Effect of Notch Geometry on the Fatigue Life of UNS S31803 Duplex Stainless Steel

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Abstract - *Popular steel grade UNS S31803 Duplex stainless steel is utilised in maritime and military applications. The goal of the current study is to compare the fatigue life of the aforementioned steel under notched and unnotched conditions. At the midpoint, the specimen's surface is cut out with various geometries of notches, and the fatigue life is assessed for each example. According to ASTM E606 standard, CNC lathes are used to create fatigue specimens. On the basis of the Taguchi L9 orthogonal array, the notch's depth, width, and centre angle are adjusted. Quantifying how the notch characteristics mentioned above affect material fatigue is the project's main goal. A 25KN Nano UTM was the subject of a fatigue analysis.*

The current project clearly shows that the reduction in fatigue life of UNS S31803 is influenced by the depth of the notch (31.55%), the notch central angle (26.41%), and the notch breadth (18.48%).

Key Words: Notch Geometry, Fatigue Life, Duplex Stainless Steel,

1.INTRODUCTION

1.1 Fatigue of Marine Structures

Fatigue failure refers to the degrading of a material as a result of cyclic loading that results in progressive and localised structural degradation followed by the development of cracks. Every load cycle, a previously initiated crack will progressively enlarge until it reaches a critical size, which occurs when the stress intensity factor of the crack exceeds the material's fracture toughness. This causes the component or structure to quickly propagate and typically fracture completely. The phrase "metal fatigue" originated from the usual association between fatigue and metallic construction failure.

The cyclic loads that ship structures are subject to from the wind, waves, and cargo operations come in many different forms, and these loads can cause fatigue damage to the structures. Fatigue cracks typically appear earlier than anticipated in a number of sites on ships and other maritime constructions, which has a significant impact on their performance.

By using innovative stainless steel variations with improved strength to weight ratios in ships, developments in construction technologies made this possible. The first ship ever to carry more than 21,000 TEU is the OOCL Hong Kong. With increased size, tidal loads pose a greater hazard to the ship's structure, which can lead to fatigue damages and jeopardise its design and safety. Therefore, based on accepted guidelines and practises, ship structures should be constructed with sufficient fatigue strength.

Despite following established guidelines and stress-based construction techniques, fatigue-related breakdowns are nonetheless sometimes seen in ship structures. Fatigue cracks develop significantly sooner than anticipated in ships due to the significant uncertainties involved in the fatigue design process, such as different wave conditions, unpredictable hydro-dynamic repeated loads, stress concentrations, etc.

The lack of/insufficient use of strain-based techniques during fatigue studies is one of the causes of ships having inadequate fatigue designs.

During the fatigue design, consideration must also be paid to the existence of abrupt geometry changes, notches, and cracks on the surface. As a result, without strain-based fatigue analysis, ship structures cannot be designed to withstand fatigue stress.

1.2 Current Research Problem

The study seeks to investigate the fatigue life or strength classes of marine steel UNS S31803 utilising a strain-based technique. The aim of the study is to investigate the low cycle fatigue life of the parent material of the two steel variations mentioned above and the similarity and differences between their friction welded joints. The research of the impact of the notch parameters (depth, width, and notch central angle) on the fatigue life of the aforementioned steels and their similar and different friction-welded joints is also included in the scope. By performing notches with a variety of parameters through a Taguchi L9 orthogonal array, the effect of notch parameters on the fatigue life is assessed using experimental design. The investigation's purview also covers how HVOF ZrO2 coating affects AISI 316L's fatigue life and ability to resist corrosion.

1.3 Outline of the Research

The current research is presented in the following way for clarity. It contains details of the experimental methods where the information related to the materials undertaken is embedded, and data analysis is dealt with. It also deals with empirical and finite element methods to estimate the endurance limit, Stress (vs. Fatigue Life and Strain Amplitude (vs. Fatigue Life curves for the materials undertaken. References, a list of publications, and an appendix are mentioned after that.

1.4 Objectives of the Research

The objectives of the current research are to carry out:

Objective-1: Fatigue analysis of two grades of marine steels using strain life approach UNS S31803 (AISI F55).

Objective-2: Fatigue analysis of the similar/dissimilar friction welded joints of the chosen steels.

Objective-3: Quantification of the influence of notch parameters which are width, depth and notch central angle on the fatigue life of the chosen steels and their similar/ dissimilar friction welded joints

2. Literature Review

2.1 Fatigue

M. Kamal et al (2018) fatigue is slow, restricted, and permanent failure that happens in a component exposed to fluctuating stresses that are often much lower in magnitude than the materia's tensile strength. Fatigue loading may initially create cracks and cause fracture after an adequate number of fluctuations. Fatigue failure consists of three stages [1]:

- Preliminary fatigue failure and initiation of crack.
- Propagation of the crack to a critical size.
- Ultimate abrupt fracture in the residual cross-section.

Damage due to fatigue loading is instigated by the simultaneous acts of cyclic stress, plastic strain and tensile stress. If any of these is absent, fatigue crack does not crop up and propagate.

Ernianzhao et al (2020) the plastic strain which is a consequence of cyclic stress causes the crack and the tensile stress makes the crack to propagate. Vigilant quantification of strains depict that plastic strains though microscopic in nature could exist even at lower magnitudes of stress where the strain if observed at macroscopic level appear to be totally elastic. Even though compressive stresses do not cause fatigue failure, compressive loads may crop up local tensile stresses [2].

J.H Ong (1993) fatigue strength of steels is generally considered to be proportional to hardness and tensile strength, but this generalization may not be factual always. Processing operations, fabrication methods, heat/surface treatments, finishing done, and service conditions profoundly impact the behavior of a material exposed to cyclic loading [3]. Jun-Hyub Park et al (1995) forecasting the fatigue life of a component is complex as materials are usually sensitive towards minor variations in loading pattern, stress concentrations etc. Any component's resistance to fatigue damage is dependent even upon the manufacturing methodology (forming, brazing, welding, machining etc.) and surface conditions like roughness and the amount of residual stresses present [4]. N. Shamsei et al (2009) Fatigue tests undertaken using small specimens are insufficient to exactly estimate the fatigue life of materials/components [5]. Kamaya, M et al (2014) these can be helpful in evaluating the resistance of a material towards cyclic stressing. Apart from material properties and magnitude of loads, the criteria for design must take into cognizance, the type of loading applied load pattern, overall dimensions of the part, fabrication methodology, magnitude of peak stresses, surface roughness, corrosion impact, temperature of operation, environment, defects induced due to service etc [6]. C.R Williams et. al (2003) Customarily, fatigue life is reticulated as the count of stress cycles needed for a crack to initiate and develop big enough to produce the disastrous breakdown i.e. parting into two pieces [7]. Zhongping Zhang et. al (2093), expressed fatigue data as a function of total life that holds good for small laboratory samples but for real components, crack initiation may occur in very few cycles when compared to the total life of the component [8]. J. Jagadesh Kumar et al (2008) fatigue data can as well be articulated as a function of crack growth rate. Earlier, it was presumed commonly that total fatigue life entailed primarily, the crack initiation phase which is the first stage of fatigue failure, and the time needed for the tiny fatigue crack to develop and cause failure was a small fraction of the total life [9]. J. Jagadesh Kumar et al (2019) however, with the advancements in crack detection methods, it was found that cracks often develop as early as after 10% of total lifetime and grow endlessly till complete failure happens. This finding inspired researchers to use the growth rate of crack for the forecast of total fatigue life. The occurrence of fatigue failures can be significantly reduced by cautious consideration to design particulars and manufacturing [10].

3. Experimental Methods

The materials used in the current research work are UNS S31803, which is a super duplex stainless steel. The materials were procured as round rods with a diameter of 14 mm in hot rolled and annealed condition. The grade of steels chosen are marine grade stainless steels and the current work aims at evaluating the effect of notch geometry on the fatigue life of the chosen steels and their friction welded joints. The fatigue strength of similar material of above said steel are evaluated with different notch scenarios and un-notched scenario. The chemical composition (wt%) and mechanical properties of the materials undertaken for the research are tabulated and presented in Tables 3.1 and 3.2.

Table -3.1: Chemical composition (wt %)

Element	UNS S31803	
	Catalogue	Actual
C	Max 0.030	0.025
Si	Max 1.0	0.865
Mn	Max 2.00	1.856
P	Max 0.030	0.028
S	Max 0.020	0.018
Cr	21.0-23.0	21.450
Mo	2.50 – 3.50	2.985
Ni	4.50 – 6.50	5.685
N	0.080-0.20	0.100
W	--	--
Cu	--	--
Fe	Balance	Balance

Table -3.2: Mechanical Properties

Property	UNS S31803	
	Catalogue	Actual
Modulus of Elasticity (GPa)	192-199	193
Poisson's ratio	0.27 – 0.30	0.27
Brinell Hardness (HBW)	149 – 217	184
Tensile strength (MPa)	500 - 700	698

Note: Brinell Hardness Number (BHN) is designated by the most commonly used test standards (ASTM E10-14 and ISO 6506-1:2005) as HBW (H from hardness, B from Brinell and W from the material of the indenter, tungsten (wolfram) carbide). Brinell hardness is mentioned in Table 3.2 using the above standard notation.

3.1 UNS S31803

The values of Elastic Modulus, Rigidity Modulus & Poisson‟s Ratio are computed, for the above said steel by using Deflection and Torsion Tests. Deflection test calculations are depicted here.

W = Applied Load

L = Length of the rod E = Elastic Modulus

I = Moment of Inertia

δ = Deflection of the beam

Here, $I = \frac{\pi d^4}{64}$,

For circular cross-section where d = Diameter of the rod.

The deflection test experiment is conducted two times for error reduction and Reliability of the answer. The first and second trial results of deflection test are presented in Table 3.3 and 3.4.

Table -3.3: Trail – 1 of deflection test

Parameter	Value	Units	Value Type
L	1000	mm	Pre-defined
D	14	mm	Pre-defined
I	1886.5	mm^4	Pre-defined
δ	1.1	mm	Measured
W	19.25	N	Measured
E	**193259.1**	**N/mm^2**	**Calculated**

Table -3.3: Trail – 2 of deflection test

Parameter	Value	Units	Value Type
L	1000	mm	Pre-defined
D	14	mm	Pre-defined
I	1886.5	mm^4	Pre-defined
δ	1.23	mm	Measured
W	21.5	N	Measured
E	**193034.6**	**N/mm^2**	**Calculated**

3.2 UNS S31803 Specimens Fabrication

The values of Elastic Modulus, Rigidity Modulus & Poisson's Ratio are arrived at, for the above said steel by using Tensile Test and Torsion Test. The tensile testing is carried out on a Computerized Universal Testing machine (Make: Fine manufacturing group) of 100 KN capacity.

Tensile testing is also performed on UTMs of other organizations for validating the results. The UTM which is primarily used for the current research along with typical specimens before and after failure is depicted in the Figure 3.1

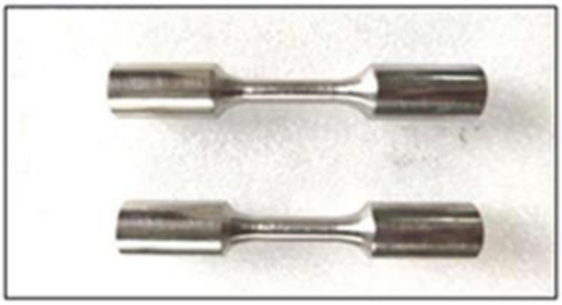

Fig -3.1: Specimen before faiolure

Fig -3.2: Failure Specimen

Fig -3.3: UTM used for Tensile Testing along with specimens

Hence Passion's ratio is taken as 0.3 from the literature survey.

3.3 Standard Fatigue Specimen

The fatigue specimens were fabricated for strain-controlled fatigue testing as specified by ASTM E606 standard. The gauge length is 15 mm for the specimen undertaken and the drawing of the specimen is presented in Figure 3.3.

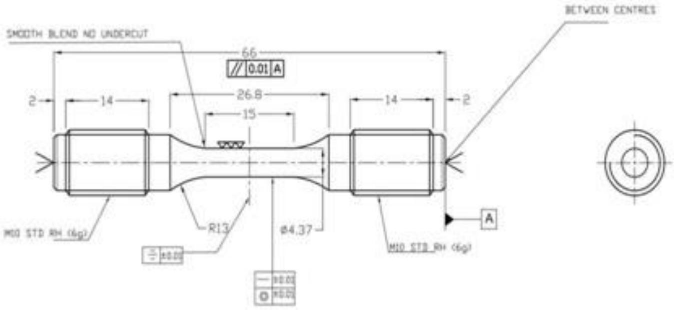

Fig -3.4: Standard Fatigue Specimen

Specimens are also fabricated with V-notches at the midpoint of the gauge length. Geometric parameters of the V-notch are depicted in Figure 3.4.

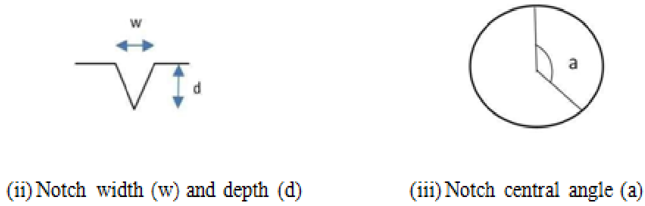

Fig -3.5: Fatigue Specimen and Notch Geometry

3.4 Specimen Fabrication

The specimens are fabricated on a CNC Lathe Machine (Figure 3.5) and the notches are made using a CNC Milling machine.

Fig -3.6: Jyoti DX200 CNC Lathe Machine

Typical un-notched and notched specimens after fabrication are shown in the Figure 3.7.

Fig -3.7: Un-notched Specimen

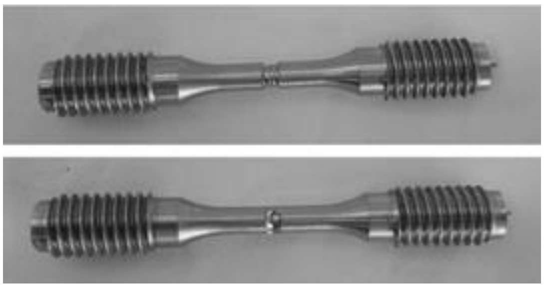

Fig -3.8: Notched Specimens

3.5 Empirical and Finite Element Methods

In the current Endurance Limit, "Stress (vs) Fatigue Life" curve, "Strain Amplitude (vs) Fatigue Life" curve are estimated for the materials undertaken using empirical and finite element methods.

Table -3.4: Fatigue Life cycles for 9 Specimens results for UNS S31803

S.No	Von-Miser Stress (MPa)	Fatigue Life (Cycles)
1	786.47	2825
2	858.04	1969.8
3	898.7	1635.4
4	800.2	2626.4
5	794.42	2707.7
6	957.6	1274.9
7	769.2	3105.2
8	777	2973.6
9	114.54	651.16

3.5 Equivalent Stress

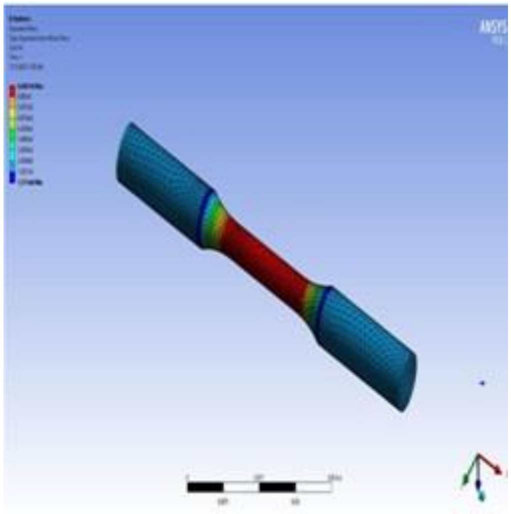

Fig -3.9: Equivalent Stress for No-Notch Specimen – 1

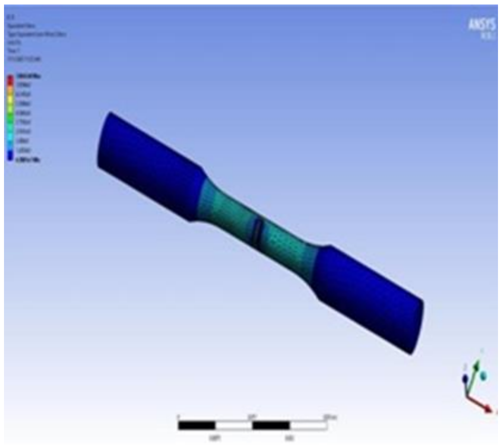

Fig -3.10: Equivalent Stress for Notch Specimen - 1

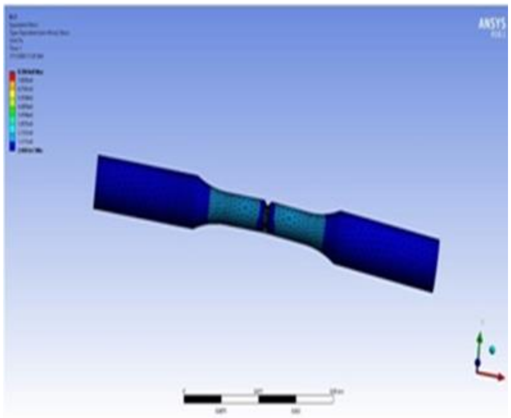

Fig -3.11: Equivalent Stress for Notch Specimen – 2

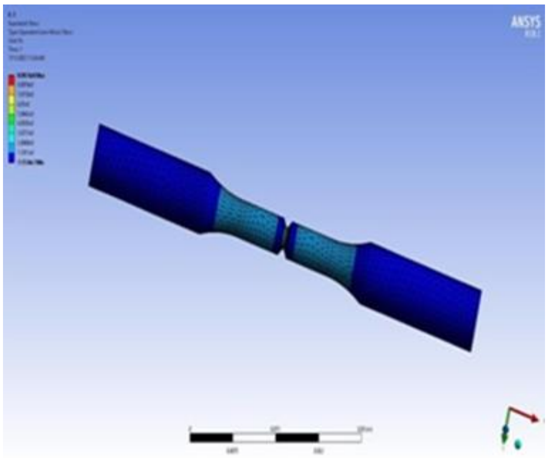

Fig -3.12: Equivalent Stress for Notch Specimen – 3

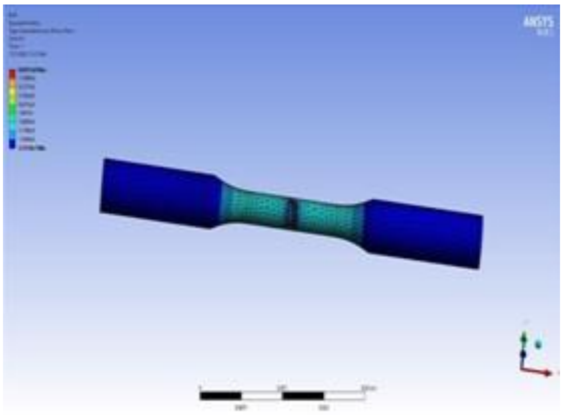

Fig -3.13: Equivalent Stress for Notch Specimen – 4

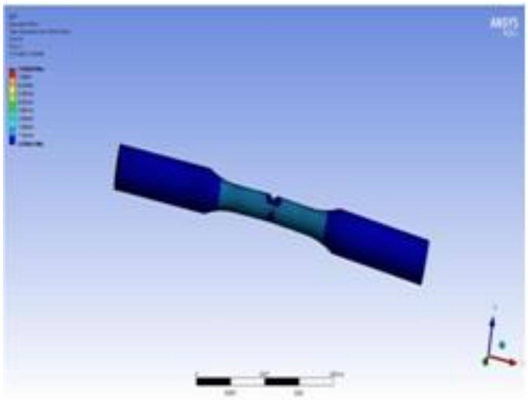

Fig -3.14: Equivalent Stress for Notch Specimen – 5

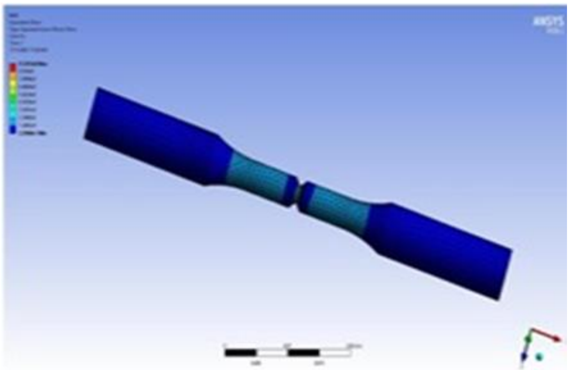

Fig -3.15: Equivalent Stress for Notch Specimen –6

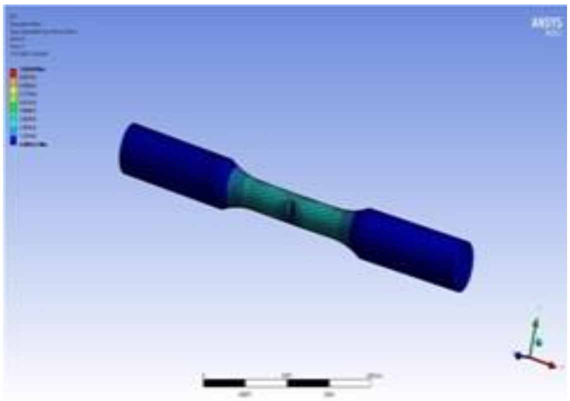

Fig -3.16: Equivalent Stress for Notch Specimen – 7

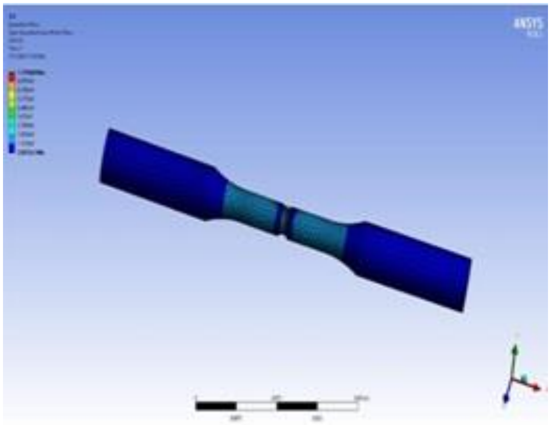

Fig -3.17: Equivalent Stress for Notch Specimen - 8

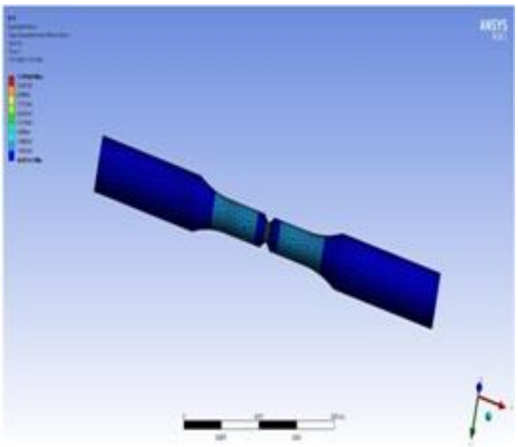

Fig -3.18: Equivalent Stress for Notch Specimen - 9

Fatigue life cycles for No- Notch specimen in Ansys18.1

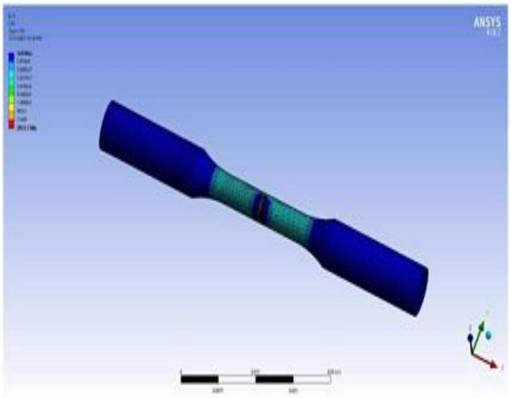

Fig -3.19: Fatigue Lifecycles for No-Notch Specimen

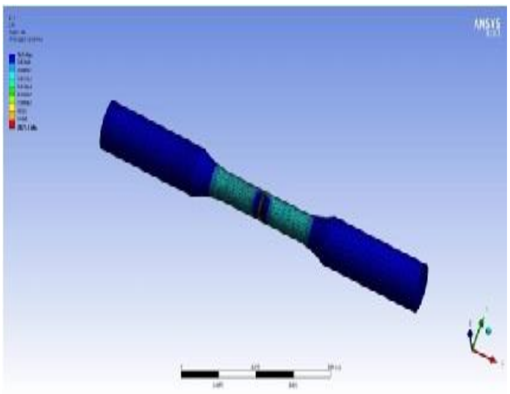

Fig -3.20: Fatigue Lifecycles for Notch Specimen – 1

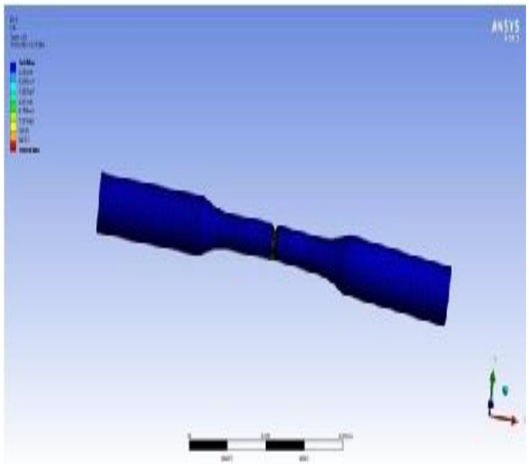

Fig -3.21: Fatigue Lifecycles for Notch Specimen – 2

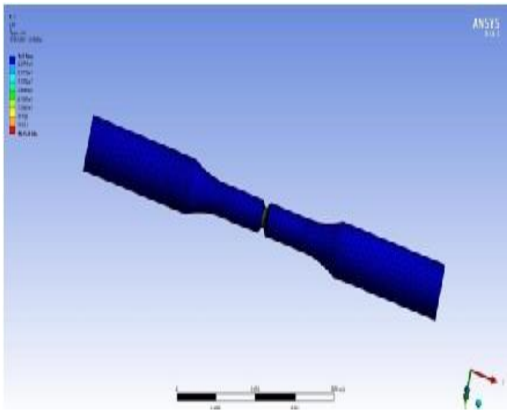

Fig -3.22: Fatigue Lifecycles for Notch Specimen - 3

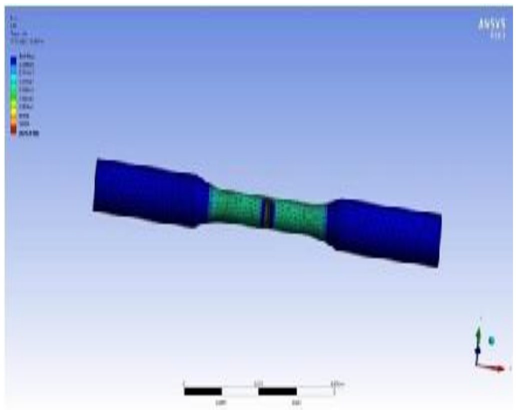

Fig -3.23: Fatigue Lifecycles for Notch Specimen – 4

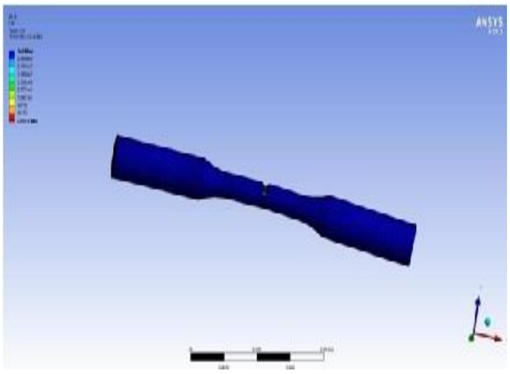

Fig -3.24: Fatigue Lifecycles for Notch Specimen – 5

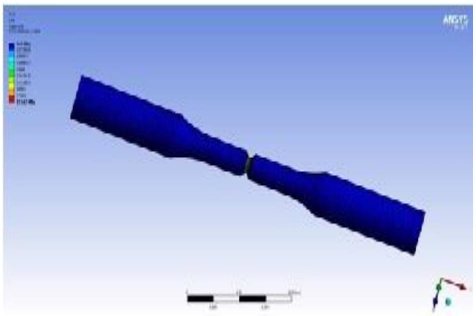

Fig -3.25: Fatigue Lifecycles for Notch Specimen – 6

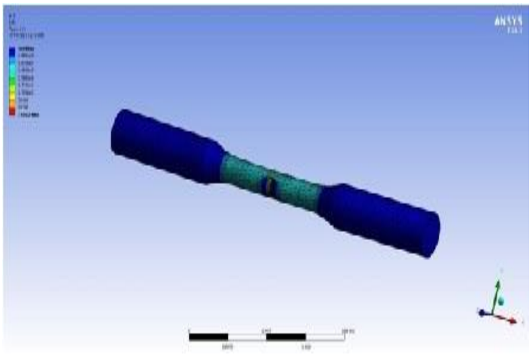

Fig -3.26: Fatigue Lifecycles for Notch Specimen – 7

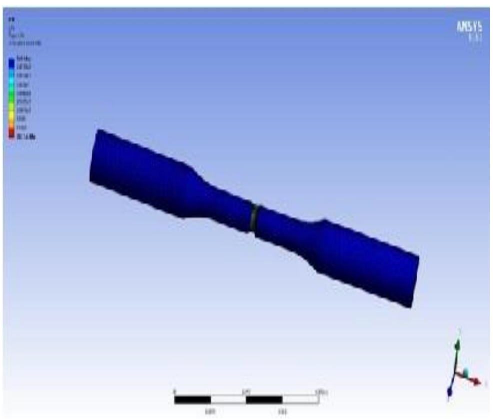

Fig -3.27: Fatigue Lifecycles for Notch Specimen – 8

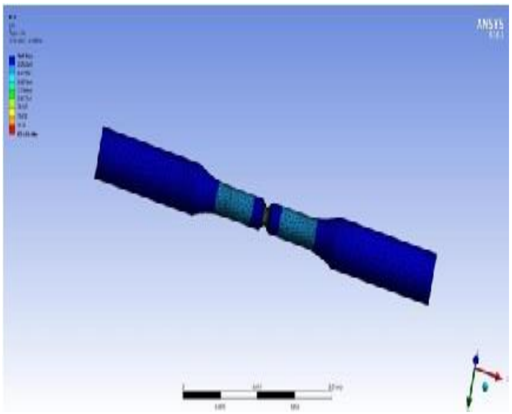

Fig -3.28: Fatigue Lifecycles for Notch Specimen - 9

4. Experimentation

4.1 Impact of Notch Geometry on the Fatigue Life

Specimens without notch and with various types of notches as per Taguchi L9 orthogonal array were fabricated using a CNC Lathe. Both parent material and welded samples were used to fabricate the specimens based on the scenario. Strain controlled fatigue runs were executed with 0.3% strain amplitude on the specimens till there was an appreciable crack observed on the specimen. Fatigue runs were initially undertakenon the specimen without any notch on its surface and the fatigue life in cycles was recorded. Thereafter, the fatigue test runs were undertaken for the nine specimens with various types of notch geometries on their surfaces and the fatigue lives were noted.

Fig -4.1: UNS S31803 specimens post fabrication

Fig -4.2: UNS S31803 un-notched specimen after failure

Table -3.4: Fatigue Life cycles for 9 Specimens results for UNS S31803

Table -4.1: Different notches

7) UNS S31803 Notch Scenario 7 Width(mm) 1.5 Depth (mm) 0.5 Fatigue Life (cycles) 2196 Notch Central Angle 360° 	8) UNS S31803 Notch Scenario 8 Width(mm) 1.5 Depth (mm) 0.75 Fatigue Life (cycles) 3790 Notch Central Angle 120° 	9) UNS S31803 Notch Scenario 9 Width(mm) 1.5 Depth (mm) 1 Fatigue Life (cycles) 1166 Notch Central Angle 240° 

Table -4.2: Different notches

Run	w	d	a	Fatigue Life (cycles)		
				Trial 1	Trial 2	Average
1	-1	-1	-1	2560	2388	2474
2	-1	0	0	2361	2321	2341
3	-1	1	1	542	620	581
4	0	-1	0	6583	6612	6597.5
5	0	0	1	1392	1296	1344
6	0	1	-1	2663	2595	2629
7	1	-1	1	2196	2202	2199
8	1	0	-1	3790	3622	3706
9	1	1	0	1166	1205	1185.5

5. Summary

1. Endurance Limit for the materials undertaken was estimated using empirical and finite element methods. Following are the estimated values of the endurance limit.

UNS S31803	
Empirical Method	FE Method
299.47 MPa	303.95 MPa

2. S-N plot from Shigley's empirical method, S-N curve from Finite Element method and the $\Delta\epsilon/2$ – N curve from Muralidharan-Mansion method gave the datum to the experimental investigation.

3. Fatigue test results of un-notched specimens of different test scenarios of UNS S31803 fatigue life.

Fatigue test results of un-notched specimens	
Test scenario	Fatigue Life (cycles)
UNS S31803 parent material	2474

4. The percentage contribution of the three notch parameters (width, depth and notch central angle) on the reduction of fatigue life is summarized and it is evident that depth of notch has vital impact on the fatigue life when compared to the other two parameters.

% Contributions of notch parameters from ANOVA for Taguchi Analysis			
Test scenario	w	d	a
UNS S31803 parent material	18.48	31.55	26.41

6. Conclusions

1. Endurance limit values estimated through empirical and finite element methods are in consonance with the actual value of the materials. For UNS S31803, endurance limit from empirical method is 299.47 MPa and from finite element method (ANSYS 18.1) the value is 303.95 MPa.

2. Taguchi analysis based on L9 orthogonal array shows that the depth of notch has 31.55% effect, notch central angle has 26.41% effect and width of the notch has 18.48% effect on the reduction of fatigue life of the chosen materials and their similar.

3. Duplex Steel UNS S31803 is an incredibly versatile stainless-steel alloy that offers numerous benefits due to its combination of austenitic and ferritic phases, which gives it exceptional mechanical properties. It is evident from the current project results that this material has very good fatigue properties even under notched conditions.

4. For UNS S31803, the optimal parameters are found to be, width and notch central angle at their mid levels while the depth at its lowest level.

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