Predicting Fatigue Lives of Carburized Steels Based on Residual Stress Profiles and Microstructural Influences

K.O. Findley[1], G. Krauss[1], D.K. Matlock[1]
[1]*Advanced Steel Processing and Products Research Center, Colorado School of Mines, Golden, CO, USA*

Abstract

Carburized steels are used widely in structural applications that are subjected to both low and high cycle fatigue conditions; however, predicting fatigue lives in these components is a complex problem. Multiple factors must be considered as a crack grows through a carburized layer, including changes in residual stress profile due to the carburizing treatment and local transformation of retained austenite to martensite around a crack tip. Both dynamic changes can reduce the effective stress intensity, and thus, slow the rate of crack growth. As a result, traditional short and long crack growth models, more suitable to microstructurally stable systems, must be modified to account for these effects. This paper will discuss the stages of fatigue crack growth in gas-carburized steels and use multiple methods that account for residual stress profiles and microstructural influences to predict fatigue lives, which are then compared to data acquired from bending fatigue experiments.

1. Introduction

Low carbon steels are carburized to increase surface hardness, wear resistance, and fatigue life. Carburized steels are widely used in structural components subjected to both low and high cycle fatigue conditions; however, predicting fatigue lives in these components is a complex problem due to the large number of alloying, microstructural, and carburizing process variables that can influence crack nucleation and growth. This paper focuses on predicting fatigue lives based on bending fatigue crack growth in as-carburized steels that have been quenched and tempered directly after the carburizing treatment; the bending fatigue experiments were conducted on specimens that simulate the root of a carburized gear tooth [1]. However, the methodologies presented may be applied to any carburized component subjected to various fatigue load configurations.

Steels, typically containing 0.2 wt.% C or less, are carburized to increase surface concentrations of carbon to 0.8 wt.% or more [2]. A carbon gradient is produced with depth depending on the carburizing conditions. When the carburized steel is quenched, the carbon gradient results in a gradient of microstructures that ranges from high carbon plate martensite and retained austenite near the surface to low carbon martensite or other mixtures of phases in part interiors. The focus of this work is primarily on fatigue crack interaction with the plate martensite-austenite microstructure at the surface, which is shown in Figure 1; plates of martensite are etched dark and retained austenite is white. The retained austenite plays a significant role during fatigue because it transforms through a stress or strain-induced process to martensite, which is a larger volume phase and thus induces a local compressive residual stress. Other factors that may influence fatigue crack nucleation or growth include prior austenite grain size, case and core grain sizes, surface oxidation, impurity concentrations (sulfur and phosphorous), case carbon content, carburizing depth, and residual stresses due to carburizing and post-processing such as shot peening [3].

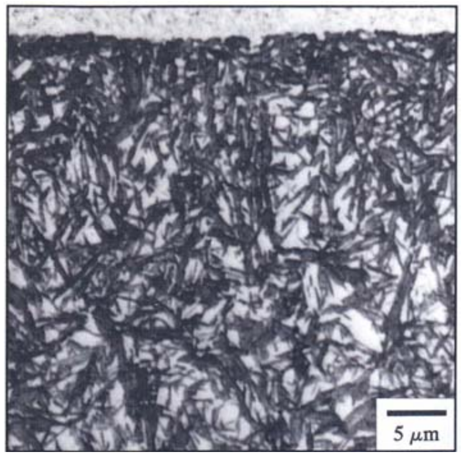

Figure 1. Plate martensite-retained austenite microstructure at the surface of a gas-carburized AISI 8719 steel alloy fatigue specimen [4]. Light micrograph, nital etch.

2. Fatigue Crack Growth in Carburized Steels

2.1. Stages of Fatigue in Carburized Steels

The fatigue life of a component can be divided into stages: the number of cycles to nucleate a crack, N_n, the number of cycles it grows as a short crack, N_{SCG}, and the number of cycles it grows as a long crack before failure, N_{LCG}. These stages of the fatigue life can be directly applied to the stages of crack growth in carburized steels. As originally defined by Hyde *et al.* [5], fatigue life in direct-quenched carburized steels consists of two primary stages: stage I, the nucleation of an intergranular crack at stresses above the endurance limit; and stage II, transgranular stable crack growth of a semi-elliptical crack. In stage I, an intergranular crack forms along prior austenite grain boundaries embrittled by phosphorous segregation and cementite formation in a mechanism termed quench embrittlement [6-9]. Intergranular oxidation of case austenite grain boundaries exacerbates crack nucleation. In stage II, the crack propagates through the crystals of tempered martensite and retained austenite. The latter stages of fatigue life in carburized steel bending fatigue specimens beyond stages I and II are discussed elsewhere [5], but their effect on total fatigue life is insignificant.

Figure 3 is an SEM micrograph of stage II stable transgranular crack growth defined by the semi-elliptical region within the dotted line and characterized by a depth, a, and width, 2c. The stage II crack growth is on the order of 100 μm or more depending on the applied stress amplitude. Linear elastic fracture mechanics research [10-14] has suggested that this crack drives towards an aspect ratio, a/c, of 0.8-0.9, independent of the material.

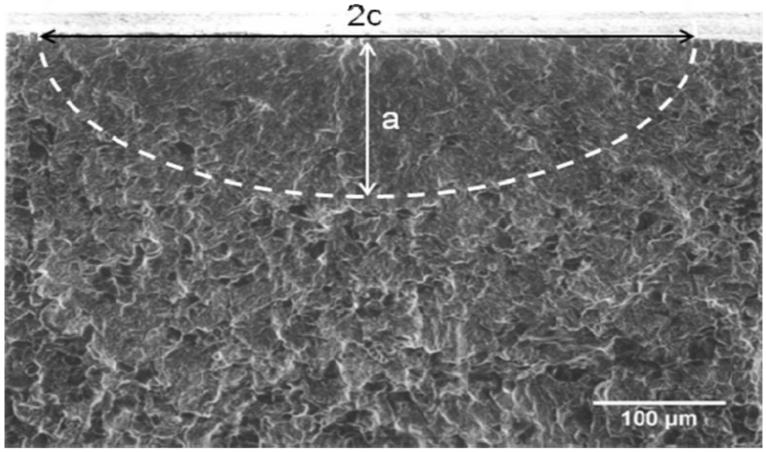

Figure 3. Region of transgranular stable crack growth, defined by the dotted line, on a carburized 4320 steel bending fatigue fracture surface [1]. SEM micrograph.

2.2. Long and Short Crack Behavior in Carburized Steels

In order to predict fatigue life during low cycle fatigue of carburized steels, it is necessary to predict or model the rate of crack growth during the stable transgranular stage II region, which can be accomplished through fracture mechanics analysis. The linear elastic fracture mechanics (LEFM) parameter, K, is determined based on the applied load and geometry of the crack and part. In the case of Stage II semi-elliptical crack growth, the value of K depends on the crack length, a, the crack aspect ratio, a/c, the relative crack depth, a/t, where t is the thickness of a bar, and the width of the bar, w. Solutions for K exist for a surface semi-elliptical crack subjected to various load configurations [15]. The value of K changes depending on the location along the crack front, so the crack growth rate around the crack front is not necessarily equal. Existing linear elastic solutions can be used to calculate the number of cycles required for the crack to grow from the crack nucleation length to the length where transgranular crack growth ends or where the maximum applied K exceeds the fracture toughness of the material.

2.3. Applicability of LEFM Models to Carburized Steels

Very little data exist on fatigue crack growth rates through the carburized layer in carburized steels. The data that do exist highlight important and interesting trends. Figure 4 shows data from da Silva *et al*. [16], who measured fatigue crack growth rates versus crack length in 8620 carburized steel at different stress amplitudes. At all three stress amplitudes shown in the figure, major crack decelerations were measured for crack lengths between approximately 10 and 75 μm. It is not clear from the data if long crack growth behavior is reached in the region plotted or if the crack accelerated as a physically short crack. Data of a similar form were published by Murtaza and Akid [17] for low alloy tempered martensitic spring steel. The non-proportionately of the crack growth rate precludes the use of a Paris Law fit unless it is assumed that the deceleration in crack growth rate can be related to the macroscopic residual stress in the carburized layer or the microscopic residual stress adjacent to the crack tip, which requires a modified ΔK solution.

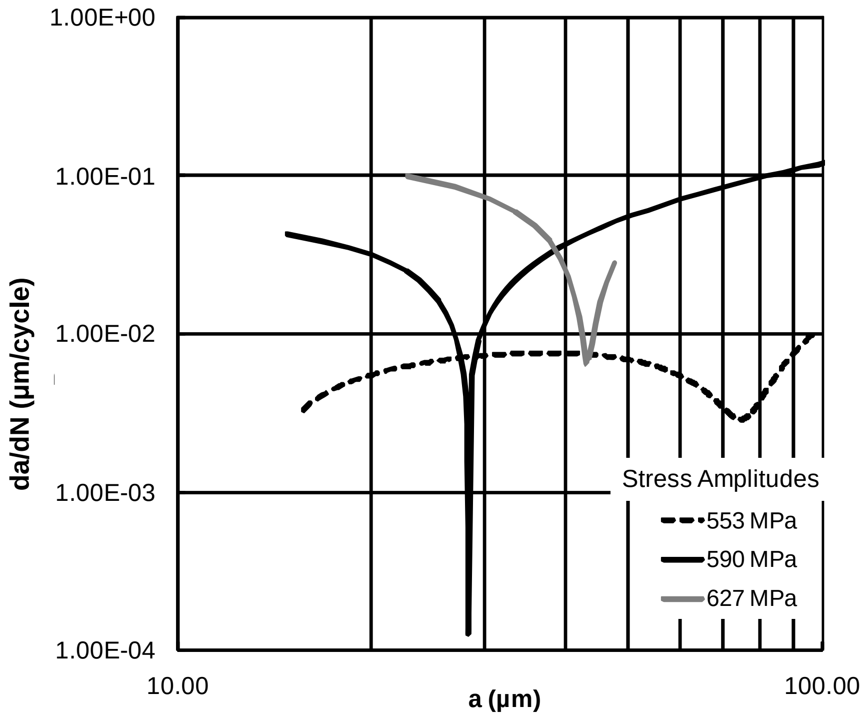

Figure 4. Crack growth rate versus crack length data for carburized 8620 steel (modified from da Silva *et al*. [16]).

Assuming that linear elastic fracture mechanics (LEFM) can be applied to stage II crack growth in the carburized steel specimens used to produce the data for Figure 4, the plastic zone due to cyclic loading was calculated. Material parameters required for this calculation, such as yield stress and strain hardening exponent, were extracted from compression tests conducted on medium carbon steels quenched to form martensite [18]. The calculated plastic zone size ranges between 1 and 11 μm for crack lengths between 15 and 100 μm when the applied stress amplitude is 600 MPa. Thus, the size of the cyclic plastic zone is always much smaller than the crack sizes shown in Figure 4; so at least one criteria is satisfied for linear elastic fracture mechanics to be applied.

Furthermore, the approximate crack length where the crack behavior transitions from short to long was calculated according to Equation 1 [19]:

$$a_o = 1/\pi(\Delta K_{th}/1.12\Delta\sigma_e) \quad \text{(Eqn.1)}$$

where ΔK_{th} is the threshold stress intensity factor (~ 4 MPa*$m^{0.5}$), $\Delta\sigma_e$ is the smooth specimen endurance limit (1070 MPa in the present work [1]), and a_o is the transition crack length. By substituting these values, the transition crack length is 3.5 μm, which is smaller than the nucleated crack length and implies that LEFM should apply for the whole range of crack growth. However, crack deceleration still implies that a microstructural feature or local residual stress strongly influences crack growth.

3. Crack Growth Models Applied to Carburized Steels

Two models are presented here to predict crack growth in carburized steels, hereafter named: "Weight Function model" and "Transformation model". The "Transformation model" is broken into subsets named the "Uniform Transformation Model" and the "Linear Transformation model"; these are described in the section below. The crack growth models evaluated are applied to data from Sanders [1], who studied the fatigue behavior of gas-carburized, quenched, and tempered 4320 steel. The effects of shot-peening were also examined, but only data on as-quenched specimens are used here. A modified Brugger specimen that simulates a single gear tooth [20] was used for the fatigue experiments; the specimen was subjected to bending fatigue loads cycled at 30 Hz with a minimum to maximum load ratio of 0.1. The endurance limit was determined and several experiments at stress amplitudes greater than the endurance limit were also performed.

If it is assumed that LEFM can be applied, the root form of the equation relating stress intensity to the semi-elliptical crack geometry is (Eqn. 2):

$$K = F(a/c, a/t, w, \phi) * \sigma\sqrt{\pi a} \quad \text{(Eqn. 2)}$$

where φ denotes the location along the crack front, σ is the applied stress, F is a geometrical correction factor, and the other variables have already been defined. This stress intensity equation can be modified in a variety of ways to account for residual stress, the stress induced by the transformation from austenite to martensite (transformation stress), and crack closure. K or ΔK, which is the difference between the maximum and minimum applied K during fatigue, can then be related to the crack growth rate through the Paris Law.

The fatigue specimen geometry parameters used to calculate stress intensity, including the thickness (t) and width (w) dimensions, are consistent with the experimental specimen geometry. Crack growth rates were calculated by solving for the stress intensity around the crack front using the aforementioned models and then applying the Paris Law. The Paris Law constants were obtained from crack growth rate data from 52100 martensitic steel [21]. Then, the amount of crack growth in a defined number of cycles was determined with the calculated crack growth rate. Subsequently, the procedure was repeated with calculation of the applied stress intensity, rate of crack growth, and amount of crack growth in a defined number of fatigue cycles. Using this iterative method, the number of fatigue cycles to reach the end of stage II crack growth based on experimental measurements [1] is determined for a given applied stress range. All of the computations were performed with a computer program such as Excel or Matlab. In this work, the number of cycles for an iteration varied between 20 and 50.

3.1. Weight Function Model

The residual stress field due to the carburizing process can be accounted for using the Weight Function model (Eqn. 3), a fracture mechanics solution for a specific crack geometry:

$$K = \int_0^a \sigma(x) m(x,a) dx \qquad \text{(Eqn. 3)}$$

where $\sigma(x)$ is the stress distribution in the direction of crack growth and $m(x,a)$ is the weight function. Weight function solutions for semi-elliptical cracks exist [22, 23].

3.2. Transformation Model

The Uniform and Linear Transformation models are based on the work of Mei and Morris [24], who investigated fatigue crack propagation in 304-type stainless steels where the austenite to martensite transformation also strongly influences crack growth. They developed a modified stress intensity solution to account for transformation strains ahead of a crack tip (Eqn. 4):

$$K_{eff} = K - BV_f \varepsilon^T \sqrt{w} \qquad \text{(Eqn. 4)}$$

where B is the bulk modulus, V_f is the volume fraction of transformed martensite around the transformation zone ahead of the crack tip, ε^T is the transformation strain, and w is the width of the transformation zone. The second term in Equation 4 reduces the effective stress intensity due to the volume expansion associated with the austenite to martensite (γ to α') transformation. This equation can be further modified by assuming a distribution of martensite ahead of the crack tip. Two different distributions of the transformed martensite were assumed. The uniform distribution assumes that all of the retained austenite transforms to martensite within the monotonic plastic zone ahead of the crack tip. The linear distribution assumes that all of the retained austenite transforms to martensite at the crack tip and the fraction transformed decreases linearly to zero at the edge of the monotonic plastic zone.

4. Model Results and Discussion

Data from bending fatigue testing of carburized 4320 steel [1] are utilized here to assess the applicability of the above mentioned stress intensity models to predict fatigue lives of carburized steels subjected to low cycle fatigue. Since a fatigue crack is assumed to nucleate in one cycle at stresses greater than the endurance limit, the fatigue life can be predicted based on crack growth models for the stage II region. It is assumed that the starting crack dimensions are a = 15 μm and c = 30 μm and that during crack growth, a semi-elliptical geometry is maintained, consistent with experimental observations. Figure 5, a plot of applied stress range versus fatigue life, compares data from the assessed models with experimental results [1] plotted on an applied stress range versus cycles to failure chart; the experimental data are plotted as individual data points for each applied stress range and average cycles to failure for each stress range. Both the Weight Function and the Transformation Models data fall within the range of scatter in the experimental fatigue data.

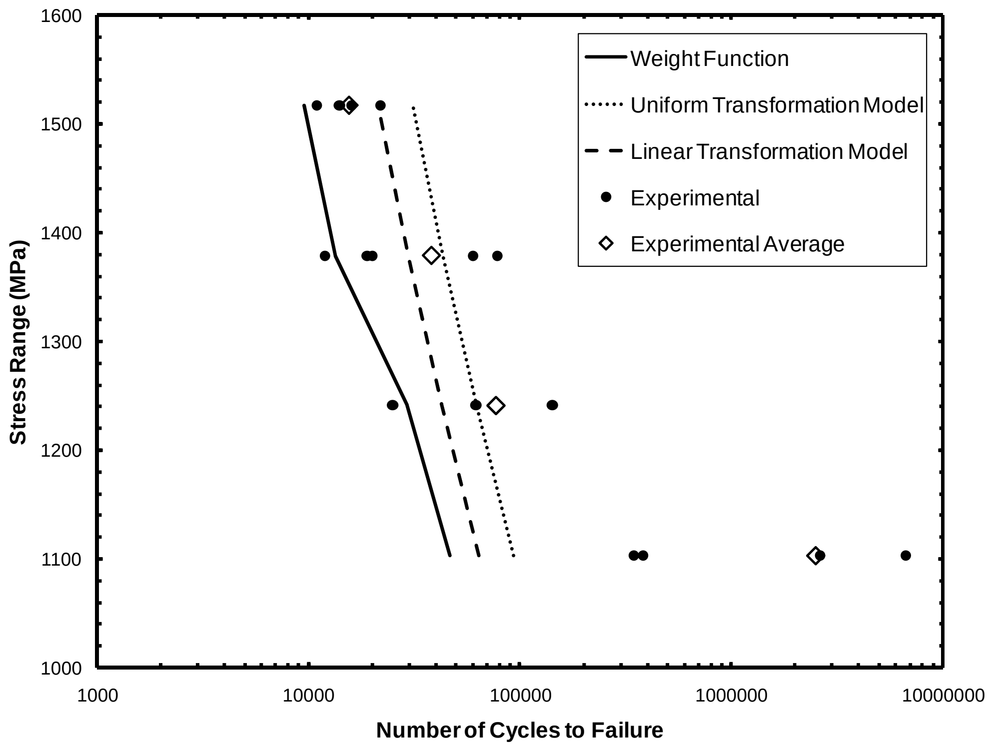

Figure 5. Experimental fatigue life data for carburized steels (data modified from [1]) compared with models used to predict fatigue life.

The transformation models, which account for the modified stress intensity due to the γ to α' transformation directly ahead of the crack tip, were reasonably successful in predicting fatigue life in the LCF region. At the largest applied stress ranges, the calculated fatigue life from both assumed distributions, especially the Uniform Transformation model, overestimate the fatigue life. The effect of the phase transformation strain is probably overshadowed by the crack driving force at these high stress ranges. However, as the applied stress range decreases, both transformation models become more accurate with respect to the average experimental fatigue lives. Neither the Weight Function nor the transformation models predict fatigue life well for the stress range close to the endurance limit when the assumption that crack nucleation occurs in one cycle may be questionable.

As described in the previous section, the Weight Function model can be used to incorporate the applied stress distribution, including residual stresses, into the calculation of stress intensity. A notable variation in the residual stress field from the surface to the interior of the carburized bars was measured [1]. After 10^7 cycles at the endurance limit, the residual stress field evolved to be more compressive, which is probably due to the compressive stresses associated with the γ to α' transformation. As an upper bound estimate of the macroscopic effect of the γ to α' transformation, this residual stress distribution was superimposed on the applied bending stress to simulate the actual stresses on the bar. Mathcad® was used to calculate the resulting stress intensity, crack growth rates, and number of cycles to reach the end of stage II crack growth in an iterative program similar to the one described above. As shown in Figure 5, the weight function method predicts the lower bound of fatigue lives. This implies that the residual stress field from the carburizing process and the macroscopic stress induced by the γ to α' transformation does not have as significant effect on the rate of crack growth as other factors such as the transformation strains immediately ahead of the crack tip. Lin *et al*. [25] also utilized a weight function method in conjunction with a fracture mechanics based life prediction computer program called CRACKS® to predict fatigue lifetimes of carburized steels. Their results at the highest stress ranges have better agreement than the work presented here, but they also observed greater deviation from experimental results at lower applied stress ranges. They did not publish the Paris Law constants they used, so the model data presented here cannot be directly compared to their research.

5. Summary and Conclusions

The applicability of long and short crack growth models for predicting fatigue lifetimes in carburized steels was assessed based on stage II crack growth, the dominant stage during the fatigue life of direct quenched carburized steel fatigue specimens. Two LEFM based models were assessed: a Weight Function model to account for residual stresses in the carburized layer and a Transformation model divided into subsets based on microstructure distributions. The following conclusions are derived based on the model comparisons with experimental data [1]:

1) The weight function model predicts the lower bound of fatigue lives, suggesting that the macroscopic residual stress field has a small contribution to the overall fatigue crack growth rate compared to other factors such as the austenite to martensite transformation or short crack interactions with the microstructure. The residual stresses would probably have more influence if shot-peening after carburizing was used to increase the compressive residual stress field.

2) The uniform and linear transformation models have better agreement with the average low cycle fatigue experimental data, which implies that the strains induced by the austenite to martensite transformation in the immediate vicinity of the crack tip have a significant effect on the fatigue crack propagation rate for as-carburized steels. Neither the linear nor uniform distribution of transformed

martensite in front of the crack tip may be representative of the actual distribution, which could lead to disagreement between the model and experimental results.

3) Both of the assessed models predict fatigue lives within the range of experimental data scatter, so both may be used to predict fatigue lives; though the Weight Function model is conservative and the Uniform Transformation model over predicts fatigue life at the highest applied stress range. In order to use the LEFM based models to predict fatigue life, knowledge of the fatigue crack growth rates and fracture toughness of the material is required. The only model that requires input about the microstructure of the material is the Transformation Model, which requires information about the distribution of martensite that transforms from retained austenite in front of the crack tip during fatigue loading; thus, these models are the most physically-based. The Weight Function model only requires a macroscopic residual stress profile.

6. Acknowledgments

The authors gratefully acknowledge the support of the sponsors of the Advanced Steel Processing and Products Research Center, an industry/university cooperative research center at the Colorado School of Mines.

7. References

[1] J. Sanders, "The Effects of Shot Peening on the Bending Fatigue Behavior of a Carburized SAE 4320 Steel," M.S. Dissertation, Colorado School of Mines, Golden, CO, 1993.
[2] G. Krauss, "Microstructure and performance of carburized steel. I. Martensite", Advanced Materials Processes, vol. 147, 1995, pp. 40Y-40BB.
[3] J.P. Wise and D.K. Matlock, "Bending Fatigue of Carburized Steels: A Statistical Analysis of Process and Microstructural Parameters," SAE Technical Paper Series No. 200-01-0611, SAE, Warrendale, PA, 2000.
[4] J. Pacheco and G. Krauss, "Carburized Steel: Microstructure and High Bending Fatigue Strength," Journal of Heat Treating, Vol. 7, 1990, pp. 82-87.
[5] R.S. Hyde, R.E. Cohen, D.K. Matlock, and G. Krauss, "Bending Fatigue Crack Characterization and Fracture Toughness of Gas Carburized SAE 4340 Steel," SAE Technical Paper Series No. 920534, SAE, Warrendale, PA, l992, also in Transactions of Journal of Materials & Manufacturing, Vol. 101, Section 5, September, 1993.
[6] G. Krauss, Steels Processing, Structure, and Performance, ASM International, Materials Park, OH, 2005.
[7] R.S. Hyde, D.K. Matlock, and G. Krauss, "Quench Embrittlement: Intergranular Fracture Due to Cementite and Phosphorus in Quenched Carbon and Alloy Steels," in Proceedings of the 40th Mechanical Working and Steel Processing Conference, ISS, Warrendale, PA, 1998, pp. 921-928.
[8] R.S. Hyde, G. Krauss, and D.K. Matlock, "Phosphorus and Carbon Segregation: Effects on Fatigue and Fracture of Gas-Carburized Modified 4320

Steel,” Metallurgical and Materials Transactions A, Vol. 25A, 1994, pp. 1229-1240.
[9] B.E. Cornelissen, G. Krauss, and D.K. Matlock, "Effects of Alloying and Processing on Surface Oxidation and Bending Fatigue of Carburized Steels,” Proceedings of the 5th ASM Heat Treatment and Surface Engineering Conference in Europe, ASM International, Materials Park, OH, 2000, pp. 117-127.
[10] J. Bush, “Stress intensity factors for single edge crack solid and hollow round bars loaded in tension,” J. Test. Eval., Vol. 9, 1981, pp. 216-223.
[11] M. Caspers , C. Mattheck, and D. Munz, “Fatigue crack propagation in cylindrical bars,” Z Werkstofftech, vol. 17, 1986; pp. 327–333.
[12] X.B. Lin and R.A. Smith, “Shape growth simulation of surface cracks in tension fatigued round bars,” Int J Fatigue, vol. 19, 1997, pp. 461–469.
[13] A. Carpinteri, “Shape change of surface cracks in round bars under cyclic axial loading,” Int J Fatigue, vol. 15, 1993, pp. 21–26.
[14] K.O. Findley, S.W. Koh, A. Saxena, “J-Integral Expressions for Semi-Elliptical Cracks in Round Bars,” Int J Fatigue, 2007, vol. 29, pp. 822-828.
[15] J.C. Newman and I.S. Raju, “An Empirical Stress Intensity Factor Equation for the Surface Crack,” Engineering Fracture Mechanics, vol. 15, 1981, pp. 185-192.
[16] V.F. da Silva, L.F. Canale, D. Spinelli, W.W. Bose-Filho, O.R. Crnkovic, “Influence of Retained Austenite on Short Fatigue Crack Growth and Wear Resistance of Case Carburized Steel,” Journal of Materials Engineering and Performance, vol. 8, 1999, pp. 543-548.
[17] G. Murtaza and R. Akid, “Modelling Short Fatigue Crack Growth in a Heat-Treated Low-Alloy Steel,” Int. J. Fatigue, vol. 17, 1995, pp. 207-214.
[18] M.A. Zaccone, G. Krauss, “Elastic limits and microplastic response of Hardened Steels,” Metallurgical Transactions A, vol. 24, 1993, pp. 2263-2277.
[19] A. Saxena, Nonlinear Fracture Mechanics for Engineers, CRC Press, 1998.
[20] R.E. Cohen, D.K. Matlock, and G. Krauss, "Specimen Edge Effects on Bending Fatigue of Carburized Steel,” Journal of Materials Engineering and Performance, vol. 1, 1992, pp. 695-703.
[21] J.M. Beswick, “Fracture and fatigue crack propagation properties of hardened 52100 steel,” Metallurgical Transactions A, vol. 20A, 1989, 1961-1973.
[22] G. Shen and G. Glinka, “Weight Functions for a Surface Semi-Elliptical Crack in a Finite Thickness Plate,” Theoretical and Applied Fracture Mechanics, vol. 15, 1991, pp. 247-255.
[23] X. Wang and S.B. Lambert, “Local Weight Functions for Semi-Elliptical Surface Cracks in Finite Thickness Plates,” Theoretical and Applied Fracture Mechanics, vol. 23, 1995, pp. 199-208.
[24] Z. Mei and J.W. Morris, Jr., “Influence of Deformation-Induced Martensite on Fatigue Crack Propagation in 304-Type Steels,” Metallurgical Transactions A, vol. 21A, 1990, pp. 3137-3152.
[25] H. Lin, G.A. Fett, R.R. Binoniemi, “Bending Fatigue Life Analysis of Carburized Components Using Strain Life and Fracture Mechanics Approaches,” SAE Transactions, vol. 112, 2003, pp. 699-709.