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Effects of Tempering Temperatures and Corrosion on the Fatigue Behaviours of AISI 410 Stainless Steel Rods

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Abstract: The effects of tempering temperatures of range 30 to 600°C and corrosive action of saltwater medium on the fatigue properties of AISI 410 stainless steel rods were experimentally investigated and presented. Fatigue limit was found to decrease with increase in tempering temperature; at 10^7 cycles to failure, the fatigue strength of non-corroded as-received specimen increased from 310 to 520 MPa after quenching, while the as-quenched value later decreased to 400 and 340 MPa due to tempering for 30 min at 400 and 600°C, respectively. Also, fatigue life was observed to decrease with increase in tempering temperature. At fatigue stress of 550 MPa, the fatigue life of non-corroded as-received specimen was elongated from $10^{3.8}$ to $10^{5.7}$ cycles to failure after quenching, while tempering as-quenched specimen at 400 and 600°C caused its fatigue life to be shortened to $10^{4.8}$ and $10^{4.0}$ cycles to failure, respectively. Corrosion in saltwater for 30 days decreased the fatigue strength of as-received specimen at 10^7 cycles to failure to 292 MPa, while the corroded as-quenched, 400 and 600°C-tempered specimens exhibited relatively improved values of 466, 370 and 316 MPa, respectively. Above $10^{5.5}$ cycles to failure, decline in fatigue limit due to corrosion was found to decrease with increase in tempering temperature. Also, at the same fatigue stress, corrosion has adverse effects on the fatigue life of the specimens; corrosion caused the fatigue life of as-received specimen to decrease from $10^{3.8}$ to $10^{3.6}$ cycles to failure, while the corroded as-quenched, 400 and 600°C-tempered specimens displayed relatively elongated fatigue life values of $10^{5.4}$, $10^{4.7}$ and $10^{3.9}$ cycles to failure.

Key words: Tempering temperature, corrosion, fatigue limit, fatigue life, cycles to failure

INTRODUCTION

Fracture of components due to fatigue is the most common cause of service failure, particularly in shafts, axles, aircraft wings, etc., where cyclic stressing is taking place. Fatigue failures can and often do occur under loading conditions where the fluctuating stress is below the tensile strength and, in some materials, even below the elastic limit. Because of its important, the subject has been extensively researched over the last one hundred years. Fatigue has become progressively more prevalent as technology has developed a greater amount of equipment such as automobiles, aircrafts, compressors, pumps, turbines, etc. that are subjected to repeated loading and vibrations. Consideration of fatigue is important because it is the single largest cause of failure in metals; it is estimated to comprise approximately 90% of all metallic failures (American Society for Testing and Materials, 1971). Furthermore, failure by fatigue is catastrophic and insidious; it occurs very suddenly and without warning (Callister, 1997).

Also, corrosion often causes remarkable losses of materials, energy and money; it results in increased maintenance, unplanned shutdowns and possible serious accidents in engineering installations. A major form of corrosion-assisted failure in structures and machine components is corrosion fatigue resulting from the simultaneous action of a cyclic stress and chemical attack (McEvily and Stahehle, 1972). When corrosion and fatigue occur simultaneously, the chemical attack greatly accelerates the rate at which fatigue cracks propagate. Even fatigue tests in air at room temperature had been shown to be influenced by corrosion fatigue. Fatigue tests on copper showed that the strength was higher in a partial vacuum than in air (Gough and Sopwith, 1946b). Separate tests in oxygen and water vapour showed little decrease over the fatigue strength in vacuum. It was concluded that water vapour acts as a catalyst to reduce the fatigue strength in air, indicating that the relative humidity may be a variable to consider in fatigue testing. Additional studies on the effect of environment on fatigue cracking have been given by Achter (1967).

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In the recent past, the inhibition of stress corrosion of metals in aqueous media had been the major considerations of some research works (Pallos and Wallwork, 1982; Lotto, 1992; Oni, 1977). Hydrogen embrittlement was found to assist stress corrosion of ferrous metals while corrosion inhibition was found to be effected by substances forming insoluble products with iron (Parkins, 1972; Oni and Ashaolu, 1991). Also, the presence of brine had been attributed to the corrosion fatigue of offshore structures interacting with crude oil medium (Gough and Sopwith, 1946). The corrosion fatigue of a manganese steel, ST 60 Mn steel, in different media had likewise been investigated (Olaosebikan, 1991; Odebisi, 1991; Olubisi, 1995; Oluwole, 2001).

However, in the present research, the effects of tempering temperatures and corrosion on the fatigue behaviours of AISI 410 stainless steel rods is investigated because of the versatile usage of stainless steel in industrial applications. Stainless steels are used in storing food and corrosive materials in the food and chemical process industries, the utilities industries and offshore installations

MATERIALS AND METHODS

The research materials were 8mm-thick hexagonal rods of AISI 410 stainless steel of the same batch obtained from a steel market in Lagos, Nigeria. The result of chemical analysis showed the composition of the stainless steel as 0.15%C, 12.5%Cr, 1.00%Mn, 0.04%P, 0.04%S, other very-low percentage impurities and the remainder Fe. The rods were cut into a number of pieces and machined on a lathe to conform to Standard E 466: Standard Practice for Conducting Constant Amplitude Axial Fatigue Tests of Metallic Materials. The fatigue test specimen is shown in Fig. 1.

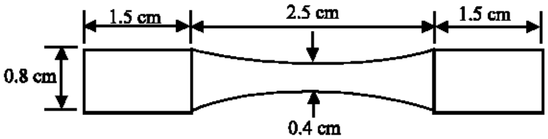

Fig. 1: Fatigue test specimen

Heat treatment: Some fatigue test specimens were retained as as-received, while the rest were heated in a furnace to austenising temperature of 1000°C for 30 min. They were then removed and quenched in oil (SAE 40/50) and allowed to cool to room temperature. Thereafter, some of these specimens were retained as as-quenched, while the others were heated to respective isothermal tempering temperatures of 400 and 600°C for 30 min, removed and cooled in still air.

Corrosion: The respective as-received, as-quenched, 400 and 600°C tempered specimens were divided into two; some were retained as non-corroded by preserving them with cotton wool in a moisture-free case, while the other were, respectively immersed in sodium chloride solution containing 3.5% weight of solute prepared from 97.5% table salt. The saltwater approximates to the average salt concentration in quiet seawater (Kamma and Anagbo, 1989). After 30 days of immersion in the corrosive medium, the specimens were removed and set for fatigue test.

Fatigue test: The fatigue properties of the specimens were determined by, respectively clamping them on the grips of a completely reversed Avery 7305 Bending Fatigue Testing Machine with a zero mean stress. A bending load was then imposed on a non-corroded as-quenched specimen by an oscillating spindle driven by means of a connecting rod, crank and double eccentric until a bending moment which corresponds to maximum fatigue stress amplitude of 640 MPa was reached. While being bent, tensile and compressive stresses were simultaneously imposed on the specimen as it was rotated via a flexible coupling by a high-speed motor. The revolution counter fitted to the motor recorded the numbers of cycles to failure when the specimen fractured. This procedure was repeated on identical specimens at progressively decreasing stress amplitudes of 610, 580, 550, 520, 490, 460, 430, 400 370, 340, 310 and 280 MPa until over 10^7 cycles to failure was attained. Cyclic loading at the specified stress amplitudes were also, respectively applied on non-corroded 400 and 600°C-tempered and as-received specimens until over 10^7 cycles to failure was reached.

Similar, tests were carried out on as-quenched, 400 and 600°C-tempered and as-received specimens that were corroded in the saltwater medium with a view to determining the effect of the corrosive actions of the medium on the fatigue behaviours of the specimens.

RESULTS AND DISCUSSION

Effects of tempering temperatures and saltwater medium on the fatigue limit and fatigue strength: Table 1 and 2 show, respectively the variations of number of cycles to failure, N_f and the logarithmic scale, log N_f, for non-corroded and saltwater corroded specimens with stress amplitudes. However, the graphical representations of these variations are, respectively shown in Fig. 2 and 3 as the plots of stress amplitude versus number of cycles to failure logarithmic scale (i.e. S-N curves). Non-corroded as-quenched specimen was observed to display highest

Table 1: Variations of number of cycles to failure, N_f, of non-corroded specimens with stress amplitudes

	Non-corroded specimens							
Fatigue stress Amplitude,	As Quenched		400°C Tempered		600°C Tempered		As-Received	
S (MPa)	N_f	log N_f	N_f	log N_f	N_f	log N_f	N_f	log N_f
640	40738	4.61	13490	4.13	2630	3.42	1148	3.06
610	79433	4.90	19055	4.28	6026	3.78	2818	3.45
580	138038	5.14	36308	4.56	8128	3.91	4786	3.68
550	575440	5.76	67608	4.83	10715	4.03	6761	3.83
520	75857757	7.88	87096	4.94	17783	4.25	8912	3.95
490	_	_	120226	5.08	20417	4.31	13183	4.12
460	_	_	141254	5.15	26303	4.42	15136	4.18
430	_	_	851138	5.93	38019	4.58	18197	4.26
400	_	_	40738028	7.61	41687	4.62	28184	4.45
370	_	_	_	_	69183	4.84	33884	4.53
340	_	_	_	_	36307805	7.56	117490	5.07
310	_	_	_	_	_	_	26302680	7.42

Table 2: Variations of number of cycles to failure, N_f, of saltwater-corroded specimens with stress amplitudes

	Saltwater-corroded specimens							
Fatigue stress Amplitude,	As Quenched		400°C Tempered		600°C Tempered		As-Received	
S (MPa)	N_f	log N_f	N_f	log N_f	N_f	log N_f	N_f	log N_f
640	22909	4.36	6918	3.84	1778	3.25	871	2.94
610	54954	4.74	10471	4.02	4169	3.62	2344	3.37
580	66069	4.82	20417	4.31	5129	3.71	3311	3.52
550	257040	5.41	50119	4.70	8710	3.94	4365	3.64
520	338844	5.53	52481	4.72	11220	4.05	7586	3.88
490	1096478	6.04	69183	4.84	19055	4.28	10471	4.02
460	23988329	7.38	85114	4.93	22909	4.36	11220	4.05
430	89125094	7.95	208930	5.32	22909	4.36	11749	4.07
400	_	_	870964	5.94	33884	4.53	22909	4.36
370	_	_	11481536	7.06	44668	4.65	27542	4.44
340	_	_	66069345	7.82	162181	5.21	74131	4.87
310	_	_	_	_	17378008	7.24	446684	5.65
280							43651583	7.64

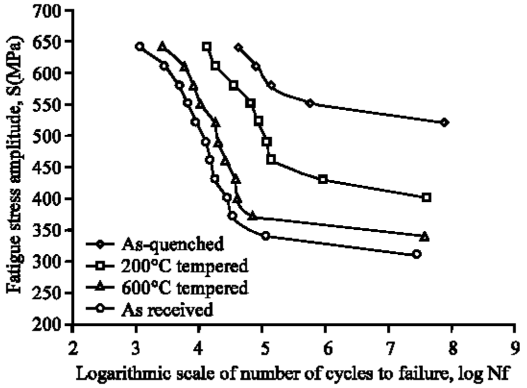

Fig. 2: Plot of fatigue stress amplitude versus logarithmic scale of number of cycle to failure for non-corroded specimens

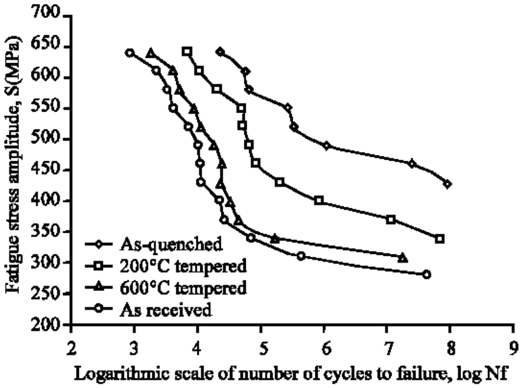

Fig. 3: Plot of fatigue stress amplitude versus logarithmic scale of number of cycle to failure for saltwater corroded specimens

fatigue limit and fatigue limit was found to decrease with increase in tempering temperature, while as-received specimen has the least fatigue limit. The fatigue limit is the maximum stress below which the specimen can theoretically endure an infinite number of stress cycles.

Also, the corrosive action of saltwater medium was observed to have reduction effects on the fatigue limit. From the S-N curves, it was also deduced that at a particular cycle to failure, the least value of fatigue strength was displayed by saltwater-corroded as-received

Table 3: Fatigue strength of specimens at 10^6 and 10^7 cycles to failure

	Fatigue strength, S (MPa) at 10^6 cycles to failure			Fatigue strength, S (MPa) at 10^7 cycles to failure		
Types of specimen	Non-corroded	Saltwater -corroded	Reduction in fatigue Strength due to corrosion	Non-corroded	Saltwater-corroded	Reduction in atigue limit due to corrosion
As-Quenched	538	490	48	520	466	54
400-Tempered	424	394	30	400	370	30
600-Tempered	340	328	12	340	316	24
As-Received	315	304	11	310	292	18

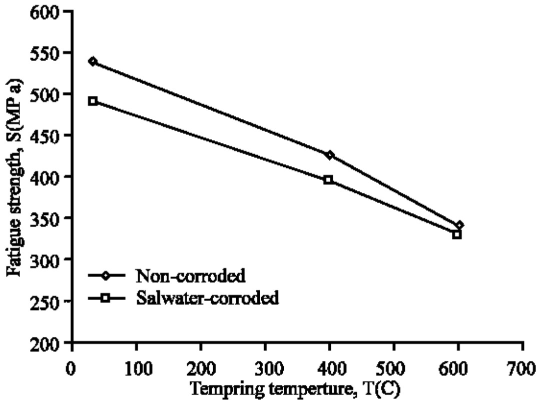

Fig. 4: Plot of fatigue strength, at log Nf = 6, versus tempring temperature

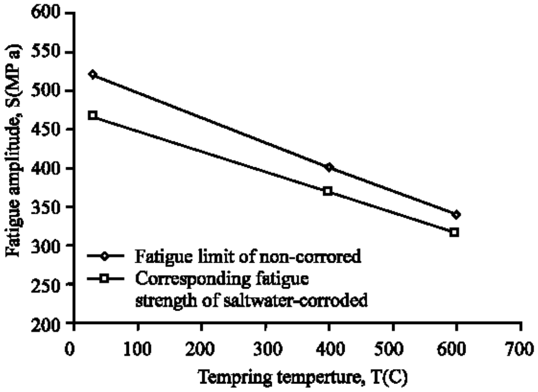

Fig. 5: Plot of fatigue strength, at log Nf = 7, versus tempring temperature

specimen and fatigue strength was found to increase as the tempering temperature decreases thereby causing non-corroded as-quenched specimen to exhibit highest fatigue strength. Likewise, corrosion has reduction effects on the fatigue strength of the specimens. Fatigue strength is a measure of the cyclic stress amplitude that a material is capable of withstanding.

The fatigue strengths of specimens at 10^6 and 10^7 cycles to failure are shown in Table 3. The fatigue strength of non-corroded as-received specimen, at 10^6 cycles to failure, increased from initial value of 315 MPa to 538 MPa after quenching. However, further tempering to isothermal temperatures of 400 and 600°C caused the fatigue strength to decrease from 538-424 MPa and 340 MPa, respectively. The decline in fatigue strength could be attributed to the stress concentration effects of thin carbide films that are formed during the tempering of martensite (Garwood *et al.*, 1951). The least fatigue strength value of 315 MPa exhibited by non-corroded as-received specimen suggests that the as-received specimen could probably be an annealed type because, according to Budinski and Budinski (1999), most stainless steel shapes are purchased in the annealed condition. Corrosion in saltwater for 30 days caused the fatigue strength of as-received specimen to decrease to 304 Mpa from 315 Mpa, while the corroded as quenched, 400 and 600°C tempered specimens exhibited relatively improved corrosion fatigue strength values of 490, 394 and 328 MPa, respectively. These variations are graphically shown in Fig. 4.

Also, the fatigue strength of non-corroded as-received specimen, at 10^7 cycles to failure, increased from 310-520 MPa after quenching, while the as-quenched value later decreased to 400 and 340 MPa due to tempering at 400 and 600°C, respectively as shown in Table 3 (Table 1 and Fig. 2). Corrosion in saltwater decreased the fatigue strength of as-received specimen to 292 MPa, while the corroded as-quenched, 400 and 600°C tempered specimens displayed relatively improved values of 466, 370 and 316 MPa, respectively. The plots of fatigue strength of non-corroded and corroded specimens, at 10^7 cycles to failure, versus tempering temperatures are shown in Fig. 5.

Figure 6 shows the plot of reductions in fatigue strength at 10^6 and 10^7 cycles to failure, due to corrosion, versus tempering temperatures. Increase in tempering temperature was found have decreasing effect on the values. At 10^6 cycles to failure, highest reduction in fatigue strength, i.e. 48 MPa, due to corrosion was exhibited in as-quenched specimen followed successively by 400 and 600°C tempered specimens exhibiting reduction values f 30 and 12MPa, respectively while as-received specimen displayed the least reduction value of 11 MPa (Table 3). Also, at 10^7 cycles to failure, maximum and minimum reductions values of 54 and 18 MPa in fatigue strength were displayed by as-quenched and as-

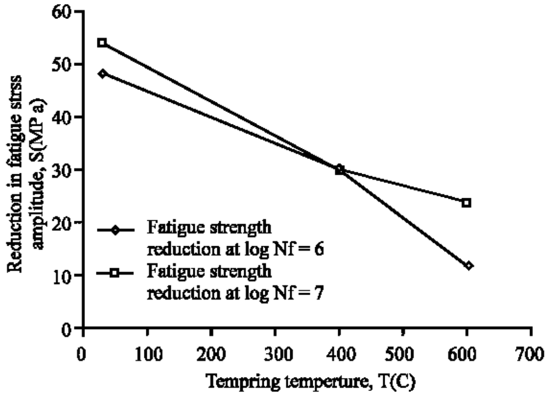

Fig. 6: Plot of fatigue strength reduction at log Nf = 6 and 7, due to corrosion

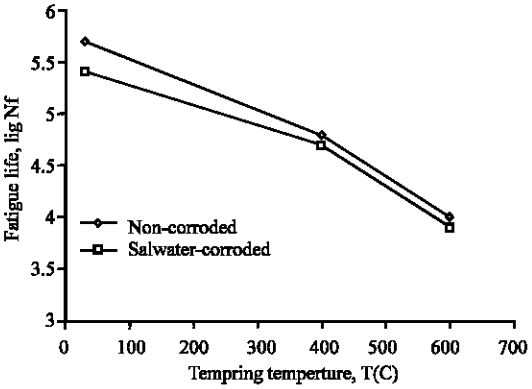

Fig. 7: Plot of fatigue life, at 550 Mpa stress amplitude, versus tempring temperature

received specimens, respectively while the reductions in fatigue strength of 400 and 600°C tempered specimens due to corrosion were found to be 30 and 24 MPa, respectively (Table 3). The highest reduction in fatigue strength exhibited by as-quenched specimen, due to corrosion, could be attributed to the largest accumulation of galvanic corrosion cells by the action of quenched-in solute atoms and distorted lattice coupled with impedance to dislocation motions.

Effects of tempering temperatures and saltwater medium on the fatigue life: The number of cycles to failure of a specimen, when subjected to specific stress amplitude, is a measure of its fatigue life at that particular fatigue strength. Table 4 shows the fatigue life of non-corroded and corroded specimens at 550 MPa stress amplitude, while the graphical form of the variations of the fatigue life with tempering temperatures is shown in Fig. 7. The fatigue life of non-corroded as-received specimen was elongated from $10^{3.8}$ to $10^{5.7}$ cycles to failure after quenching.

Table 4: Fatigue life of specimens at 550 MPa stress amplitude

Types of specimens	Fatigue life, N_f, at 550 MPa stress amplitude Non-corroded	 Saltwater-corroded
	log N_f	log N_f
As-Quenched	5.7	5.4
400°C Tempered	4.8	4.7
600-°C Tempered	4.0	3.9
As-Received	3.8	3.6

On the other hand, tempering as-quenched specimen at temperatures of 400 and 600°C caused its fatigue life to be shortened to $10^{4.8}$ and $10^{4.0}$ cycles to failure, respectively. The shortest fatigue life of as-received specimen further corroborates the presumption that it was in annealed state when purchased. Corrosion caused the fatigue life of as-received specimen to decrease from $10^{3.8}$ to$10^{3.6}$ cycles to failure, while the corroded as-quenched, 400 and 600°C tempered specimens displayed relatively elongated fatigue life values of $10^{5.4}$, $10^{4.7}$ and $10^{3.9}$ cycles to failure.

CONCLUSION

The findings in this research can be concluded as follows:

- At a specific fatigue stress amplitude, fatigue life (which is measured by the number of cycles to failure) decreases with increase in tempering temperature. Fatigue limit, the maximum stress amplitude below which the specimen can theoretically endure an infinite number of stress cycles, also decreases with increase in tempering temperature. However, as-received specimen exhibited the least fatigue limit.
- Corrosion in saltwater decreases the fatigue strength of the specimens. Above $10^{5.5}$ cycles to failure, decline in fatigue strength due to corrosion was found to decrease with increase in tempering temperature. Also, at the same fatigue stress, corrosion has adverse effects on the fatigue life of the specimens.

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