Comparative and assessment study of torsional fatigue life for different types of steel

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Abstract

Different types of steel specimens were tested using low cycle torsional fatigue tests to evaluate the torsional behavior. During previous years many authors have developed empirical relationships related to stress amplitude with the life of failure in many types of steel materials. Studies continue to find the best experimental relationships for different subjects. In this study two main problems were considered: torsional fatigue study and comparing the behavior of different steel materials under the influence of torsional fatigue. The effect of temperature on the properties of these substances was also studied. A comparison and evaluation of torsional fatigue for different types of steel were found in this study. Three groups of steel specimen were selected for the present investigation, these included low carbon steel AISI 1020, stainless steel AISI 316L, and cold worked stainless steel AISI 304H. The tests were carried out for each group of the steel specimen using a fatigue machine under fully reversed low cycle at ambient temperature and 100 °C. The temperature range was chosen from room temperature to 100° C because the low carbon steel AISI 1020 material showed high ductility above 100 °C. The shear strain amplitude applied was selected between the max. and min. values of 0.18 and 0.02 respectively. A comparison was carried out between the three steel groups at ambient temperature, it was noticed that the ratio of life to failure for both AISI steels 316L and AISI 304H with respect to AISI 1020 showed an increase of 4 and 2.3 times respectively. Also, the ratio of life to failure showed an increase of 4 and 3.5 times respectively at 100 °C. That is mean the ratio of life to failure for AISI steel 316L with respect to AISI 1020 has no effect with the temperature change because their cycles of life have been affected in the same manner. AISI 304H showed a good withstand to the temperature change because the ratio of life to failure with respect to AISI 1020 has been increased.

Keywords Torsional fatigue · Low-cycle · AISI 316L · AISI 304H · AISI 1020 and fatigue life

List of symbols

ϵ'_f	Axial fatigue ductility coefficient	b_o	Torsional fatigue strength exponent
σ'_f	Axial fatigue strength coefficient (MPa)	G	Shear modulus (GPa)
c	Axial fatigue ductility exponent	σ_u	Ultimate tensile strength (MPa)
b	Axial fatigue strength exponent	σ_y	Yield strength (MPa)
e	Elastic modulus (GPa)	El	Elongation
N_f	Number of cycle to failure	RA	Reduction in area
γ	Shear strain	ν	Poisson's ratio
$\Delta\gamma/2$	Total torsional strain amplitude		
γ'_f	Shear fatigue ductility coefficient (MPa)		
τ'_f	Shear fatigue strength coefficient (GPa)		
c_o	Torsional fatigue ductility exponent		

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1 Introduction

Fatigue of the metal is the phenomenon of failure caused by periodic loading due to movement or rotary parts. It is progressive localized damage due to fluctuating stresses or strains on the material [1]. In case of torsional fatigue failure, the damage to the torque shafts caused by torsional loading which leads to a different form of throwing stress. It is change the breakage level from 90 degrees to 45 degrees from the axis of the shaft [2]. The external observation of failure can be classified into three stages [3]. For explaining the major surface shape that is seen on almost every fatigue face; Origins, peach marks, and Instantaneous zone. In fact, the components fail to adhere to relatively high stress in the low number of cycles. This is called LCF, so the test under LCF is usually used to describe low cycle fatigue resistance in deferent case of loading axial or torsional [4]. The results of the fatigue tests for many authors [5] generally showed an inverse relationship between stress amplitude (or strain) with the overall life of failure. On the other hand, high temperature generally has effects on the stress strain curve [6] by increasing thermal elongation and toughness, while reducing the yield stress, elasticity modulus, hardness and the strain hardening exponent (n). This is also leads to decrease the life to failure.

It can be said that the effect of companies to increase the temperature using LCF leads to more periodic dilution behavior throughout life [7]. The Coffin–Manson relationship between fatigue life and total strain [8] consider for low-cycle fatigue because it produces a high-quality value for explaining the nature of fatigue. Several authors were found empirical relations for the steels that related to the amplitude strain and the number of life to failure [9]. The aim of the present study is to find an empirical equation that relates the shear strain amplitude with a number of cycle of failures of three types of steel AISI 1020, AISI 316L and AISI 304H. The prediction equations provided a comparative evaluating to the torsional fatigue behavior for these types of steel in both ambient temperature and 100° C. The number of failure cycles is estimated and found by the S–N curve.

2 Experimental procedures

Many of tests were achieved for different steel specimens metal (stainless steel AISI 316L, stainless steel AISI 304H and low carbon steel AISI 1020) for which the compositional analysis was calculated as shown in Table 1. Monotonic tensile tests at ambient temperature and torsional fatigue tests at both ambient temperature and at 100 °C were achieved. A torsional fatigue machine

Table 1 Compositional analysis results

Steel	C	Si	Mn	P	S	Cr	Mo	IMi	Fe
316L	0.02	0.42	0.81	0.043	0.019	16.55	2.04	10.09	70.00
304H	0.10	0.30	1.98	0.01	0.01	17.85	0.16	8.68	70.50
1020	0.20	0.27	0.50	0.003	0.002	0.13	0.004	0.096	98.46

Fig. 1 Fatigue test machine

Table 2 Summary of monotonic axial properties for tested metals at ambient temperature

Steel AISI	σ_u (MPa)	σ_y (MPa)	E (GPa)	EI (%)	RA (%)	G (GPa)	ν
316L	630	435	197	51	72.0	77	0.28
304H	951	750	196	36	57.7	76.5	0.25
1020	320	250	200	20	64.0	77.5	0.29

Table 3 The estimated monotonic axial properties for steels metal at 100 °C

Steel AISI	σ_y (MPa)	σ_u (MPa)	E (GPa)	G (GPa)
316L	360.3	556.0	189	73.8
304H	665.4	853.4	188	73.5
1020	250.0	312.5	200	77.5

shown in Fig. 1 was used to conduct the torsional tests with details given in Ref. [9] with a constant frequency. There are five different angles of twist was applied during the test on each specimen. The steel specimens were also conducted under torsional fatigue at 100 °C with the same frequency. All experimental relationships of experimental data were calculated according to the way of life of the strain [8] and obeyed Coffin–Manson Eq. (1).

$$\tau_f' \frac{\Delta\gamma}{2} = \frac{\tau_f'}{G} (2N_f)^{b_o} + \gamma_f' (2N_f)^{c_o} \quad (1)$$

where; $\Delta\gamma/2$ is a shear strain amplitude in mm/mm, τ_f' was a torsional fatigue strength coefficient in MPa, γ_f' and G was shear modulus in GPa. The torsional fatigue ductility coefficient was and b_o, c_o were strength and ductility torsional fatigue exponent respectively, since the reversal time to failure was $(2N_f)$.

2.1 Axial monotonic properties at ambient temperature

The monotonic axial properties of all the tested steel (AISI 316L, AISI 304H and AISI 1020) at ambient temperature were achieved in the laboratory of Basrah University, the results were demonstrated shown in the Table 2. Shear modulus have been calculated from it is relation with elastic modulus as [6]:

$$G = \frac{E}{2(1 + \nu)} \quad (2)$$

2.2 Axial monotonic properties at 100 °C

The shear modulus has been calculated from Eq. (2). The same values of Poisson's ratio (ν) at room temperature have been used to calculate the value of G at 100 °C, according to Eurocode 3 [10], because un sensible change of at 100 °C [11], the results were listed in Table 3 below:

2.3 Experimental test

The test was conducted by means of the torsional fatigue machine for the studied specimens namely steel AISI (316L-304H-1020) at ambient temperature and 100 °C, where each specimen fixed within the machine, see Fig. 2a. Thirty specimens were employed for the present investigation as shown in Fig. 2b. Each ten specimens (group) was machined from the steels AISI (316L-304H-1020) according

Fig. 2 Steel specimens **a** fixing specimens inside the test machine, **b** 30 tested steels specimens

to ASTM standard E2207-08 [12]. Every group for each type of materials divided into two cases, the first case was tested at ambient temperature and the other case tested at 100 °C. The shear strain amplitude that applied from the mechanism of the equipment was selected between the maximum value of 0.18 and the minimum of 0.02.

$\sigma_y \sigma_u$

At the end of the test, the number of revolutions were recorded and converted to cycles. Where the speed of rotating jaws (r) per minute (m) [9] was 5.357 *r.p.m.* Any complete reversal revolution of the jaws (or specimen) represent a cycle. Therefore, the number of cycles to failure (N_f) certainly equals to total time to failure of revolution the specimen until failure multiply by a speed of rotating jaws and the relation will be [9]:

$$N_{f(cycle)} = 5.357 * \frac{t_{r(s)}}{60} \quad r.p.s. \quad (3)$$

Fig. 3 Typical fracture of stainless steel AISI 304H specimens tested under torsional low-cycle fatigue with different angle of twist of the present study

Fig. 4 a, b Top view of fracture surface of stainless steel AISI 304H specimens under torsional low-cycle fatigue in the present study at room temperature

where; N_f is number of cycles to failure. 5.357 is a speed of rotating jaws (*r.p.s.*). t_r is time to failure of each specimen (in second).

3 Results and discussions

The external observations of the fractured specimens are given in Figs. 3 and 4a,b under fully reversed torsional fatigue which was agreed with the figures that published by ASM [3].

Results regarding fatigue crack growth and fatigue limit show that the impact of biaxial stress on the specimen surface is minimal and that the maximum principal stress governs fatigue behavior under torsional load, Ref [13].

3.1 Torsional fatigue properties

Actually, many tests with a constant amplitude based on strain fully reversed torsional fatigue were used to determine the shear strain-life curve are shown in Fig. 5. To express the experimental results, it deemed appropriate

to use a Coffin–Manson equation with most forms modification. The predictions of the shear strain amplitude behavior for the metals AISI (316L-304H-1020) are given in torsional parameter for both ambient temperature and 100° C. Material torsional parameters can be determined through curve fitting based on the discrete

Fig. 5 Experimental and predicted shear strain amplitude versus fatigue life at both **a** ambient temperature and **b** 100 °C

(a) Experimental and predicted shear strain amplitude versus fatigue life at 100°C

Fig. 5 (continued)

(b) Experimental and predicted shear strain amplitude versus fatigue life at ambient temperature

experimental data pairs on a log–log scale coordinates system for the Fig. 5. The total results verifications are considered more reasonable to improve the certainty of the experimental torsional. Properties. The optimal material parameters for each grade of steel are summarized in Tables 4 and 5.

3.2 Axial fatigue properties and verifications

Verifications have been carried out as follows: convert the calculated predicted relations that given in Fig. 5 to axial relations forms as described in Ref [9]. The Tresca, Von Mises and Maximum principal Strain criterion were used to convert the torsional cyclic properties, listed in the Tables 4

Table 4 Summary of torsional and axial fatigue properties at room temperature

Material	Torsional cyclic properties					Axial cyclic properties				
	G (GPa)	τ'_f (MPa)	b_o	γ'_f	c_o	E (GPa)	σ'_f (MPa)	b	ϵ'_f	c
316L	77.0	900	−0.12	2.00	−0.56	197	1152	−0.12	1.00	−0.56
304H	76.5	705	−0.12	1.52	−0.56	196	902.4	−0.12	0.76	−0.56
1020	77.5	270	−0.09	0.98	−0.56	200	467.6	−0.09	0.565	−0.56

Table 5 Summary of torsional and axial fatigue properties at 100 °C

Material	Torsional cyclic properties					Axial cyclic properties				
	G (GPa)	τ'_f (MPa)	b_o	γ'_f	c_o	E (GPa)	σ'_f (MPa)	b	ϵ'_f	C
326L	73.8	700	−0.10	1.40	−0.54	189	896.0	−0.10	0.700	−0.54
304H	73.5	600	−0.10	1.23	−0.53	155	768.0	−0.10	0.615	−0.53
1020	77.5	200	−0.08	0.50	−0.50	200	346.4	−0.08	0.346	−0.50

and 5, to an axial mode for getting axial fatigue properties at both room temperature and 100 °C. These axial relations forms compared with an another axial relations which calculated from five different methods, Universal Slopes, Mitchell, Modified universal slopes, Uniform Material Law and Median's method. These methods described in Ref [14] where used the monotonic properties for steel only.

The true fracture ductility (ϵ_f) values for each metal determined according to the Eq. (4) at room temperature based on the value of the reduction in area. At 100 °C, the Baume and Seeger was used to calculate the true fracture ductility value:

$$\epsilon_f = \ln \frac{100}{100 - RA} \quad (4)$$

$$\epsilon_f = 1 \quad \text{for } \frac{\sigma_u}{E} \leq 0.003$$

$$\epsilon_f = 1.375 - 125.0 \times \frac{\sigma_u}{E} \quad \text{for } \frac{\sigma_u}{E} > 0.003 \quad (5)$$

The best closer methods for axial cyclic properties among the five methods [15] and [16] of verification was shown in Fig. 6. Mean percentage error are also summarized, see Table 6.

After verification the axial properties consider more reasonable to improve the certainty of the experimental torsional properties.

The compared experimental torsional properties obtained from experimental testing for the three metals steels specimens are shown at both ambient temperature and 100 °C in Figs. 7 and 8.

Figures 6 and 7 showed the life curve. Hence, for best comparisons, the applied torsional strain value of 0.1 for three metals was selected. It has been found that the number of cycles to failure for AISI 1020 is 30 cycles,

while for 304H stainless steel is 79 cycles. This is mean that the number of fatigue life for 304H is 2.3 times than for AISI 1020. On the other hand, for the stainless steel AISI 316L, the number of fatigue life increased by 4 times than for AISI 1020 which is equal to 118.

At 100 °C, The AISI 1020 showed the lowest fatigue life to failure compared to other steels. The stainless steel 304H failed at 63 cycles, which means 3.5 times than for AISI 1020. Additionally, the number of fatigue life for the stainless steel 316L increased by 4 times than for AISI 1020 which is equal to 76 cycles approximately at same shear strain amplitude.

Also, From the results and analyzes presented, all three steels tend to become rigid when periodic torsional loading is applied, but the AISI 316L and AISI 304H stainless steels exhibit a longer life span than the AISI 1020 carbon steel. The ratio of life to failure for AISI steel 316L with respect to AISI 1020 has no effect with the temperature change because their cycles of life have been affected in the same manner. AISI 304H showed a good withstand to the temperature change because the ratio of life to failure with respect to AISI 1020 has been increased.

Table 7 shows the equilibrium of experimental relationship of strain-life to failure (N_f) in terms of carbon steel AISI 1020. The mechanical properties can deteriorate under fatigue failure due to increased temperature. That certainly leads to depression in the values of mechanical properties for the metals under investigation, see Tables 4 and 5. This behavior occurs as a result of a decrease in the ductility of the metal. This point agrees with Y. Murakami-K.J [4], especially with regard to the impact of plastic stress on the life of fatigue. Properties of the carbon steel alloys will be changed under the applied a cyclic load which directly effect on the fatigue limit [17] and [18].

(a) Verification of the predicted axial fatigue life based on monotonic data at 100°C

Fig. 6 Verification of the predicted axial fatigue life based on monotonic data at both **a** ambient temperature and **b** 100 °C

(b) Verification of the predicted axial fatigue life based on monotonic data at ambient temperature

Fig. 6 (continued)

Table 6 Verification for axial strain amplitude relations

Steel AISI	Temperature of test	Criteria of Failure	Closer method of verification	Mean percentage error (%)
316L	T room	Maximum principal strain	Mitchell	0.07
	100° C	Maximum principal strain	Mitchell	1.3
304H	T room	Maximum principal strain	Mitchell	1.1
	100° C	Maximum principal strain	Mitchell	0.7
1020	T room	Von Mises	Uniform material law	1.5
	100° c	Von Mises	Median	3.3

Fig. 7 Comparisons between torsional predicted equations versus fatigue life for metals AISI 316L, AISI304H and AISI1020 at ambient teperature **Fig. 8** Comparisons between torsional predicted equations versus fatigue life for metals AISI 316L, AISI 304H and AISI 1020 at 100°C

Table 7 Comparisons of ratio of life to failure

N_f Stainless steel	N_f Stainless steel (in terms of N_f Carbon steel)	
	Room temperature	T = 100 °C
N_f AISI 316L	N_f AISI 1020 *4	N_f AISI 1020*4
N_f AISI 304H	N_f AISI 1020 * 2.3	N_f AISI 1020 * 3.5

4 Conclusions

From the results of this investigation, the following conclusions can be summarized as follows:

1. A temperature increase of 100° C leads to a decrease in fatigue life for the three metals tested in the present study as a result of increased plastic stress leading to loss of flexibility and strength.
2. It was observed that both steel AISI 316L and AISI 304H show a high life to failure than for AISI 1020 at both ambient temperature and 100 °C.
3. The ratio of life to failure for AISI steel 316L with respect to AISI 1020 has no effect with the temperature change because their cycles of life have been affected in the same manner
4. AISI 304H showed a good withstand to the temperature change because the ratio of life to failure with respect to AISI 1020 is increased.
5. Finally, it can be noticed that carbon steel AISI 1020 was failed at the lowest value of cycles under fully reversed shear strain compared to stainless steel AISI 316L and AISI 304H, while the steel AISI 316L has a superior number life to failure (N_f) among the other steels in the present investigation.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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