Defect and Diffusion Forum *Online: 2020-01-10*
ISSN: 1662-9507, Vol. 398, pp 147-155

Analytical Study of the Effect of NaCl Solution on Fatigue Resistance of Rotating Shafts

Sabah Hatam Obaid[1,a*], Adnan Noori Ahmed[2,b] and Hadi Raheem Ibrahim[3,c]

[1,2,3]Al-Mussaib Technical Institute, Al-Furat Al-Awsat Technical University, 51009 Babylon, Iraq

[a]inm.sbh@atu.edu.iq, [b]inm.ad1@atu.edu.iq, [c]inm.hadi@atu.edu.iq

*The corresponding author

Keywords: Dynamic shear stress, Heat treatment, Chloride corrosion.

Abstract. Dynamic shafts subjecting to salty rain water, especially in places with no rain water drainage networks, is undesirable because this media causes corrosion of the parts of shaft that increases as increasing of shaft immersion in a salty media (NaCl) also, increasing of concentration which in turns reducing number of operation runs. Increasing salt concentration from 3% to 6% NaCl results in decreasing of operation runs from 25600 to 17100 runs. Also, increasing salt concentration leads to raise the effect of alternating stress that makes strain hardening factor drop to 0.45 and ratio of dynamic shear stress to static one raise to 2.44 that affects shaft metal performance to resist fatigue. Samples were also, treated by oxy acetylene surface hardening and were cooled by immersion in oil then immersion in 6% NaCl salty solution, the results showed that number of operation runs before failure had increased up to 71022, the effect of alternating stress had decreased down to 6100 N/m^2, surface strain hardening factor had increased up to , also ratio of dynamic shear stress to static one had decreased down to 0.839. This is a good indicator of the effectiveness of surface hardening process of shaft parts that subject to salty rain water during maintenance operations.

Nomenclature

Q : Torsional Torque, A : Cross section area of model. μ : Jouravski factor for cicular cross section (1.33). φ : Angular displacement., ω :Angular velocity., υ :Stress translate velocity.
G : Modulus of material rigidity .
=Angular distortion ratio ρ: Material density ($\Theta(\ell,t)/\Theta_0$)
AVRSS = Angular velocity ratio to shear strain, SSSR=Surface shear stress

$$\frac{\alpha(x,t)}{\alpha_o} = Ratio\ of\ shear\ strain\ dynamic\ to\ shear\ strain\ stati$$

P=Mechanical power. d = diameter of shaft.
σ_r = Rate of cycle alternating stress on model.
N_f = Failure revolutions. K=Mechanical properties factor with constant value (300)

1. Introduction

Most theories of shafts design depend upon the analysis of bending and torsion moments or both. The dynamic behavior of elastic torsion vibration for revolving shafts is affected by the internal resistance forces of the shaft causing torsion. The resulting deflection from these forces affecting on the shaft can be explained by the methods of analysis of different stresses. The resistance of the torsion of shaft metal causes the angular deflection in the shaft section and leads to the loss of shaft alignment, so when designing shafts , the amount of torsion angle of a shaft section must be verified that causes the deflection and lead to loss of shaft alignment[1].

One of the most important defects of shafts manufacturing are capillary cracks which increase in volume when fatigue is occurred in the metal of shaft that lead to failure if not defected from the beginning before the operation. The most important variables in the case of the crack generated on the surface of the revolving shaft is the location of crack , its depth and its angle with respect to the longitudinal axis of the shaft , where the transverse crack affects by periodic alternating stresses leading to fatigue state. All of the above mentioned variables can affect the value of natural frequency of the rotating shaft system and may cause resonance with devices close to rotating shaft system [2, 3]. The reversible forces of the shaft material, the design damping structure of the shaft and the durability of the shaft material are variables that effect on the dynamic rotation system. All the previously mentioned variables are applied in a linear formula to facilitate their solution in a factor analysis method [4, 5]. One of the most important devices used in the tests of fatigue stress is fatigue tester by applying bending forces on one end of the revolving shaft. This device was used to evaluate the volume of effect of the fatigue resistance for steel structures in a high humidity environment, one of the variables in this research is making a low depth notch along the axis of the shaft and observing the crack initiating and growing throughout the shaft metal. The research discussed the possibility of treating the capillary crack by using emery method in order to stop the growth of the crack and then occurrence of failure. The other two variables in this research are changing the diameter of the revolving shaft and the humidity ratio in the atmosphere. The results showed that the fatigue resistance is increased as the model size to the diameter ratio is decreased, the ionizing water also reduces the resistance of the steel to the fatigue [6]. The erosion that occurs in the axels and driving shafts in vehicles because of rain water that carries a proportion of salt (NaCl) which can be remedied by improving the particular specification with resistance of steel for fatigue as result of erosion. In this study (Kitagawa) scheme was used to evaluate the defects of corrosion, the relationship between the size of defect of the mechanical part and the slit growth was also used [7]. Screws and nuts are always made of high strength steel of stresses, especially fatigue stress. The simple difference between thread pitch of screw and nut is considered as a variable that effects on their performance. The difference between the thread pitch of screw and nut has determinants, if it was within these standard determinants, the age of service of the mechanical part connected by these screws and nuts increases to one and a half times under appropriate values of fatigue stresses [8]. The steel is commonly used that contains elements such as chromium, nickel and Molboduim which change its phases. The steel falls into groups: martensite steel, ferritic steel austenitic steel, it is possible to obtain corrosion resistant steel by combining (Ferriti – Austenite) as well as solidified steel, can be obtained by precipitation. The above mentioned types of steel resist corrosion and maintain mechanical properties at high temperatures and are widely used in automotive parts such as driving shaft at high speed, it can be used in the vehicles chassis in a form of sheets [9]. (X–Ray) technology can be used to observe the variations that happen to the crystalline structure of steel shaft model (Q23) immersed in acidic rain water and it was concluded that corrosion rate increases with decreasing of SARph values [10].

2. Methodology

2.1 Models preparation and configuration of fatigue tester by bending

Ten models were manufactured by turning operations that was done at the technical institute workshop Almusaib. And according to model measurements of fatigue tester by bending at metals of mechanic department as it is shown in Figs. 1 and 2, where they show the utilized steel model (CK_{35}) before and after the test. This test has been tested for its components in the public company of mechanical industry and the results are tabulated in Table 1.

Fig. 1 Fatigue Tester by bending at Technical Institute, AL-Musaib, mechanic department.

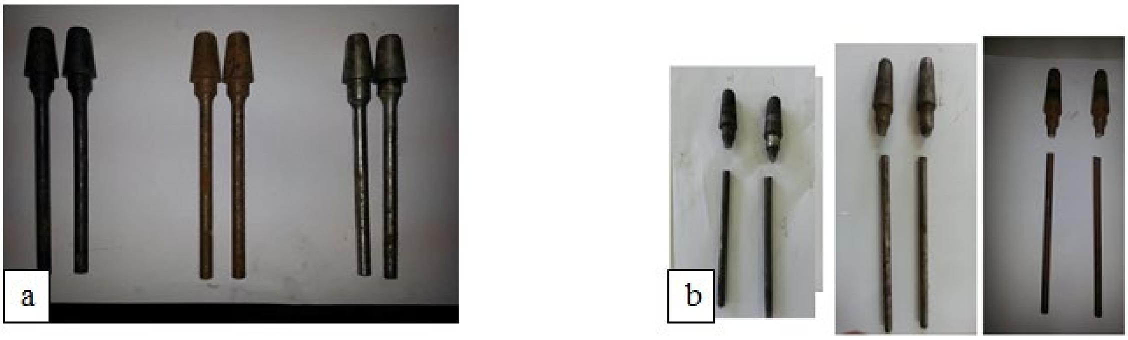

Fig. 2 (a) Steel models before fatigue test. (b) Steel models after fatigue test.

Table1 The components of steel model CK_{35}.

Element	C %	Si %	Mu %	P %	S %	Cr %	Mo%	Ni %	V %	Cu %	% Fe
The actual value (wt%)	0.35	0.212	0.57	0.015	0.03	0.026	0.082	0.027	0.003	0.015	Rew

2.2 Steps of exposing the steel models to corrosion and treatment

1) Immersion of two models in the salty solution with concentration of 3% NaCl at temperature of 47C^0 and for variation duration for each model (960 hrs, 1440 hrs) respectively.
2) Immersion of two models in the salty solution of 6% NaCl concentration at temperature of 47C^0, also each model would be exposed to a different duration (960 hrs, 1440 hrs).
3) Conducting a surface hardening process with oxy-acetylene flame and neutral flame for each model then cooling them with cooling solution, which is a mixture of water, oil and additives demonstrated in Table 2 [11]. Then the two models are immersed in the salty solution of 6% NaCl concentration at temperature of 47C^0 and one of the models is immersed for 960 hrs while the other remains for 1440 hrs in the salty solution.

Table 2 Cooling fluid formula.

Material	Function	Content (% Volume/ Volume of fixed oil)
Fixed oil	Base oil	80
Washing soap	Emulsifier	10
Phenol	Disinfectant	5
Sulphur	Extreme pressure agent	5

2.3 Examination of models with fatigue tester by bending

After the immersion of unhardened and hardened models at temperature of 47C^0 to conform bending has been conducted in mechanic department laboratory at technical institute, Al-musaib. The results of the test could be observed through the Figs. 3, 4, 5 and 6, for the hardened models by oxy-acetylene and neutral flame were cooled with oil and additives mixture also, have been immersed in salty solutions of 3% NaCl for one model and 6% NaCl for the other. While Figs. 7, 8, 9 and 10 represent the results of the test concerning the unhardened models that have been immersed in salty solution with specified concentration for each model as was previously mentioned and the exposure time for one model was (960 hrs and 1440 hrs) for the other. Also, Figs. 11 and 12 are showing the results of neutral oxy-acetylene flame hardened models that have been cooled naturally under ambient air with concentration 3% NaCl for different times (960 hrs, 1440 hrs).

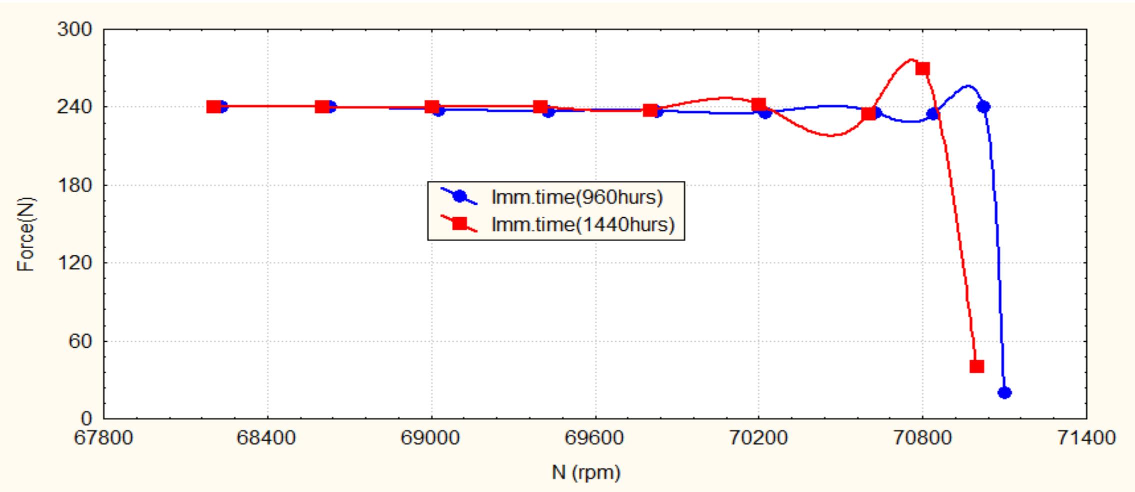

Fig. 3 The results of fatigue sample hardening with Oxy-acetylene & immersing in salty solution of 3% NaCl for interval time (960hrs) and (1440hurs)

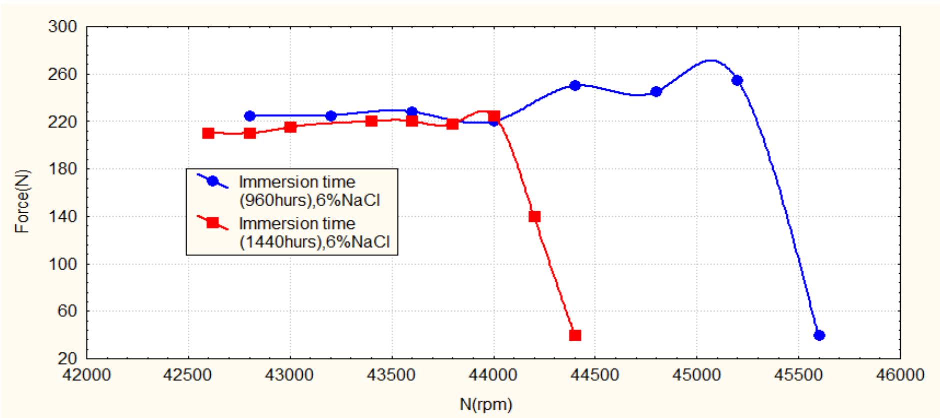

Fig.4 The results of fatigue model hardening with Oxy-acetylene immersing in salty solution 6% for interval time (960 and 1440 hurs).

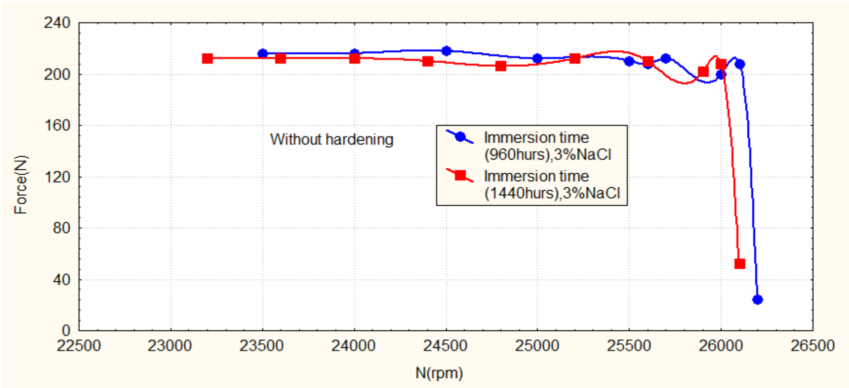

Fig. 5 The results of fatigue model immersing in salty solution at 3% NaCl without hardening for interval (960 and 1440 hurs.

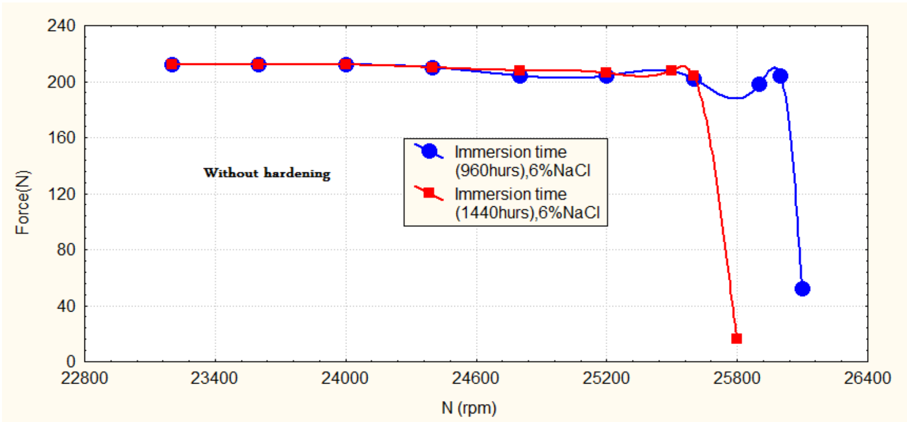

Fig. 6 The results of fatigue model immersing in salty solution at 6% NaCl without hardening for interval (960 and 1440 hurs).

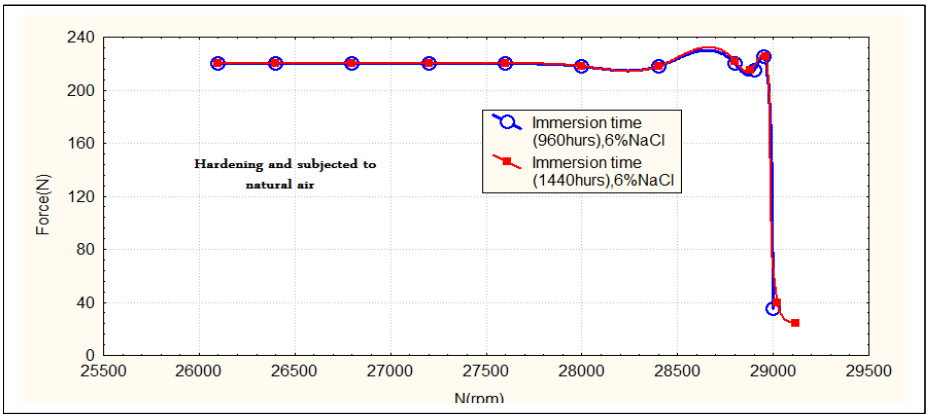

Fig. 7 The results of fatigue model subjected to natural air for interval time (960 and 1440hurs).

2.4 Calculation of static shear stress for steel model

The same previously mensioned steel type has been used in static shear stress test by shear tester shown in Fig. 13. Practical result revealed that torsion moment at failure was 24 N.m. Then by applying (Jouravski) equation, static shear stress value for the steel can be computed [12].

$\tau_{0gc=\mu \cdot \frac{Q}{A}}$ ....(1), Static shear stress for the utilized steel was equal to 4066 Pa.

Fig. 13 Shear tester.

2.5 Analysis of torsion stresses applied on the revolving shaft

When the undamped revolving shafts stop or start running. They will subject to a torsion stress that may cause an angular displacement (Δφ) of the shaft section to occur which its increasing results in shear failure due to angular shear strain growing(Δφ/φ). The angular displacement will be variant along the shaft while torsion moment will change with time. The general solution by variable separation method was applied [13, 14].

$$\emptyset(x,t) = \sum_{i=1,2,3,..}^{\infty} \emptyset_i(x).Q_i(t) \quad (2)$$

Torque function is a periodic function that its solution.

$$Q_i(t) = A_i cos w_i + B_i sin w_i t \quad (3),$$

By substitution corporation the similar limits [14, 15]

$$\emptyset_i''(x) = \frac{-w_i^2}{v^2}.\emptyset_i(x) \quad (4),$$

Where: $v = \sqrt{\frac{G}{\rho}}$

The solution of equation 4:

and by substitution in equations produce: $\emptyset_i(x) = C_i \cos\left(\frac{w_i}{a}\right)x + D_i \sin\left(\frac{w_i}{a}\right)x$ (5)

$$= \sum_{i=0,1,2}^{\infty} [A_i cos w_i t + B_i sin w_i t][C_i \cos\left(\frac{w_i}{a}\right)x\emptyset(x,t) + D_i \sin\left(\frac{w_i}{a}\right)x] \quad (6)$$

And by applying the conditions of solution to determine the constants (A_i, B_i, C_i, D_i).

From previously mentioned equations, an equation that related to the shaft metal will be concluded which represents the ratio between dynamic angular displacement to the static angular displacement [13,14,15].

$$\frac{\emptyset(\ell,t)}{\emptyset_o} = 8 \sum_{i=1,3.5}^{\infty} (-1)^{\frac{i-1}{2}} \frac{1}{\pi^2 i^2} [(-1)^{\frac{i-1}{2}} \cos\left(\frac{i\pi a}{2\ell}\right)t + \frac{w_o}{\alpha_o v} \sin\left(\frac{i\pi a}{2\ell}\right)t \quad (7)$$

And to determine stress function hence, the application of shear strain by the expression $\left(\alpha(x,t) = \frac{\partial\emptyset(x,t)}{\partial\emptyset}\right)$ and applied it in equation (7)

$$\frac{\alpha(x,t)}{\alpha_o} = 4 \sum_{i=1,3,5.}^{\infty} \cos(\frac{i\pi x}{2\ell}).\frac{1}{i\pi}[(-1)^{\frac{i-1}{2}} \cos\left(\frac{i\pi a}{2\ell}\right)t + \frac{w_o}{\alpha_o v} \sin\left(\frac{i\pi a}{2\ell}\right)t \quad (8)$$

Can be used (shear stress-shear strain) law according to following formula.

$\sigma_s(x,t) = G.\alpha(x,t), \sigma_{s0} = \alpha_o.G$

And by definition, dynamic stress at shaft fixed area to static shear stress produce [surface shear stress (SSSR)] or according to the following formula.

$$SSSR = \frac{\sigma_s(0,t)}{\sigma_{s0}} = 4\sum_{i=1,3,5}^{\infty}\frac{1}{i\pi}[(-1)^{\frac{i-1}{2}}\cos\left(\frac{i\pi a}{2\ell}\right)t + AVRSS\sin\left(\frac{i\pi a}{2\ell}\right)t \qquad (9)$$

Where: $AVRSS = \frac{w_0}{\alpha_0\, v}$

By using the computer program (Visual Fortran), the theoretical ratio of dynamic angular shear stress to the static stress can be obtained by applying equ.9. From the experimental results of number of revolutions at failure and applying the formula, the dynamic shear stress can be calculated then dividing by static shear stress of metal, that has mentioned in article 5, the practical ratio can be produced. Surface strain hardening values (h) can be calculated by knowing the values of the rate of cycle alternating stress (σ_r) during revolutions failure (N_f) and mechanical properties factor (K). Results are tabulated in Table 3.

$P = T.\omega$ (10), $\omega = \frac{2\pi N_f}{60}$ (11) , $\sigma_{s\ dynamic} = \frac{16\,T}{\pi d^3}$ (12) , $\sigma_r^h.N_f = K$ (13)

Table 3 The experimental and theoretical results.

State	N_f (rpm)	AVRSS	σ_r (N/m^2)	h	$(SSSR)_{exp.}$	$(SSSR)_{th.}$
Hardening by oxy-acetylene torch,3%NaCl,960hrs	71022	653	6100	0.63	0.839	0.8
Hardening by oxy-acetylene torch,3%NaCl,1440hrs	69210	653	6250	0.62	0.877	0.82
Hardening by oxy-acetylene torch,6%NaCl,960hrs	45600	419	9750	0.548	1.365	1.29
Hardening by oxy-acetylene torch,6%NaCl,1440hrs	44400	405	10050	0.544	1.411	1.32
Immersed in salty water without hardening,3%NaCl,960hrs	26000	239	17100	0.459	2.4	2.1
Immersed in salty water without hardening,3%NaCl,1440hrs	26000	239	17100	0.459	2.4	2.1
Immersed in salty water without hardening,6%NaCl,960hrs	26080	240	16950	0.46	2.39	2.2
Immersed in salty water without hardening,6%NaCl,1440hrs	25600	235	17350	0.45	2.44	2.3
Quenching by normal air,3%NaCl,960hrs	29200	268	15280	0.48	2.14	1.95
Quenching by normal air,3%NaCl,1440hrs	28800	265	15550	0.47	2.17	2
Standard deviation = 0.17						
Correction factor (R^2) = 0.84						

Using statistical equations (14,15 and 16) shown below to calculate standard deviation and correction factor., N= Number of statements.

$$S.D. = \sqrt{\frac{\sum[\Delta SSSR]^2}{N}} \quad (14)$$

N = No. of statements.

$$\Delta SSSR = (SSSR)th. - (SSSR)exp. \quad (15)$$

$$R^2 = \frac{\sum[(SSSR)th. - (SSSR)mean.]^2}{\sum[(SSSR)exp. - (SSSR)mean.]^2} \quad (16) \qquad (SSSR)mean = \frac{\sum(SSSR)exp.}{N}$$

3. Results and Discusion

The figures of practical test shown that the operating runs, until failure occurs, was high in the oxy acetylene hardened models that were cooled with oil after immersion in salty solution similar to salty rain water. But, these operating runs start to decrease whenever the immersion period has increased also the concentration of NaCl in water has increased. These results are demonstrated in Figs. 3 and 4. It can be concluded from Figs. 5 and 6 that concerning to the practical fatigue test of models that are immersed in salty water similar to rain water, that operating runs are low about (26080 - 25600) run/min until failure occurs and reduced as immersion time increased, also increasing NaCl concentration in water. It can be noticeable that the figures 11 and 12 of practical fatigue test of immersed models in salty water, that is similar to rain water, and the models were also thermally treated and ambient air cooled. Salts concentration was 3%NaCl. Number of operating runs will decrease as the immersion duration increases. The factor AVRSS as shown in table 3 is a function to change revolving velocity of the model where the velocity of stress transfer (υ) depends on constant values of material density, modulus of material rigidity and static shear strain of material. Also, the factor AVRSS increases by increasing the rotational velocity of model.

By taking a look at table 3, it could be observed that the oxy acetylene hardened samples have their surface shear hardening factor increased (0.62 – 0.63). So that the varying stress has its impact to be reduced on the surface about (6250 – 6100). Also, it was observed that extending immersion period and raising NaCl salts proportion will lead to decrease surface hardening factor and effect of alternating stress on model surface.

Models that have been subjected to oxy acetylene flame hardening and later cooling with ambient air have their number of runs decreased before failure (29200–28800) at constant salty concentration 3% NaCl. This decrease is related to changing immersion duration. And surface strain hardening factor was nearly equal for both case. Models that have been immersed in salty solution without hardening, their results show that the number of operating runs were (25600 – 26080 – 26000) that have decreased before failure as result of increasing immersion duration and salt concentration ratio in water.

As it can be seen in table 3, the practical ratio ($\frac{SSSR_d}{SSSR_0}$) values are high in the case of unhardened case and immersion in salty solution. While in the case of oxy-acetylene hardening and ambient air cooling, the ratio decrease slightly, but this decrease increases significantly in the case of oxy-acetylene hardening and cooling with oil solution.

4. Conclusion

Based on the theoretical and experimental works,

The hardening with oxy acetylene flame processes and cooling with oil mixed with additives, gave good results represented in increasing operating runs number before failure and this could be utilized locally in maintenance cases for revolving mechanical parts. As the revolving part becomes more hardener and more durable, as result of surface hardening, it will become less affected with alternative stresses (σ_r) when revolving and the opposite is true. The current research proved that strain hardening factor (h) increases by increasing surface hardening of metal. And this factor decreases in the case of immersing shafts in salty water and the affect the performance of shaft metal during revolving. Due to revolving and loading on shaft, this will lead to raise a dynamic shear stress. And by applying shear vibration equations, the ratio of shear stress ($\frac{SSSR_d}{SSSR_0}$), in the case of hardened shafts with oxy-acetylene flame and cooled with oil mixed with additives, was less than 1. Subsequently, static stress of metal overcomes on the dynamic stress and this conserve the shaft against failure for a satisfying operating duration, and the opposite is true, Practical and theoretical results are in good agreement, this indicates the accuracy of the results.

References

[1] M. T. El-Sayed, M. N. A. Nasr, B. M. El-Souhily, Internal torsion resistance in deflected shafts, Alexandria Engineering Journal. (2017)

[2] S. J. Davis Hans and P. selvakumar, Vibration Analysizeis of propeller shaft with crack, National Conference on Intelligent manufacturing system, (NCIMS 2011).

[3] P. Jayaswal, A. K. Wadhwani, K. B. Mulchandani, Machine Fault signature Analysis, International Journal of Rotating Machinery, (2008)

[4] Zhou S. and Shi J., On- line estimation of nonlinear and time varying Effect in Rotor system using QR orderly recursive method, Ain Arbor, MJ 48109, U. S. A., (2001)

[5] Y. Ren, Y. Zhang, Free Vibration and damping composite shaft with a constrained layer damping, Shock and Vibration Journal, (2016)

[6] Haftirman, The size effect on fatigue strength of steel materials in high- humidity Environment, proceedings of International conference on applications and design in mechanical Engineering, Malaysia, (2009)

[7] S. Beretta, M. Carboni, A. Loconte, Corrosion Fatigue and European axeles steel, Amour 2004 project, Maintenance of freight trains, (2004)

[8] Y. Takas, N. A. Noda, X. Chen, Y. Sano, R. Fujisawa, H. Maruyama, M. A. Wahab, Fatigue strength Evolution For Bolt-Nut connection Having slight pitch Difference considering incomplete threads of nut, Internal Journal of fracture fatigue and wear, (2015)

[9] F. Y. Ma, Corrosive Effects of chlorides on Metals, Republic of china (Taiwan) INTECH

[10] Y. H. Wu, T. M. Liu, C. Sun, J. Xu and C. K. Yu, Effect of simulated acid rain on corrosion Behavior of Q_{235} steel in acidic soil, corrosion Engineering, Science and technology Journal, 2010, Vol.45, No.2

[11] S. A. Lawal, M. S. Abolarin, B. I. Ugheoki, E. O. Onche, Performance evaluation of cutting fluid, Developed from fixed oils., Leonardo Electronic Journal of practices and Technologies, (2007)

[12] B. Dupen, Applied strength of materials for Engineering Technology, Indian University, Purdue University Fort Wayne, (2014)

[13] H. R. Ibrahim, Analytical study of torsional vibration effect on turning shafts in sudden stop case, Journal of Babylon University, (2012)

[14] S. H. Obaid, The effect of longitudinal Vibration on tool Planning in suddenly stop, Journal of Babylon University, (2008)

[15] Q. He,D. Du, Modeling and Calculation Analysis of torsional vibration for turbine Generator shaft, North china Electric power University Journal of Information and Computational Science, (2010)