Study the Effect of Welding Joint Location on the Fatigue Strength and Fatigue Life for Steel Weldment

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Abstract:

The welding process is one of the oldest joining processes between the materials, this paper try to find the effect of welding joint location in the steel on the fatigue strength of steel.

The welding process done by electrical arc welding to joining steel samples at different locations at (X/L=0.25, X/L=0.5, and X/L=0.75), where (X) the location of welding zone centre and sample subjected to fully reversed bending stress, then comparing the fatigue test results with un-welded sample. The experimental results show that the welding joint decrease the tensile strength of steel and the fatigue failure strength also decreased specially for that with (X/L=0.5 and X/L=0.75) and failure occur at welding zone, but the sample with (X/L=0.25) had less effected by welding joint and the failure occur at the support not at welding zone. The results show fatigue life affected by the welding joint when draw (S-N) diagram for each sample especially for sample with (X/L=0.5 and X/L=0.75).

Keywords: welding of steel, fatigue, S-N diagram, finite element analysis, fatigue behavior of steel weldment.

1. Introduction:

Welding fabrication is one of the most common joining procedures of metallic structure.

The vast majority of component fatigue failures take place at the welded connections when the welded structures subjected to fatigue and impact loading. [1]

Fatigue of materials is a very complex process, which is still today not fully understood and it is known as (material subjected to a repetitive fluctuating load and will eventually fail at load much lower than that required to cause fracture on single application of the load) .[2]

The damage of the material in fatigue starts in the crystalline structure and becomes visible in a later stage by plastic deformation, formation of micro-cracks on slip bands, coalescence of micro cracks and finally propagation of a main crack . Many influence factors complicate the subject. The behavior of different materials and the effect of these influence factors has been extensively investigated. Very often, the phenomena are analyzed and further evaluated with the aim of wider application, figure (1), show sample of fatigue crack surface

Fatigue of welds is even more complex. Welding strongly affects the material by the process of heating and subsequent cooling as well as by the fusion process with additional filler material, resulting in inhomogeneous and different materials. Furthermore, a weld is usually far from being perfect, containing inclusions, pores, cavities, undercuts etc. The shape of the weld profile and non-welded root gaps create high stress concentrations with widely varying geometry parameters. Last but not least residual stresses and distortions due to the welding process affect the fatigue behavior.

Therefore, fatigue failures appear in welded structures mostly at the welds rather than in the base metal, even if the latter contains notches such as openings or re-entrant corners. For this reason, fatigue analyses are of high practical interest for all cyclic loaded welded structures, such as ships, offshore structures, cranes, bridges, vehicles, railcars etc. In view of the complexity of the subject and the wide area of application, it is not surprising that several approaches for fatigue analysis of welded joints exist. However, it is almost impossible to follow up the great amount of related literature dealing with fatigue testing and the development or application of approaches to consider all the different influence parameters.[3]

The welds consist of base material, heat affected zone (HAZ) and deposited metal, figure (2.) shows the schema of the weld microstructure. The filler material and part of the base material meltdown during welding and form solidified weld metal, while the base material in the close vicinity undergoes a transformation. The (HAZ) formation is result of an applied thermal cycle caused by the heat source movement which necessary to melt the material. The effects of the thermal cycle diminish with distance from the fusion line. Materials close to the weld metal are heated almost to melting point and the high temperature produces a grain growth. The result is the formation of coarse-grained microstructure in the so-called coarse-grain heat-affected zone (CGHAZ) adjacent to the fusion line. This microstructure influences the mechanical properties such as impact toughness and fatigue strength**. [**4]

2. The aim and scope :

The aim of this work is the study the effect of the location of welding joint on the fatigue life and fatigue strength of rotating steel shaft and finding the best location for welding joint. The scope of this work is applied mechanics and the design of welding joint location.

3. Determining fatigue performance of welded structures: [5]

Welded components are less tolerant to fluctuating loads than their non-welded counter-parts for three reasons:

a) Welds contain internal flaws, which act as the initiation site for crack propagation.

b) Welds create external stress raisers, which act as the initiation site for crack propagation.

c) The process of welding introduces residual stresses in the region of the weld exacerbating the applied fluctuating stress.

The fatigue tolerance of welded structures can be classified into “detail categories” according to the type of weld and its orientation with respect to the applied fluctuating loads. The detail categories for steel structures are found in AS 4100 and AS 5100 and are used by structural steel designers when fluctuating loads occur during service. The detail category for any given weld configuration is a number between 36 and 180 that represents the stress range in (MPa) that can be tolerated for two million (2x106) fluctuating load cycles, figure (3) show the (S-N) diagram for steel .

4. Stress concentration factor: [6,7]

The fatigue fracture of structural details subjected to cyclic loads mostly occurs at a critical cross section with stress concentration. In a welded joints fatigue crack initiates at the weld toe and propagates through the main sample to a final fracture.

The local weld geometry affect the stress concentration factor and welding process create crack like defects, which together cause a large scatter in fatigue life depending on differences in these factors. Stress concentration factors should be use for parent metal as well as weld. There is often a trade off between stress concentration and over all size of weld. As the size of the weld grow so does the strength; unfortunately so dose the stress concentration, so the over all strength may be about the same.

5. Experimental Work :

4.1 Tensile test:

The samples of experimental work for tensile and fatigue tests were cutting from steel that had chemical composition shown in table (1).

Table.1
Chemical composition of steel samples (tensile and fatigue sample)

Component	C	Mn	Si	P	S
Percentage %	0.29	1.8	0.55	0.04	0.04

The steel samples will tested according to specification DIN 50125 to find the properties of sample like (young modulus, yield strength, and ultimate strength) via tensile test with using universal test machine that shown in figure (4). [8]

The sample was prepared by using lather machine until reach to the required dimensions as shown in figure (5).

To find the properties of welded joint, we cut the tensile sample at middle and the welded again by using electric arc welding technique (EAW) with weld metal type (AWS E6013) according to American Welding Society that had chemical composition shown in table (2), with mechanical properties of (yield strength 380MPa, ultimate strength 462MPa, and young modulus of 150GPa).[9]

Table.2
Chemical composition for weld metal type (E6013). [7]

Component	C	Mn	Si	P	S
Percentage %	0.06	0.32	0.23	0.012	0.013

5.2 Fatigue Test:

The fatigue testing done by using fatigue test machine as shown in figure (6), according to specification (ASTM E467) for the fatigue sample that shown in figure (7). [10]

The first group of fatigue samples did not cut, the second group of sample was cutting and welded at (X=0.25L), the third group at (X=0.5L), and the fourth group (X=0.75L). The group of loads (60N, 80N, 100N, 120N, and 150N) applied downward at free end of sample of diameter (8mm), while the other end of (12mm) diameter were fixed, and so that the sample will subjected to fully reverse bending stress when rotation at constant speed of (2800 r.p.m), and recording the number of cycles (fatigue life) for each sample till failure. For each test, we used two samples and take the average value for them.

6. Calculations:[11]

In most laboratory fatigue testing, the specimen is loaded so that stress it is cycled either between a maximum and minimum tensile stress or between a maximum tensile stress and specific level of compressive stress. The letter of the two, considered a negative tensile stress, are given an algebraic

minus sign and called the minimum stress.

The mean stress (σ_m) is algebraic average of maximum stress and minimum stress in one cycle :

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \qquad \text{equ.(1)}$$

The range of stress (σ_r) is algebraic difference between maximum stress and minimum stress in one cycle:

$$\sigma_r = \sigma_{\max} - \sigma_{\min} \qquad \text{equ.(2)}$$

The stress amplitude (σ_a) is one-half the range of stress in one cycle:

$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{\max} + \sigma_{\min}}{2} \qquad \text{equ.(3)}$$

The stress ratio is the algebraic ratio of two specific stress values in stress cycle :

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \qquad \text{equ.(4)}$$

The nominal stress in fully reversed bending loading test is:

$$\sigma_b = \frac{32M}{\pi * d^3} \qquad \text{equ.(5)}$$

$$M = P*L \qquad \text{equ.(6)}$$

d----- Sample diameter (m)

P-----Bending load (N)

The stress concentration factor (K_t) for stepped shaft depend on the dimension of stepped sample as shown in figure (10). [12]

According to ratio ($\frac{D}{d} = \frac{12}{8} = 1.5$) and ($\frac{r}{d} = \frac{2}{8} = 0.25$) with using the stress concentration factor curves as shown in figure (9), can find that the (K_t=1.41).

The fatigue stress concentration factor (K_f) depend on the value of stress concentration (K_t) and the notch sensitivity factor (q), that can found from notch sensitivity curve as shown in figure(10) and according to radius of notch (r=2mm) and ultimate strength for sample (σ_{ult}=715MPa) , can find the value of notch sensitivity (q=0.83).

The value of fatigue stress concentration according to equation (7).

$$K_f = 1 + q\,(K_t - 1) \qquad \text{equ.(7)}$$

So that value of fatigue stress concentration factor(K_f) can find by equation (7) as:

K_f =1+ 0.83 (1.41 -1) =1.34

So the value of actual fatigue stress is now equal to = Nominal fatigue stress *Fatigue stress concentration factor.

$$\sigma_{f_{act}} = \sigma_{f_{Nom}} * K_f \qquad \text{equ.(8)}$$

7. The Results and Discussion :

1- Figure (11) show the experimental stress-strain diagram for steel samples, and from this figure, can find the yield strength of sample is (465MPa), the ultimate tensile strength is equal to (715MPa), and the young modulus is (201MP) and these properties give good idea about the behavior of the samples under loading.

2- Figure (12) , show the experimental stress-strain diagram for steel sample that welded at middle point by using weld metal type (AWS E6013) , and the maximum stress for sample is decreased from (715MPa) to (425MPa) because the grains in fusion area been bigger than grains in base material and the carbon content increased in fusion area, so that the strength of the weld joint will be less than base material.

3-Figure (12) show the fatigue bending stress for welded and un-welded sample, and its show that the un-welded sample had behavior better than the welded samples and it need more load to failure under fatigue stress , so that it so clear the welded joint will make sample weaker than sample without welded joint.

4- Figures (13 to 16) show the (S-N) diagrams for welded and un-welded samples, and from this figures, can find the value of endurance strength for these samples.

-The endurance strength for sample welded at (X/L=0.25) is (170MPa) <u>but failure happened at the support end</u> not at welding zone with fatigue life is (210365 cycles) as shown in figure (13).

- The endurance strength for sample welded at (X/L=0.5), is (61MPa) and failure happened at the welding zone with fatigue life (156321cycles) as shown in figure (14).

- The endurance strength for sample welded at (X/L=0.75), is (88MPa) and failure happened at the welded zone with fatigue life (40883cycles) as shown in figure (15).

- The endurance strength for un-welded sample the endurance strength is (190MPa) and failure happened at the supported with fatigue life (281019 cycles) as shown in figure (16).

From these results, can notice that the welded joint in steel sample decreasing the endurance limit and fatigue life for welded samples with respect to un-welded sample.

5-Figure (17) show the failure location for fatigue samples that loaded at different location , and can notice that the failure occur at welding zone accept the sample welded at (X/L=0.25) , the failure occur at the support.

8. The Conclusion :

The welding joint in steel will reduce the fatigue life about (25%) for sample welded at (X/L=0.25) ,but failure occur at the support not at the welding zone by bending stress of (400MPa) , fatigue life reduces about (40%) for sample welded at (X/L=0.5) and the failure occur at (X/L=0.5) by bending stress of (61MPa) , and fatigue life reduces about (84%) for sample welded at (X/L=0.75) and failure occur at(X/L=0.75) by bending stress of (89.54MPa) . The stress failure affected by the location of welding zone and especially for samples that welded far of the point of load applying. The better location for welding is closest to point of load applying (bending load) to reduce the bending moment at welding zone and that reduce the fully reversed bending stress at welding zone. The tensile strength of steel decreased about (40%) when it welded and it behave as brittle material. For future work may can study the effect of welding joint location on the another materials like brass, aluminum and etc , and may be study the effect another factors that affected by welding joint location.

9. References:

1- C. Rubio-Gonzalez, Effect of Fatigue Damage of The Dynamic Tensile Behavior of Carbon Steel Welded joints, 2010.

2- Sindo Kou, Welded Metallurgy, 2nd Edition, WILEY INTERSCIENCE, 2003.

3-Wolfgang Fricke, Fatigue Analysis of Welded Joints: State of Development, Elsevier, Marine Structure, Vol.16, 2003, p (185-200).

4-T. Vuherera, A.Godina, Fatigue Crack Initiation From Microstructurally Small Vickers Indentations, Metabk Vol.46, p.(237-243) , 2007.

5-Introduction to Fatigue of Welded Steel Structure and Post-Weld Improvement Techniques, Welding Technology Institute of Australia, 2006.

6-Zoran D.Perovic, The Weld Profile Effect On Stress Concentration Factors in Weldments, 15th International Research /Expert Conference (Trends in The Development of Machinery and Associated Technology) Czech Republic, 2011.

7-Eric Sawyer, Weld Poster Explanation, Dagmar Customs, 2012.

8-Tensile Testing Data, G.U.N.T Geratebau GmbH, Hamburger, 2007.

9-Basic Welding Filler Metal Technology, Corresponding Course Lesson 1, ESAB Group, 2000.

10- Fatigue Testing Data, G.U.N.T Geratebau GmbH, Hamburger, 2007.

11-Bruce Boardman, Fatigue Resistance of Steels, ASM Handbook, vol.1, p(673-688) , 1990 .

12- Walter D.Pilkey, Petersons Stress Concentration Factors, 2nd Edition, WILEY INTERSCIENCE, 1997.

13- Module 3, Design for Strength, Stress Concentration, Lesson 2, Version 2 ME, Kharagpour, 2010.

Figure.1. Fatigue crack surface. [2]

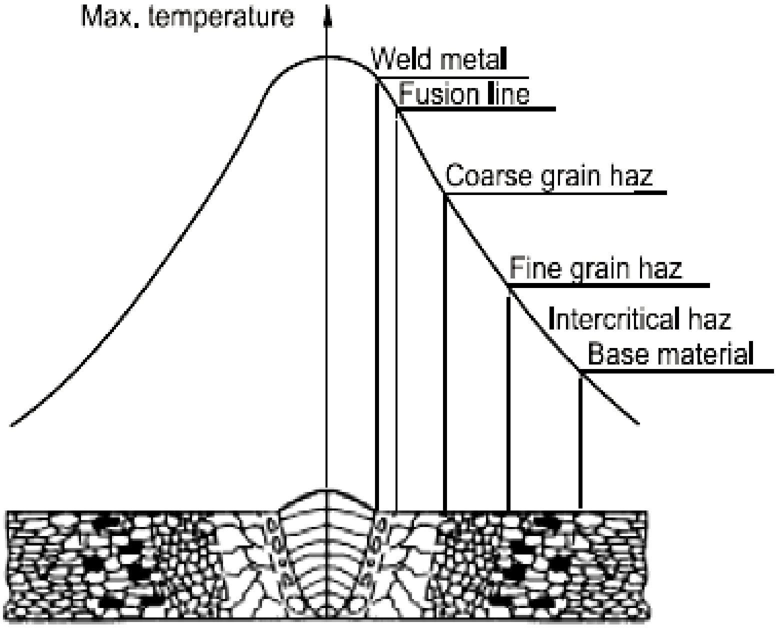

Figure.2. The microstructure across the weld. [4]

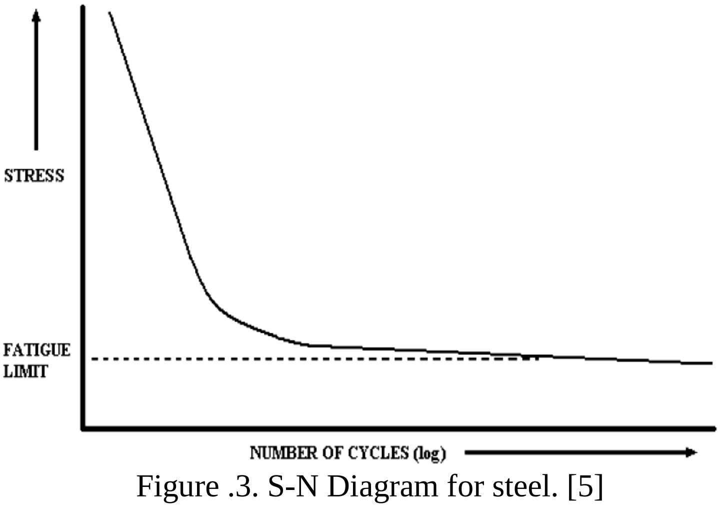

Figure .3. S-N Diagram for steel. [5]

Figure .4 Tensile test machine.

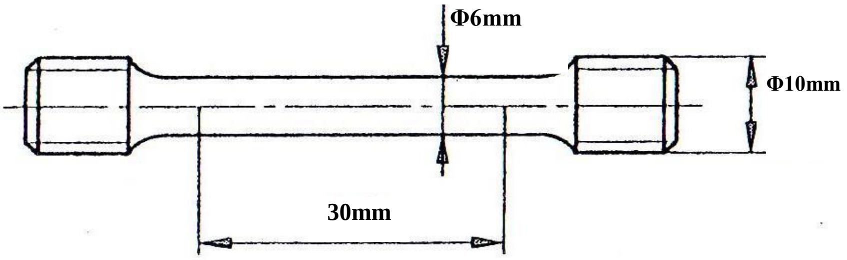

Figure .5. Tensile test sample

Figure .6.Fatigue test machine

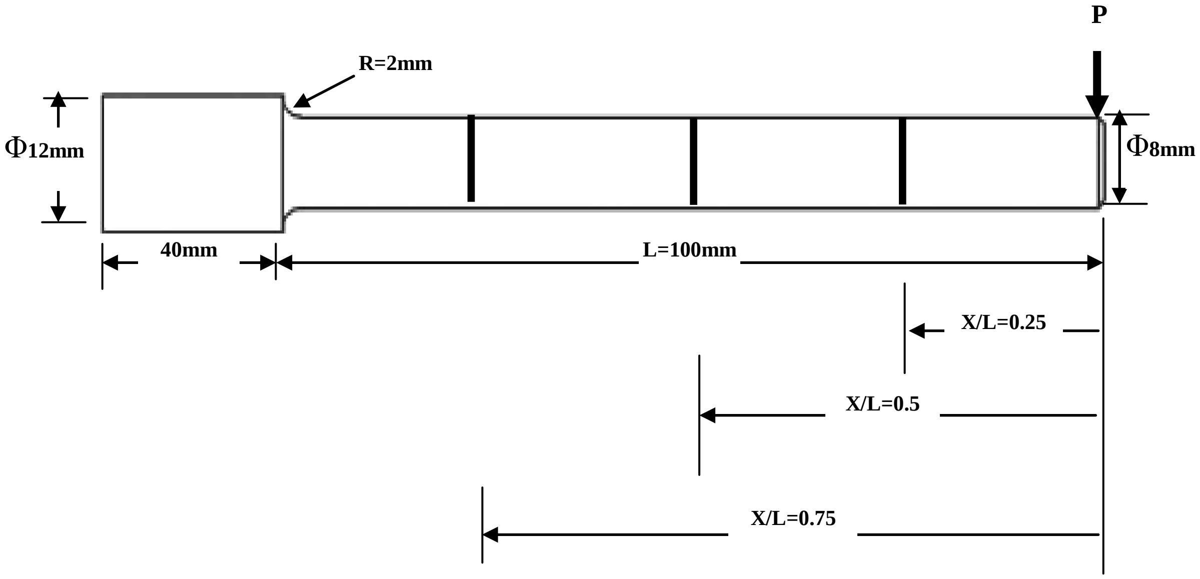

Figure .7.Fatigue test sample

Where: (X) is the location of welded joint.

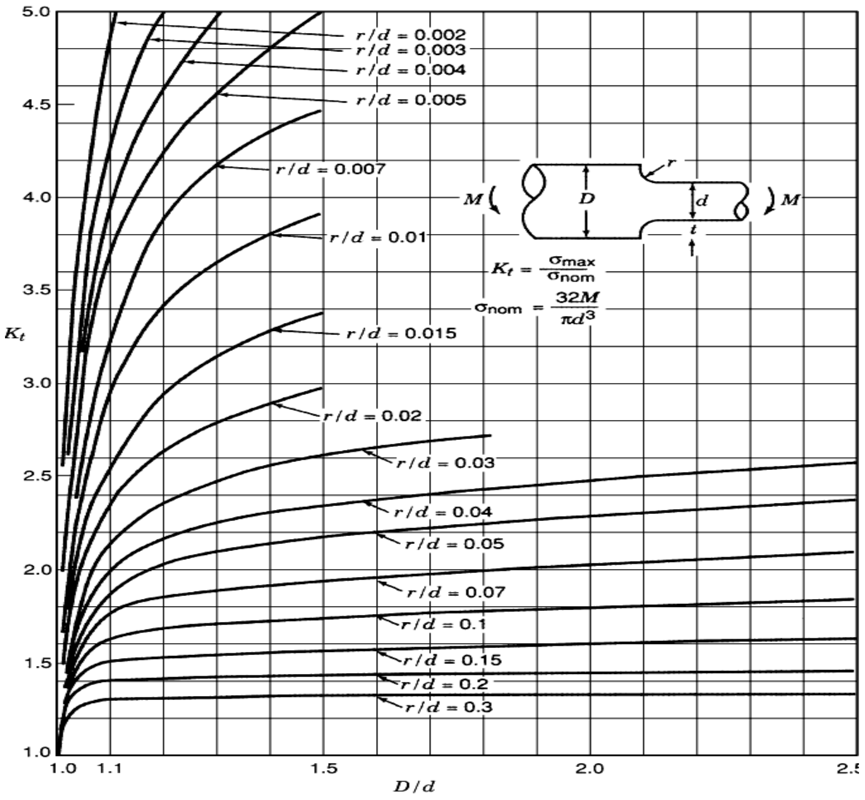

Fig.8. Stress concentration factor curve. [12]

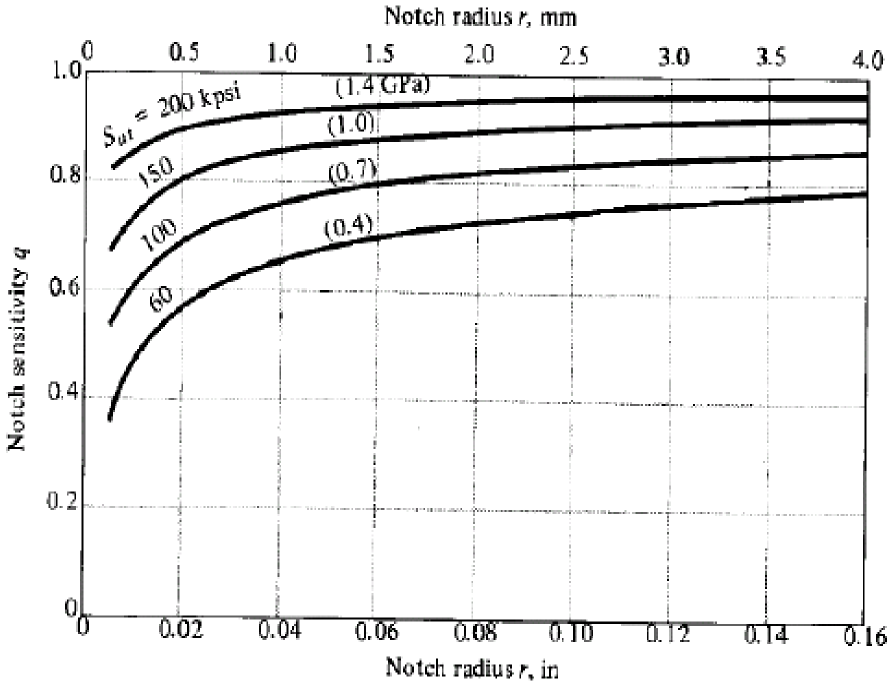

Fig.9. Variation of Notch sensitivity (q) with notch radius (r) for steel of different ultimate tensile strength (UTS) . [13]

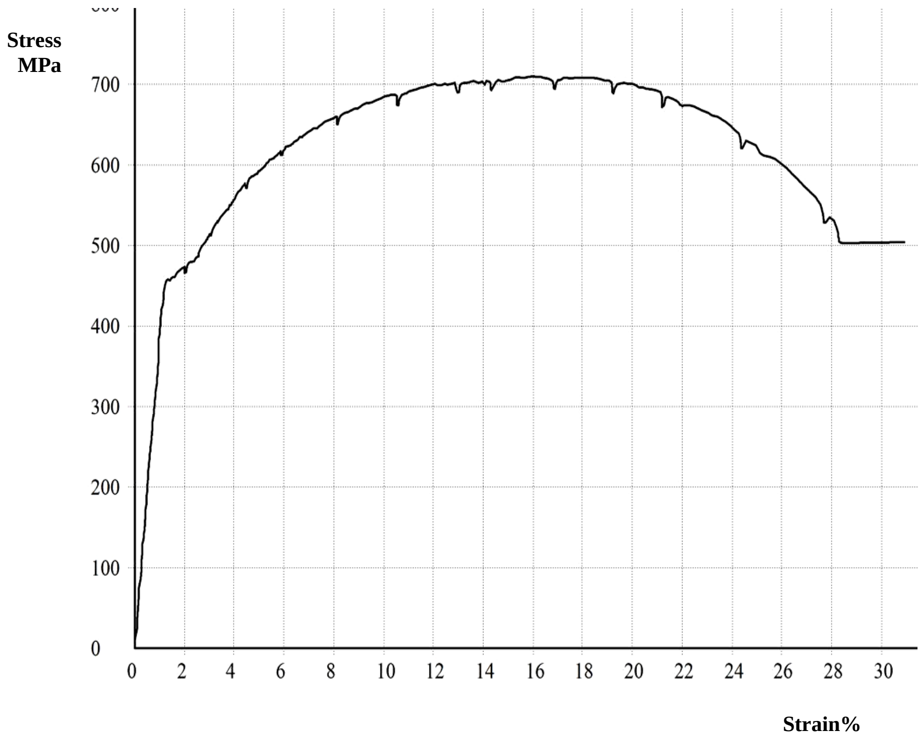

Fig.10. Stress-strain diagram for steel sample.

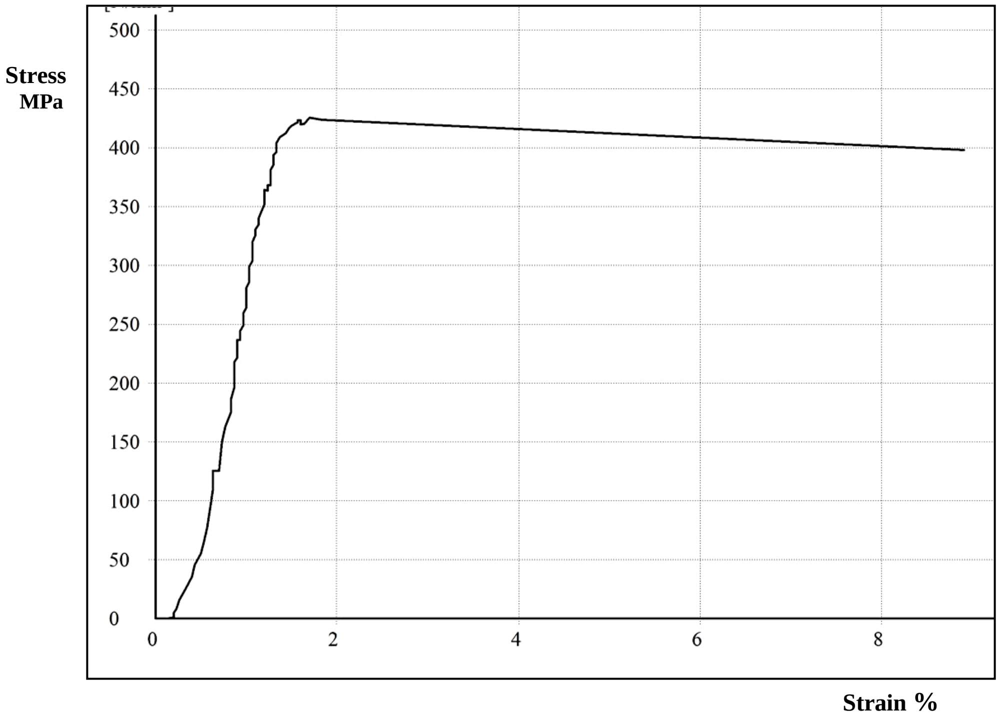

Fig.11. Stress-strain diagram for welded steel sample

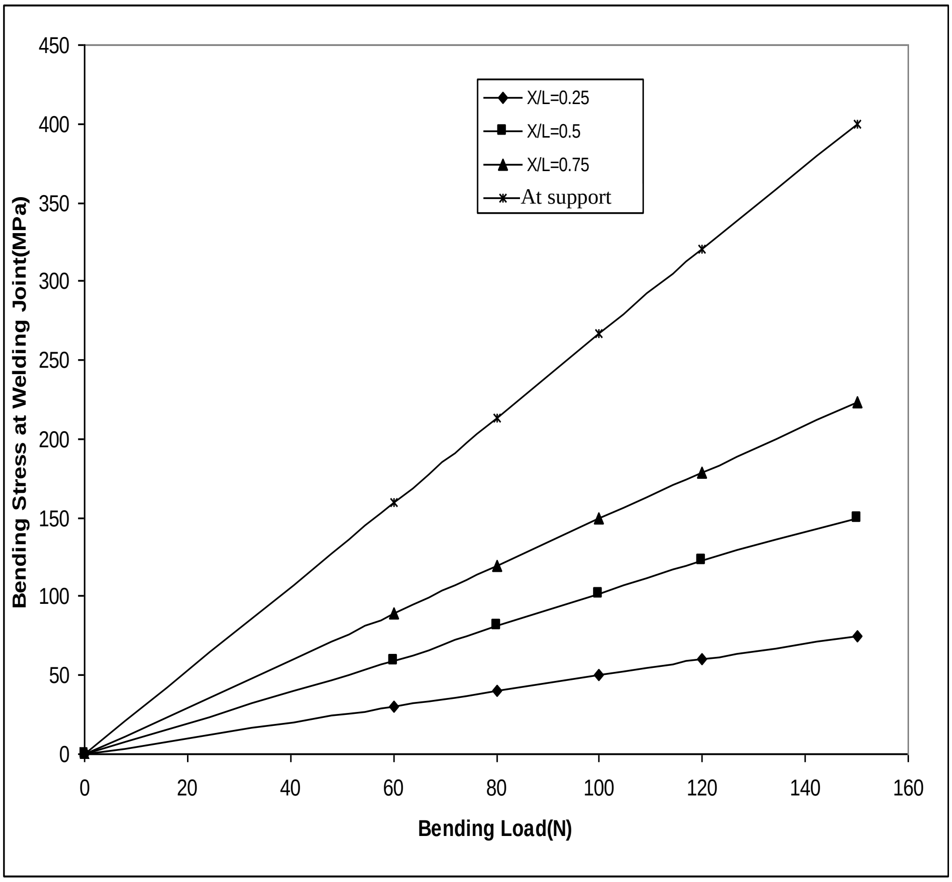

Fig.12. Experimental fatigue bending stress at welding zone for welded and un-welded samples.

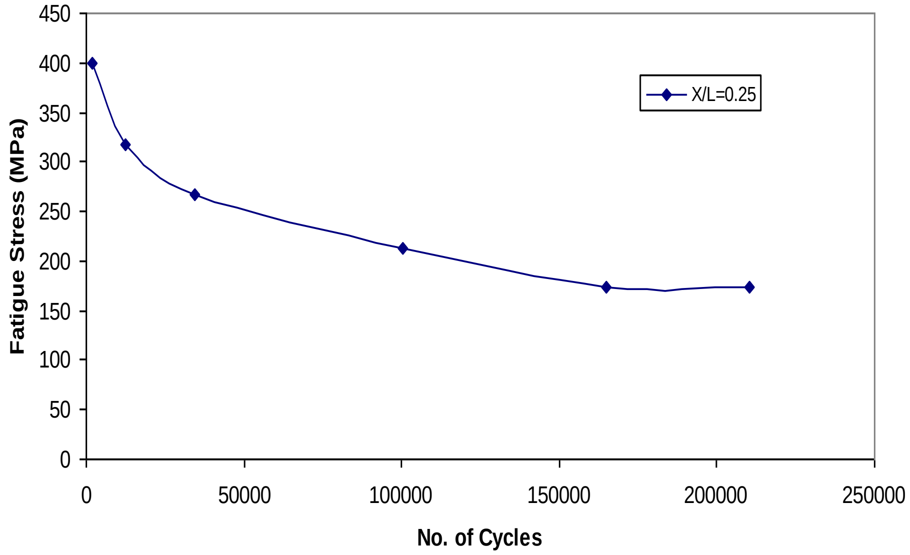

Fig.13. (S-N) diagram for (X/L=0.25) sample

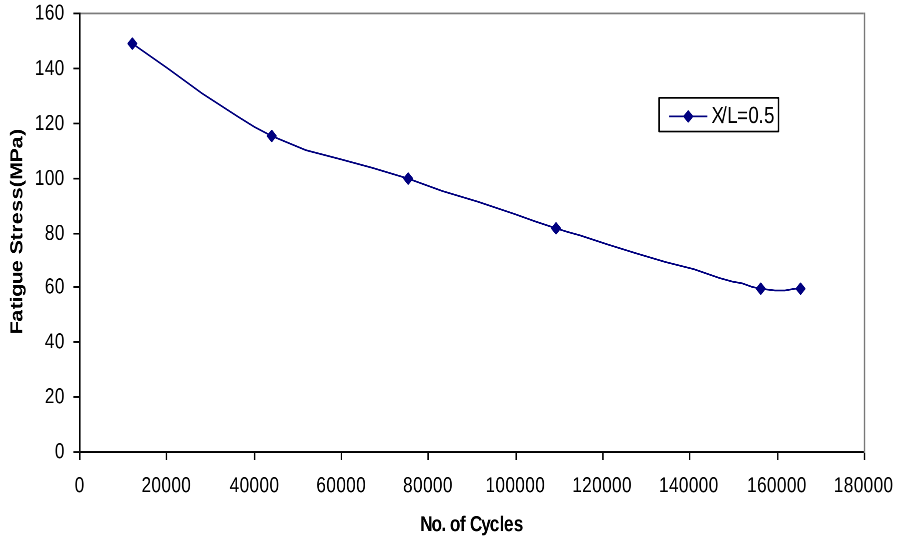

Fig.14. (S-N) diagram for (X/L=0. 5) sample

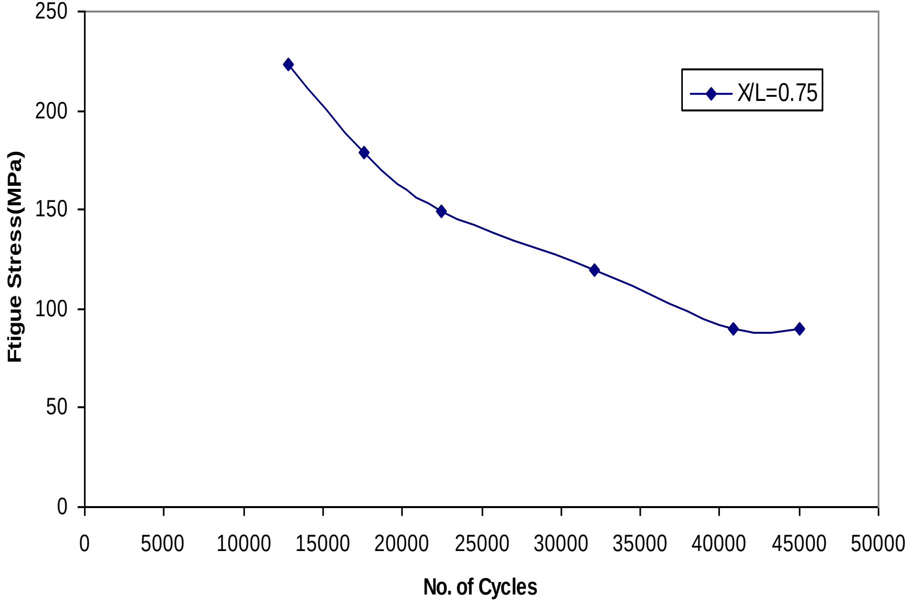

Fig.15. (S-N) diagram for (X/L=0. 75) sample

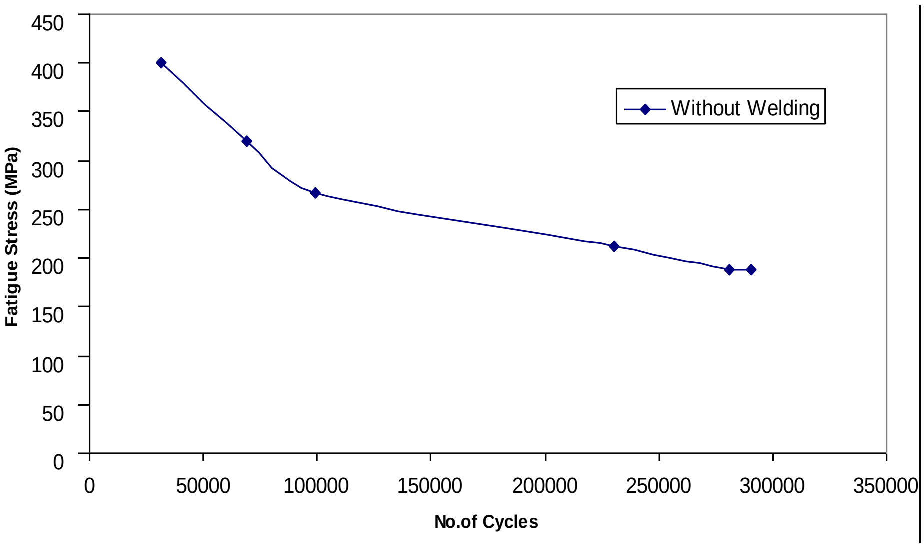

Fig.16. (S-N) diagram for un-welded sample

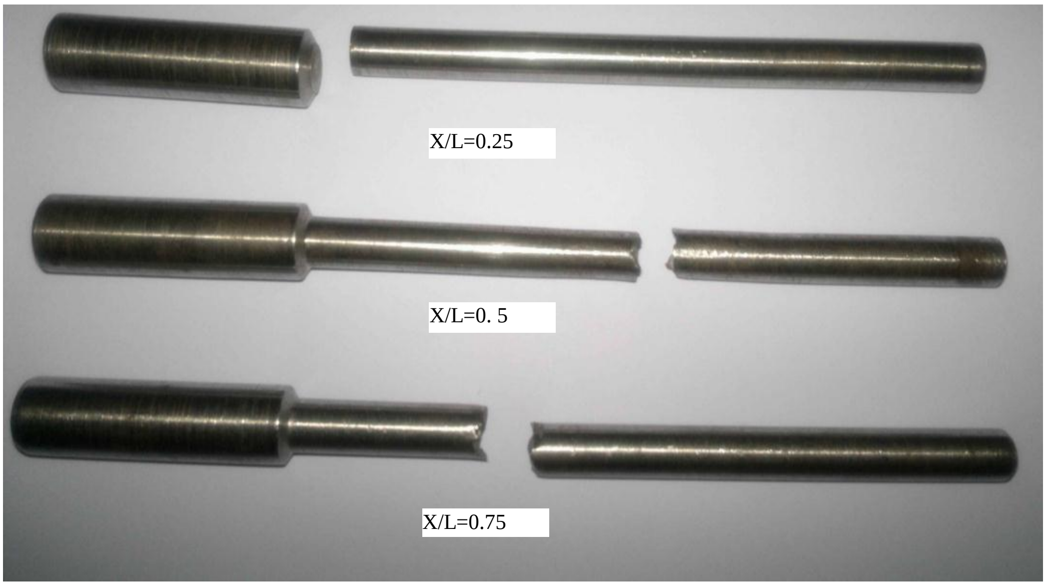

Fig.17. The fatigue failure of steel samples at different location of welding.