IOP Conference Series: Materials Science and Engineering

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To cite this article: K A Mohammad *et al* 2012 *IOP Conf. Ser.: Mater. Sci. Eng.* **36** 012012

Fatigue behavior of Austenitic Type 316L Stainless Steel

K. A. Mohammad[1], Aidy Ali[1], B. B. Sahari[2] and S. Abdullah[3]
[1]Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang Selangor, Malaysia
[2]Institute of Advanced Technology (ITMA), Universiti Putra Malaysia, 43400 UPM, Serdang Selangor, Malaysia
[3]Department of Mechanical and Materials Engineering, Universiti Kebangsaan Malaysia, Bangi, 43600 UKM Bangi, Selangor, Malaysia

E-mail[1]: k.amohd@yahoo.com

Abstract. The aim of this work is to determine the fatigue life of 316L stainless steel. The mechanisms of fatigue of 316L stainless steels were investigated and discussed. The fatigue tests were carried out at constant-amplitude cyclic loading with load ratio R=0.1. Scanning Electron Microscope (SEM) is then used to examine the fracture surface. The results show that the fatigue limit of 316L stainless steel was 146.45 MPa.

1. Introduction

In leading-edge toward global market, many engineering components experienced fatigue mechanism in daily life and it is one of the oldest problems which concern scientists and engineers. Plenty of steel in the world has been investigated for a lot of application in the science and technology market. Fatigue caused the structure failed. Due to the complicated nature of fatigue mechanisms and the large number of factors that influence fatigue life, there is so far no unified approach that can treat all fatigue problems [1]. For instant, engineering components used in aviation, nuclear industry, transportation, including in oil and gas plant may be contain defect due to imperfection of manufacturing process. Examples of these applications include the utilizing of industrial piping in petrochemical refineries, aerospace, ship building industries, construction, repair nuclear power facilities, and ground vehicle industries. Safety and predicted life are the most significant in these industries. Therefore damage tolerant design can be used to predict residual life of components.

During the last decades, lots of designers, engineers and researchers investigated and explored to develop prediction models for high cycle fatigue (HCF) life, as since it take enormous time and efforts to construct a stress life (S-N) curve [2]. According to Landgraf [3], the HCF is recognized as highly influenced by microstructural variables such as grain size, the volume fraction of secondary phase and the amount of solute atoms or precipitates. In the other hand, many investigator have examined the fatigue crack initiation and propagation modes where manipulate the failure of component to breakdown [4-6]. From the authors Chen et al. [7], mentioned that the starting point of failure under low cycle fatigue is mostly related to the geometrical discontinuities on the specimen surface and furthermore of creep-fatigue-environment may enhance the cracking problem.

Due to its application for daily use, life prediction of 316L steel is one element of the complex and crucial in designing a component into tubular or cylinder shape working in various of alternative loading. Up till now, a small number of researches work have been carried out in investigating and study the mechanism of tubular components cause by complexity of geometry to compare with simple plate geometry in order to predict the lifetime of steel before rupture.

In this paper, the proposed of this work is characterizing the fatigue life of austenitic stainless steel 316L at room temperatures which is subjected to variable loading.

2. Materials

In this study, austenitic type 316L stainless steel was used and studied and it chemical compositions are given in Table 1. Meanwhile Table 2 represents the mechanical properties for hourglass specimen of austenitic steel. Austenitic steel in form of tubular specimens were provided by local supplier, S.N Machinery Services Sdn. Bhd. that is designed and fabricated carefully in accordance with ASTM E606. In fatigue tests, the specimen image with its dimensions of austenitic Type 316L stainless steel specimen designs which was tested in transverse direction of axial fatigue testing as shown in Figure 1.

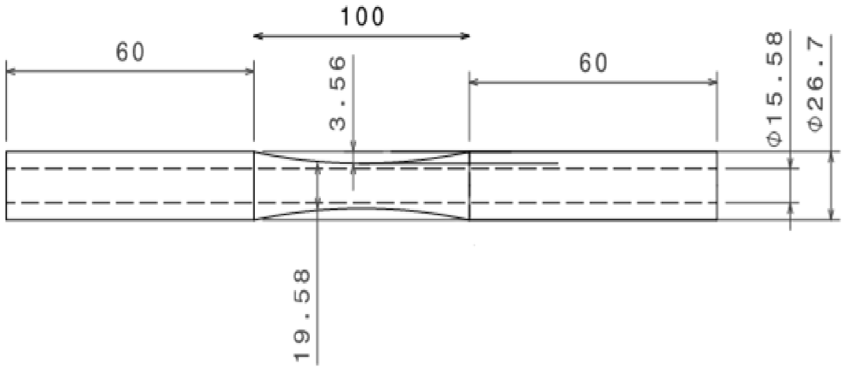
Table 1. Chemical compositions of Type 316L stainless steel [8]

Element (%)	**C**	**Ni**	**Cr**	**Mn**	**P**	**S**	**Si**	**Mo**	**N**
316L	0.020	11.21	17.38	1.86	0.027	0.0054	0.51	2.36	0.038

Table 2. Mechanical Properties of Type 316L Stainless Steel

Mechanical Properties	**Type 316L stainless steel**
Yield Point, MPa	332
Tensile strength, MPa	673
Modulus of Elasticity, GPa	165
Strength at break, MPa	586
Elongation at break, mm	35.5

(a)



(b)

Figure 1. (a) Austenitic Type 316L Stainless Steel and (b) its dimensions

3. Jig Design

The jig is made out of carbon steel 45SC in this fatigue test as shown in Figure 2. The designed jig was accommodated to hold and grip specimens for fix it into the actuator of machine as additional supporter bar. In addition, use of jig also preventing specimen from slips and scratched.

Figure 2. Jig

4. Experiment

The fatigue specimens were tested in push-pull fatigue test using Fast Track Hydraulic Universal Testing Machine Instron 8802 of 250 kN load capacity as shown in Figure 3. The machine is attached with computed Waveform Generator Software to record the fatigue data. The tensile test was carried out before commencing the fatigue test as guidance in order to determine the maximum load that the specimen could sustained. All fatigue tests for austenitic steel were performed in constant load amplitude, constant frequency of 5 Hz and a stress ratio, R equal to 0.1. Figure 4 shows the specimen undergoing fatigue test. Fatigue test results were plotted in graph in term of stress versus life data. Best fit curve were plotted for data analysis.

Figure 3. Fast Track Hydraulic Universal Testing Machine Instron 8802 of 250 kN load

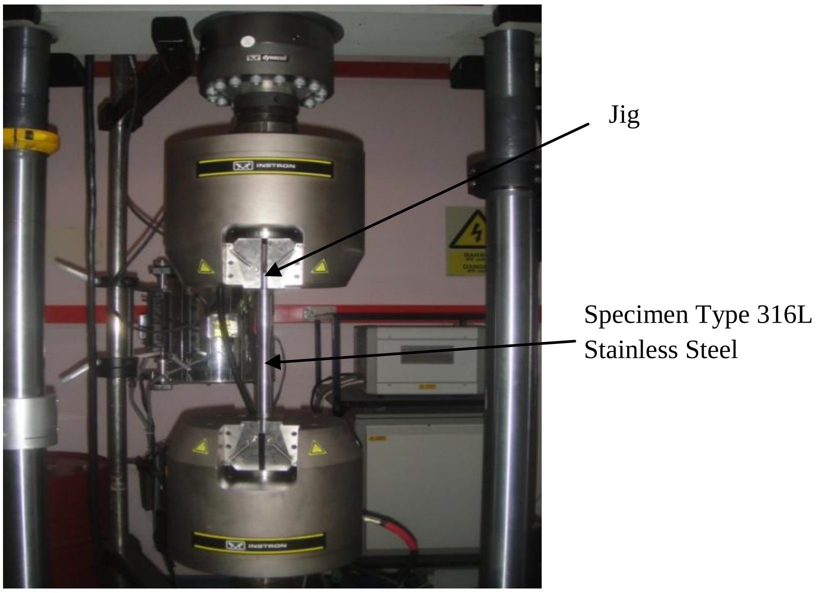


Figure 4. Specimen undergoing fatigue testing

5. Results and Discussion

In experimental, the fatigue tests were conducted using different loadings. The fatigue life of specimen obtains as shown in Table 3 in terms of number of cycles to failure. With considering eight's value of means and amplitude stresses used for carried out in tension-tension fatigue by applied loads on specimens in order to get life time at variable amplitude loading. From the results in Table 3, stress amplitude versus fatigue life is plotted to view the significant difference of fatigue life at high stress compared to lower stress.

Table 3. Stainless Steel Type 316L in term of Number of Cycles.

Load Ratio (R)	**Stress Amplitude (MPa),** σ_a	**Life (Cycles)** $2N_f$
0.1	334.00	4,628
	290.93	17,340
	275.20	55,478
	234.33	164,938
	220.15	450,447
	180.11	1,033,948
	160.69	4,832,284
	146.45	7,893,764

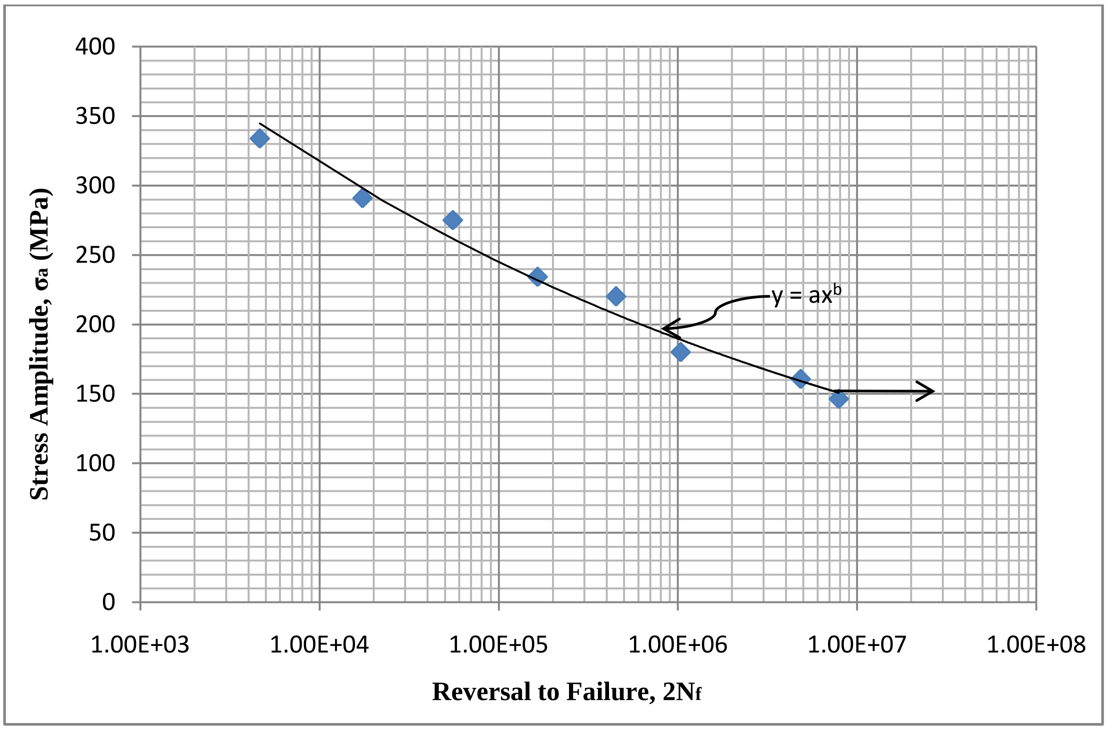


Figure 5. S-N curve

Fatigue data at different load were acquired with a data acquisition system. The results are plotted in S-N curve is shown in Figure 5. From the figure shows that variation of curve of fatigue test will decrease as different loading applied on specimen till fatigue failure. It is mentioned that type 316L stainless steel undergoes harden under cyclic loading [9]. The data collected from the test have been fitted by power law curves in order to describe the specimen fatigue behavior. The equations of power law curves are given by:

$$y = ax^b \tag{1}$$

This equation shown the relation between fatigue life and applied load is called Basquin relation. The Basquin relation is the general equation represents typical S-N curve and its expression developed from log–log S-N graphs. It is the most widely used equation. This equation is usable in the stress-based approach to fatigue analysis and design. The relation is given by:

$$S_a = S_f' \left(2N_f\right)^b \tag{2}$$

where S_a is stress amplitude, S_f' is the fatigue strength coefficient and b is the fatigue strength exponent. The fatigue experimental data was fitted with equation of Basquin Equation whereby the value of b exponent obtains from the slope of line in log-log scale. It is show that behavior of fatigue strength on type 316L stainless steel was hardening and followed by softening at surrounding condition [10].

From the experimental results, it can be observed that the data is decrease as applied load at different variable into fatigue endurance zone. At range of 10^3-10^4, it is categorized as low cycle fatigue where stress amplitude's value between 334 MPa – 290.93 MPa yields cycle ranging 4628 – 17340 measured for hazardous area where the fatigue life is very low. Meanwhile range of 10^5 and above could be categorized as high cycle fatigue has 55478 – 7893764 cycles and it is considered it will have a much longer fatigue life. Each life's component would be replaced by another one since it reaches at this stage more than a 1000000 cycles. The arrow represents the specimen beyond 1 millions cycles did not break even after applied many specimen throughout the tests. From observation the graph, it can be that fatigue limit is successfully characterized for type of 316L stainless steel in this research and found to be 146.45 kN at 7,893,764 cycles.

6. Fractographic Analysis of Fracture Surface

In order to investigate the morphological-microstructure relationship of failed specimen, fracture surface were investigated using SEM in terms of the pattern crack would be irregularities can degrade fatigue strength. The fracture initiate at surface irregularities such as voids and inclusions in according to Lah et al. [11]. This experiment was carried out by Scanning Electron Microscope (SEM - Hitachi S-3400N) as shown in Figure 6.

Figure 6. Hitachi S-3400N Scanning Electron Microscope (SEM)

In the Figures 7, 8 and 9 show SEM fractograph for Low Cycle Fatigue (LCF) regime of specimen tested at 334 MPa. The specimen shows evidence of beachmark due to fatigue failure. Crack initiation and early propagation exhibits the transgranular fracture mode in fracture surface specimens for first stage of fracture surface also shown in Figure 7. It shows the fracture strip and which reveals the shear surface morphology. Otherwise, from the figure revealed also the fracture surface has more than one porosity initiation site.

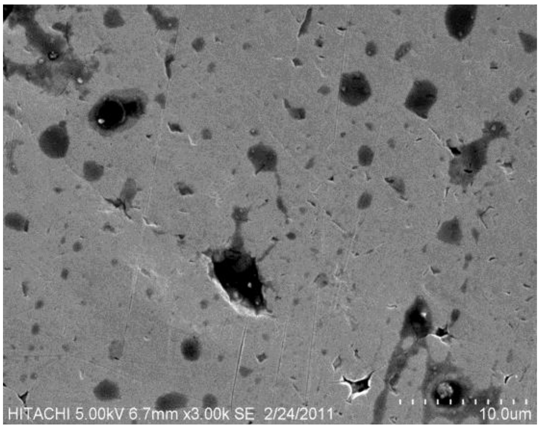


Figure 7. Nucleation Crack

At second stage, fracture surface of the specimen shows a propagation zone where mixed fracture path completely intergranular mode in fracture behavior of specimen as shown in Figure 8.

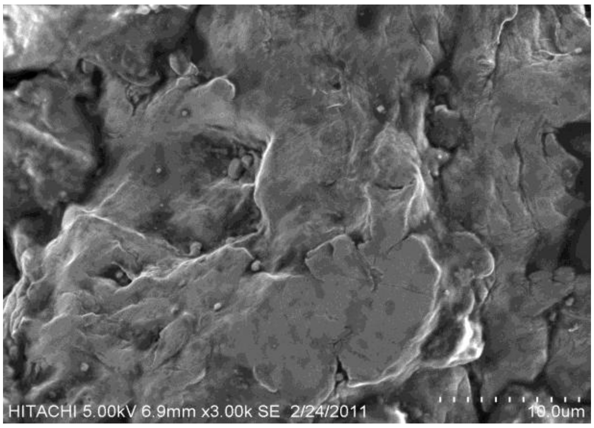


Figure 8. Propagation Crack

Figure 9 represents the captured picture on fracture surface at third stage before failed. Unstable of mode between intergranular fracture and transgranular fracture in this specimen tests was found in final stages (rupture zone). In this stage, fracture surface is look like changed from intergranular to transgranular before reach unstable stage to rupture.

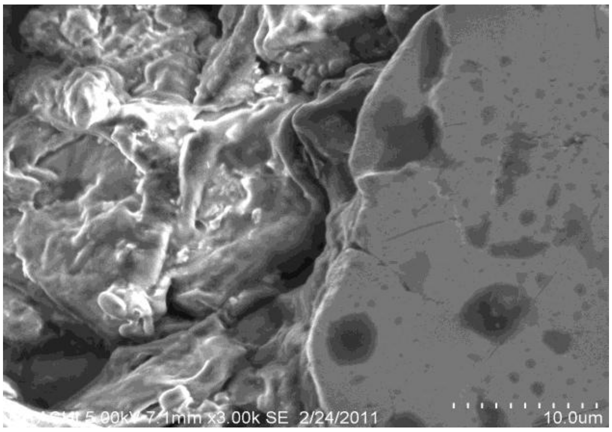


Figure 9: Unstable Rapid Crack Growth before Rupture

7. Conclusions

As conclusions, the fatigue life of austenitic stainless steel 316L is successfully characterized from the experiment conducted at ambient temperature. Since experimental results have higher loading causes the specimen to fail tremendously fast instead of lower load. Fatigue test imposed a limit of fatigue life of 10^7 cycles due to cost and time limitation. The fatigue limit from the result is 146.45 kN at 7,893,764 cycles for this specimen. Meanwhile with observation using SEM show that the nucleation crack was transgranular mode, intergranular in crack propagation, and last stage exhibits mixed of transgranular and transgranular mode in continuous cyclic loading in this research.

Acknowledgement

The author would like to thank to University Putra Malaysia for the scholarship under Special Graduate Research Assistant (SGRA) under grant University (Project No.: 91726) which made to pursuit of this research achievable.

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