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Effects of Heat Treatment on the Corrosion Rates of Pipe Weldments and Pipe-Whip Restraint Devices in Saltwater Medium

[1]J.T. Stephen, [1]A.J. Alawode and [2]O.I. Oluwole
[1]Department of Mechanical Engineering, [2]Department of Civil Engineering,
University of Ado-Ekiti, P.M.B. 5363, Ado-Ekiti, Nigeria

Abstract: The effects of heat treatment on corrosion rates of pipe weldments and pipe-whip restraint devices in saltwater medium were investigated and presented. Mild steel pipes were preheated within temperature range of 30-200°C before respective circumferential welding of single-, double- and triple-passes. Thereafter, pipe weldment zones of 10 mm width were cut out and immersed in saltwater. The corrosion rate of single-pass weldment of as-received pipe immersed in saltwater for 90 days was found to decrease by 8.47 and 20.0% due to pipe preheat at 100 and 200°C, respectively. Also, the corrosion rates of double-pass and triple-pass weldments of as-received pipes were correspondingly higher than the 6.85 mpy value for single-pass weldment of identical as-received by 3.21 and 6.57%. This shows that corrosion rate decreases with increase in pipe preheat temperatures but increases with increase in welding pass. Though, weight loss increases with increase in immersion time, corrosion rate does not follow the same trend due to the concentration of stagnant ions blocking the creation of more ions and thus reducing Fe^{2+} activities in the solution. Corrosion rate of U-bar specimens was also found to decrease with increase in immersion time and with increase in tempering temperature. The findings of this research work shows that appropriate heat treatment could be used to minimize the corrosion rates of metallic structures in a corrosive medium.

Key words: Heat treatment, stress corrosion rate, pipe weldment, pipe-whip, seawater

INTRODUCTION

The study of the circumferential weld between two cylinders is important because of the versatile practical applications of welded cylinders. The stresses at and near the inner wall of the pipes are of greater interest than those near the outer wall in industrial piping stress corrosion cracking problems (Cheng and Finnie, 1985) because critical cracks due to tensile stresses initiate through flaws growing from the inside surface of the pipe. When a pipe cracks, the escaping fluid causes sections of the fractured pipe to acquire high lateral velocities as they rotate about localised region of deformation in the pipe. This phenomenon is called pipe-whip. The arrest of fast running cracks in pipelines is extremely important since, fast fractures have been known to run for kilometres. It is therefore very necessary to use devices restraining whipping pipe from causing havoc since industrial pipe networks are not usually entirely isolated from one another. The restraint devices should be able to absorb and dissipate the kinetic energy of the pipe expansion and be capable of undergoing enough plastic deformation to absorb all the energy input from the pipe (Bisconti *et al*., 1976). Also, the absorber must operate at a load level greater than the pipe-whip driving force so that the pipe is decelerated, but not at so fast a rate to cause excessive deceleration which could lead to water hammer or excessive load on the supporting structure (Hernalstein and Leblois, 1976).

The energy-absorbing device mostly used to minimise pipe-whip is U-bar. The pipe is housed in the U-bar and the ends of the "U" are securely attached to a rigid support. To spread the load around a remarkable portion of the pipe circumference, the curved gap between the pipe and the U-bar is usually padded with appropriate metal sheet. Fabricating, installing and disconnecting the U-bar absorbers is easy to facilitate in-service inspection and modification. The width of the U-bar is small hence several of them are usually connected to either side of suspected crack locations to arrest longitudinal crack propagation. Other energy-absorbing restraint devices include copper bumpers and concrete ring surrounding the pipes (Hernalstein and Leblois, 1976; Johnson and Reid, 1978; Kukkola, 1976).

Corresponding Author: J.T. Stephen, Department of Mechanical Engineering, University of Ado-Ekiti, P.M.B. 5363, Ado-Ekiti, Nigeria

Several research investigations had been carried out on fracture initiation, propagation and arrest in cylindrical vessels and gas pipelines. In such works Maxey *et al.* (1972) and Fearnehough (1974), studies were based on the assumptions that crack arrest will occur at a characteristic stress intensity and the actual dynamic fracture toughness investigated was with a view to improving the understanding and hence prediction of crack arrest. Stress corrosion of steel in aqueous environments had also been investigated. The investigative research works were on stress corrosion cracking of dual-phase steel in carbonate/bicarbonate solutions (Stiksma and Bradford, 1985), corrosion of carbon steel in aqueous environments containing carbon dioxide (Ogundele and White, 1986) and inhibitions of corrosion of mild steel in different media (Pallos and Wallwork, 1982; El-Hosany and Saleh, 1985).

However, the present research evaluates the effects of preheat and degrees of circumferential welding on the corrosion rates of mild steel pipe weldments. Also, the influence of tempering temperatures and time on the corrosion rates of U-bar energy absorber specimens were experimentally investigated. The corrosive medium was seawater.

MATERIALS AND METHODS

Test materials and specimen preparations: The test materials used in this research work were mild steel pipes and U-bars; the pipes having approximate chemical composition of 98.1% Fe, 0.25% C, 0.04% S, 0.8% Si, 0.75% Mn and 0.06% P. The mild steel pipes obtained were of the same batch. They have 114 mm outer diameter and 6 mm thickness and were cut into pipe specimens of 560 mm lengths.

Single V-grooves of 60° bevel, 3 mm depth and 3 mm root opening were circumferentially made on the pipe specimen at 140 mm intervals from one end using a lathe machine.

Mild steel bars of the same batch, having 30 mm width and 6 mm thickness, were cut into pieces of lengths 360 mm. With margins of 10 mm, the edges were drilled and the bars were bent into U-shape to house the pipe specimens. The U-bars were then held with bolts and nuts to maintain the shape and static bending stresses. To avoid or overcome galvanic corrosion, which may obscure the desired results, mild steel bolts and nuts were used as fasteners.

Welding of pipe specimens: There was a need to simulate the heating conditions for the weldment between 2 pipes and avoid the difficulty of aligning 2 pipes precisely before welding. Hence, for simplicity sake, single, double and triple-pass welds were separately made on the V-grooves on the pipe specimens with heat conditions such that melting occurred virtually to the inner wall. This represents circumferential welding of four pipes of length 140 mm each.

An arc welding machine set at an output current of 150 Amps, using titania-covered electrode (gauge 12) of 4.0 mm diameter made by Electrode Nigeria Limited under license of Oerlikon with ASME 11CSFA5.1 and ISO 2560 classifications was employed for welding. As-received pipe specimens were the first set to be welded on a fabricated fixture. The electric arc was kept stationary on the V-groove while the pipe specimen was relatively turned at an average welding speed of about 2.0 mm $\sec^{-1}$. This made the welding to almost be semi-automatic.

Pipe welding at 100°C was preceded by firstly heating specimen in the furnace to a temperature slightly above 100°C and clamping it on the fabricated fixture. The pipe specimen was then welded in a similar way as soon as the temperature dropped to 100°C. The same procedure was repeated for pipe welding at 200°C.

Tempering of U-bars: U-bar specimens were heated to austenitic temperature of 900°C in an electric furnace (made by Plant for Electryk Fornages, Baltchyk, Bulgaria, Type CHO-MT 1.5-2.5$^{1}/_{10}$, Serial No 8007, Maximum Temperature 1000°C) for 30 min, removed and quenched in oil (SAE 40/50) to room temperature. Some U-bar specimens were retained as as-quenched while others were isothermally tempered within temperature range of 200-600°C for 30 min, removed and cooled in still air. To obtain correct heat treatment, the settings on the electric furnace were calibrated with a thermocouple.

Pipe-whip restraint model assembly: Figure 1 shows industrial pipe-whip restraint assembly using energy-absorbing U-bars (Johnson and Reid, 1978). However, experimental pipe-whip restraint models were assembled using mild steel U-bars to house the pipe specimens, as shown in Fig. 2.

Stress corrosion in seawater: Sodium chloride solution containing approximately 3.5% weight of solute, prepared from 97.5% table salt, was used as the corrosive medium. This approximates to the average salt concentration in quiet seawater (Kamma and Anagbo, 1989).

Single, double and triple-pass weldment zones of 10 mm width having the weld line at the centre were cut out from as-received, 100 and 200°C-preheated pipe specimens. They were separately immersed in beakers containing the sodium chloride solution. The as-quenched and tempered U-bar specimens were also separately immersed in the corrosive medium. Corrosion

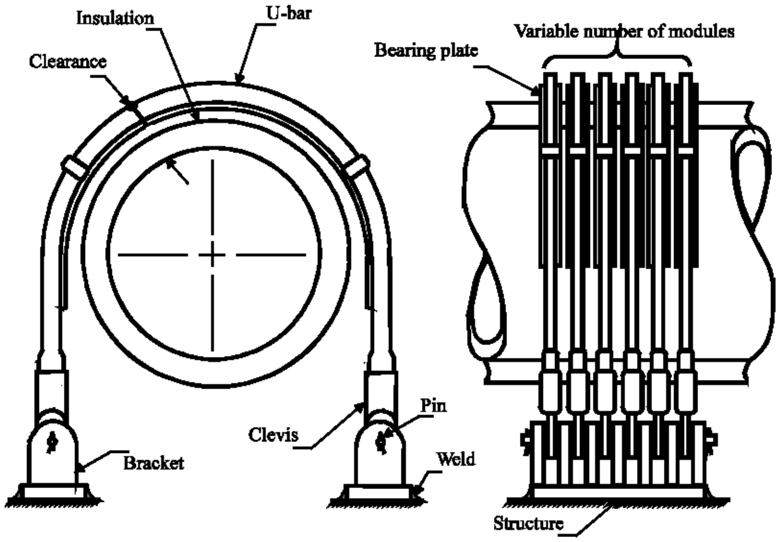

Fig. 1: U-bar Energy Absorber

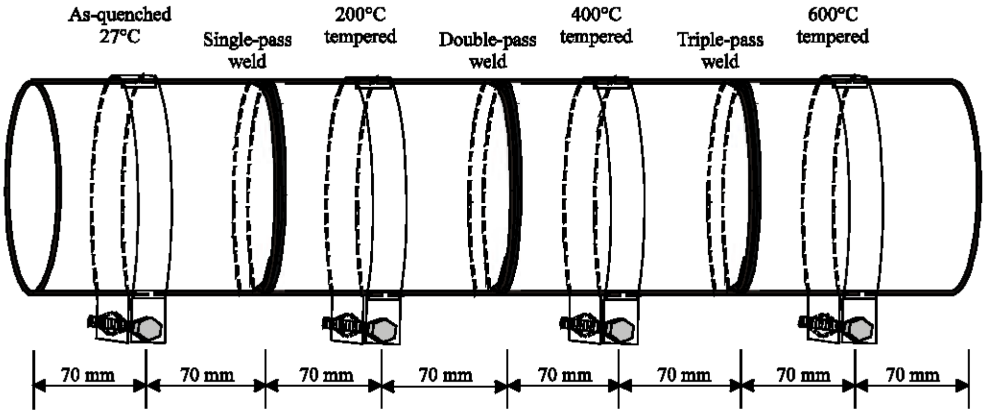

Fig. 2: Experimental pipe-whip restraint model with U-bar

is time-dependent hence the specimens were totally immersed in the solution for 90 days, however, the pipe weldment zones and the U-bar specimens were taken out and separately weighed at 15 day intervals to evaluate their weight losses and corrosion rates.

Corrosion rate of a material is evaluated (Fontana and Greene, 1978) as CR (mils/year) = $534w/\rho At$
where mils/year is mil per year

w : is weight loss of material, mg.
ρ : is density of material, g/cm^3.
A : is area of immersion in corrosive medium, sq.in.
t : is time of immersion in corrosive medium, h.

For pipe weldments, $A = \pi\,(114)(10) / (25.4)^2 = 5.55$ square inches, $\rho = 7.86$ g cm^{-3}.
For U-bar specimens, $A = (360)(30) / (25.4)^2 = 16.74$ square inches, $\rho = 7.86$ g cm^{-3}.

Table 1: Corrosion rate as a function of weight loss

Exposure time, t (day)	Corrosion rate of pipe weldment as a function of weight loss	Corrosion rate of U-bars as a function of weight loss
15	mils/year = 0.0340 w	mils/year = 0.01127 w
30	mils/year = 0.0170 w	mils/year = 0.00564 w
45	mils/year = 0.0113 w	mils/year = 0.00376 w
60	mils/year = 0.0085 w	mils/year = 0.00282 w
75	mils/year = 0.0068 w	mils/year = 0.00225 w
90	mils/year = 0.0057 w	mils/year = 0.00188 w

The corrosion rates of pipe weldments and U-bar specimens are shown in Table 1 as a function of weight loss.

RESULTS AND DISCUSSION

Effects of preheat temperatures and multi-pass welding on corrosion rate of pipe weldments: Table 2 shows the variations of weight loss of single-pass, double-pass and

Table 2: Variation of weight loss of pipe weldments with preheat temperatures

Pipe preheat temperature, T (°C)	Weight loss, w (mg) Immersion time for single-pass weldments, t (day)						Immersion time for double-pass weldments, t (day)						Immersion time triple-pass weldments, t (day)					
	15	30	45	60	75	90	15	30	45	60	75	90	15	30	45	60	75	90
As-received, 27	215	420	602	830	1040	1202	231	450	625	865	1068	1241	239	466	648	899	1110	1280
100	195	380	563	735	900	1100	210	415	606	770	951	1160	221	433	634	801	1002	1220
200	175	325	506	667	835	962	183	342	528	686	850	971	197	358	561	736	880	1075

Table 3: Variation of corrosion rate of pipe weldments with preheat temperatures

Pipe preheat temperature, T (°C)	Corrosion rate, CR (mils/year) Immersion time for single-pass weldments, t (day)						Immersion time for double-pass weldments, t (day)						Immersion time triple-pass weldments, t (day)					
	15	30	45	60	75	90	15	30	45	60	75	90	15	30	45	60	75	90
As-received, 27	7.31	7.14	6.80	7.05	7.07	6.85	7.85	7.65	7.06	7.35	7.26	7.07	8.12	7.92	7.32	7.64	7.55	7.30
100	6.63	6.46	6.36	6.25	6.12	6.27	7.14	7.05	6.87	6.54	6.47	6.61	7.51	7.36	7.18	6.81	6.81	6.95
200	5.95	5.52	5.72	5.67	5.68	5.48	6.22	6.78	5.98	5.83	5.78	5.53	6.70	6.09	6.36	6.25	5.98	6.13

triple-pass weldments with preheat temperatures and immersion time in seawater medium,while Fig. 3-5 show the respective graphical representations. The weight loss of the respective weldment was observed to increase with increase in immersion time in the corrosive medium. Increase in weight loss of single-pass weldment of as-received mild steel pipe from 15-90 days of immersion in seawater was found to be 987 mg i.e. 459% increase from initial value of 215 mg. Also, increase in pipe preheat temperature was experimentally found to cause reduction in weight loss while increase in welding pass has increasing effect on weight loss of the pipe weldment.

The variations of corrosion rate of the pipe weldment with preheat and immersion time in seawater are shown in Table 3 and the graphical forms are shown in Fig. 6-8. Corrosion rate was observed to decrease with increase in preheat temperature. This could be attributed to thermal cooling gradient, during weld solidification, which decreases with increase in pipe preheat. Lower thermal cooling gradient facilitates lower residual stresses after stress relaxation and redistribution in the pipe weldment. This implies that corrosion rate of the specimens is a function of the state of internal stresses of the pipe weldment. The corrosion rate of single-pass weldment of as-received pipe immersed in seawater for 90 days decreased by 8.47 and 20.0% due to pipe preheat at 100 and 200°C, respectively.

Also, corrosion rate was found to decrease with increase in immersion time in seawater and this could be attributed to the concentration of stagnant ions blocking the creation of more ions and thus reducing the activities of Fe^{2+} (thereby causing a decrease in concentration gradient of the specimen and its precipitates) in seawater medium.

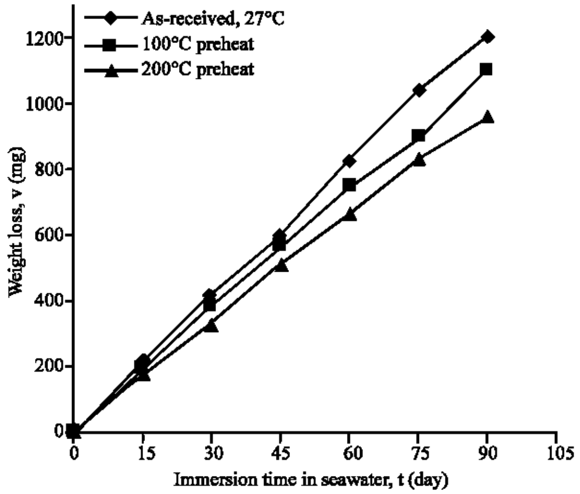

Fig. 3: Plot of weight loss of single-pass pipe weldment with immersion time in seawater

Corrosion rate increases with increase in welding pass; for an immersion time of 90 days in seawater, the corrosion rate of double-pass and triple-pass weldment of as-received pipe are 3.21 and 6.57% higher than the corresponding value for single-pass weldment. This shows that internal/residual stress of pipe weldment increases with increase in welding pass since corrosion rate is residual stress dependent.

Effects of tempering temperatures and time on corrosion rates of pipe-whip restraint specimens: Variations of weight loss and corrosion rate of U-bar energy absorber specimens with tempering temperatures and time are shown in Table 4. However, Fig. 9 and 10 shows respectively the plots of weight loss and corrosion

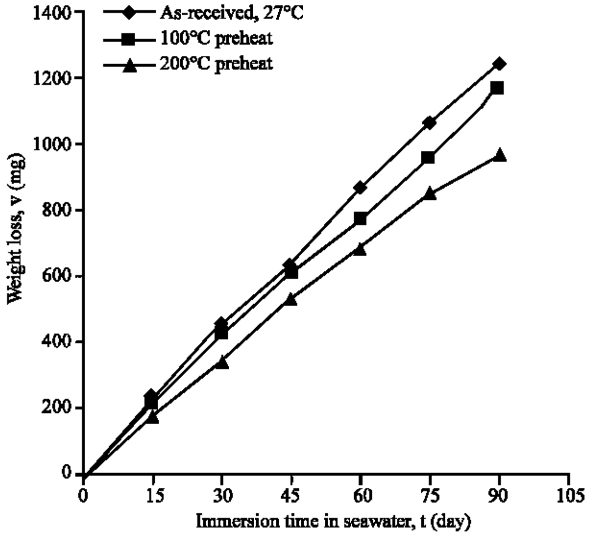

Fig. 4: Plot of weight loss of double-pass pipe weldment with immersion time in seawater

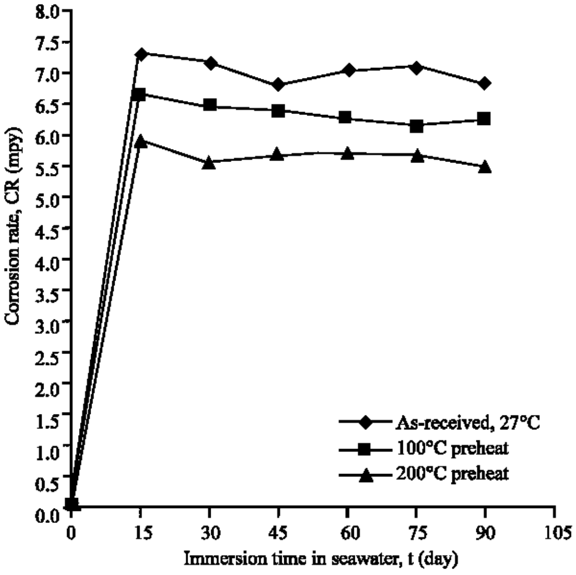

Fig. 6: Plot of corrosion rate of single-pass pipe weldment with immersion time in seawater

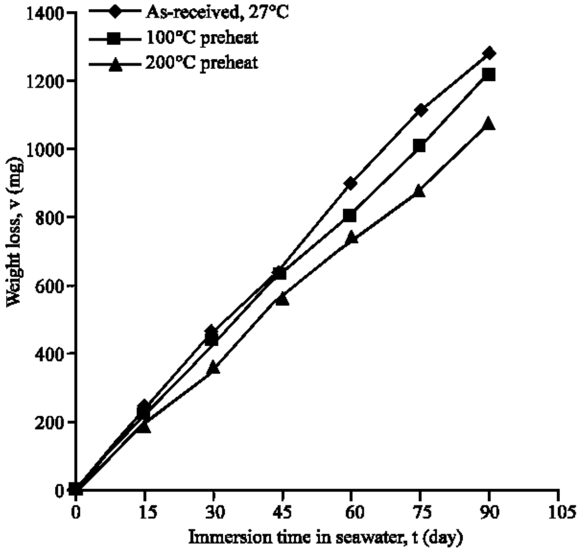

Fig. 5: Plot of weight loss of tripple-pass pipe weldment with immersion time in seawater

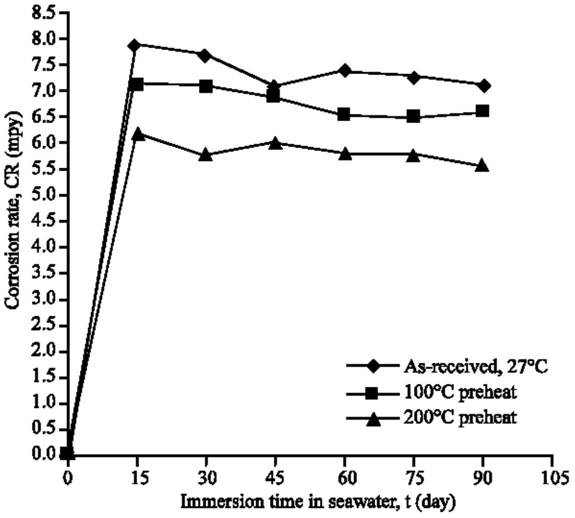

Fig. 7: Plot of corrosion rate of double-pass pipe weldment with immersion time in seawater

rate with tempering temperatures. The weight loss of the U-bars was also observed to increase with immersion time in seawater but decrease with increase in tempering temperatures. From 15-90 days of immersion in seawater, increase in weight loss of as-quenched U-bar was found to be 3604 mg.

Increase in tempering temperature was found to reduce the weight loss of the U-bar specimens. The weight loss and corrosion rate of as-quenched U-bar specimen was, on the 15th day of immersion, found to decrease by 9.02, 14.8 and 19.1%, respectively when tempered to isothermal temperatures of 200, 400 and 600°C.

Also, corrosion of the U-bar specimen was found to decrease with immersion time in seawater. The corrosion rate of as-quenched U-bar specimen decreased from 8.75-8.23 mpy within 15 to 90 days of immersion. However, increase in tempering temperature has reduction effects on the corrosion rate. On the 90th day of immersion, the corrosion rate of as-quenched U-bar specimen decreased

Table 4: Variation of weight loss and of corrosion rates of U-bars with tempering temperatures and time

Tempering temperature, T (°C)	Weight loss, w (mg) Immersion time, t (day)						Corrosion rate, CR (mpy) Immersion time, t (day)					
	15	30	45	60	75	90	15	30	45	60	75	90
As-quenched, 27	776	1500	2268	2940	3713	4380	8.75	8.46	8.52	8.29	8.37	8.23
200	706	1391	2063	2723	3502	4041	7.96	7.84	7.75	7.67	7.88	7.59
400	661	1302	1932	2501	3163	3685	7.45	7.34	7.38	7.05	7.13	6.93
600	628	1260	1837	2371	3008	3495	7.08	7.11	6.90	6.69	6.78	6.57

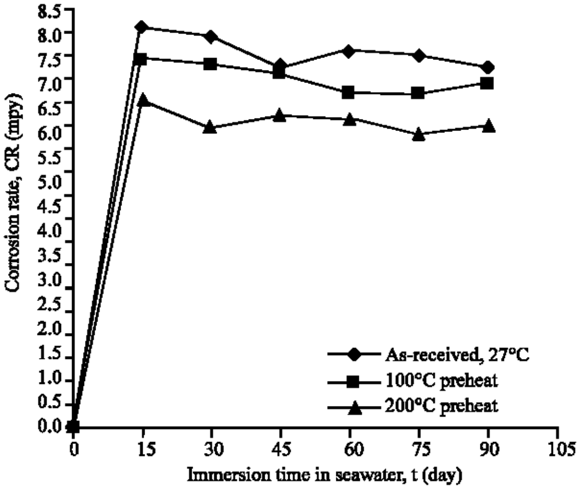

Fig. 8: Plot of corrosion rate of tripple-pass pipe weldment with immersion time in seawater

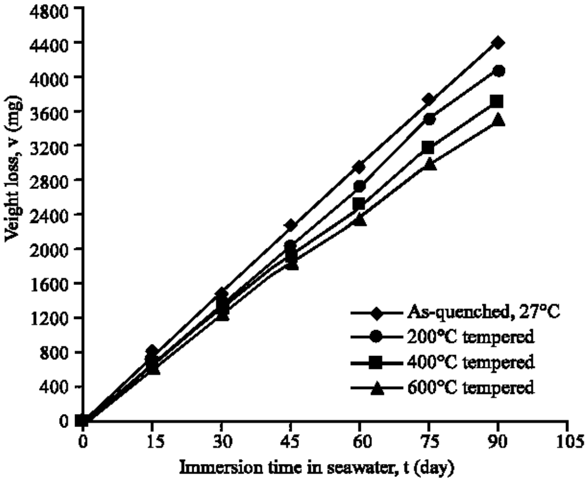

Fig. 9: Plot of weight loss of tempered U-bars with immersion time in seawater

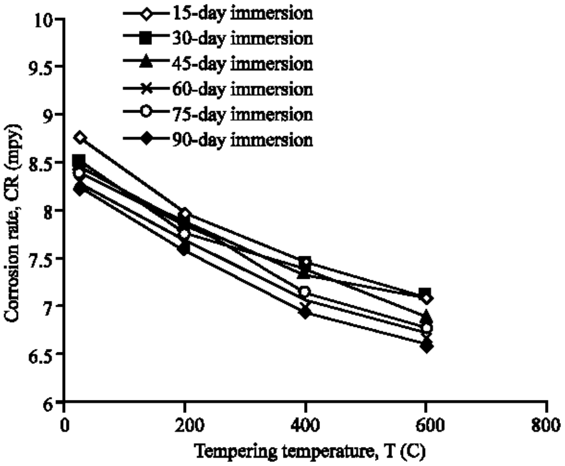

Fig. 10: Plot of corrosion rate of U-bars with tempering temperatures

from 8.23-6.57 mpy due to tempering to 600°C. During quenching, transformation from austenite to martensite in the metal matrix predominates and this increases the hindrance to movement of dislocation resulting in increased state of internal stresses and hardness. However, tempering necessitated the formation of ferrite and cementite particles. Above tempering temperature of 200°C, the fine cementite precipitate particles coarsened into larger and fewer particles thereby increasing the inter-particle spacing. The stress required to move a dislocation in the metal matrix is inversely proportional to the average inter-particle spacing (Raghavan, 1990), hence hindrance to dislocation motion was reduced due to the reduced state of internal stress. This, invariably, is responsible for the reduction in corrosion rates with increase in tempering temperatures and it further corroborates the fact that corrosion rate is a function of the level of internal or residual stress of a specimen.

Also, at the microstructural level, the two phases of ferrites and cementite formed during tempering often form galvanic couple; cementite and ferrite being cathode and anode, respectively (Raghavan, 1990; Oni, 1999). Hence, in a corrosive medium, ferrite corrodes and the finer the distribution of ferrite and cementite particles, the more the formation of galvanic cells and the faster the corrosion rate. At tempering temperature of above 200°C, cementites coarsen into larger particles resulting in reduction in galvanic cell formation and consequent remarkable reduction in corrosion rates.

CONCLUSION

Preheating as-received mild steel pipe specimens, within temperature range of 100 to 200°C before circumferential welding, has appreciable reduction effect on the corrosion rate of pipe weldment due to lower thermal cooling gradient in the weldment. Also, multi-pass welding increases the corrosion rate of pipe weldment because of increased thermal stresses during welding. Increase in tempering temperature reduces the corrosion rate of U-bar specimen, a typical example of pipe-whip restraint device in pipeline. However, though weight loss of the specimens was found to increase with increase in immersion time in saltwater, corrosion rate decreases due to the reduction in Fe^{2+} activities.

This experimental research work shows that corrosion of pipe weldments and pipe whip restraint devices in offshore applications could be controlled or minimised with appropriate heat treatments. However, corrosion-resistant steels are preferred to mild steels in offshore applications.

It can be difficult to evaluate the actual corrosion behaviour of any alloy in service based on laboratory data alone hence the results of this research work can only serve as approximate guideline, since corrosion rates are greatly affected by the conditions of actual exposure.

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