OPEN ACCESS
Saudi Journal of Engineering and Technology
Abbreviated Key Title: Saudi J Eng Technol
ISSN 2415-6272 (Print) |ISSN 2415-6264 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Original Research Article

Influence of Vibration on the Fatigue Limit of Epoxy Based Coating Used for Water Storage Tanks

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DOI: 10.36348/sjet.2022.v07i03.009 | **Received:** 17.02.2022 | **Accepted:** 23.03.2022 | **Published:** 30.03.2022

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Abstract

The fatigue damage and the stress distribution in potable water tanks coatings can be influenced by different factor particularly the vibration that results from various sources. In this paper, study the effect of vibration on fatigue resistance of two types of epoxy coatings (polyamine and polyamide epoxy coatings) used for potable water tanks. The vibration fatigue test apparatus is collected in the laboratory and used for testing. As a result the vibration reduced the fatigue limits of both types of coats compared to static case. Also, there is a reduced in values of the constants of Basquin's equation for vibration fatigue tests compared to the static case. The applied coatings improve the fatigue resistance of stainless steel.

Keywords: Epoxy coating, fatigue limit, vibration, potable water tank, AISI 316 steel, S-N curve.

1. INTRODUCTION

In Iraq cities, two types of large tanks are generally used and its spreads in all positions to store drinking water. These two types of tanks are elevated tanks and resting tanks on the ground. Corrosion, fatigue and vibration are the main problems of these tanks. These tanks are built by the welding process of various types of stainless steel like AISI 316, AISI 316L and ASTM 304. The applied epoxy coating is the best methods used to protect these tanks from the effect of water corrosion. The tanks are exposed to continuous full and empty process by drinking water and this exhibition the coatings to stress reach larger values when filled and lower value when tanks are empty, this causing the coatings subjected to fatigue behavior and emergence of cracks [1].

The storage tanks are subjected to vibration loading caused by different sources essentially high wind velocities, earthquake, high pumping flow rate and pumping pressure variations during fill… etc. [2]. These vibration loadings effect on fatigue behavior of the tank material and coating [3, 4]. In most cases, the term vibration-fatigue failure is used. This term is used to describe the fatigue behavior materials (fatigue damage) caused by the applied of forced vibration that can result from different sources [5]. Usually the fatigue tests results are drawn as a curve between applied cyclic stresses (S) against the number of cycles (N). The S-N curve is used to assess the lifetime and the fatigue limit properties of tank materials and epoxy coatings during service life. The fatigue limit is defined as the amplitude of stress for which the material can withstand unlimited values of cycles without fractures. For metals and most polymer coating a number of cycles 10^7 are selected to represent the fatigue limit [6].

Many works have been achieved on stainless steel used for drinking water storage tanks, but most of them focused to study the fatigue behavior only or vibration of tanks only. Huang [7] outline the procedure to assess and estimation the fatigue damage of the piping and tanks system. The results explained that the piping and tank responses resulting from vibration induced by pump with the limited test data. Tommy *et al.* [8] Developed a new novel testing technique for evaluating the fatigue limit strength of materials at high frequencies and corresponding to a very large number of cycles up to 10^6 or 10^7. Prinz *et al.* [9] analyzed the fatigue failure at the tank shell-to-base connections under vibration effects results from earthquake ground motions. Results of their analyses indicate excess capacity to fatigue damage in the shell-to-base connection. Jiang *et al.* [10] proposed vibration fatigue test and numerical simulation method to investigate the effects of Gaussian and non-Gaussian random excitation. They studied various factors that affect the vibration fatigue life of steel, include root mean squares of acceleration, power spectral bandwidth, power spectral density and kurtosis. Tongyu [11] investigated the static and fatigue behavior of two types of water ballast tank coatings. The results show the static and fatigue behaviors of the tested coatings depend on coating thickness, toughness, abscond size and residual stress. Livanskiy *et al*. [12] describes the effects of ultrasonic vibrations in the paint preparation before the coating process. Their results indicated that the applications of ultrasound vibrations during the paint preparation before the coating process are improved the paint properties due to decrease the initiation of polymerization reaction and viscosity of paint. Singh *et al*. [13] experimentally determined the effect on vibrations on various types of coating materials include metals, ceramic, polymer and epoxy coating. Their results in general show that the damping capacities of the specimens have different types of coats are increased in compared to the uncoated test specimen. Donoghue *et al*. [14] studies and characterizes the alkylated amine epoxy contains epoxy phenolic resin for internal applications of vessels, tanks and pipes. The results show that this type of coating has high temperature resistance for insulated steel and rapid cure characteristics. Halfpenny *et al*. [15] review of stress-life (S-N) vibration fatigue analysis. The starting point for vibration- fatigue analysis is usually expressed the stress and strain vs. time signal. Fatigue occurs as a result of stress or strain reversals in the time history. These are known as cycles. The significant aspects of these are the amplitude and the mean stress in the cycle. This information is extracted from the time signal using a procedure known as Rainflow cycle counting. Aymeric *et al*. [16] developed a new test bench experimental setup to carry out vibration fatigue tests on a beam with an electrodynamic shaker. They applied acceleration, velocity and displacement profile instead of an excitation force and the specimen notched beam is fixed on the armature of the shaker. Their results indicated that this kind of test has non-linearities and the proposed fixture enables a better reproducibility in the experiment. Wang *et al*. [17] summarized the some aspects of vibration fatigue behavior of automotive components and systems to help in understand the testing methodologies, requirements and the strategies for improving the vibration fatigue performance that supporting the testing and design purposes.

In this paper, the static and vibration fatigue test were conducted experimentally to evaluate the effect of vibration in fatigue limits of AISI 316 stainless steel coated by the two types of epoxy coatings used for potable water tanks. Various parameters include coating composition and vibration effects are discussed.

2. EXPERIMENTAL APPROACHES

2.1 Types of Epoxy Based Coatings

The epoxy coatings used for drinking water tanks are free of solvents that cause human health and water pollution [18]. Commercially, different types of epoxy coating are used to coat drinking water tanks. These epoxy coatings contain two separate base and hardener liquid components that are mixed together and left to chemically cure after applied coatings to the tank material surfaces. Three types of Jotun epoxy coatings were used for studying in the vibration fatigue tests (one type used as undercoat primer). These coatings are:

- Penguard Primer COMP. A, PM3192, epoxy primer based on a high molecular weight epoxy resin. This type is produced by Jotun Henry Clark Ltd, UK and used as primer under coots.
- Tankguard 412 consists from polyamine cured pure epoxy coating. This type of coat is referred as model A.
- Penguard HB contains polyamide cured pure epoxy coating. This type of coat is referred as model B.

The models A and B of coatings are produced by Jotun paints Company of Emirates LLC, Sharjah, U.A.E.

2. 2 Specimen Preparation and Coats for Static Test

The material used for testing is the commercial stainless steel AISI 316 (EN 1.4401) that is widely used to constrict water storage tanks on the Iraqi cites. Table 1 shows their AISI 316 stainless steel chemical compositions (mass %) [19]. Identical fatigue test specimens are machined from AISI 316 plates in accordance with ISO Code 1143 standards [20]. Figure 1 A and Figure1 B shows the fatigue test specimens dimensions and configuration respectively. Figures 1 C and D show the specimen's shape and dimensions before and after the two coatings types were applied. First, the specimen's surface is clean and dry, and then the Penguard primer epoxy coat was applied. The two classes of Jotun coatings (models A and B) were applied by airless spray at nominally standard dry film thicknesses to steel substrates as given by the producing company. The main function of the primer was to enhance the adhesion of the epoxy coatings applied to the surface of stainless steel. The coating thickness is measured using paint thickness tester (Gain Express Holdings Ltd, China) to verify the coatings thickness in range of uses according to standard ASTM D1005 [21]. The coated specimens were left to cure for 14 days at $25^{o}C$ and atmosphere pressure. A total 12 specimen were used for testing.

Table-1: The Percentages of the constituent elements of AISI 316 Steel [19].

Element	Cr	C	Ni	N	Mn	Mo	Si	P
Mass %	0.08	0.08 max	10-14	0.1	2	2-3	0.75	0.045

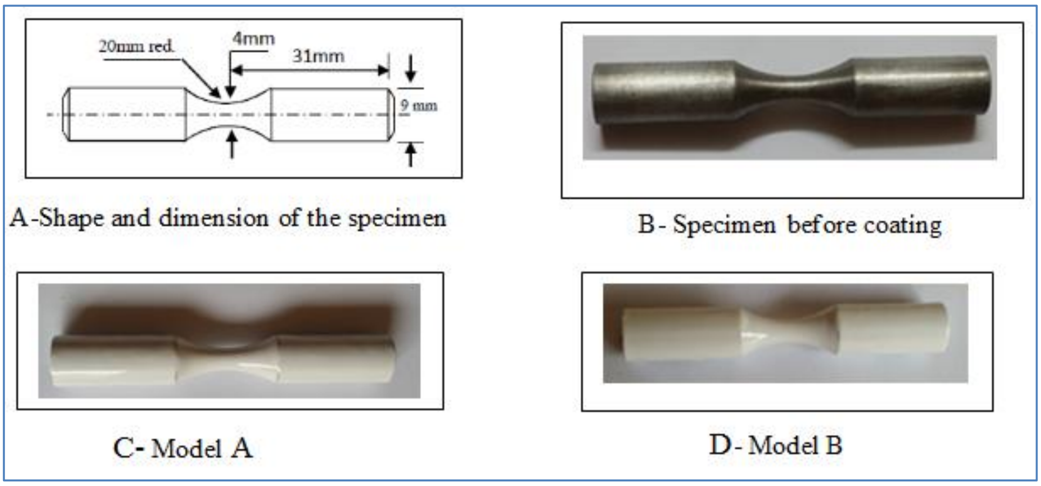

Fig-1: Specimens before and after coatings for static test

The percentage increase or reduction rate of fatigue limits for applied coatings under different environments was calculated using the formula [22]:

$$\% \, FL = \frac{\sigma_c - \sigma_{uc}}{\sigma_{uc}} \qquad (1)$$

Where σ_c and σ_{uc} are the fatigue limits of the coated and uncoated specimens respectively.

The S-N data plots of the fatigue tests results under static and vibration have a power law relationship or so called Basquin's equation that represent the part of the S-N curve in the region N < 10^6 and expressed as followers [23]:

$$S_{max.} = A \; N^b \qquad (2)$$

Where,
N: Number of cycle to failure.
S_{max}: The maximum Stress is obtained.
A, b: Material constant that depends on material and its characteristics.

2.3 Specimen Preparation and Coats for Vibration Fatigue Test

A conventional vibration fatigue specimen shown in Figure 2 was used for vibration fatigue test [24, 25]. The test specimen has 120 mm × 20 mm × 2 mm dimensions. The minimum width in the center is 10 mm. The specimen material used for testing same as that used in static test, i.e., the stainless steel AISI 316 (EN 1.4401). The two holes in the right side are used for mounting bolts to fix the specimen on the testing system. The geometry of the conventional vibration fatigue specimen is taken from a Chinese testing standard HB 5277 [26], which are widely used in the field of vibration-based fatigue testing.

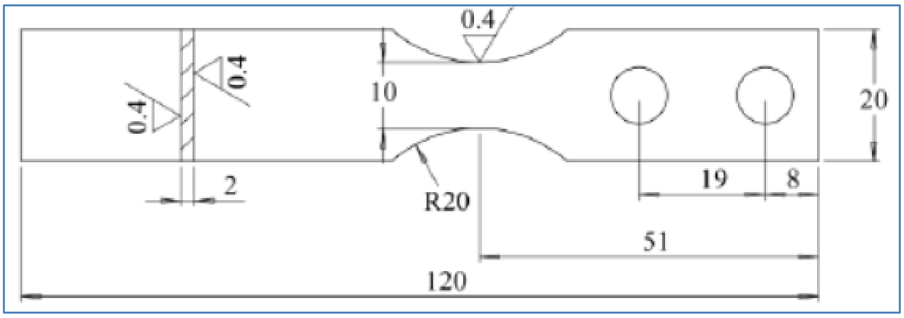

Fig-2: Geometry of the vibration fatigue specimen (unit: mm).

The fatigue tests were conducted in room temperature. The loading frequency for vibration fatigue test was 240 Hz. Fig.3 show the test equipment collected used in test. The vibration-based fatigue testing system, consists of the major body is an electrodynamic shaker (ES-10D-240 Electrodynamic Shaker System) located in a soundproof room and a closed-loop control system that allows precise control. The maximum loading capacity of the shaker is 10 kN and the frequency range is 5 to 3000 Hz, which meets the mode of bending vibration testing requirement of the present specimens. The vibration amplitude is measured and recorded through an accelerometer (PCB Group Inc., Depew, NY, USA) on the specimen tip, and the stress is calculated accordingly. Similar to conventional fully-reversed bending fatigue tests, the ratio between the maximum and minimum stress in the test is equal to -1. All testing was carried out at structural analysis of industrial equipment department, Dalian university of technology, China.

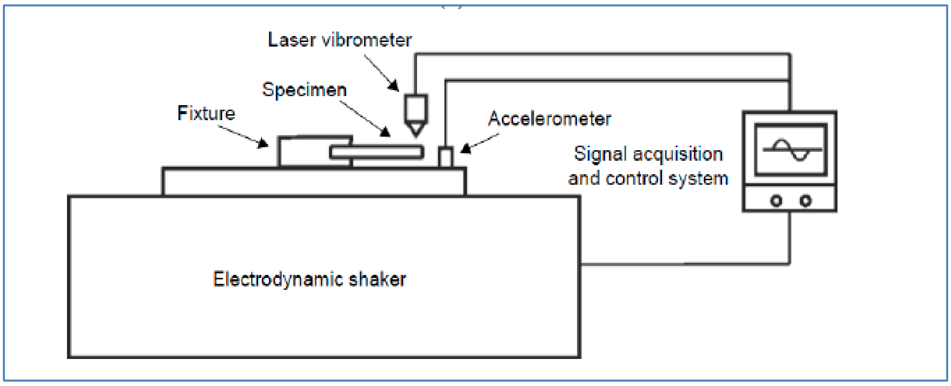

Fig-3: Sketch of the experimental equipment test

3. RESULTS AND DISCUSSION

Figures 4 illustrates the S-N diagram obtained from the static and vibration fatigue testing of the uncoated AISI 316 stainless steel and for that coated samples by the two types of epoxy coatings. As shown all S-N curves are similar in the tendency and shape. It can be seen from Figure 3, at the beginning of vibration-fatigue testing, i.e., at high stress level, there are a large decrees in fatigue life up to 2* 10^3 cycles, but after this cycle the slope begins to drop to a large values. The S-N curves recognized that the fatigue properties of the steel AISI 316 steel were enhanced after applied the two types of epoxy coatings. This improvement in the fatigue properties were attributed to the epoxy coating asset the strength to the AISI 316 steel. The adhesion between the epoxy coating layer and steel surface support the fatigue test specimen during vibration fatigue testing.

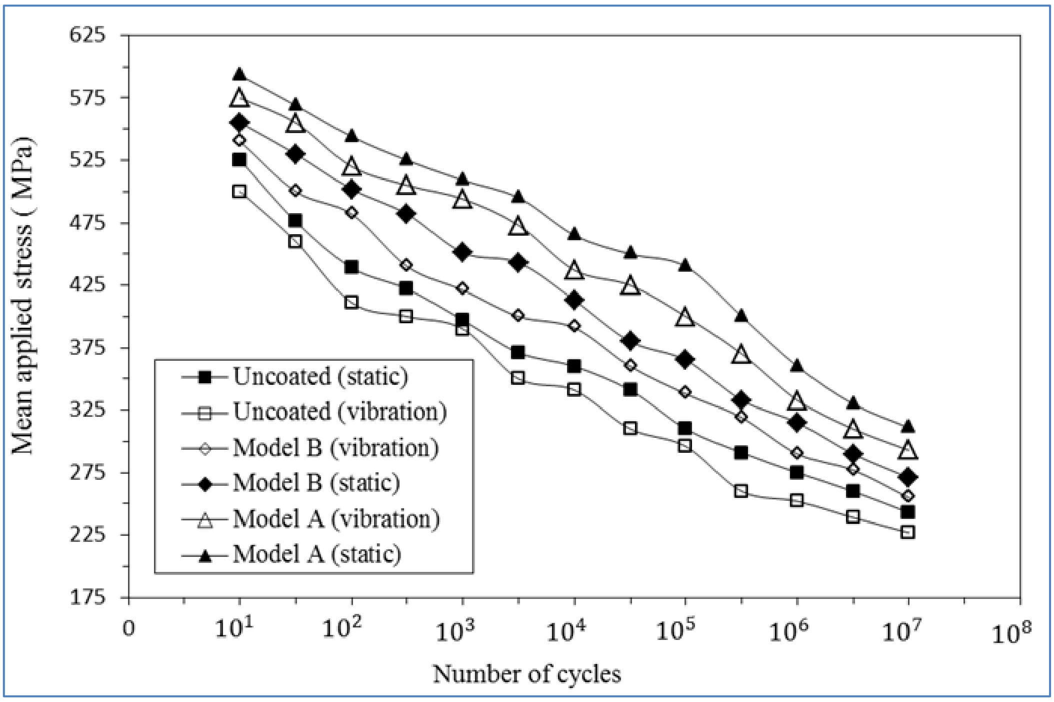

Fig-4: The S-N curves of AISI 316 and coating specimen tested

As shown in Figure 4, the coating applied improves fatigue resistance and increases the fatigue limit compared to uncoated AISI 316 stainless steel. The vibration process reduces the fatigue limit of both coated and uncoated samples. The vibration effects and reduces the strength bond between the epoxy coating compounds and between coating and the substrate of AISI 316 stainless steel. The decreasing in bond strength improves generation of cracks in epoxy coatings and propagates toward the steel substrate and then enhances failures.

The final points in the curves of the Figures 4 shows that the uncoated and coated AISI 316 stainless steel by the two types of epoxy coats was not fracture at 10^7 cycles but at the next cycles. The estimation of the fatigue limits values at 10^7 cycles from Figure 3 are outlined in the Table 2. As indicated in Table 2, model B coating polyamide epoxy coats have less fatigue limits compared to model A consists from polyamine epoxy coats. The vibration process reduces the fatigue limit compared to the static case for uncoated and coated AISI 316 stainless steel by both models.

Table-2: Fatigue limit values obtained from fatigue test at different environments

Property	Models					
	Uncoated		Model B		Model A	
	Static	Vibration	Static	Vibration	Static	Vibration
Fatigue limit values (MPa)	243	227	274	253	311	288

The percentage increase in the fatigue limits of the coated specimen was calculated using Eq.(1) and the results are shown in Table 3. As indicated, for models A and B coats, there are a difference in percentage increase in fatigue limit values.

Table-3: Percentage increase of fatigue limits under different conditions

Property	Models			
	Model A		Model B	
	Static	Vibration	Static	Vibration
Fatigue limit values (MPa)	12.76	11.45	27.98	26.87

Table 4 summarizes the parameters of Basquin's constant obtained by the least square method. Basquin's power law relationship was used to characterize the baseline fatigue behavior. It is observed that there is a reduced in values of the constants of Basquin's equation for vibration fatigue compared to static case. This attributed to several factors: due to defects occurs during the preparation of coatings, the machining process of test specimens and also to fatigue strength which has by each type of epoxy based coatings.

Table-4: The values of parameters of Basquin's equations

Samples	Static		Vibration	
	A (MPa)	n	A (MPa)	n
uncoated	572.41	-0.389	553.55	-0.413
Model A	677.44	-0.333	653.84	-0.340
Model B	631.55	-0.367	600.78	-0.377

The polyamines coating is generally made up of atoms of hydrogen and nitrogen. Hydrogen bonds link the two hydrogen atoms, while a weak Van Der Waals bond links the nitrogen atoms to the alkyl group. As polyamine coating exposure to the vibration process, the bonds are started to stretch and disintegration, which affects fatigue resistance and reduces the fatigue limit values. Polyamides are crystalline material have a lone pair of electrons on the nitrogen atom and have a long chain aliphatic structure of amide (–$CONH_2$), making the polyamide more flexible after exposed to vibration process.

4. CONCLUSIONS

Fatigue tests were carried out under static and vibration fatigue to understand the basic fatigue processes of stainless steel AISI 316 and it is coatings. It's found that the applied epoxy coatings increases the fatigue limits. The Vibration reduces the fatigue limit of uncoated and coated specimen compared to static case. There is a reduced in values of the constants of Basquin's equation for vibration fatigue compared to static case. Both static and vibration fatigue experimental results show non-linearities. There are different mechanisms of initiation and propagation of fatigue crack and it is effected by the vibration process.

5. ACKNOWLEDGEMENTS

The author express thanks to staff engineers at a laboratory of structural analysis of industrial equipment, Dalian university of technology, China for helps during preper the specimens and testing.

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