Hill, R., "The Mathematical Theory of Plasticity" (Oxford at the Clarendon Press, 1964), 248.
15) Noguchi, T., Nagaoka, K., AFS Trans. 82-64 (1982), 323.