Fatigue Notch Behavior of Gray Cast Iron

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ABSTRACT. *Fatigue design of notched parts is customarily performed using the concepts of elastic stress concentration and material notch sensitivity. However, if this methodology is applied to gray cast irons the predictions appear far from satisfactory. Due to its microstructure, gray cast iron exhibits a marked brittle behavior and a low notch sensitivity. Various authors have proposed alternative approaches: among them fracture mechanics based approaches and critical distance methods. This paper examines fatigue crack initiation at sharp notches in gray cast iron from both the experimental and the theoretical point of view. Fatigue life and fatigue crack initiation experiments are conducted on V-notches specimens extracted from castings in fully pearlitic gray iron. Different values of notch root radii are examined. From a theoretical point of view, the notch root stresses in the test specimen geometries are investigated with the FE method. The role of the notch elastic stress concentration on the microstructure is discussed and the possibility to identify microstructure-dependent value of a critical distance or intrinsic fatigue crack length at a V notch is investigated.*

INTRODUCTION

Gray cast iron is traditionally used in many industries because it is characterized by a flexibility of use, excellent castability, low cost and wide range of achievable mechanical properties. Gray cast irons are selected according to their tensile strength: when high modulus of elasticity, good wear resistance and ability to be machined to a fine finish are desired, a high-strength cast iron is selected, [1]. The excellent engineering properties of gray cast iron is exploited in the fabrication of fluid power components because they have a complex 3D geometry with ducts and are high speed machined in robotized tool centers. The competitive global market, however, increasingly pushes not only for lowering costs and short time-to-market but also for high product durability.

The existing fatigue design approaches are difficult to apply to notched gray cast iron parts for the complex interaction between material microstructure and localized stress concentration, [2, 3].

Geometrical details of special concern for this contribution are the sharp V-notches that are obtained by milling raw castings. Because they serve specific functions, notches of this kind are often inevitable in practice. The industrial experience in the fluid power sector shows that the fatigue response of notched parts is still difficult to predict.

This contribution is aimed at investigating the influence of sharp notches on the fatigue response of gray cast iron microstructures.

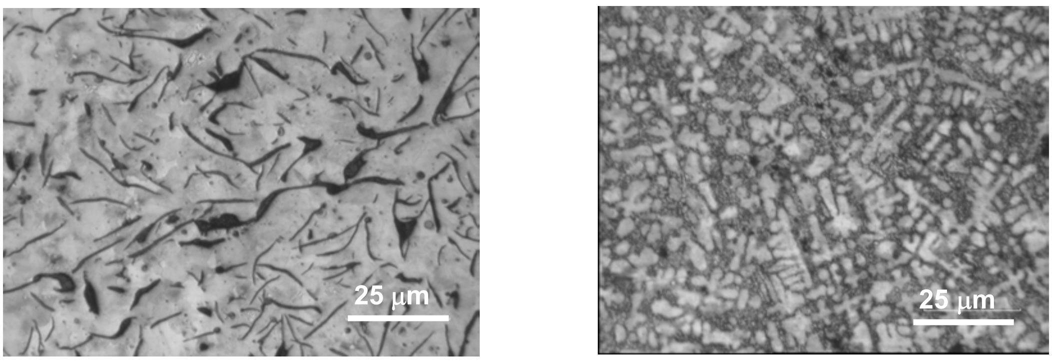
MATERIAL

The material considered is a pearlitic gray cast iron (i.e. EN GJL-300) extensively studied elsewhere, [4]. The chemical composition of the cast iron provided by the foundry is given in Tab. 1. It is a hypoeutectic cast iron, since the equivalent carbon (EC) value is < 4.3%. Limit of proportionality and ultimate strength are 200MPa and 230MPa respectively, elongation to failure is equal to 0.6%.

Table 1. Chemical composition of EN GJL-300 gray cast iron

C	Si	Mn	P	S	Cr	Mo	Ni
3.29	1.52	0.79	0.055	0.03	0.15	0.005	0.029
Cu	Sn	Ti	V	Al	Pb	Mg	EC
1.34	0.009	0.013	0.011	0.002	0.003	0.001	3.815

Previous rotating bending fatigue tests were conducted on smooth specimens extracted from actual castings. An extensive metallographic characterization was previously conducted and reported in [4]. The micrographs of Fig. 1 show two typical graphite morphologies found in the present gray cast iron. Micrographs have the same magnification factor. The Type A graphite of Fig.1a is charactrized by long and randomly dispersed lamellae in the pearlitic matrix. The Type D graphite of Fig. 1b has a random interdendritic dispersion of small lamellae in pearlitic/ferritic matrix, [5].



a) Type A *b) Type D*

Figure 1. Graphite morphologies observed in gray cast iron

EXPERIMENTAL DETAILS

Notch geometry

The treatment of the notch effect in fatigue has been subject of extensive investigation that led to development of now classical approaches for the prediction of the fatigue limits of notched parts, [2]. They are based on the elastic stress concentration and fatigue notch sensitivity factors, which depended on the notch root radius and on a material constant. The general idea is that the plain specimen fatigue limit must be exceeded not only at the hot spot but also within some region ahead of the notch, i.e. the critical volume.

The practical application of Peterson's and Neuber's approach, [6, 7], to gray cast iron suggests that this material has no notch sensitivity. It means that the root radius does not influence the fatigue limit of a gray cast iron part. This hypothesis is tested with the experimental program here presented. Flat specimens were extracted from actual castings and controlled 90-deg V-notches were inserted by milling. Details of the specimen geometries are shown in Fig. 2. The notched sheet in tension configuration is considered to allow a straightforward definition of net section reference stress and associated elastic stress concentration factor.

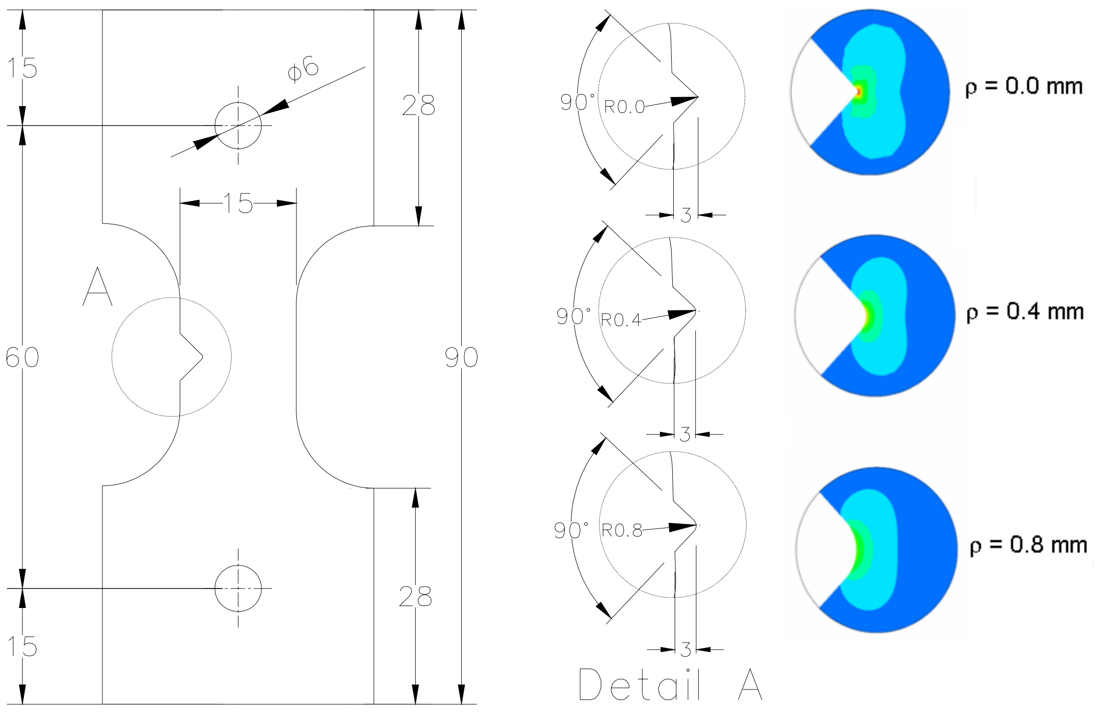


Figure 2. Specimen geometries (thickness 2.5mm) and map of principal elastic stress at the notch (nominal tension 40MPa)

Three root radii were defined, $\rho \approx 0$, $\rho = 0.4$ mm and $\rho = 0.8$ mm, and multiple specimens produced for a systematic study. To assess theoretically the role of the root radius on the local notch stress distribution, the finite element method was used and the three specimen geometries meshed and analyzed, [8]. A typical stress map is shown in Fig. 2 on the right. Fig. 3 shows the principal elastic stress distribution acting normal to the plane of potential crack propagation ahead of the notch for an applied net section stress equal to 40 MPa. While the stress distribution is independent of the material, the extent of the material volume subjected to relatively high stresses depends on the material (static and fatigue) strength. As expected the stress concentration is strongly and inversely correlated to the root radius: $\rho \approx 0$ $K_t > 10$; $\rho = 0.4$mm $K_t = 8$ and $\rho = 0.8$mm $K_t = 6$.

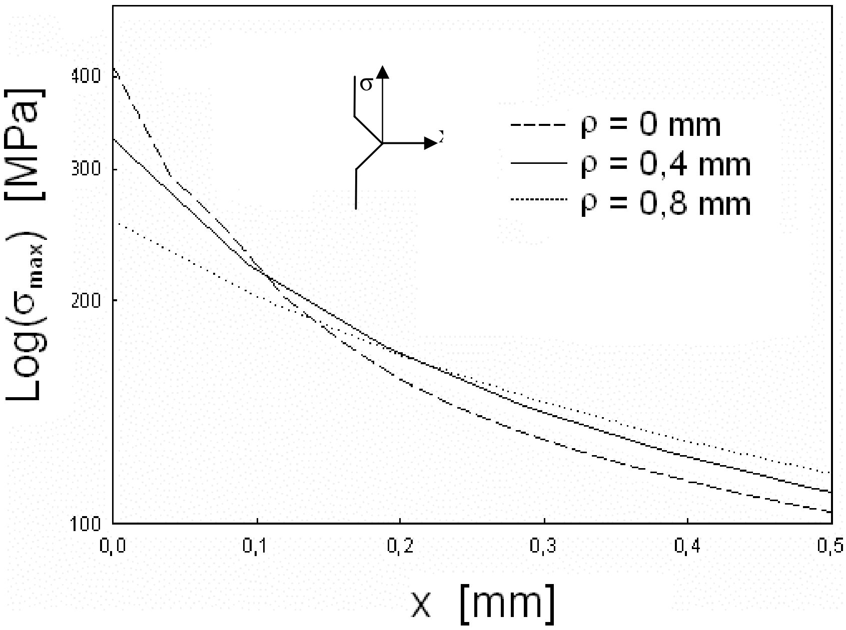


Figure 3. Stress distributions ahead of sharp V- notches in tension

Test method

To investigate the interaction of the notch stress gradients with the two typical microstructures of gray cast iron shown in Fig. 1, two sets of notched specimens were prepared. Each set was made of multiple notched specimens to be used in the determination of the fatigue life and, especially, the fatigue limit of the notched geometry (i.e. the limit loading condition, which does not cause failure in 10^7 cycles). The fatigue tests of the notched specimens were performed on a Amsler vibrophore operating at about 100 Hz. The applied loading ratio was R=-1. Initial tests were used to estimate an S/N curve of each notch type, applying a decreasing loading procedure till to obtain a run-ot condition. Then the Locati procedure was used to efficiently estimate the fatigue limit, [9]. It is based on a single test in which a specimen is loaded with subsequent blocks of cycles at increasing load until failure.

RESULTS

Fatigue results

All the fatigue test results are presented in Fig. 4 and Fig. 5, for type A and type D graphite respectively. The solid and dashed lines represent interpolating power-law function curves of data points in the finite life region.

Type A graphite

The fatigue data of the notched specimens with the Type A microstructure are shown in Fig. 4. It is observed the high scatter and the difficulty in identifying a notch dependence of the fatigue life, as indicated in the darkened band. Similarly the estimated fatigue limits for the three notch geometries are basically the same, see Tab. 2.

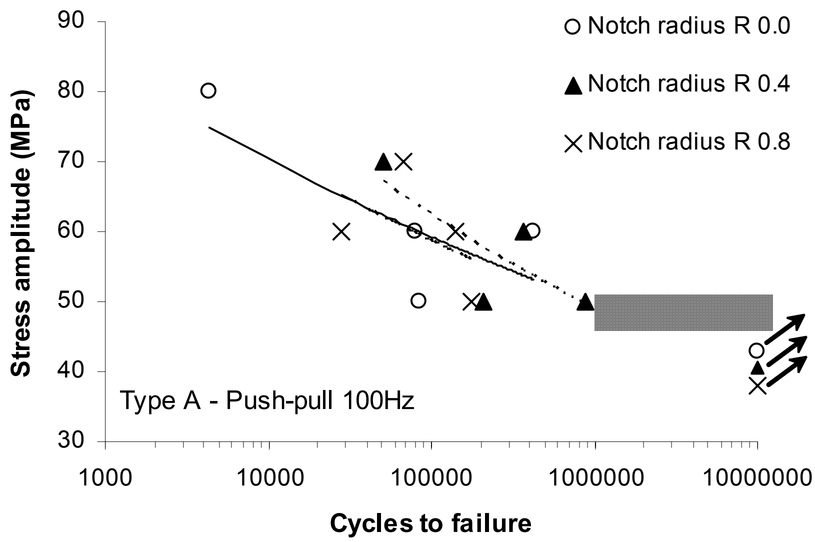


Figure 4. Fatigue test results of the sharp V- notched specimen of Type A gray cast iron microstructure.

Type D graphite

The fatigue data of the notched specimens with the Type D microstructure is shown in Fig. 5. In this case the scatter is quite limited and it is possible to identify a notch geometry dependence of the fatigue life, if the interpolating S/N curve are extended up to 10^7 cycles. The estimated fatigue limits for the three notch geometries differ significantly, as reported in Tab. 2.

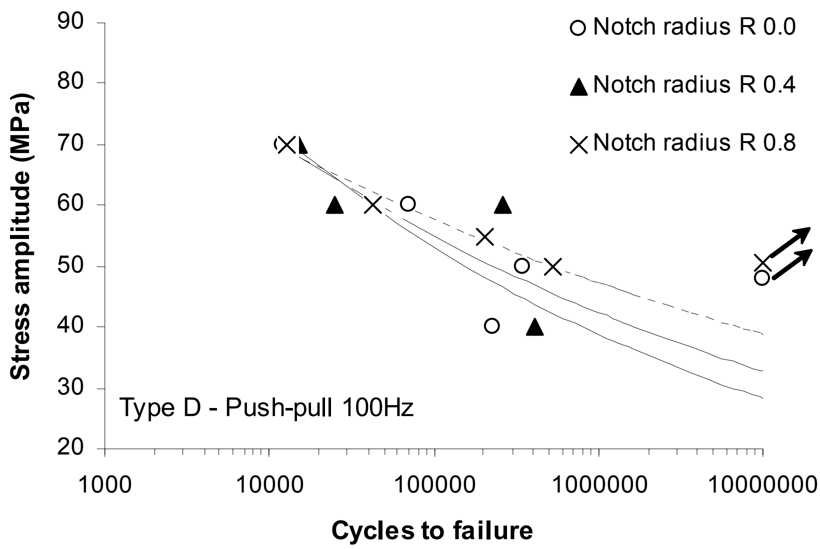
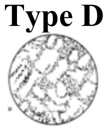


Figure 5. Fatigue test results of the sharp V- notched specimen of Type D gray cast iron microstructure.

Table 2. Fatigue limit of Type A and Type D gray cast iron

Graphite type	Notch root radius (mm)	Fatigue limit (MPa)
Type A 	0	36.2
	0.4	38.1
	0.8	35.5
Type D 	0	20.9
	0.4	25.7
	0.8	34.3

DISCUSSION

The experimental program has shed new light on the fatigue response of gray cast iron. The traditional view of the notch insensitivity of gray cast iron has been confirmed only for a Type A microstructure. In Figure 6 a microstructural FE model of a flake graphite is reported with the aim of explaining and interpreting the role of microstructure on the notch sensitivity of the material. It is shown that near a graphite lamella (modeled as a void and with a realistic shape) of length 90μm, which is a typical value found in practice, the longitudinal stress is up to 16 times the nominal net-section stress, at its tips which act as sharp stress concentrators. It is evident after this consideration the relatively small influence of the notch root radius on the stress concentration and field ahed the notch, if we think to a homogeneous, random dispersion of graphite flakes into the microstructure.

To predict the fatigue limit of notched parts, concepts based on the fracture mechanics may be the most suitable. In [10] the so-called critical distance methods have been proposed. On the other hand the frequently found Type D microstructure is associated to a behavior typical of a homogenous material for which the notch accuity is significant. The different experimental responses suggest that the uncertainty in the fatigue behavior of gray cast iron part found in practice has a microstructural origin and requires a specialized design approach that is presently under development.

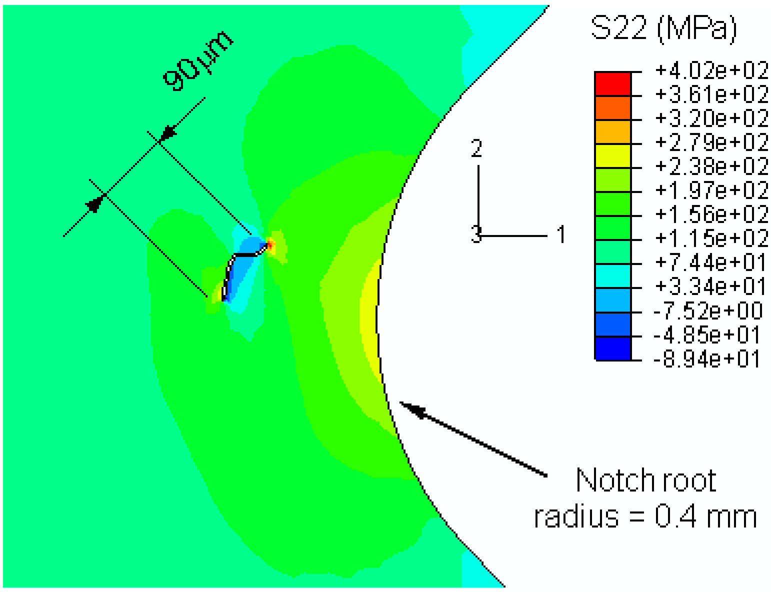


Figure 6. FE longitudinal stress distribution near the notch root, introducing a graphite lamella (net section nominal stress is 25MPa).

CONCLUSIONS

The paper examines fatigue crack initiation at sharp notches with different values of radii in two gray cast iron microstructures: in type A cast iron matrix is fully pearlitic with long and sharp randomly dispersed graphite lamellae; type D graphite has a random interdendritic dispersion of small lamellae in pearlitic/ferritic matrix. The following main conclusions can be drawn:

- in type A graphite no notch sensitivity is found on the fatigue behavior, while in type D microstructure a strong notch root-dependence appears

- as a design consideration, the unexpected material variability can strongly affect the fatigue life of casted components
- the influence of sharp notches on the fatigue response of gray cast iron has been demonstrated to require microstructural considerations.

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REFERENCES

1. Davis J.R. Editor: ASM Specialty Handbook – Cast Irons, ASM International, 1996.
2. Dowling N.E.: Mechanical behavior of materials, Prentice Hall, 1999
3. Mills K. *et al.*, Metals Handbook, Vol. 9: Metallography and Microstructures, ASM, 1985
4. Baicchi P., Nicoletto G., Konečná R.: Mechanical behavior of EN-GJL300 cast iron from three foundries, Procs. SEMDOK, Sulov, SK, 2005
5. Anon., ASTM A247, American Society for Testing and Materials Standard Designation
6. Peterson R.E. Notch sensitivity. In: Metal fatigue, New York: McGraw-Hill, 1959
7. Neuber H. The theory of notch stresses. Berlin: Springer, 1958
8. Branzi F.: Influence of sharp notches on the fatigue behavior of gray cast iron, MS Thesis in Mech. Engineering Univ. of Parma, Italy, 2005
9. Locati, L.: La fatica dei materiali metallici, U. Hoepli, Milano, 1950 (in italian)
10. Taylor D., Wang G., in *Fatigue Fract Engng Mater Struct,* **23** (2000), 387-394