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EVALUATION OF FATIGUE STRENGTH OF ANSI 304 STEEL PIPE WELDS

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ABSTRACT

ANSI 304 austenitic steel is alloy steel with high Ni and Cr content, and this steel has high strength, heat resistance, corrosion resistance, is not magnetized, and is especially easy to weld. However, regarding the welding process of ANSI 304 steel, the heat-affected area is very sensitive and leads to hot cracking of the weld metal. The higher hot crack forming characteristics of the Austenitic group than other alloys, along with a higher coefficient of thermal expansion, lower coefficient of thermal conductivity, welding mode, etc., are the factors that strongly affect the quality of ANSI 304 steel welds. Tensile strength and fatigue strength of welds are two important parameters characterizing the life and safety of the structure. In this paper, an experimental method is used to evaluate the influence of welding materials, welding mode, and weld geometry parameters on the tensile strength of welds when welding ANSI 304 steel pipes. Thereby, find the optimal set of welding mode parameters to fabricate the test samples. Using the Weibull distribution function and Loga normal distribution function, the fatigue graph and fatigue regression equation are built to evaluate the fatigue strength of ANSI 304 steel pipe welds.

Keywords: ANSI 304 steel, Austenitic, welding mode, tensile strength, fatigue strength.

1. INTRODUCTION

ANSI 304 steel pipe is widely used in harsh environments such as in the pipeline and petrochemical industry. Due to the high cost of this steel along with high-reliability requirements during use, the correct selection of welding mode plays an important role in avoiding economic losses. In which, fatigue strength is an important criterion that determines the reliability of the weld. Through the survey, there have been a number of studies related to this issue, such as in the study [1] by the authors Vikas Chauhan and RS Jadoun, who studied "Optimizing the parameters of MIG welding for stainless steel ANSI 304 and low carbon steel using the Taguchi design method". The authors made some conclusions that the Taguchi method can be used to determine the influence of welding mode parameters such as welding current, voltage, and speed on the tensile strength of the weld. In which, the two parameters that most affect the tensile strength are voltage and welding speed. The effect of the parameters on the final tensile strength can be ranked in descending order as follows: voltage, welding speed, and amperage. The results also show that Argon gas is considered an effective shielding gas with the least spatter during welding. Pawan Kumar *et al*. [2] analyzed the influence of three parameters of welding mode, namely welding current strength, arc potential, and shielding gas flow. The results show that the welding amperage has the most significant influence on the hardness of the base metal, the weld area, and the heat-affected zones, followed by the pool potential optics and shielding gas flow. This result plays an important role in controlling welding parameters. K. Krishnaprasad *et al*. [3] studied the fatigue crack growth of welds of different materials between stainless steel and carbon steel. In this study, the authors used a pair of materials, SS316L stainless steel plate and IS2062 Grade A carbon steel, using TIG welding and SS309 auxiliary welding wire. With cracking initiated in the base metal region, the weld metal region, and the heat-affected zones. As a result, the crack growth rate was found to enhance the weld and the base metal stress. The fatigue crack growth rate in the heat-affected zone was the lowest in stainless steel, while in carbon steel; the crack growth rate was faster. Moreover, the scattering range of the data was found to be narrower. The crack resistance was found at different locations of the weld, and the crack resistance was found to have the lowest value at the weld and the highest value in the weld heat-affected zone. Wichan Chuaiphan *et al*. [4] studied the feasibility of welding two different materials between AISI 304 stainless steel and AISI 201 carbon steel plates with a thickness of 15 mm. The welding process applied his electrode arc welding without melting in an inert gas atmosphere and manual arc welding. In this study, we conducted an experimental study to evaluate the fatigue strength of ANSI 304 steel pipe welds by TIG welding because TIG welding can produce welds with good mechanical properties and anticorrosion.

2. MATERIALS AND METHODS

2.1 Experimental Modeling

The block diagram of the system for measuring the tensile and fatigue strength of the weld is shown in Figure-1. The results of the tensile test were used for welding the test specimens for the fatigue test. The obtained results are the fatigue curve graph and the experimental regression equation.

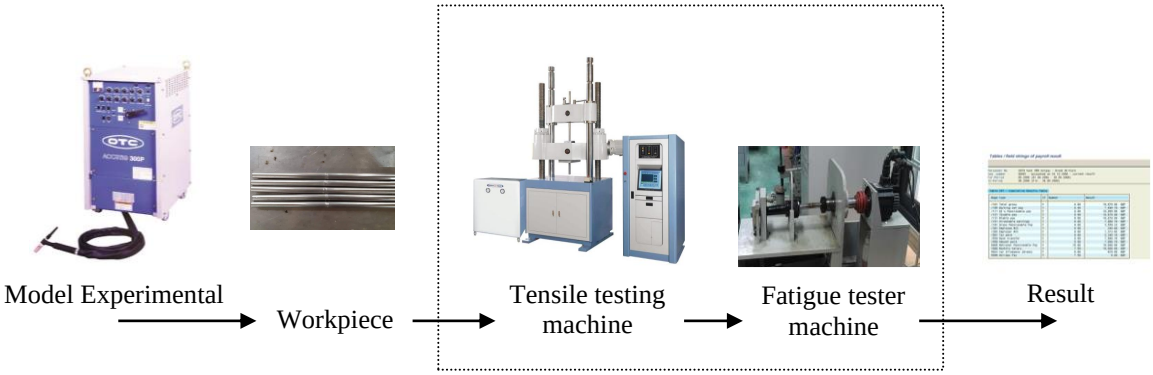

Figure-1. Block diagram of the measuring system.

2.2 Equipment and Test Workpieces

a) The welding machine

TIG welding machine OTC 300P - Daihen - Japan (see Figure-2) with its specifications shown in Table-1.

Figure-2. TIG welding machine OTC 300P.

Table-1. Specifications of TIG welding machine OTC 300P.

No	Parameters	Value
1	Power	18 KVA
2	Input power	AC - 3 phase / 380 V
3	Output power	AC/DC
4	Welding amperage	50 to 350 A
5	Dimensions of the machine	600x750x750

The welding parameters using the TIG welding method are shown in Table-2.

Table-2. Welding mode parameters.

Number of welding layers	Welding method	Diameter of welding rod (mm)	Welding amperage (A)	Voltage (V)	Current/ Electrode type	Protective gas delivery (L/min)
1	141	1.6	50÷70	10÷12	=/(-)	6÷8

b) Experimental workpieces

The ANSI 304 pipe workpiece has the size as shown in Figure-3. The chemical composition is shown in Table 3. Using a 308 stainless steel additive welding rod, the diameter of the welding rod is 1.6 mm, and the electrode is 100%W, the electrical diameter of the electrical pole is 2.4 mm, using shielding gas is 99.99% Ar gas. The test specimen after welding is shown in Figure-4 [5].

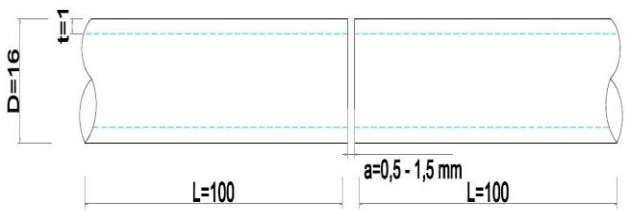

Figure-3. Experimental workpiece drawing before welding.

Figure-4. Experimental workpieces after welding.

Table-3. Chemical composition of ANSI 304 steel [6].

Standard	Steel brand	C	Cr	Ni	Mn	Other
AISI	304	0.08	18.0÷20.0	8.0÷10.5	2.00	-

c) The tensile testing machine

Using hydraulic tensile testing machine CY - 6040A12 - Taiwan to test the tensile strength of the weld with the specifications as Table-4.

Figure-5. Tensile testing machine CY - 6040A12.

Table-4. Specification of tensile testing machine CY - 6040A12.

No	Parameters	Value
1	Maximum load	100 ton
2	Accuracy	± 1%
3	Maximum test speed	50 mm/min
4	Workpiece diameter range	12 to 55 mm

d) The fatigue testing machine

The fatigue testing machine is based on a two-point bending principle, using a servo motor to adjust rotational speed. The machine's specifications are as shown in Table-5. The experimental workpiece works under repeated stress conditions according to cycle. When the weld is subjected to force, the inside of the weld will appear micro-cracks, they grow to a certain extent that will destroy the connection of the weld. Based on that, we tested the fatigue strength of the weld when the experimental workpiece was bent to both sides continuously during the fatigue test period.

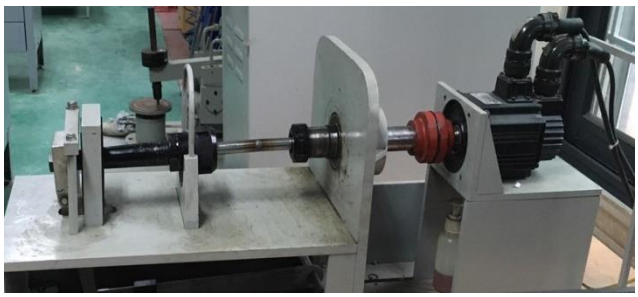

Figure-6. Fatigue testing machine of the weld.

Table-5. Specification of fatigue testing machine.

No	Parameters	Value
1	Power	1 kW
2	Load range	0.5 to 10 kg
3	Maximum workpiece length	250 mm
4	Workpiece diameter range	10 to 20 mm
5	Control parameters: Force, speed, position	

2.3 Taguchi Experimental Design to Evaluate the Tensile Strength of Welds

Conduct test for 9 ANSI 304 workpieces with different welding currents and clearances, using Taguchi L9 orthogonal table [7-9] with three input parameters as welding amperage (I_h), welding speed (V_h), and joint clearance (a), each parameter varies according to the three test levels. The parameter used to evaluate is the tensile strength (σ_k), as shown in Table-6.

Table-6. Taguchi L9 orthogonal table.

No	I_h (A)	V_h (cm/min)	a (mm)	σ_k (N/mm^2)
1	50	3	0.5	663
2	50	4.5	1.0	648
3	50	6	1.5	634
4	60	3	1.0	620
5	60	4.5	1.5	614
6	60	6	0.5	605
7	70	3	1.5	592
8	70	4.5	0.5	580
9	70	6	1.0	572

To consider the effect of the inputs I_h, V_h and a on the tensile strength, the signal factor SN is used (Signal to noise ratio):

$$SN_i = 10\log\frac{\bar{y}_i^2}{S_i^2} \quad (1)$$

In which:

Mean value of measurements for an experiment:

$$\bar{y}_i = \frac{1}{N_i}\sum_{u=1}^{N_i} y_{i,u} \quad (2)$$

Variance value:

$$S_i^2 = \frac{1}{N_i - 1}\sum_{u=1}^{N_i}(y_{i,u} - \bar{y}_i) \quad (3)$$

i - Experimental (i = 1÷9)
u - Experimental time (u = 1÷3)
N_i - Number of tests for experiment i (N_i = 1).

In the case of the largest requirement for the value of σ_k, SN_i is determined by the formula:

$$SN_i = -10\log\left[\frac{1}{N_i}\sum_{u=1}^{N_i}\frac{1}{y_u^2}\right] \quad (4)$$

Table-7. SN_i coefficient calculated for σ_k.

Experimental	I_h (A)	V_h (cm/min)	A (mm)	σ_k
				SN_i
1	50	3	0,5	56.430
2	50	4,5	1,0	56.232
3	50	6	1,5	56.042
4	60	3	1,0	55.848
5	60	4,5	1,5	55.763
6	60	6	0,5	55.635
7	70	3	1,5	55.446
8	70	4,5	0,5	55.269
9	70	6	1,0	55.148

The SN coefficient is calculated for each metric and level as follows:

$$SN_{P1,1} = \frac{(SN_1 + SN_2 + SN_3)}{3} \quad SN_{P1,2} = \frac{(SN_4 + SN_5 + SN_6)}{3}$$

$$SN_{P1,3} = \frac{(SN_7 + SN_8 + SN_9)}{3} \quad SN_{P2,1} = \frac{(SN_1 + SN_4 + SN_7)}{3}$$

$$SN_{P2,2} = \frac{(SN_2 + SN_5 + SN_8)}{3} \quad SN_{P2,3} = \frac{(SN_3 + SN_6 + SN_9)}{3}$$

$$SN_{P3,1} = \frac{(SN_1 + SN_6 + SN_8)}{3}$$

$$SN_{P3,2} = \frac{(SN_2 + SN_4 + SN_9)}{3}$$

$$SN_{P3,3} = \frac{(SN_3 + SN_5 + SN_7)}{3}$$

Table-8. The SN coefficient is calculated for each metric and level of I_h, V_h, and a.

Level	σ_k		
	SN coefficient of I_h	SN coefficient of V_h	SN coefficient of a
1	56.235	55.908	55.778
2	55.749	55.754	55.742
3	55.288	55.608	55.751
Δ	0.947	0.300	0.027
Rank	1	2	3

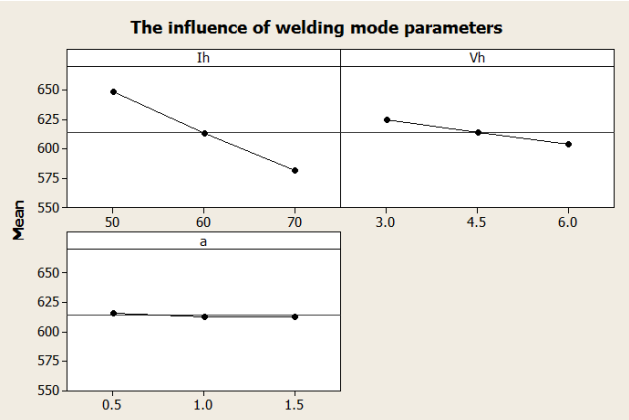

Figure-7. Graph of the influence of each main parameter on the tensile strength of the weld.

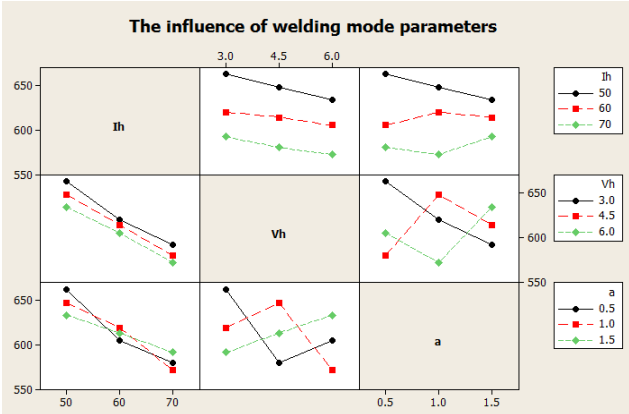

Figure-8. Graph of interactive effects of parameters on tensile strength of the weld.

Based on the influence ratings of welding parameters as shown in Table-8 and Figure-7, it can be seen that the I_h has the greatest influence on tensile strength σ_k compared to V_h and a. When the welding amperage is low and the joint gap is small, the weld does not overheat. It does not harden, making the weld more flexible and, therefore, the tensile strength higher. When the welding current and the gap are larger, it often causes overheating, making the weld harden, organizing the crystal lattice in a rough form, causing the phenomenon of easy breakage. As a result, the tensile strength decreases. The graphs in Figures 7 and 8 also show that to achieve the maximum tensile strength in the investigated region, I_h = 50 A, V_h = 3 cm/min, and a = 0.5 mm. Use this welding routine to weld 12 test specimens of ANSI 304 steel pipes for the purposes of assessing the fatigue strength of the weld.

3. RESULTS AND DISCUSSIONS

By using experimental data to compare with the estimated sample, four methods are used: standard method, Weibull method, Loga standard method, and Logit method [10-14]. Then proposed a new method:

Table-9. Compare methods.

Method	Relationship	Medium	% error	Sample size
Loga standard	$K_{N,a,g} = \frac{R}{f_N} = t\sqrt{\frac{1}{n} + u^2\left(y^2 - 1\right)}$	4,7066	5,4	7
Weibull	$K_{w,a,g} = \frac{R_w}{f_w} = \frac{t}{\sqrt{n-1}}\sqrt{\frac{c_n^2 c.n.V_0}{c^2 \left(n01\right)}}$	3,6224	4,76	10
Suggested (Weibull)	$K_{w,a,g} = \frac{R_w}{f_w} = \frac{t}{\sqrt{n-1}}\sqrt{\frac{c_n^2 c.n.V_0}{c^2 \left(n01\right)}}$	4,2158	5,08	9

ASTM 370 [5] defines two types of test:

- Preliminary test/survey or research and development
- Permissive design or reliable data

Table-10. Summary of recommendations for minimum sample sizes according to standards.

Test purpose	Minimum number of samples (ASTM E379)	Regeneration level	Number of repeat tests at repeated stress level	Number of stress ranges in test program	Conforms to ISO 12107
R&D	6	Minimum (=33%)	2	4	No
R&D	6	50%	3	3	Yes
Design	12	75%	4	3	Yes

Fatigue test data at low-stress levels will be more scattered because fatigue cracking is controlled by crack initiation and is less suitable for regression analysis when the values deviate towards the slope according to the regression results. Therefore, stress ranges must be chosen to produce lifetimes from 10,000 to 1,000,000. This will avoid the transition domain of the fatigue curve.

The above analysis selects the number of test pieces equal to 12 samples with stress levels according to the increment of the load of the testing machine (Increment of the load by 0.5 kg). By carrying out the test on the fatigue testing machine, the results are shown in Table-11.

Table-11. Measurement data on fatigue testing machine.

No	Stress (MPa)	Cycle N (Rotation)
1	86.95693215	1200000
2	115.9425762	850000
3	144.9282203	620000
4	173.9138643	400000
5	202.8995084	280000
6	231.8851524	160000
7	260.8707965	125000
8	289.8564405	85000
9	318.8420846	45000
10	347.8277286	25000
11	376.8133727	13500
12	405.7990167	3500

Fatigue test data were processed using Minitab 16.0 software. Enter data into the spreadsheet of the software, check the fit of the lifetime data with the Weibull distribution and the Loga normal distribution with 95% confidence. We have the graph of the data according to two distributions as Figure-9 and Figure-10. Comparing the two graphs, we find that the fatigue test data of the above weld is more consistent with the Loga normal distribution because, with the Weibull distribution, the scale parameter equals 261.339 is an inappropriate parameter.

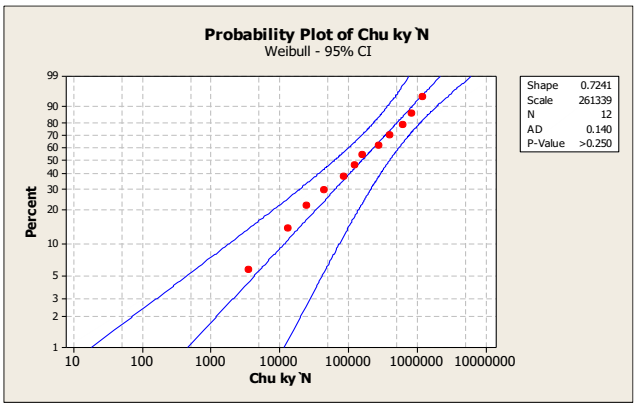

Figure-9. Fatigue reliability of the test sample (Weibull graph).

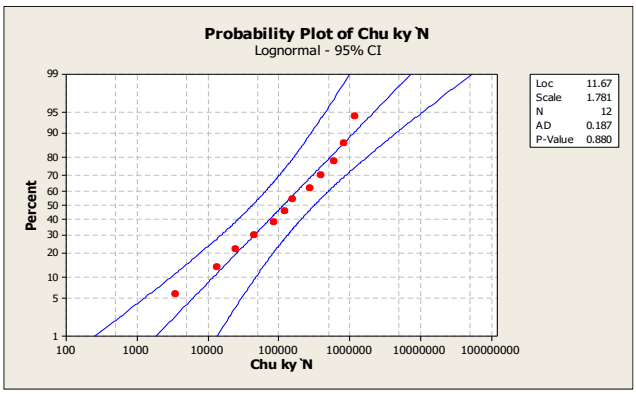

Figure-10. Fatigue reliability of the test sample (Loga standard graph).

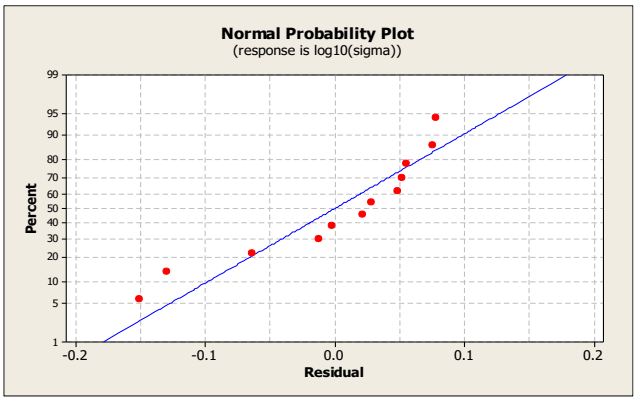

Figure-11. Graph of the residual standard error of the regression.

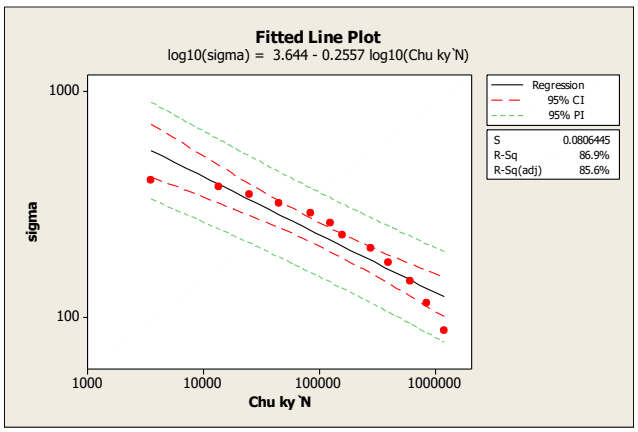

Figure-12. Weld fatigue curve graph.

Use ANOVA analysis for linear regression analysis of fatigue test data. The analysis of variance data is as shown in Table-12.

Table-12. Analysis of variance.

Source	DF	SS	MS	F	P
Regression	1	0.43008	0.43008	66.13	0.000
Error	10	0.06503	0.00650		
Total	11	0.49512			

The coefficients of the regression equation:

S = 0.0806445 R - Sq = 86.9% R - Sq(adj) = 85.6%

$$\log C = 3.644$$

$$m = \frac{1}{0,2557} = 3,91$$

The fatigue curve equation is as follows:

$$\log N = 3,644 - 3,91 \log s \quad (5)$$

The results comparing the theoretically calculated value with the experimental value verified in the experimental domain of the mechanical properties are quite consistent, which confirms the reliability of the theory and research results.

Through Figure-12 and Equation (5), it can be seen that the stress is inversely proportional to the number of cycles. However, the experimental fatigue curve shape is not exactly the same as the theoretical curve. Because of the position of the welding connection, there are differences in mechanical properties.

The number of cycles leading to part failure is recorded on the test table and analyzed based on the fatigue curve graph of the material. From the fatigue curve graph, we can calculate the fatigue strength of the material. In fact, the number of cycles N obtained (under the same stress conditions) is not exactly the same for each test. The number of cycles N in practice is usually less than the number of periods N in theory.

4. CONCLUSIONS

The width and depth of penetration of the welded joint depend mainly on V_h and I_h. If welding with small V_h and increasing I_h, then weld width increases. TIG welds with filler metal have a finer structure and better weld quality than conventional welds.

The tensile strength of the weld depends on the welding parameters to varying degrees. Welding amperage has the greatest influence then on welding speed, and the weld gap has the least influence of the three parameters.

In the experimental range, the welding parameters I_h = 50 A, V_h = 3 cm/min, and a = 0.5 mm have been found to achieve the maximum tensile strength.

Experimentally, the fatigue curve equation has been built, showing the relationship between stress and the number of cycles. These results predict the fatigue strength of ANSI 304 steel pipe welds and control welding parameters for production applications, especially mass production.

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