Low Cycle Fatigue of 316L Stainless Steel

B.Tech. Project Report

Submitted by

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Abstract

The research endeavor investigates the behavior of 316L Stainless Steel, a low-carbon austenitic stainless steel that is widely recognized for its exceptional strength and resistance to corrosion, especially in conditions where it is repeatedly subjected to cyclic loading. The impetus arises from the imperative to utilize materials that can withstand the severe conditions encountered by pressure vessel (RPV) components in nuclear reactors and possess exceptional strength and resistance to corrosion. The objective of this project is to examine the cyclic stress response of 316L Stainless Steel by conducting controlled low cycle fatigue experiments at ambient temperature with a strain amplitude of 0.65%. By inducing recurrent strains, the cyclic loading reveals particular properties of the material's mechanical behavior. The examination of the experimental findings reveals a cyclic stress response in which the total stress (TS) initially undergoes cyclic hardening as the number of cycles increases, then decreases signifying softening, and finally stabilizes. An in-depth examination of the microstructural origins of friction stress and back stress, which are critical determinants of the material's reaction to cyclic loading, provides additional insight into this behavior. The Bayesian Change Point Detection (BCPD) algorithm is utilized in the investigation to identify sudden shifts in the cyclic stress response curve. By utilizing the algorithm on stress-strain hysteresis loop data, critical points in the material's behavior that signal transitions between cyclic hardening, softening, and stabilization can be identified. It is crucial to comprehend the cyclic stress response of 316L SS, particularly with regard to materials utilized in RPV components, which are subjected to repetitive stress cycles. The findings of the project yield significant knowledge regarding the cyclic characteristics of 316L SS, thereby enhancing comprehension of its mechanical reaction when subjected to cyclic loading. These results provide support for the continuous endeavors in the design and choice of materials for nuclear reactor implementations, guaranteeing longevity, security, and dependability in the face of severe operational circumstances.

1. Introduction and Background

Materials that are subjected to cyclic loading conditions are of utmost importance in contemporary engineering applications, especially in components that are subjected to repetitive stress cycles across diverse industries. Comprehensive investigation and comprehension are imperative due to the fact that the performance and reliability of materials in demanding environments are predicated on their cyclic stress response behavior. The objective of this project is to investigate the cyclic stress response of 316L Stainless Steel (comprising 12% Ni, 17% Cr, 2.5% Mo, 2% Mn, 1% Si, 0.03% C max, Rem. Fe). This material is crucial for applications involving repeated cyclic loading due to its exceptional corrosion resistance, strength, and versatility.

The basis of the project is situated within the domain of pressure vessel (RPV) components for nuclear reactors, wherein materials are subjected to rigorous operational conditions that entail

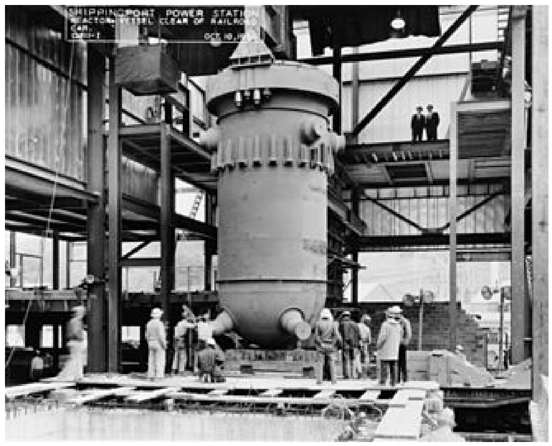
recurrent cyclic stress cycles. For the safety and efficiency of nuclear power facilities, the integrity and dependability of these materials, particularly in the reactor vessel, control rods, nuclear fuel cladding, and coolant systems, are of the utmost importance.
316L Stainless Steel, classified as a low-carbon austenitic stainless steel, was selected for its distinctive characteristics, which comprise weldability, mechanical strength, and superior resistance to corrosion and intergranular corrosion. Consequently, this material is well-suited for implementation in nuclear reactors. Despite this, there continues to be significant research and interest regarding the performance of 316L Stainless Steel when subjected to cyclic loading, specifically in scenarios involving low cycle fatigue.
The principal aim of this endeavor is to examine and assess the cyclic stress response characteristics of 316L Stainless Steel via controlled low cycle fatigue trials executed under predetermined parameters. The objective of these experiments is to replicate the recurrent stress cycles that materials within RPV components undergo throughout the operational lifespan of a nuclear reactor. The research aims to investigate various phenomena that impact the cyclic behavior of 316L Stainless Steel, including its mechanical response, cyclic hardening, softening, and stabilization, as well as the microstructural origins of friction stress and back stress that contribute to this behavior.

2. Literature review

The domain of nuclear reactors represents the zenith of scientific advancement, as it utilizes the immense energy liberated during nuclear fission. The importance of designing and developing materials that can withstand extreme conditions within the reactor core increases in tandem with the demand for pure, efficient energy. This segment examines the progress made in the development of materials for nuclear reactors and investigates the critical role played by the reactor pressure vessel (RPV) as an essential element in nuclear power facilities.
Numerous novel strategies have been incorporated into the development of materials utilized in nuclear reactors in an effort to improve performance and safety. The creation of sophisticated alloys, ceramics, composites, and nanostructured materials are all noteworthy developments. The purpose of these materials is to alleviate the difficulties that arise from exposure to radiation, elevated temperatures, and pressure in reactor environments. Ceramic Matrix Composites (CMCs), which possess remarkable thermal and mechanical characteristics, show promise as a viable approach to enhance the durability and effectiveness of reactor components.

2.1 Materials Used in Reactor Pressure Vessels:

Central to nuclear power facilities is the reactor pressure vessel (RPV), an indispensable containment structure that guarantees the reactor's secure operation. Critical operations include the containment of nuclear fuel, the preservation of a high-pressure environment, and the verification of structural soundness and safety. RPVs, which are critical to the operation of the reactor, require durable materials and careful design deliberations in order to endure severe conditions and maintain functionality for the duration of their operational lifespan. The process of material selection for RPVs is characterized by its attention to detail and diverse set of requirements. The assortment of materials employed in the construction of RPVs includes austenitic stainless steel cladding, low-alloy ferritic steels, nickel-based alloys, and titanium alloys. The utilization of austenitic stainless steel, specifically Type 316L, which is widely recognized for its outstanding characteristics and appropriateness for vital elements within nuclear reactors, is particularly noteworthy.



Reactor Pressure Vessel

2.2 Significance of Austenitic Stainless Steel (316L Stainless Steel):

Nuclear reactor applications are predicated on the exceptional corrosion resistance, fatigue strength, formability, and weldability of 316L stainless steel. The selection of 316L Stainless Steel for reactor components is supported by a number of crucial considerations.

AISI 316L stainless steel

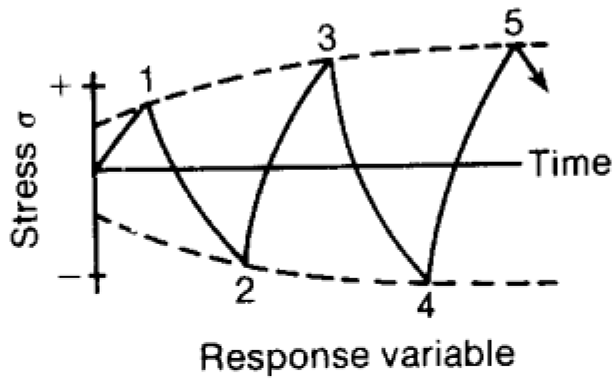
- *Corrosion Resistance:* The primary factor contributing to the corrosion resistance of 316L Stainless Steel is its chromium, nickel, and molybdenum composition, which collectively form a resilient passive layer. This is of utmost importance in the corrosive environments that are commonly encountered in nuclear reactor environments. It is an optimal choice due to its resistance to chlorides, acids, and other aggressive substances found in refrigeration systems.

- *High-Temperature Performance*: The ability of 316L Stainless Steel to maintain mechanical strength and structural integrity at elevated temperatures ensures its suitability for components subjected to thermal cycling and high-temperature conditions within the reactor system.
- *Weldability and Low Carbon Content*: Prominent characteristics include its remarkable weldability, which facilitates fabrication and assembly processes—vital when constructing intricate components for RPVs. In high-temperature applications, the reduced carbon content of 316L Stainless Steel further mitigates the occurrence of sensitization and subsequent intergranular corrosion.
- *Industry Acceptance and Regulatory Approval*: 316L Stainless Steel has garnered widespread acceptance and regulatory approval owing to its demonstrated reliability and performance in challenging environments, cementing its position as a trusted material in nuclear reactor systems.

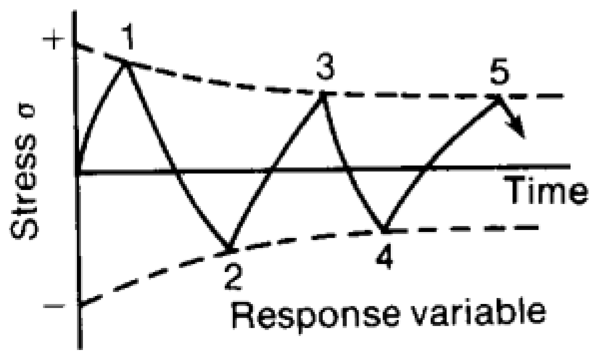
Role and Applications of 316L Stainless Steel in RPVs: 316L Stainless Steel is a highly adaptable material that is utilized in a wide variety of RPV applications, including cladding, liners, internal components, structural elements, instrumentation, and welded connections. Its compatibility with the conditions of nuclear reactors renders it an indispensable option, guaranteeing durability, security, and dependability in a wide range of components exposed to rigorous operational circumstances.
Exceptional Properties of 316L Stainless Steel: 316L Stainless Steel is favored in numerous industries, including nuclear power facilities, chemical processing, and marine environments, due to the alloy constituents that impart it with exceptional corrosion resistance, fatigue strength, and formability.

2.3 Understanding Cyclic Stress Response:

The cyclic stress response is a crucial parameter in the assessment of fatigue characteristics, as it represents the way in which a material reacts to cyclic loading or vibrations. The material's essential attributes consist of elastic and plastic deformation, strain-induced hardening and softening, and eventual failure or stabilization.
Stress-strain hysteresis loops are indispensable for conducting a thorough evaluation of materials as they function as crucial indicators of energy dissipation and cyclic behavior. The cyclic stress response of a material refers to its behavior when subjected to repeated or cyclic loading, which can lead to fatigue failure over time. This phenomenon occurs in materials under fluctuating stress levels, even if the maximum stress applied is below the material's yield strength. Cyclic hardening refers to the phenomenon where a material progressively increases in hardness or strength as it undergoes repeated cycles of loading and unloading. Cyclic softening involves the material's decreasing strength.



Cyclic Hardening

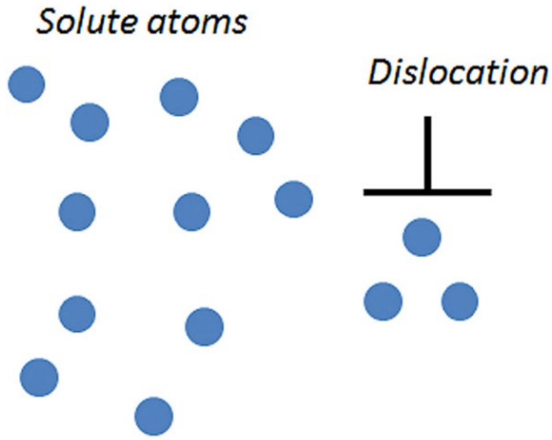


Cyclic Softening

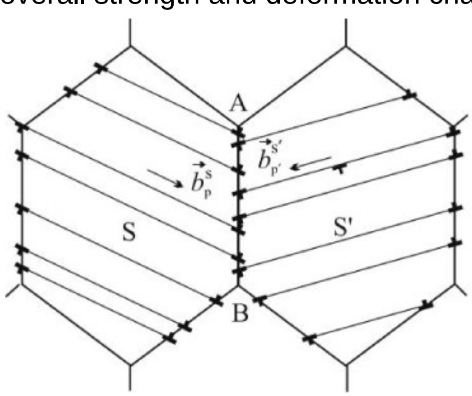
2.4 Insights into Friction Stress and Back Stress:

Back stress and friction stress are critical determinants that significantly impact the behavior of materials when subjected to external loading conditions. The origin and consequences of these internal stresses are determined by the complex interplay among dislocations, lattice imperfections, and impediments within the crystal lattice. These stresses have a substantial impact on the plasticity, strength, and deformation characteristics of the material.

Friction stress in materials pertains to the opposition that dislocations, which are minuscule imperfections present in the crystal lattice, face while traversing the lattice configuration of a given material. As dislocations travel through the crystal lattice, they encounter resistance comparable to friction as a result of their interactions with lattice atoms. A disparity between the stress fields of the dislocations and the lattice atoms gives rise to this resistance. Friction stress originates from the impeding effect of this disparity within the microstructure, which impedes the dislocations' seamless motion across the crystal lattice.



Back stress is a material phenomenon characterized by the impediment or obstruction of dislocation motion within the crystal lattice, specifically in the direction of grain boundaries or other impediments. Internal stress, which is caused by the interaction between dislocations and different microstructural features, restricts the unrestricted movement of dislocations within a material. Dislocations confront resistance or pinning effects when they come into contact with obstacles such as grain boundaries, precipitates, or other dislocations. These effects impede their motion and result in the accumulation of internal stress referred to as back stress. Back tension is generated at the microstructural level through the interaction between dislocations and lattice imperfections or obstacles, which results in dislocation pile-ups or obstructions that impede their glide motion. The resistance to dislocation motion causes an accumulation of stress in the area surrounding these barriers, which subsequently induces back stress in the material. Back stress is a substantial factor that influences the mechanical characteristics of materials that are undergoing deformation or external loading. It regulates the motion of dislocations, impacts the plastic flow of the material, and determines its overall strength and deformation characteristics.



Schematics of Back stress

3. Objective

In order to enhance the performance of 316L stainless steel for the aforementioned applications, it is necessary to investigate its cyclic stress response. First we explore the literature in order to understand the cyclic stress response. Following experimentation, the obtained data is analyzed. Then, in order to obtain the parametric value, we would utilize machine learning, more specifically the Bayesian Change Point Detection algorithm, which is frequently applied to comparable statistical data. Ultimately, the response is derived from the parametric values. Continuous improvement is the goal in identifying changes that can be implemented to enhance the material.

4. Experimentation:

4.1 Methodology

Materials and Equipment:

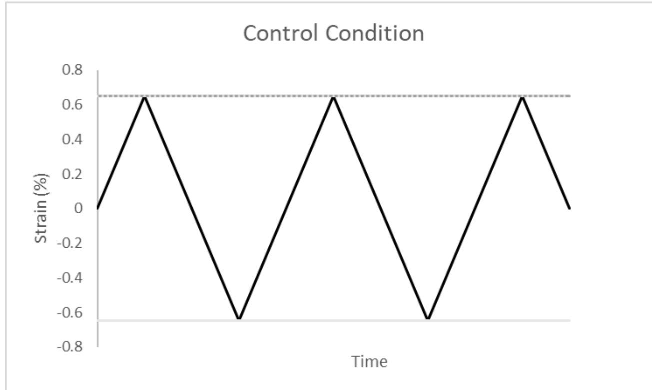
- Material: 316L stainless steel
- Specimen geometry: Standard cylindrical or flat dog-bone specimen
- Testing machine: Servo-hydraulic or mechanical fatigue testing machine
- Extensometer: High-precision extensometer for strain measurement
- Data acquisition system: For recording strain and load data
- Fatigue crack growth measurement tools (optional): Optical microscope or scanning electron microscope (SEM)

Procedure:

1. Specimen preparation:
    - Prepare the 316L stainless steel specimens according to the chosen standard.
    - Machine the surface finish to a specific roughness.
    - Measure and record the initial dimensions of the specimens.

2. Test setup:
    - Mount the specimen in the grips of the fatigue testing machine.
    - Attach the extensometer to the gauge section of the specimen for accurate strain measurement.
    - Connect the extensometer and load cell to the data acquisition system.

3. Test parameters:

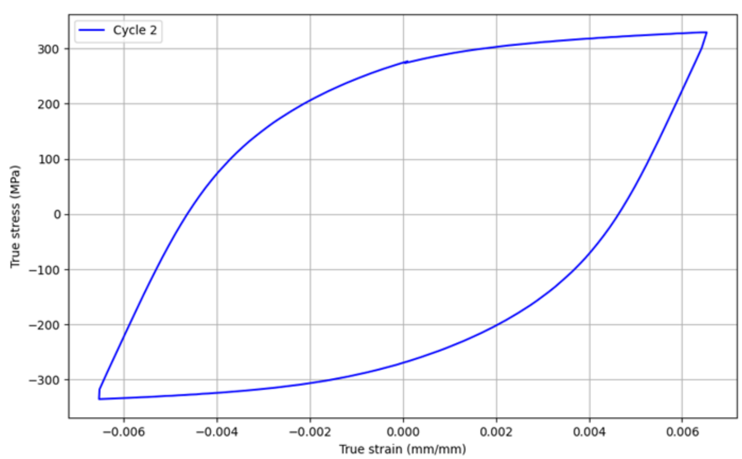


Strain vs time

- Strain amplitude is 0.65%.
- Strain rate is $3*10^{-3}$ s^{-1}.
- Here choose a triangular waveform for the cyclic loading.
- Test termination criteria is failure of material (we got 1818 cycles).

4. Test execution:
    - Start the test and monitor the applied strain and load values throughout the test.
    - Record the data continuously.
    - Stop the test when the defined termination criteria are met.

5. Post-test analysis:
    - Analyze the recorded data to obtain the stress-strain hysteresis loops.
    - Calculate the fatigue life (number of cycles to failure) for each specimen.
    - Plot the stress-strain amplitude and strain-life curves.
    - Examine the fracture surface of the specimen using an optical microscope or SEM (optional) to identify the dominant damage mechanisms.



After Experiment

Additional Considerations:

- Maintain a constant temperature and humidity throughout the testing.
- Use appropriate lubrication to minimize frictional heating at the specimen grips.
- Conduct multiple tests at different strain amplitudes to obtain a reliable fatigue curve.
- Compare the experimental results with existing data for 316L stainless steel or with theoretical models.

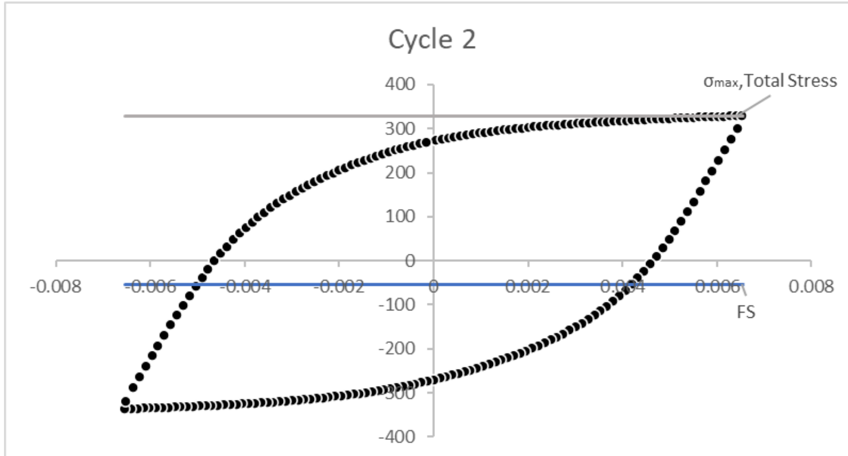
From this experimentation we got stress-strain data. Throughout the test, the strain applied to the specimen and the corresponding load response are continuously recorded. This data is used to plot the stress-strain hysteresis loops.
Now moving on to the analysis part of the experiment.

4.2 Analysis:

Utilizing techniques such as Statistical Analysis of Experimental Data, In-Situ Mechanical Testing, Indentation Methods, Crystal Plasticity Finite Element Modeling (CPFEM), and Dislocation Dynamics Simulations, it is possible to experimentally investigate the behavior of 316L stainless steel under cyclic loading. These methodologies play a crucial role in conducting a thorough evaluation of the dislocation characteristics, microstructure of the material, and mechanical properties that are essential for the precise estimation of friction stress and back stress. Here, Statistical Analysis of Experimental Data was implemented.

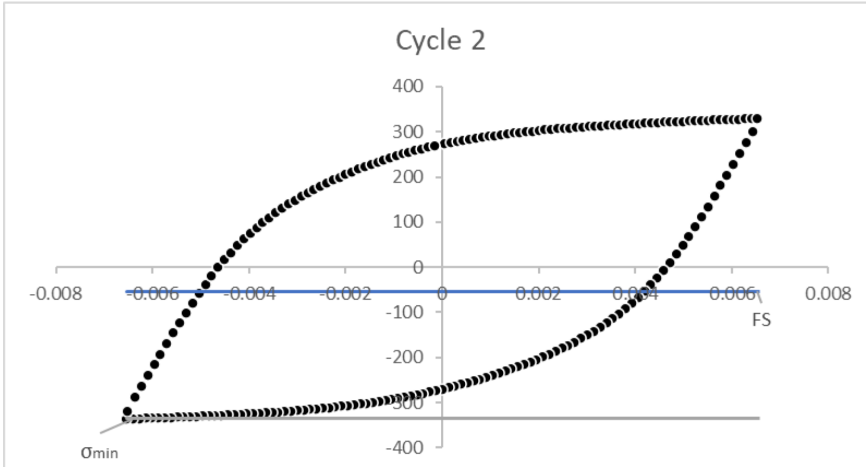
4.3 Calculation of friction and back stress:

The main objective of the analysis was to determine the friction stress, which is an essential internal stress that dislocations experience while moving through the crystal lattice of the material. The Bayesian Change Point Detection (BCPD) algorithm has been identified as a crucial instrument for distinguishing alterations in the stress-strain hysteresis loops acquired through cyclic loading. Critical points denoting transitions in the material's response were identified through the utilization of BCPD. The algorithm operated in an iterative manner, evaluating prospective change points, estimating probability distributions using Bayesian inference, and applying penalties to prevent overfitting; this ensured a balanced detection of significant change points.



Friction Stress Calculation

Determination of Back Stress: Analogous to the estimation of friction stress, the BCPD algorithm was employed to approximate the back stress within the material. The algorithm demonstrated proficiency in distinguishing cyclic behavior, slope variations, and discontinuities from stress-strain curves. By calculating the difference between the minimum stress and the point at which the inclination changes substantially, critical transitions that indicate the material's back stress could be identified. By employing this methodology, it was possible to measure the internal stresses that impede the motion of dislocations within the crystal lattice. As a result, a more comprehensive comprehension of the material's plasticity, strength, and deformation characteristics was achieved.
The operation of the BCPD algorithm was dependent on the following processes: model selection, segmentation, Bayesian inference, and the implementation of penalties. The application of window size parameters in conjunction with linear regression analysis enabled the identification of linearity within segments. Through the utilization of Bayesian information criteria and cost computations that assessed data homogeneity, the algorithm effectively detected optimal change points while preventing overfitting. The utilization of penalty settings in conjunction with parameterization of minimum and maximum segment lengths enabled rigorous analysis, guaranteeing the detection of critical turning points without excessive intricacy.



Back Stress Calculation

Results and Implications: The implementation of the BCPD algorithm effectively enabled the detection of transition points within stress-strain hysteresis loops, providing insight into pivotal junctures in the behavior of materials subjected to cyclic loading. The utilization of this approach to differentiate friction stress and back stress yielded crucial knowledge regarding the internal stress mechanisms that impact the cyclic response of the material. The aforementioned values established the foundation for subsequent analyses, which facilitated a comprehensive comprehension of the fatigue characteristics and deformation mechanisms of the material being examined.

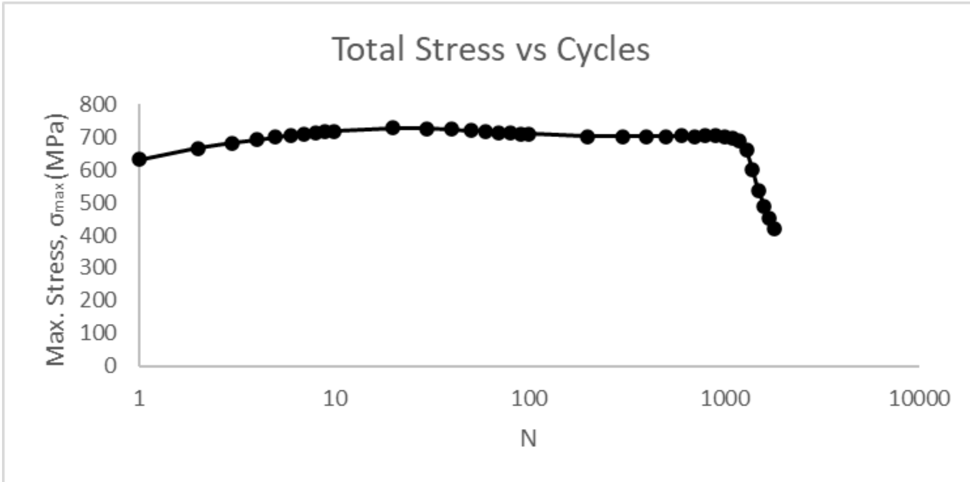
Subsequently, calculated friction stresses and back stresses were plotted against the number of cycles, made possible by the analysis. The parameters that were utilized to analyze the subsequent results were the plotted data, which provided insight into the behavior of the material when subjected to cyclic loading conditions.

5. Results and Discussion

The analysis comprised the computation of friction stress, back stress, and total stress over an extensive spectrum of cycles, which extended from one to 1818. The analysis of stress behavior trends versus cycle count unveiled discrete phases within the cyclic response of 316L stainless steel.

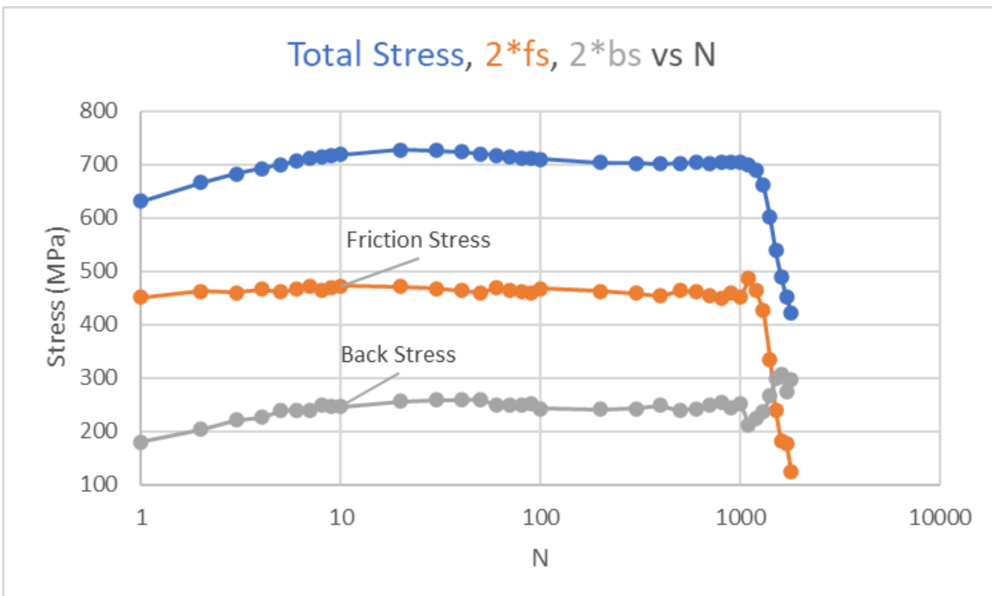
- *Total Stress (σ_{max}) and Number of Cycles (N):*

The data that was acquired revealed an initial pattern of increasing total stress during the initial twenty cycles, which suggests the presence of a cyclic hardening phase in the material. Cyclical softening was indicated by the decrease in total tension from approximately 20 cycles to nearly 200 cycles that followed this phase. Following this, a phase of stabilization occurred, during which the overall stress remained relatively constant, indicating that the material's stress response had reached equilibrium. However, a rapid decrease in total tension became evident after approximately one thousand cycles, signifying the material's impending failure. In the end, the material completely failed following 1818 cycles.



Total Stress (σ_{max}) *vs N*

We found that the major contribution in the change in total stress value is due to back stress despite the larger value of friction stress.



*(σ_{max}), 2*fs, 2*bs vs N*

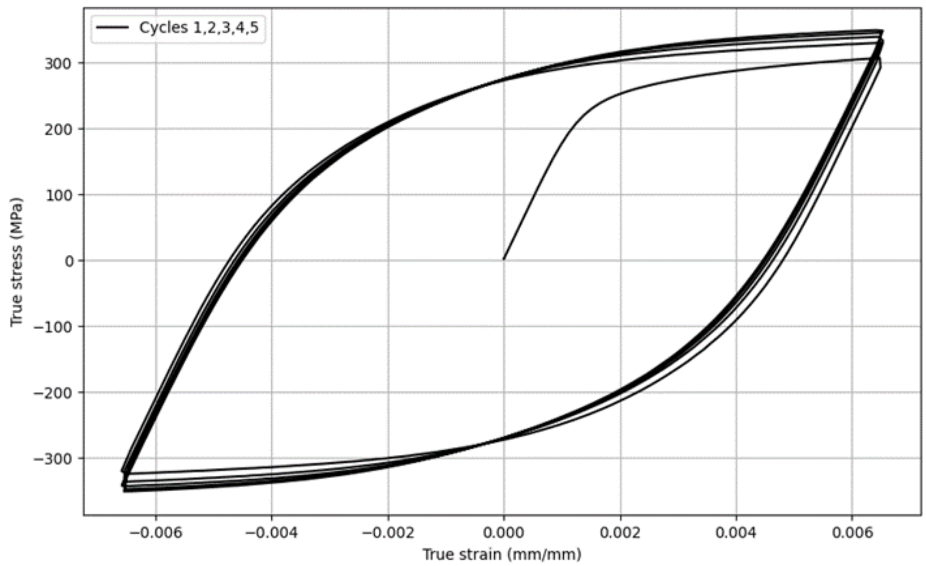
An intriguing feature of the cyclic stress response of 316L stainless steel is revealed by the observation of a constant friction stress value during the low cell fatigue test. Friction stress, which signifies the opposition dislocations confront as they traverse the crystal lattice, remains constant in spite of fluctuations in total stress. This indicates that the material's interface interactions are exceptionally resilient. The friction stress's consistency indicates that the obstacle dislocations encountered while traversing the lattice remained comparatively stable throughout the cyclic loading period. This occurrence could potentially be attributed to the persistent presence of microstructural impediments or imperfections in the crystal lattice, which impede dislocation motion in a consistent manner and thus maintain a constant friction stress value.

This understanding is further supported by the fact that, notwithstanding the greater magnitude of friction stress, the variations observed in total stress are primarily influenced by back stress. Back stress, which arises from the obstruction of dislocation motion caused by microstructural characteristics, exerts a substantial influence on the mechanical properties of the material. The significant effect it has on variations in total stress during cyclic loading suggests that it has a more pronounced effect on the overall response of the material. Hence, the stability of friction stress in the face of fluctuations in total stress could potentially be explained by a delicate equilibrium between the persistent resistance faced by dislocations (friction stress) and the pervasive impact of back stress on the cyclic stress response of the material. The stability of friction stress observed during cyclic loading may be attributed to a sustained interaction between dislocations and microstructural impediments, which is potentially represented by this equilibrium. Understanding the substantial influence of back stress in the cyclic stress response of 316L stainless steel presents an avenue for strategic alterations to enhance its mechanical behavior. Given the prominence of back stress in influencing total stress changes, modifying the microstructural aspects that contribute to back stress could potentially enhance the material's fatigue resistance. Introducing alterations at the grain boundaries or within the crystal lattice to mitigate the hindrance encountered by dislocations might be a viable approach. By refining the material's microstructure or employing grain boundary engineering techniques, the impediments to dislocation motion can be minimized, thereby reducing the magnitude of back stress. This strategy aims to promote smoother dislocation movement through the lattice, subsequently mitigating the strain accumulation and contributing to improved cyclic fatigue performance.

Additionally, focusing on heat treatment methodologies or alloying strategies to tailor the material's microstructural features could be pivotal. By optimizing the material's grain size, distribution, or texture, it's possible to influence the interactions between dislocations and microstructural elements, thereby potentially altering the back stress contribution. Moreover, targeted alloying elements or thermomechanical processing techniques that facilitate the formation of more favorable microstructural configurations may aid in mitigating back stress. Through such strategic modifications aimed at minimizing back stress, there's potential for enhancing the cyclic fatigue resistance of 316L stainless steel, thereby improving its overall performance in demanding cyclic loading conditions. Now moving on to the behaviors of the curves (various stages of cyclic stress response):

- *Cyclic hardening:*

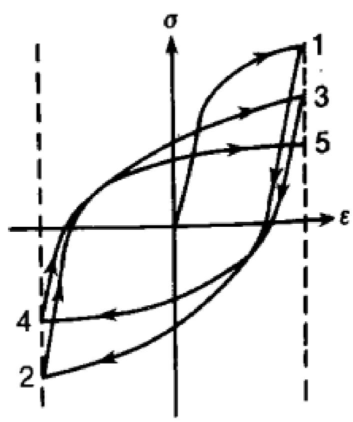
The identified stage of cyclic hardening can be explained by a number of microstructural mechanisms at play. The elevated flow stress was a direct result of the proliferation of dislocations that occurred during cyclic loading, which substantially increased dislocation density and impeded further dislocation movement. Moreover, the solidification process was exacerbated by the accumulation of dislocations in substructures, such as cell walls, which impeded dislocation mobility. Cyclical deformation may, under certain conditions, cause austenite to undergo a transmutation into martensite, a more rigid phase that concurrently increases flow stress. This type of behavior is seen from cycle 1 to 20:



Cyclic Hardening in from cycle 1 to 5

- *Cyclic softening:*

After the phase of maximum tension has passed, the observed cyclic softening may be attributed to a multitude of mechanisms. A decrease in dislocation density resulted from dynamic recovery and recrystallization, particularly under protracted cyclic loading conditions or at elevated temperatures, which caused the material to become softer. Cross-slip or ascent to new glide planes by dislocations additionally contributed to softening. Moreover, material softening and eventual fracture resulted from the nucleation and development of microvoids at grain boundaries or second-phase particles under conditions of high strain amplitudes. This type of behavior is seen from cycle 20 to 200:



Cyclic softening schematics

- *Stabilization:*

A certain number of cycles is required to reach a state of equilibrium in the stress amplitude, which is referred to as the stabilization phase. The material obtains a relatively constant stress amplitude during this phase. Cyclic stabilization can occur when the material reaches a point of equilibrium between cyclic hardening and softening mechanisms. This equilibrium can be influenced by factors such as microstructural changes, strain distribution, or the balance between dislocation accumulation and recovery processes. Stabilization often occurs when cyclic loading causes certain material properties to reach a steady state without significant further changes.

Justifications for Variable Stages:

The multidimensional nature of the phases observed in the cyclic stress response of 316L stainless steel is due to the influence of numerous factors. Increased strain amplitudes, elevated temperatures that facilitate recovery and recrystallization, and increased loading frequencies have a tendency to amplify the mechanisms of hardening and softening. Additionally, the rate and extent of hardening and softening are substantially influenced by the initial microstructure of the material, which includes the particle size, dislocation density, and the presence of the second phase.

6. Conclusion:

The research work examines the complex dynamics exhibited by 316L stainless steel when subjected to cyclic loading, with a specific emphasis on its cyclic stress response, back stress, and friction stress. The study commences with an extensive examination of the existing body of literature, encompassing the importance of nuclear reactors, the components employed in reactor pressure vessels (RPVs), and the pivotal function performed by 316L stainless steel in environments characterized by extreme stress. The review provides an explanation for its inclination towards different RPV components, highlighting its outstanding resistance to corrosion, performance at high temperatures, weldability, and low carbon content.

The experimental phase ensures that strain amplitudes, strain rates, and controlled conditions are maintained throughout the low cycle fatigue testing of 316L stainless steel. The methodology is meticulously detailed during this phase. By employing a methodical approach, the outcomes untangle the material's cyclic stress response throughout a period of 1818 cycles. The results demonstrated cyclic phases of hardening, relaxation, and stabilization, providing insight into the microstructural mechanisms that underlie each phase. Increased dislocation density, dislocation substructures, and potential martensitic transformations induced by deformation all contributed to cyclic hardening. On the contrary, dynamic recuperation, cross-slip, and the creation of microvoids contributed to cyclic softening.

Furthermore, the outcomes underscored the pivotal significance of the Bayesian Change Point Detection (BCPD) algorithm when it comes to the estimation of friction stress and back stress. The critical points in stress-strain hysteresis loops were successfully identified by this algorithm, which facilitated the computation of these vital parameters. The subsequent discourse elaborated on the intricate factors that contribute to the distinct phases that were observed, establishing connections between the cyclic behavior of the material and strain amplitudes, temperature, loading frequency, and microstructural characteristics.

The fundamental purpose of the project was to conduct a comprehensive investigation into the cyclic stress response of 316L stainless steel by employing a variety of analytical instruments and methodologies. The thorough comprehension of the material's response to cyclic loading provides indispensable knowledge regarding its suitability, durability, and constraints, addressing the rigorous requirements of materials engineering in crucial sectors such as nuclear power plants and high-pressure settings.

Major contribution of back stress in the cyclic stress response of 316L Stainless Steel and minor contribution of friction stress was found.

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