MEAN STRESS IN LONG-LIFE TORSION FATIGUE

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ABSTRACT

Simple fatigue tests have been performed on two common engineering materials, cast ductile iron and low carbon steel, using three stress states, fully reversed cyclic torsion, cyclic torsion with mean shear stress and cyclic torsion with static axial and hoop stresses. Tests were designed to illustrate the effect of different types of mean stress and discriminate between normal stress and hydrostatic stress as the most suitable mean stress correction term for high cycle fatigue analysis. Nucleation and early crack growth in the low carbon steel is along maximum shear planes while for cast iron, pre-existing flaws grow on maximum normal stress planes. Data illustrates that tensile normal stress acting on a shear plane significantly reduced fatigue life and is an appropriate input for fatigue analysis of ductile materials. Static normal stresses did not significantly affect the fatigue life for the cast iron because the net mean stress on the maximum normal stress plane was zero. Mean shear stress reduced the fatigue strength of the low carbon steel. For cast iron the effect of mean shear could be modelled by resolving the mean shear into a mean tensile stress on the principal stress plane. Suitable stress based damage models for both materials are presented.

INTRODUCTION

Many successful long-life stress based models for multiaxial fatigue have the same general form and include both shear stress and a normal stress terms to account for observed mean stress and combined loading effects [1]:

$$\Delta\tau + k\sigma = \mathrm{f} \qquad (1)$$

Models of this form are based on three observations; cyclic shear stresses cause crack nucleation in ductile materials, tensile mean stresses have a detrimental effect on the fatigue life, and compressive mean stresses increase the fatigue life. Models differ in the interpretation of how shear and tensile stress terms are defined. The well known Sines criterion [2] makes use of the octahedral shear stress range, $\Delta\tau_{oct}$, while the Findley [3], McDiarmid [4] and Dang Van [5] criteria use forms of the range of maximum shear stress, $\Delta\tau_{max}$.

Mean stresses have been incorporated into the models by using either the hydrostatic stress or the normal stress on a plane. Just as the octahedral stress represents an “average” shear value for a state of stress, the hydrostatic stress can be considered as representing the average tensile stress in the material. Sines and Dang Van criteria are examples which make use of the hydrostatic stress while Findley and McDiarmid are examples of criteria of the form presented in Eq. (1) that define normal stress acting on an alternating shear stress plane as the appropriate mean stress term. Unfortunately, most of the available test data is not able to distinguish between hydrostatic or normal stress on a plane.

Socie [6] and Socie and Marquis [1] have emphasised the need for alternate fatigue damage models depending on whether a material fails predominately due to shear crack growth or due to tensile crack growth. The stress based criteria characterised by Eq. (1) have been developed primarily for ductile materials where cyclic shear has a controlling effect on the crack nucleation process. Socie [6] has shown that the Smith, Watson, Topper (SWT) parameter [7], which was originally developed to account for mean stresses in uniaxial fatigue, can be used to correlate fatigue damage in materials that fail primarily from normal stresses. Cast iron and stainless steel under some loading conditions have been shown to be normal stress dominated. Simple uniaxial tests or torsion and bending tests do not distinguish between the two types of materials because the mean stress simultaneously acts on both the plane of maximum normal stress range and the plane of maximum shear stress.

Little data is available on the effect of mean shear stress, but several early fatigue researchers concluded that mean shear has little effect on the fatigue limit strength [2,8,9]. More recently Wang and Miller [10] tested medium carbon steel specimens in torsion with various degrees of mean shear stress. They postulated that mean shear affected both the early mode II and mode I crack propagation. It was shown that a fatigue relation of the form

$$\Delta\tau \cdot \mathrm{e}^{A|\tau_\mathrm{m}|} = \mathrm{f} \qquad (2)$$

fit the torsion fatigue data in the high cycle failure regime.

This paper presents relatively simple fatigue experiments on two common engineering materials, cast ductile iron and low carbon steel. The three stress states investigated were, cyclic torsion alone, cyclic torsion with static axial and hoop stresses, and cyclic torsion with static shear stress. The intent of the study was to investigate the appropriateness of either the hydrostatic stress or normal stress on a plane in stress based long-life fatigue analysis and to show the effect of constant mean stresses on two materials with different dominant failure mechanisms.

EXPERIMENTS

Materials

Two widely used engineering materials were chosen for this study. The first was a normalised low carbon steel C45. Material was received as 40 mm dia. bar stock and later machined into the tubular specimens shown in Fig. 1. Measured hardness was BHN =193. The second material was GRP 500/ISO 1083 nodular cast iron. The iron was cast as ingots 100 x 100 x 300 mm. Ingots were slow cooled but no post cast heat treatment was performed. Ingots were sectioned and machined into specimens. Typical tensile properties for the ferritic-pearlitic iron is BHN = 200, yield strength $R_{p0.2}$ =340 MPa and ultimate strength R_m = 620 MPa.

The C45 steel is similar to SAE 1045 which has been used in many fatigue studies. Under torsion loading, fatigue life of low carbon steels is dominated by the nucleation and growth of cracks on shear stress planes. As stress level decreases the number of nucleated cracks also decreases so that at long live failure is dominated by the nucleation and growth of single cracks [1]. Relatively late in life propagation along mode I planes initiates and final failure is due to spiral cracks.

Extensive testing of the nodular cast iron has shown that fatigue failure is dominated by the nucleation and growth of individual cracks from shrinkage pores at or just below the specimen surface [11]. Shrinkage pores several hundred microns in diameter are a common feature of thick section castings such as the ingots in this investigation. At stress levels near the endurance limit, numerous microcracks are nucleated but failure is dominated by the propagation of a single crack with only limited crack coalescence.

Specimens

The round tubular test specimens are shown in Fig. 1. The gage section was polished with successively finer grades of emery paper and eventually with diamond paste to remove machining marks.

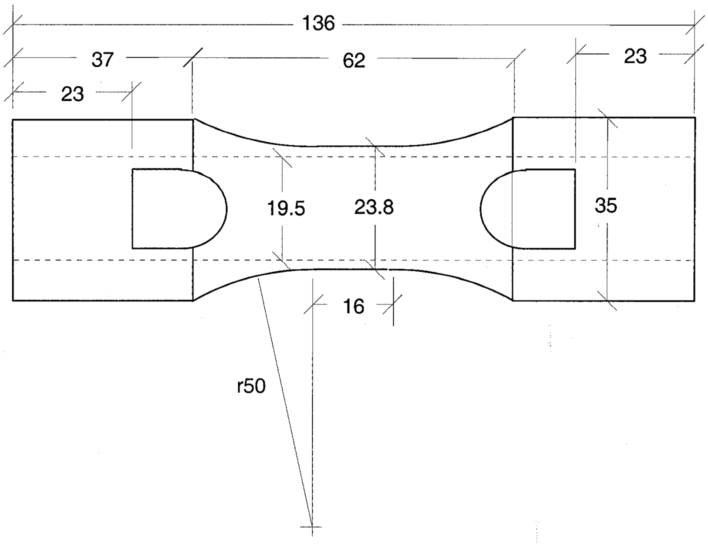

Figure 1: Torsion test specimen. Dimensions in mm.

Testing

Cyclic loading of the tubular specimens was stress (torque) controlled torsion. Loading was completely reversed torsion or cyclic torsion with a constant mean shear stress. For approximately half the completely reversed tests, static internal pressure of 20 MPa and axial compression were also applied. The hoop stress developed by the internal pressure and the axial stress along the 16 mm gage section were of equal magnitude but of opposite sign, $\sigma_{Hm} = 90$ MPa, $\sigma_{Am} = -90$ MPa. The hydrostatic stress on the external surface of the specimen was, therefore, zero in all tests. A summary of the tests performed is shown in Table 1. Loading continued until a fatigue crack propagated through the 2.15 mm thick wall of the specimen or until 2 x 10^6 fatigue cycles had been reached. Surface length of the cracks at failure was 10-20 mm.

Table 1. Test matrix.

Material	C45	GRP 500
R = -1 torsion fatigue	x	x
Torsion fatigue with mean shear τ_m=61 MPa	x	x
R = 0 torsion fatigue	-	x
Torsion with static axial and hoop stresses $\sigma_{Am} = -90$ MPa, $\sigma_{Hm} = 90$ MPa	x	x

RESULTS

Crack observations

Small cracks in C45 nucleated on maximum shear planes for all load cases. In completely reversed torsion, crack branching along maximum principal stress planes occurred after shear cracks reached a length of several hundred microns. In the case of torsion with mean shear the cracks were several millimetres in length before branching and in the case of torsion with static normal stress, failure occurred without branching. The addition of an axial compressive stress and internal pressure on the specimen forced cracks to nucleate only on the shear plane which is also subject to the tensile hoop stress. The axial compressive stress on the second shear plane inhibited nucleation. Crack nucleation on was not observed for any specimen on the plane subject to compressive mean stress. For torsion only or torsion with mean shear, cracks nucleated with equal regularity along both shear planes.

Cracks in GRP 500 nucleated and propagated on maximum principal stress planes. Final failure for all GRP specimens was the result of spiral cracks around the specimen confirming that fatigue failure of the nodular iron is dominated by mode I crack growth. Locally the crack pattern of GRP 500 is very tortuous as the crack propagates through graphite nodules, shrinkage pores and inclusions.

Fatigue life

Torsion fatigue test results for C45 for all three stress states are shown in Fig. 2. In terms of fatigue life the detrimental effect of both mean shear and static normal stresses can be clearly seen. At a given stress level the life is reduced by approximately a factor of 5 in both cases.

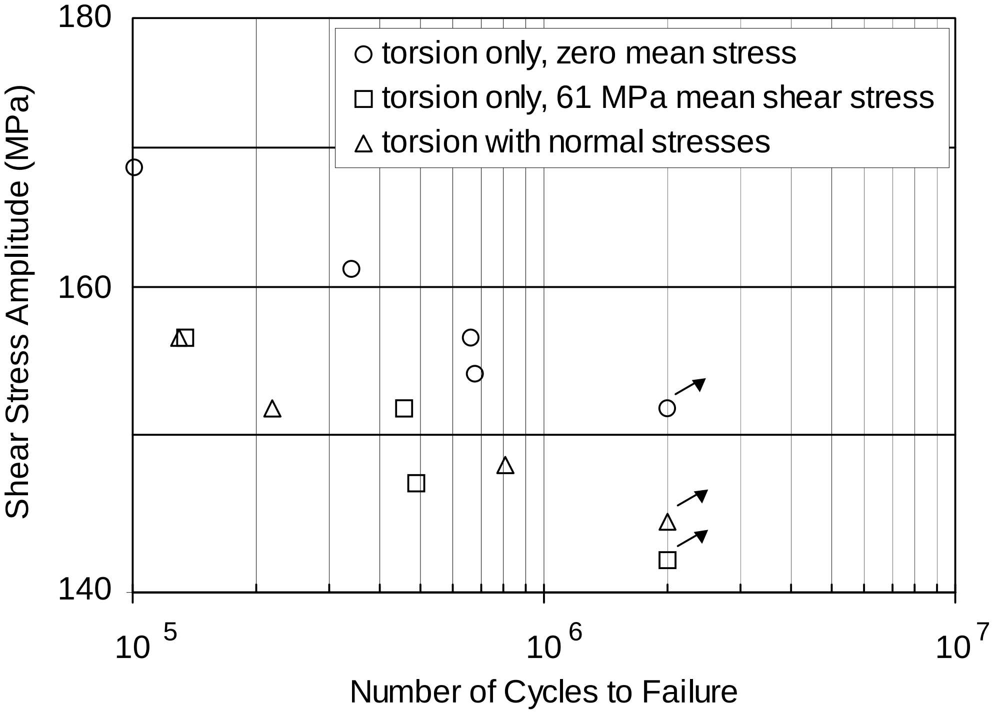

Figure 2 Applied shear stress amplitude vs. fatigue life for C45.

Comparable results for GRP 500 are given in Fig 3. The application of static normal axial and hoop stresses had only a slight effect on fatigue life while the application of a mean torque significantly reduced the fatigue strength in the high cycle regime.

DISCUSSION

Normal and hydrostatic stress

In all completely reversed torsion tests, the normal stresses due to internal pressure and axial compression were of equal magnitude but of opposite sign. Hydrostatic stress was, therefore, zero in all cases and damage models that employ hydrostatic stress would be non-conservative in predicting the fatigue life of the C45 in the case of torsion with normal stresses. Fatigue life for this material was reduced by a factor of about five by the addition of static normal stresses. Damage models based on normal stress would correctly interpret this stress state. Physically, a compressive normal stress on one shear plane is not able to compensate for the damaging effect of a tensile normal stress on another shear plane.

In much published data, hydrostatic stress appears to work for many stress states because it is related to the nominal stress on a shear plane. Published literature includes only a limited amount of test data which can distinguish between the two stresses. Single parameter fatigue damage theories which are extensions of static yield criteria cannot account for the inclusion of static mean stresses and would not predict the damaging effect of mean stresses observed for the C45. The Findley [3] and McDiarmid [4] criteria which are based on normal stress on a shear plane correctly interpret this stress state.

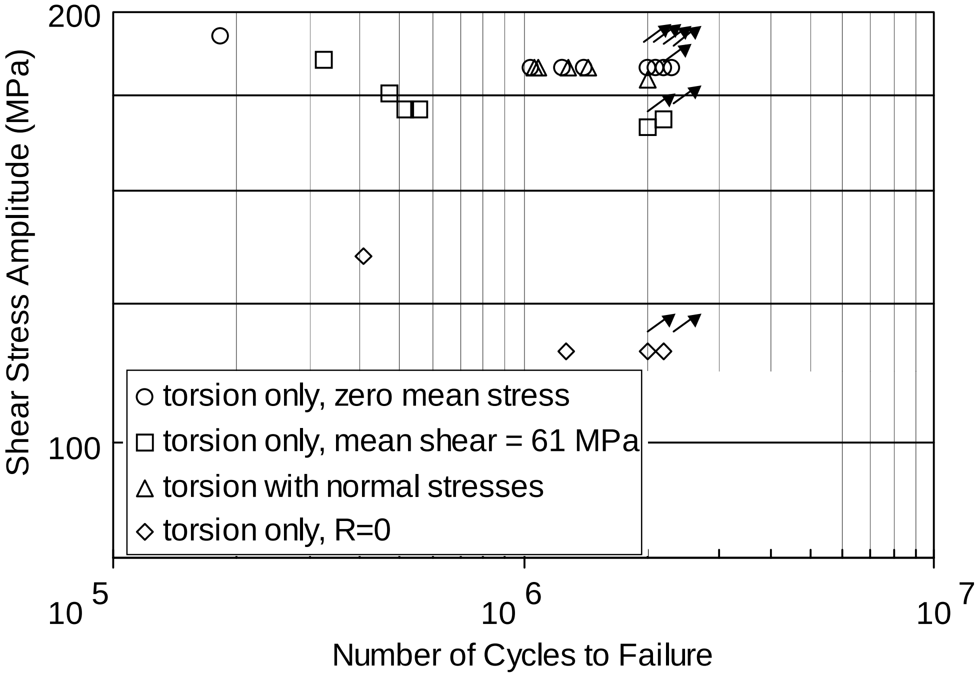

Figure 3 Applied shear stress amplitude vs. fatigue life for GRP 500 nodular cast iron.

Effect of mean shear stress

For experiments on C45 with mean shear stress, significant ratcheting of the specimens was observed. For example, the specimens tested at a stress amplitude of 156 MPa with a mean shear of 61 MPa showed an accumulated plastic shear strain at the end of testing of about 0.30 radians. a Small degree of ratcheting was observed even for the longest test run with an applied stress amplitude of 142 MPa indicating that small reversible plastic strains occurred even near the fatigue limit in torsion. If solid rather than tubular specimens had been tested using constant maximum and minimum torque, the ratcheting would have resulted in mean stress relaxation on the surface of the specimen with some of the mean torque being transferred to the material closer to the centre of the specimen. Wang and Miller [10] have made similar observations, but compensated for this effect by using plasticity principals to estimate the stabilised maximum and minimum shear stresses during a cycle. In contrast, ratcheting was not observed in any GRP500 tests.

Because mean shear also affects the maximum shear and normal stresses on various damage planes, the Findley model predicts a decreasing allowable alternating shear stress due to mean shear. The McDiarmid parameter, because it considers only the normal stress on the plane of maximum alternating shear stress does not predict a mean shear effect. The Findley parameter alone, however, is not successful in correlating all the data reported here. Large values of the normal stress sensitivity constant, *k*, are needed to unify the mean shear and completely reversed torsion data, e.g., *k* = 0.35. However, the torsion data with and without static hoop stresses is correlated only by a much lower *k* value. No single normal stress sensitivity constant correlates all the data from all three stress states.

In developing their mean shear stress model, Wang and Miller [10] postulate that the mean shear stress accelerates early crack growth by increasing the plastic zone size at the crack tip. A three parameter model can be proposed which combines the normal stress correction of Findley and the Wang - Miller type mean shear correction.

$$(\Delta\tau + k\sigma)\cdot \mathrm{e}^{A|\tau_\mathrm{m}|} = \mathrm{f} \qquad (3)$$

Using the value $A = 0.0008$ and a normal stress sensitivity constant $k = 0.1$, the data is reduced to a single set. This is illustrated in Fig. 4. which shows all three sets of data and a scatter band representing ± 1.5% in effective shear amplitude.

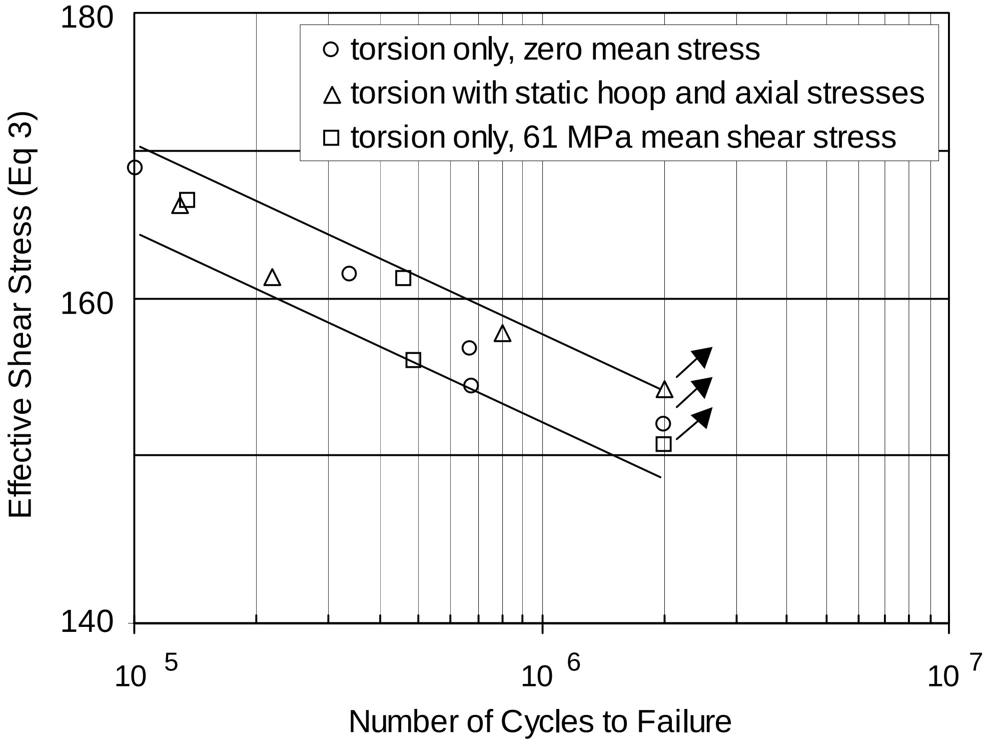

Figure 4 Effective shear amplitude, from Eq. (3), vs. fatigue life for C45.

In most cases a three parameter damage model is much less desirable than a two parameter model. The normal stress sensitivity constant in the Findley model could be selected to correlate data to within a scatter band of ± 4% in fatigue strength. However, mean shear may be significant in some design situations and it is worth re-examining some of the early test data and long held conclusions on the effect of mean shear in high cycle fatigue.

Shear and tensile damage

The general damage formulation presented in Eq. (1) is not suitable for materials like cast iron which fail primarily due to crack growth from flaws on principal stress planes. For GRP 500 the effect of applied mean shear can be modelled by resolving the mean shear into a mean tensile stress on the principal stress plane.

Marquis [12] and Marquis and Socie [13] have suggested a Goodman type endurance limit relation for GRP 500 in torsion or tension. The relation is given as

$$\left(\frac{\Delta\sigma_a}{\Delta\sigma_w}+\frac{2\cdot\sigma_m}{R_m+R_{p0.2}}\right)\cdot(1-0.25\lambda)=f \qquad (4)$$

where f = 1 at the endurance limit. In Eq. (4) $\Delta\sigma_a$ is the applied alternating stress range, $\Delta\sigma_W$ is the completely reversed tensile stress range at the endurance limit, σ_a is the mean stress and $\lambda = \sigma_2 / \sigma_1$. Figure 5 presents results from an extensive test program on two charges of nodular iron with different strengths and several mean stress levels [12]. The torsion data presented in this paper is denoted using a Δ symbol. The horizontal and vertical axes represent the mean and alternating stress both normalised by the material flow strength. It should be noted that each of the 9 tensile data points in this figure is produced by analysis of between 10 and 25 long-life fatigue tests.

Equation (4) requires that one mean stress/material combination be chosen as the baseline endurance strength value from which $\Delta\sigma_w$ is computed. In this case R = -1 uniaxial data from one charge of material was chosen as the baseline, but the good predictive ability of Eq. (4) indicates that other baseline data could be chosen. Equation (4) correlates all data well with only one mean stress/material combination having an error of greater than 10%. In all but two cases the error is less than 5%.

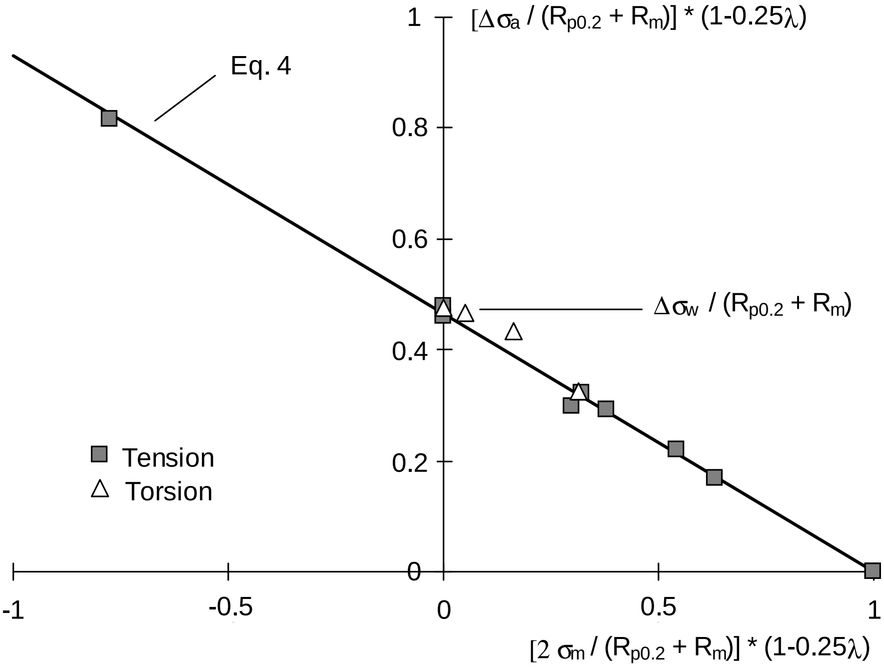

Figure 5. Predicted and measured endurance limit values for nodular cast iron for different mean stresses and stress states.

CONCLUSIONS

Relatively simple fatigue experiments on two common engineering materials, cast ductile iron and low carbon steel were performed. The three stress states examined were, fully reversed cyclic torsion, cyclic torsion with mean shear stress and cyclic torsion with static axial and hoop stresses. The effect of the hydrostatic stress and normal stress on a plane in stress based long-life fatigue analysis were evaluated.

Nucleation and early crack growth in the low carbon steel is along maximum shear planes while for cast iron, pre-existing flaws grew on maximum normal stress planes. The variation in physically observed damage indicates that no single damage model is suitable for both materials.

Static normal stresses on shear planes had a significant effect on fatigue life of the low carbon steel. Experiments clearly show that normal stress on the plane of alternating shear is more appropriate than hydrostatic stress as a parameter for estimating long-life fatigue. Mean shear stress also had a detrimental effect and a three parameter model based on earlier work of Findley and Wang and Miller is proposed.

For the ductile iron, fatigue damage occurred along tensile stress planes. Mean stress on these planes was near zero and had only a slight effect on fatigue life for this material. A mode I based damage model modified to include stress state is proposed. The model correlates data over a wide range of mean stresses for both tension and torsion loading.

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REFERENCES

1. D. F. Socie and G. B. Marquis (2000) Multiaxial Fatigue, SAE, Warrendale, PA.
2. G. Sines (1955) Failure of Materials Under Combined Repeated Stresses with Superimposed Static Stresses, Tech. Note 3495, NACA, Washington DC.
3. W. N. Findley (1959) A Theory for the Effect of Mean Stress on Fatigue of Metals Under Combined Torsion and Axial Load or Bending, J. Eng. for Ind., 301-306.
4. D. L. McDiarmid (1991) A General Criterion for High Cycle Multiaxial Fatigue Failure, Fract. Engng. Mater. Struct. 14, 429-453.
5. K. Dang-Van (1993) Macro-Micro Approach in High-Cycle Multiaxial Fatigue, In: Advances in Multiaxial Fatigue, ASTM STP 1191 (Edited by D.L. McDowell and R. Ellis), ASTM, Philadelphia, 120-130.
6. D. F. Socie (1987) Multiaxial Fatigue Damage Models, J Eng. Mat. Tech., 109, 293-298.
7. R. N. Smith, P. Watson and T. H. Topper (1970) A Stress-Strain Parameter for the Fatigue of Metals, J of Mat., 5, 767-778.
8. Smith, J. O., (1942) Effect of range of stress on fatigue strength, Univ of Illinois Eng. Dept. Station Bulletin 334.
9. Gough, H. J., (1950) Engineering Steels Under Combined Cyclic and Static Stresses, Trans. ASME. 72, 113-125.
10. C. H. Wang and K. J. Miller (1991) The Effects of Mean Shear Stress on Torsional Fatigue Behaviour, Fract. Engng. Mater. Struct. 14, 293-307.
11. G. Marquis, R. Rabb and L. Siivonen (1999) Endurance Limit Design of Spheroidal Graphite Cast Iron Components Based on Natural Defects," In: Fatigue Crack Growth Thresholds, Endurance Limits, and Design, ASTM STP 1372 (Edited by J. C. Newman and R. S. Piascik) ASTM, West Conshohocken, PA.
12. G. Marquis (2000) Long-Life Fatigue Design of GRP 500 Nodular Cast Iron Components, VTT Manufacturing Technology, Report VALB435, Espoo, Finland.
13. G. Marquis and D. Socie (2000) Long-life torsion fatigue with normal mean stresses, Fract. Engng. Mater. Struct. (accepted for publication).