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Research Article

A Novel Approach for Estimating Fatigue Behavior of Stainless Steel 304 Using Tensile Test Data

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ABSTRACT

This paper introduces a novel method for estimating the fatigue behavior of stainless steel 304 through a single tensile test. By utilizing the engineering and true stress-strain curves, the constants of the Basquin equation were derived. A significant innovation is the calculation of the true fracture stress, σ_f, using the Bridgman correction from the tensile test. This σ_f is equated to the Basquin constant σ'_f, and the fatigue limit is approximated as half the ultimate tensile strength, allowing for the estimation of alternating stress, σ_a, for infinite cycles. The Basquin constant b was then adjusted based on calculated σ_a and σ'_f values across various cycle counts. The estimated values for σ'_f and b of 304 stainless steels are 1248.7 MPa and -0.07, respectively. The resulting fatigue curve showed good correlation with established data for stainless steel 304, presenting a cost-effective and efficient alternative to traditional fatigue testing, which is beneficial for engineers designing cyclically loaded components.

1. Introduction

The increasing prevalence of fatigue-related failures in engineering components, driven by the growth of industries and the demand for durable, high-performance materials, necessitates a comprehensive understanding of fatigue behavior [1]. Fatigue, characterized by the progressive damage of materials under cyclic loading, poses a significant threat to the reliability and safety of engineering structures [2]. While traditional fatigue testing methods provide accurate results, they are often time-consuming and costly, hindering their widespread application. To accurately assess the fatigue limit of a material, extensive experimental testing is required [3], resulting in significant time and resource expenditures. However, the availability of data on tensile strength, hardness, modulus of elasticity, and other mechanical properties suggests that it may be possible to predict fatigue behavior through more efficient methods. By developing a reliable approach to estimate fatigue life based on readily available tensile test data, we can potentially reduce the cost and time associated with traditional fatigue testing.

Predicting fatigue life based on readily available mechanical properties, such as tensile strength, has been a longstanding research objective. Several studies have explored different approaches to this problem, ranging from empirical correlations to machine learning techniques. For example, Lee and Song [4] reviewed methods for

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estimating fatigue properties from hardness, including direct methods for steels, indirect methods for aluminum and titanium alloys, and the medians method for aluminum alloys. They introduced a new relationship for titanium alloys and developed a new method for estimating fatigue life from tensile data using Basquin parameters from S-N curves. Yang et al. [5] evaluated various low-cycle fatigue life estimation methods and proposed a new fatigue life prediction method. Farahmand and Nikbin [6] used a parametric/theoretical approach based on Griffith theory to derive fracture toughness properties and fatigue crack growth rate data for various alloys. Boob et al. [7] developed a neural network program to estimate strain-life fatigue properties, with an accuracy of approximately 87-98%. Genel [8] used artificial neural networks (ANN) to predict strain-life fatigue properties of 73 steels using tensile material data, indicating its potential in predicting fatigue properties. Numerous efforts have also been undertaken to ascertain the fatigue strength in a swift and economical manner. Various empirical relationships connecting fatigue strength to other mechanical parameters, including yield strength, tensile strength, and hardness, are available in different sources [9].

This research offers a novel and straightforward approach for determining the Basquin constants and, subsequently, the fatigue life of the material. Stainless steel 304, a widely used engineering material known for its excellent formability [10], weldability [11], and corrosion resistance [12], serves as the model material for this investigation. By analyzing the results of tensile tests, this work proposes a method to determine the Basquin constants, which are essential for constructing the stress-life curve. This approach involves the true fracture stress obtained from the tensile test to the corresponding values in the Basquin equation, assuming a half-cycle fatigue scenario. The cycle number exponent is estimated based on the predicted fatigue limit, which is assumed to be half the tensile strength.

2. Materials and method

2.1. Materials characterization

The actual chemical composition of the examined 304 stainless steel was ascertained using quantometer analysis, as detailed in Table 1.

2.2. Tensile Testing

The tensile specimens were machined according to the subsize dimensions specified in ASTM E8/E8M-16 Standard Test Methods for Tensile Testing of Metallic Materials. Tensile tests were conducted at room temperature using a universal testing machine with a constant crosshead speed of 2 mm/min. Tensile tests were conducted at room temperature using a SANTAM-STM 50 testing machine. Load and displacement data were continuously recorded during the tests. To address correctness of the tensile test data, we acknowledge that only three samples were tested. However, as the results obtained from these three samples exhibited consistent behavior, we opted to use the data from a single representative sample for the analysis. This decision was made to streamline the presentation and focus on the key trends and insights derived from the data.

2.3. Data Analysis

Subsequent to performing the tensile test, the force-displacement curve was transformed into an engineering stress-strain curve. Subsequently, this curve was transformed into a true stress-strain curve utilizing Eqs. (1) and (2).

$$\varepsilon = \ln(1 + e) \qquad \text{Eq.(1)}$$

$$\sigma = S(1 + e) \qquad \text{Eq.(2)}$$

Eqs. (1) and (2) are applicable solely until the necking point, which corresponds to the peak of the load-displacement curve; thus, data beyond this maximum point were excluded. The material's constants in the power-law equation, were determined using the true stress-strain data by taking the natural logarithm of both sides of the Eq. (3).

$$\sigma = k\varepsilon^n \qquad \text{Eq.(3)}$$

where k represents the strength coefficient, and n is the work hardening exponent. The true stresses and strains upon necking are calculated using the instantaneous minimum cross-sectional area (A_{min}) of the specimen, with strains derived from the area reduction of that section. Using this approach, the true fracture strain and stress are calculated by Eq. (4) and Eq. (5), respectively:

$$\varepsilon_f = ln\left(\frac{A_0}{A_f}\right) \qquad \text{Eq.(4)}$$

$$\sigma_f = \frac{P_f}{A_f} \qquad \text{Eq.(5)}$$

where A_f denotes the cross-sectional area at the

Table 1. Chemical composition (wt. %) of 304 stainless steel used in this study.

	Fe	C	Si	Mn	P	S	Cr	Mo
Ave	69.5	0.0443	0.291	1.65	0.0378	0.0255	18.8	0.336
	Ni	**Al**	**Co**	**Cu**	**Nb**	**Ti**	**V**	**W**
Ave	8.38	<0.001	0.147	0.549	0.0196	0.0024	0.0789	<0.02

fracture point, A_0 represents the initial area of the tensile specimen and P_f represent the load at fracture. Since the neck area comprises the triaxial stress state, the true stresses after necking are larger than those needed to generate flow in the specimen if simple tension prevailed. In order to offer precise mechanical properties, correction techniques to discount triaxiality are of major academic and technological interest in this context.

Several methods have been suggested to amend stress-strain curves for triaxiality effects. The Bridgman correction is regarded as the most accurate and theoretically substantiated, and will be the primary focus here. Bridgman implemented a correction based on a stress study in the neck region. His analysis pertains to cylindrical specimens. The equation representing the corrected stress, σ_c, is given by Eq. (6) [13]:

$$\sigma_c = \frac{\sigma_{ave}}{\left(1+\frac{2R}{a}\right) ln\left(1+\frac{a}{2R}\right)} \qquad \text{Eq.(6)}$$

In this context, R denotes the radius of curvature of the neck, a represents the radius of the cross-section at the narrowest part of the neck, and σ_{ave} signifies the axial, namely the average, true stress subsequent to necking, calculated using the instantaneous minimum cross-sectional area. Consequently, it is imperative to consistently observe the variations in R and a during the test to implement the necessary corrections.

The correlation between stress amplitude and the number of reversals (i.e., double the number of cycles) is expressed by the Basquin relationship, suggesting by [14]:

$$\sigma_a = \sigma'_f \,(2N_f)^b \qquad \text{Eq.(7)}$$

In this equation, σ_a represents the applied alternating stress, σ'_f denotes the true fracture strength, N_f signifies the number of load cycles to failure, and b is the constant in the Basquin equation. Traditionally, Basquin's constant is ascertained by graphing the stress amplitude against the number of cycles to failure through rigorous fatigue testing. This study presents a novel way to determine physical infinity by calculating the constant b for various cycle counts, given certain values of σ_a and σ'_f in Eq. (7). The tensile test, regarded as a half-cycle fatigue test, yields a fracture stress that can be equated to the constant σ'_f in the Basquin equation. Historical evidence indicates that the fatigue limit of metals is around a fraction of their ultimate strength. This estimate for steels corresponds to 50 percent of the ultimate strength [13]. The fatigue limit is the stress level below which an unlimited lifespan is anticipated. Consequently, to ascertain the constant b in the Basquin equation, the cyclic stress may be regarded as equivalent to half the tensile strength at an unlimited number of cycles. The estimation of this physical infinity is elucidated in the results and discussion section.

2.4. Error Estimation

Regarding error estimation, it's important to note that the majority of the data presented in this manuscript is derived from calculations based on well-established theoretical models. Thus, the calculations involved in this study are primarily deterministic and do not introduce significant sources of error. To further enhance the rigor of our analysis, we have carefully considered potential sources of error and uncertainty in the experimental measurements. These include factors such as measurement equipment calibration, sample preparation, and environmental conditions. However, due to the nature of the calculations involved, a quantitative error analysis was not feasible in this case.

2.5. Assumptions and limitations

The equations employed in this study rely on several assumptions: homogeneous and isotropic material behavior, small deformations, uniaxial stress states, ideal plastic behavior, and constant material properties. While these assumptions provide a simplified framework for analysis, it's important to recognize their limitations. The accuracy of the estimated parameters is influenced by the precision of experimental measurements, and the analysis of the necking region involves inherent uncertainties. Additionally, the Bridgman correction, used to account for triaxial stresses, has limitations in its applicability. Furthermore, the Basquin relationship, used for fatigue life prediction, is an empirical model that may not accurately capture the behavior of materials under complex loading conditions or with significant microstructural evolution.

3. Results and discussion

The tensile test results indicate that the 304 stainless steel has a tensile strength of ~587 MPa and percent elongation of ~55%. The proximity of the findings from the two tests indicates strong repeatability of this assessment. Fig. 1. displays an image of the tensile specimen post-fracture. The radius of curvature of the neck and the cross-sectional radius were measured and depicted in the figure. The axial/average true fracture stress is calculated to be 1358.5 MPa using the average stress method and 1248.7 MPa with the Bridgman correction. The true fracture strain was determined to be 1.09 by applying Eq. (4) and measuring the dimensions (D_0=9.05 mm, D_f=5.25 mm) depicted in Fig. 1.

Fig. 2. illustrates a engineering stress-strain curve. The true stress-strain curve derived from Eqs. (1) and (2) is likewise depicted in the same figure. The dashed lines denote the true stress until the fracture point, derived using the average stress method and the Bridgman adjustment post-necking. The mathematical

representation of the power-law equation indicates that applying the natural logarithm to both sides result in a linear form. Consequently, as anticipated, Fig. 3. illustrates that the slope of the natural logarithm of stress against strain corresponds to the work hardening coefficient, *n*, whereas the y-intercept represents the strength coefficient, *k*. The slope and y-intercept of the line yield the numbers *k*=1283.3 MPa and *n*=0.415.

Tensile test results indicate that the ultimate tensile strength of 304 stainless steel is ~587 MPa. Consequently, by approximating the fatigue limit to half of the ultimate tensile strength [13], the alternating stress for an infinite number of cycles is σ_a=293.5 MPa. To ascertain the physical infinity, for a given value of

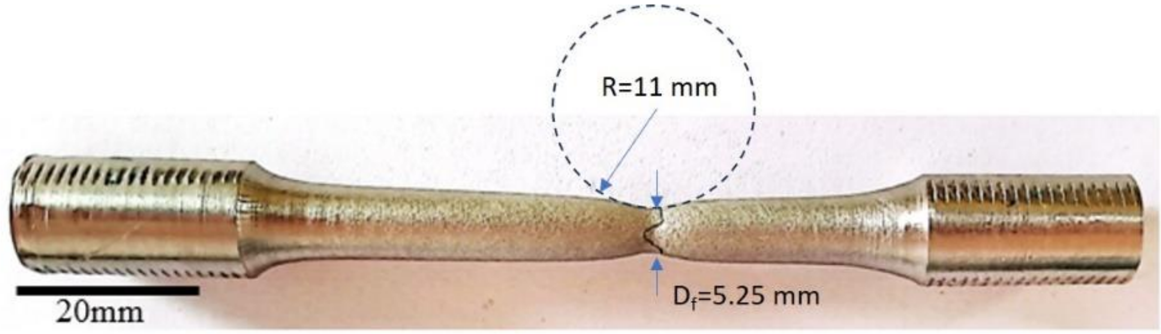

Fig. 1. The image of the tensile test specimen utilized for the estimation of fracture stress according to the Bridgman correction.

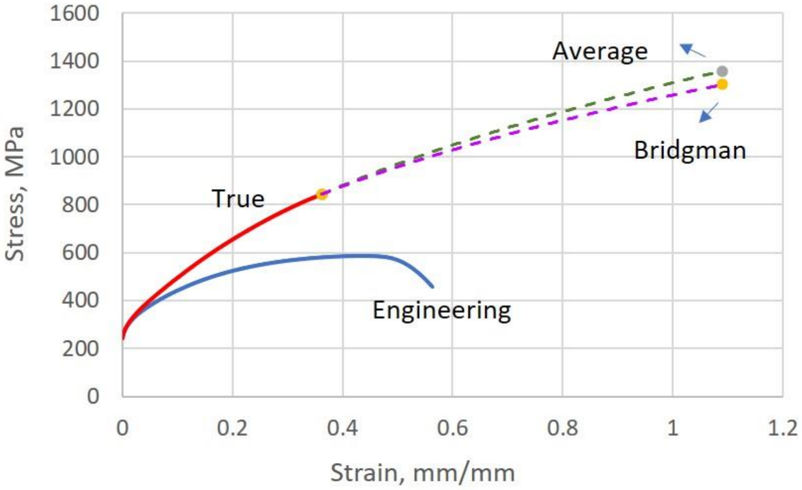

Fig. 2. The true and engineering stress-strain curves of 304 steel. The dashed lines represent the true stress up to the fracture point, calculated using the average stress method and the Bridgman correction following necking.

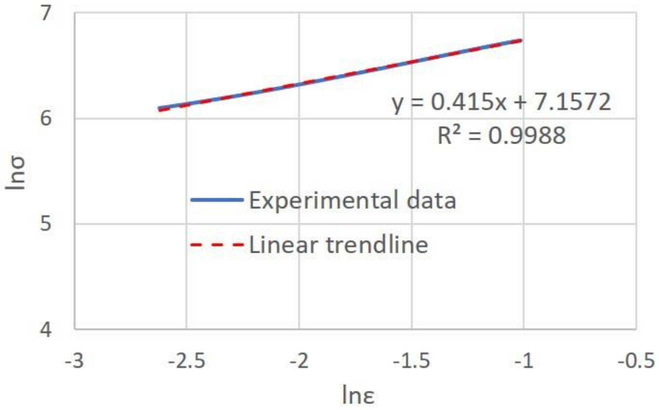

Fig. 3. The lnσ-lnε plot used to determine the constats of power-law equation.

σ_a and σ'_f in Eq. (6), the constant b can be determined for various cycle counts, as seen in Fig. 4. which indicates that after approximately one million cycles, the value of b stabilizes at approximately -0.07.

Fig. 5. illustrates the fatigue life curve of 304 stainless steel derived from the Basquin equation. This curve can be compared to the curves derived from fatigue test results, as seen in Refs. [15, 16]. The results demonstrate an apparent and comparable trend between the stress-life curve of the proposed approach and the experimental data from prior studies. The discrepancy between the values found in the cited references and the findings of this study may be caused by variations in the microstructure of the 304-steel sample that was subjected to testing. Given the significance of the topic, future studies must concurrently examine both fatigue and tensile tests on an alloy with a specific microstructure to mitigate discrepancies between the results cited in the references and those obtained through this innovative method. In conclusion, this unique method is anticipated to yield an accurate estimation of the fatigue behavior of metallic materials, owing to its simplicity, cost-effectiveness, and rapidity.

In conclusion, investigating the wider applicability of this approach is a viable pathway for future research. Future studies could involve validating this approach across various types of stainless steel and other metal alloys. This would allow us to assess the robustness and limitations of the method in diverse engineering contexts and potentially refine the methodology for more accurate predictions. By expanding the scope of this research, we aim to contribute to the development of more efficient and reliable methods for predicting fatigue life, ultimately leading to improved design and optimization of engineering components.

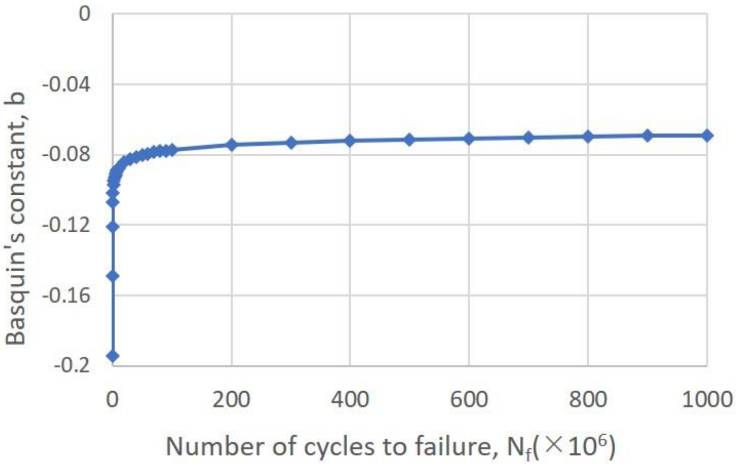

Fig. 4. The b-N_f plot utilized for the estimation of the Basquin exponent according to Eq. (7) at specified σ_a and σ'_f.

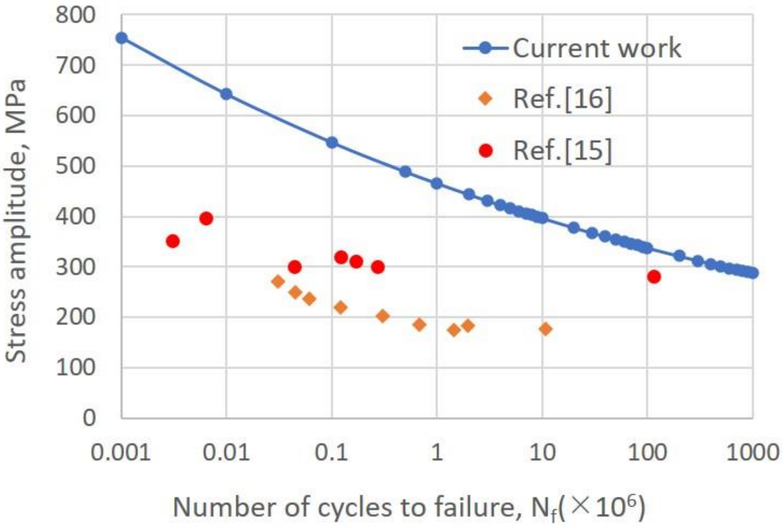

Fig. 5. Comparison of the S-N curves derived from the present study and those reported in the literature.

4. Conclusions

- This study successfully developed a novel approach for estimating the fatigue behavior of stainless steel 304 using a single tensile test. By leveraging the engineering and true stress-strain curves, the constants of the Basquin equation were accurately determined. The proposed method introduced a unique approach to calculating the true fracture stress, σ'_f, using the Bridgman correction, which was then directly incorporated into the Basquin equation. The estimated values for σ'_f and b for stainless steel 304 were found to be 1248.7 MPa and -0.07, respectively.
- The proposed method for assessing fatigue life of stainless steel 304 components under cyclic loading has been validated by a fatigue curve that aligns with experimental data. This method reduces costs and time, making it a valuable tool for engineers, enabling more efficient design decisions. The promising results suggest potential for application to other metal alloys, contributing to material science and engineering advancements.
- It is important to note that the accuracy of the estimated fatigue life depends on several assumptions, including homogeneous material properties, uniaxial stress states, and the validity of the Bridgman correction. The applicability of this method to materials with complex microstructures or under non-proportional loading conditions may be limited. Future research could explore the limitations of the proposed approach and investigate its applicability to a wider range of materials and loading conditions.

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