https://doi.org/10.22581/muet1982.2301.04

2023, 42(1) 32-41

Low temperature heat treatment of steel and the effect of quenching on the strength and oxidation behaviour

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Received: 02 November 2021, Accepted: 15 December 2022, Published: 01 January 2023

KEYWORDS

Heat Treatment

Mechanical Properties

Mild Steel

Sodium Chloride

Weight Loss

ABSTRACT

Mild steel is widely used in the engineering field because of its low carbon content that is often ductile and machinable. However, mild steel despite its hardness properties when exposed to corrosion mediums easily corrodes. This study investigates the effect of mild steel quenching after different heat treatment procedures and later exposed to corrosion environment (sodium chloride solution) to observe the corrosion behaviour of the metal. The mild steel samples were cut into dimensions of 75 mm x 25 mm x 4.5 mm and heat treated at temperatures of 100 ° C, 300 ° C, and 500 ° C, and quenched in both water and oil mediums. The temperature applied to the mild steel is expected to produce a phase structure in the pearlite region, and thereby improving its properties. The quenching medium influenced the microstructure of the mild steel, the hardness values as well as the corrosion resistant capabilities of the metal. The mechanical properties were tested using ultimate testing machine and Rockwell hardness Tester. Data obtained from this research, shows that the samples heat treated, water, and oil quenched all showed improved properties. It was observed that the percentage elongation for oil quenched at 100 °C, 300 °C, and 500 °C is 18.5 %, 14.1 %, and 12.4 % which is higher than water quenched which recorded 16.7 %, 12.3 %, and 9.8 % but the reverse was the results obtained for the other mechanical properties. The optical microscopy was used to observe surface morphology when the surface is exposed to the corrosion medium. It was observed that the oil quenched samples experience the lowest weight loss when compared to water quenched samples, and the as received sample had the highest weight loss. This shows that heat treatment and quenching provides some form of protection for the mild steel samples.

1. Introduction

Steel is used in a wide range of metallic structures and becomes the main material due to its low cost and good mechanical strength. Mild steel is one of the engineering structural materials employed in tonnages in offshore engineering, chemical processing, petroleum production and refining pipelines, mining and construction [1]. Mild steel has good mechanical, physical, and chemical properties, such as plasticity, toughness, welding, stamping and cutting performance and heat treatment is used to improve the mechanical properties of the metal alloys [2-5]. Heat treatment is a process that involves a combination of time controlled heating and cooling operation of metals without changing the product shape that will produce desired mechanical properties and microstructure after the heat treatment [6-8]. Therefore, it is expected that the performance of a metal will improve when the strength of the material is increased through heat treatment procedures [9]. Metal heating process can be divided into three main methods such as annealing, tempering and quenching. Each process consists of three stages, the first stage, the material is heated and secondly the temperature is held for certain period of time and lastly, the metal is cooled down to room temperature or in a medium for a certain period [10]. Quenching is known to be the rapid cooling of a work piece in different mediums such as water, oil or air to obtain certain material properties [11-14]. Heat treating process such as quenching prevents undesired low-temperature processes, such as phase transformations from occurring. Heat treatment does this by reducing the window of time during which these undesired reactions are both thermodynamically favourable, and kinetically accessible [15]. Other than that, quenching also can reduce the crystal grain size of both metallic and plastic materials, thereby increasing their hardness [16]. Based on environmental and economic effects, steel corrosion is considered as a major industrial problem that costs hundreds of billions of dollars yearly and one of the major disadvantages of mild steel is the low corrosion resistance it possesses [17]. Corrosion is the degradation of a material when in contact with a corrosive environment and this process; reduces the life span of components or parts because of the corrosion activities. Corrosion behaviour of steel and the effects on the microstructure on such behaviour is still an open field for investigation to correlate the metallurgical concept with the corrosion parameters [18]. There have been fewer investigations and reports on the correlation of heat treatment, quenching and corrosion behaviour of various mild steel specimens.

This study is on the effect of temperature and quenching mediums on the properties of mild steel. The mild steel undergoes three different heat treatment temperatures and then cooled rapidly using two different quenching mediums of water and oil. The mechanical properties of the mild steel were performed using ultimate testing machine and Rockwell hardness tester. The mild steel corrosion behaviour was observed using the method of weight loss analysis and the surface morphology of the corroded area was observed using the optical microscope (OM).

2. Materials and methods

2.1 Raw material

The raw material used in this research was mild steel (AISI1010) and were cut into dimensions of 75 mm x 25 mm x 4.5 mm. The mild steel raw material was purchased from a metal shop in Padang Besar, Perlis. The samples surfaces were grinded and sand papered to have a smooth surface with no corrosion residue on its surface.

2.2 Heating process

The heat treatment process is in stages, which are heating, soaking and cooling by quenching process. The first stage of the heat treatment procedure is the heating of the material into specific temperatures; secondly, the soaking stage where the material was held for a certain period of time; and lastly, for the cooling stage, the quenching of the heat treated samples in liquid mediums. The samples were heated in a furnace at temperatures of 100 °C, 300 °C and 500 °C respectively, for 1 hour with soaking time of 20 minutes and heating rate of 10 °C/ min, the samples are then removed and cooled immediately in two quenching mediums of water and oil for 20 min.

2.3 Tensile testing

Tensile test are performed to analyse the ultimate tensile strength after quenching of the mild steel. Tensile properties frequently are included in material specifications to ensure quality. Tensile properties are often measured during development of new materials and processes, so that different materials and processes can be compared. Finally, tensile properties are often used to predict the behaviour of a material under form of loading other than uniaxial tension.

The samples for the tensile testing have dimensions of 75 mm x 25 mm x 4.5 mm, were tested at a gauge length of 37 mm and crosshead speed of 10 mm/ min as per ASTM D638 standard. A total of 18 samples were prepared and the averages of three samples per temperature were utilised and the data obtained from the heat treatment and quenching procedures were used for each formulation and the data recorded for the tensile strength and the percentage elongation as shown in Table 1.

Table 1

Summary of UTS analysis

Name of test	Standard	No. of samples
UTS	ASTM D638	18

2.4 Hardness test

The Rockwell hardness test method was conducted according to ASTM E-18 shown in Table 2, the hardness test was performed on the mild steel samples that were heat treated at three different heating temperatures in other to improve the mechanical properties of the specimens. The Rockwell hardness testing used is as follows.

1. The indenter is pressed into the sample by an accurately controlled test force.
2. The force is maintained for a specific dwell time, normally 5 seconds.
3. After the dwell time is achieved, the indenter was removed leaving a round indent at the sample.
4. The size of the indent was determined optically by measuring two diagonals of round indenter using either a portable microscope or integrated load application device.

Table 2

Summary of hardness test analysis

Name of test	Standard	No. of samples
Hardness test	ASTM E-18	18

2.5 Immersion test in sodium chloride solution

For the corrosion testing, sodium chloride was prepared based on ASTM B895 standard shown in Table 3, by dissolving 35 g of sodium chloride in 1 litre of water. The aqueous solution was thoroughly mixed and the prepared mild steel samples are immersed inside the solution and kept for 2 weeks. After the 2 weeks duration, the mild steel samples is taken out from the solution, cleaned and dried in the oven at 90 ^{o}C to remove any moisture on its surface and the samples are weighed and the weight loss recorded.

Table 3

Summary of corrosion test analysis

Name of test	Standard	No. of samples
Corrosion test	ASTM B895	18

2.6 Optical microscope

The optical microscope (OM) was used to observe the surface morphology of the corroded sample surfaces, since metal corrosion is a surface phenomenon. This test is necessary in order to identify the type of corrosion present on the surface of the material.

3. Results

The Table 4 below shows the chemical compositions of the as received raw material obtained by X-ray fluorescence (XRF) characterization. The result of the XRF shows the carbon content of the mild steel sample to be 0.268 wt% and the rest of the other compositions to be 0.28 wt % of Silicon (Si), 0.04 wt % of Phosphorus (P), 0.05 wt % of Sulphur (S), 1.03 wt % of Manganese (Mn), 0.2 wt % of Copper (Cu), and 98.0 wt % of Iron (Fe). The weight percent of the mild steel sample carbon content indicates that it's a low carbon steel material that is commonly used in services because it is cheap and easy to alter its properties.

Table 4

Chemical composition of mild steel

Element	Wt.%
Carbon (C)	0.268
Silicon (Si)	0.280
Phosphorus (P)	0.040
Sulphur (S)	0.050
Manganese (Mn)	1.030
Copper (Cu)	0.200
Iron (Fe)	98.00

3.1 Mechanical properties

Heat treatment and quenching plays an important role in the improvement of the mild steel mechanical properties. The mechanical properties of the mild steel were tested by the ultimate testing machine and Rockwell hardness tester. The different heat treatment procedures include tempering, quenching, normalizing and annealing. Table 5 shows the tensile strength of the mild steel that undergoes two different quenching media of water and oil. The Table shows the strength of the samples increasing with the increase in temperature. The untreated mild steel sample recorded a tensile strength of 326.84 MPa, which is lower than the heat treated samples. The samples heat treated at 100 ^{o}C and water and oil quenched gives an improved tensile strength of 379.63 and 373.96 MPa respectively. The water quenching process which provides a faster cooling process of the samples records a higher tensile strength value when compared to the oil quenched which is as result of the microstructure that is formed during the water quenched process. When the temperature is increased to 300 ^{o}C and both water and oil quenched records tensile strength values of 395.924 and 381.97 MPa. As the temperature is increased it was also observed there was further increase in the UTS values. This result supports what other researchers reported that heat treatment procedures influence the mechanical properties of mild steel [19]. The further increase of the temperature to 500 ºC, the UTS still increases and it's higher with water quenched than the oil quenched samples. The water quenched sample records 407.093 MPa and the oil quenched sample records 404.8 MPa both cases produce UTS that is higher than the as received sample.

Comparing the water quenched and oil quenched samples, the data obtained clearly shows that the water quenched remains a better medium than the oil quench medium. The tensile strength of water quenched is far more superior that the oil even at the same temperature. It has been reported that water quenched exhibit more superior mechanical properties than the oil quenched. This is because of the properties of water contains high density and low viscosity which gives more cooling than the oil [20]. The cooling rate of the water helps the properties of the mild steel to improve quickly than the oil. Table 6 and Fig. 1 shows the UTS and yield strength of the mild steel specimens without quenching in water and oil. It was observed that the unquenched mild steel experienced increase in its tensile and yield strength but are inferior in strength when compared to the quenched samples. The untreated mild steel sample recorded a tensile strength of 326.84 MPa and yield strength of 206.32 Mpa, while the rest of the heated samples but not quenched records for UTS 330.09 Mpa and YS 214.91 MPa for 100 ºC, and at 300 ºC and 500 ºC the UTS and YS are 343.24 MPa, 220.61 MPa, 349.72MPa and 229.49 MPa. Table 7 shows the tensile strength of the obtained results compared with a few results obtained by other researchers. It was observed that despite the use of different types of steel the results recorded shows increase in the tensile strength after heat treatment. Fadare et al., (2011) [21] used NST 37 steel for annealing, normalising, and hardnening procedures and obtained the following tensile strength; the untreated mateirla had UTS of 343.80 while the at 910 ºC the annealed sample records 325.42 MPa, normalised 422.30 MPa and hardened sample records 678.70. Daramola et al., (2010) [22] used rolled medium carbon steel as shown in Table 7. The material records 598 MPa without heat treatment for its tensile strength, and when heat was applied at a temperature of 735 and 745 ºC the tensile strength of the material increased to 603 and 618 MPa respectively. This further confirms that a well-controlled heat treatment procedure the tensile strength of the material increases. Fig. 2 shows a comparative graph showing unquenched, water quenched and oil quenched mild steel samples. The most significant observation is that the UTS and YS increased for the different procedures that support several claims that heat treatment enhances mechanical properties of steel. But the quenched samples produce UTS and YS that are more superior when compared to the unquenched samples. Depending on the area of application the results obtained shows that quenched samples can be utilized in areas that require higher strength application.

Table 5

Ultimate tensile strength and yield strength of heat treated mild steel samples

Temperatue	100(ºC)	300(ºC)	500(ºC)
Water Quenched (UTS) MPa	379.631	395.924	407.093
Water Quenched (YS) MPa	237.420	246.210	254.530
Oil Quenched (UTS) MPa	373.960	381.970	404.800
Oil Quenched (YS) MPa	229.180	236.720	248.630

Table 6

UTS and YS of unquenched non-heated/heated mild steel samples

Temperature (ºC)	(UTS) MPa	(YS) MPa
-	326.84	206.32
100	330.09	214.91
300	343.24	220.61
500	349.72	229.49

Table 7

Compared tensile strength results

Temperature (ºC)	(UTS) MPa (Mild Steel)	(UTS) MPa(NST 37-2 Steel)	(UTS) MPa (Rolled medium carbon steel)
-	326.84	343.80	598
100	330.09	-	-
300	343.24	-	-
500	349.72	-	-
735	-	-	603
745	-	-	618
910 (Annealed)	-	325.42	-
910 (Normalised)	-	422.30	-
910 (Hardened)	-	678.70	-

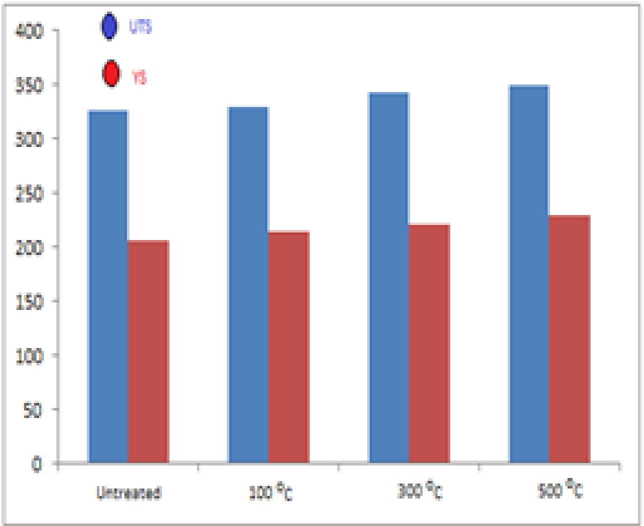

Fig. 1. Graph of UTS and YS of untreated and heated mild steel samples

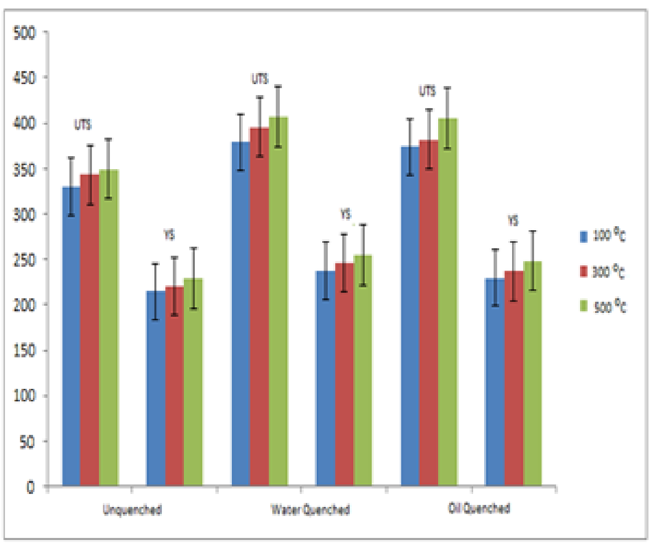

Fig. 2. Graph with error bars of unquenched, water quenched and oil quenched heated samples

The Fig. 3 shows the percentage elongation of samples heat treated at 100 ºC, 300 ºC, and 500 ºC in water quenched and oil quenched mediums. Percentage elongation which relates to the material ductility is an essential part in the mild steel mechanical properties. The sample heat treated at 100 ºC in Fig. 3 and oil quenched records the highest elongation of 18.5 %, and the correspondingly water quenched sample records a lower percentage elongation of 16.7 %. At temperatures of 300 ºC and 500 ºC also shown in Fig. 3 the percentage elongation reduces with increasing temperatures and records 14.1 % at 300 ºC, and 12.4 % for 500 ºC for oil quenched; and 12.3 % at 300 ºC and 9.8 % at 500 ºC for water quenched samples. All the quenched samples from the two quench medium shows reduction in its percentage elongation as the temperature is increased due to the increase in its hardness properties. The material with a higher percentage elongation is a more ductile material, while a material with a lower percentage will be more brittle. There have also been various research performed on heat treatment of different types of that includes 35CrMo steel [23], and 316 L stainless steel [24, 25]. Zhengxiang et al., (2022) [23] evaluated theoretically and experimentally the overall heat treatment quality of 35CrMo steel cylinder. The residual stress of the cylinder was quantitatively characterized by the relative magnetic field indexes. The structural mechanical performance of the cylinder was visually described by the magnitude of coercive force and the heat treatment process causes the hardness and coercivity of the cylinder to be higher than that of the original cylinder. This is because 35CrMo steel quenched at 850 °C forms the lath-shaped martensite, causing an increase in the grain and sub-grain boundaries leading to improvement of its mechanical properties. Xiaohui et al., 2018 [24] The mechanical and corrosion properties of gas metal arc additive manufacturing (GMA-AM) 316L optimized by modifying the volume fractions of sigma (σ) and delta-ferrite (δ) phases through heat treatment. Results show that the heat treatment at 1000 °C to 1200 °C for one hour will not obvious influence the morphology of grains in steel but largely influence the contents of σ and δ phases. The heat treatment at 1000 °C effectively increases the amount of σ phase in steel, causing both increase of UTS and YS but decrease of Elongation. The heat treatment at 1100 °C to 1200 °C completely eliminates σ phase, leading to the decrease of UTS and YS but increase of Elongation. The σ phase has better strengthening effect than δ phase, but which may degrade ductility and increase the possibility for cracks generation in steel. Other numerous researchers have all reported that there were significant changes in the microstructure, hardness, percentage elongation of steel through different heat treatment procedures which could find use in diverse application areas.

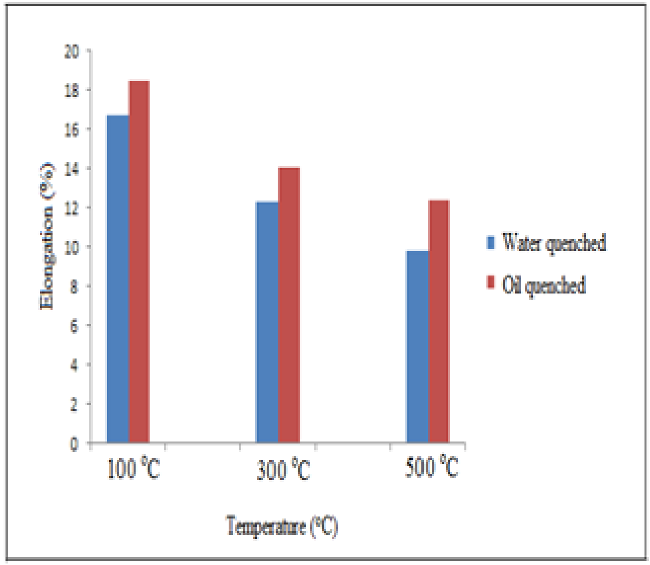

Fig. 3. Percentage elongation of heat treated and quenched mild steel samples

3.2 Hardness value

Table 8 shows the hardness values obtained by the Rockwell hardness tester for both water and oil quenched samples. It was observed from the Table shown that with every increase in temperature the hardness values of the samples also increased. At a temperature of 100 ºC the hardness value records 34.6 HRA for water quenched, 32.3 HRA for oil quenched and 30.3 HRA for the as received sample. The improved hardness property was influenced by the quenching media used. When the temperature is increased to 300 ºC, the water quenched sample records a hardness value of 35.9 HRA, and the oil quenched sample records an increase in the hardness value of 34.2 HRA. An increase in temperature to 500 ºC the hardness values still increased with water quenched sample records 38.4 HRA, the oil quenched sample records 36.7 HRA. Comparing the results obtained for both water and oil quenched mediums, the water quenched have hardness values higher than the oil quenched. This can be attributed to the difference between water and oil quenched in terms of the thermal conductivity of water which is higher than oil. Besides that, the rate of cooling of water is high than oil quenched because of water having high density and low viscosity. The oil quenched generates moderate and lesser hardness strength due to its high viscosity and low cooling rate. Tiago et al., (2021) [25] used stainless steel grade of 316 L, which provides a combination of high corrosion resistance and mechanical properties and different geometrical features and intricate parts that can now be fabricated by using the wire and arc additive manufacturing (WAAM) process. In the study, a 316 L stainless steel walls were fabricated by WAAM and submitted to several heat treatments to understand the precipitation kinetics of secondary phases and observe the δ-ferrite dissolution with synchrotron X-ray diffraction Hardness measurements. The Vickers hardness plots as a function of distance from the substrate, it was reported that higher hardness corresponds to the as-built and stress relieved sample (400 °C 1 h), ranging from 170 to 200 HV. Higher temperatures resulted in a more significant dissolution of δ-ferrite, and therefore in lower hardness values. A maximum of 174 HV is observed for the heat-treated sample at 1050 °C, while a maximum of 163 HV was found in samples heat-treated at 1200 °C. The slight difference between the means of this sample with the as-built condition is explained to be the similar hardness of the σ in comparison to that of δ-ferrite. According to Kowser & Motalleb [26], water quenched gives specific heat transfer which is better than oil, thus leading to higher hardness value, and water also as a high convection coefficient than oil in removing heat from the material.

Table 8

The hardness value of mild steel after heat treatment and quenching procedure

Hardness Strength (HRA) Water Quenched	Hardness Strength (HRA) Oil Quenched	Temperature (ºC)
34.6	32.3	100
35.9	34.2	300
38.4	36.8	500

3.3 Weight loss of the mild steel

Table 9 shows the weight loss as a result of rust at the material surface for the as received, water and oil quenched samples. The results obtained show that temperature strongly affects corrosion processes and leads to high increase in weight loss of the samples. The high temperature and rapid cooling produces surface microstructures that are susceptible to corrosion attacks when exposed to corrosion environment. At a low temperature of 100 °C the weight loss recorded are 0.093 g for water quenched samples; 0.080 g for oil quenched samples, and the as received sample records 0.200 g of weight loss. As expected the as received sample records a higher weight loss due to the untreated surface. This result is an indication that heat treated and quenched samples provides some form of corrosion protection to the mild steel material surface. When the temperature is increased to 300 °C the weight loss increases with the increase in temperature, and the water quenched sample records 0.110 g of weight loss, and the oil quenched records 0.102 g. The water quenched samples experience more weight loss when compared with the oil quenched because water containing H_2O the main factor that contributes to the increased corrosion activity when exposed and leads to more weight loss. Further increase in the temperature to 500 °C, the weight loss still increases for both water and oil quenched samples. The water quenched sample has a weight loss of 0.121 g and the oil quenched sample records 0.108 g. The increased weight loss apart from the increase in temperature, it also has to do with the surface morphology. High temperature and rapid cooling develops imperfections and cracks on the surface of the material or the grain areas which are highly susceptible to corrosion attacks. If this process continues the weight loss continues to increase until there is material failure if it's in service.

Table 9

Weight loss of water and oil quenched samples at different temperatures

Temperature (°C)	Water Quenched Grams (g)	Oil Quenched Grams (g)
100	0.093	0.080
300	0.110	0.102
500	0.121	0.108

3.4 Morphology analysis

Fig. 4 (a, b1, b2, c1, c2, d1, and d2) shows the morphologies of the as received, heat treated and both water and oil quenched samples as observed with an optical microscope. A pitting form of corrosion appears on all the mild steel samples in the figures after being immersed in sodium chloride solution for 2 weeks. The sodium chloride acts as an activator for the corrosion process because of the presence of the chloride ions. Fig. 4 (a) shows the OM micrograph of as received mild steel sample that was exposed to corrosive medium. The surface shows the corrosion attack from the chloride ions on the sample, this shows that it's more susceptible to corrosion attack because of the unprotected surface. Fig. 4 (b1, b2, c1, c2, d1, and d2) also experience similar attacks from the chloride ions, and all the samples had pitting form of corrosion attack on its surfaces indicated by the dark spots. Corrosion is very serious problems that occur on the metal surface and this make things difficult for many engineers. The effect of corrosion activity affects the performance of the mild steel in the industries. Its common knowledge that unprotected mild steel easily corrodes that could lead to material failure. The heat treated and quenched samples provide some form of protective layer over the metal surface, which minimizes the corrosion attack on its surface. The quenching allows a closed form of arrangement with tight bonding in the microstructure preventing any form of continued oxidation process from taking place. The water quenched samples experience slightly higher corrosion activity when compared with the oil quenched samples. In the presence of H_2O the oxidation of the material is eminent and prolonged with the support of the chloride ions, which penetrates the material surface and creating pits all over the surface. The electrochemical process of steel corrosion is a process in which iron reacts with oxygen when exposed to the atmosphere or environment and forms an iron oxide which is usually reddish brown. The oxidation reaction occurs at the anode and the reduction reaction occurs at the cathode. At the anode the iron is oxidised to the ferrous ions and the electrons which are released moves to the cathode. The ferrous ions are further oxidized by the oxygen which forms rust and subsequent weight loss. The heat treatment procedure forms a form of protective layer due to phase change and re-arrangement of its microstructure with a tight bond within the structure, this behaviour tends to slow the corrosion rate of the material.

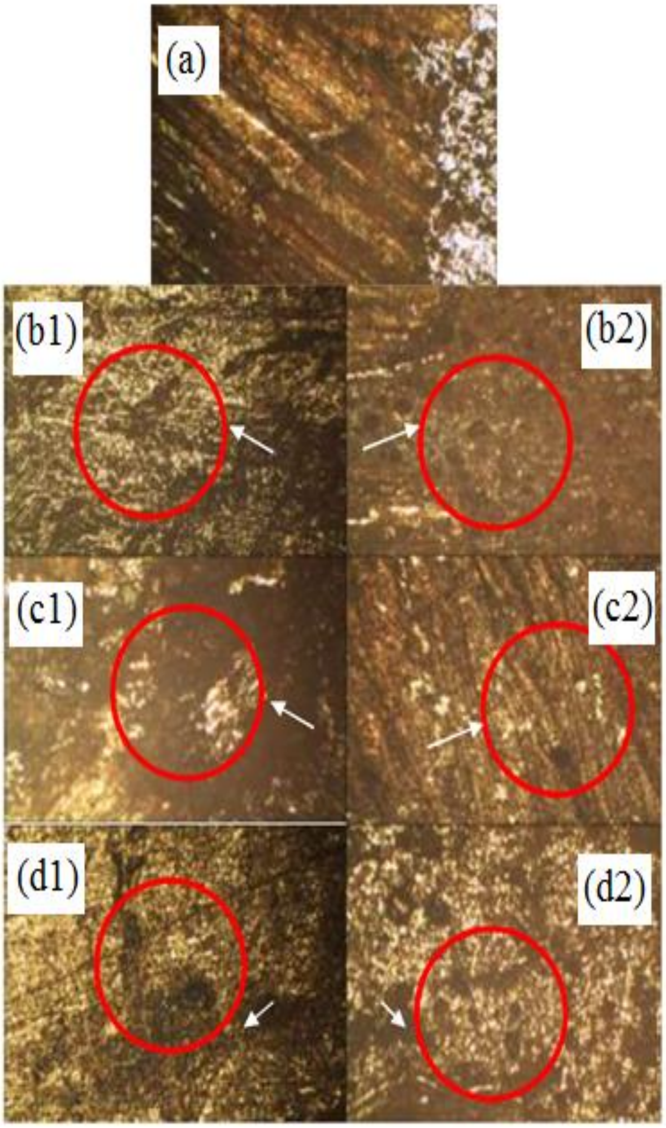

Fig. 4. Surface morphology of the samples immersed in NaCl solution for 2 weeks. (a) Untreated mild steel; (b1) 100 °C heat treated sample and water quenched; (b2) 100 °C heat treated sample and oil quenched; (c1) 300 °C heat treated sample and water quenched; (c2) 300 °C heat treated sample and oil quenched; (d1) 500 °C heat treated sample and water quenched; (d2) 500 °C heat treated sample and oil quenched

4. Discussion

Heat treatment is a very important process of influencing or changing material properties for the different areas of application because it alters the microstructure of the material when heat treated and quenched. It involves the heating of the materials to the desired temperature and then cooling the material in a media in a controlled way to acquire the necessary mechanical properties. This heat treatment and quenching procedures is used to make a metal stronger or malleable, or ductile and more corrosion resistant. The results obtained from UTS indicates that water quenched samples produced higher UTS when compared to the oil quenched which has to do with the rate of cooling and heat flow in the media. Similar behaviour was also observed for the hardness test and the reverse was observed for the percentage elongation process. Furthermore the untreated mild steel records a YS of 206.32 MPa which was the least when compared with the YS of heated samples but not quenched at 100 ºC, 300 ºC, and 500 ºC records 214.91 MPa, 220.61 MPa, and 229.49 MPa respectively. The water quenched samples records the highest followed by the oil quenched samples for 100 ºC, 300 ºC and 500 ºC produces YS of 237.42 MPa, 246.21 MPa, 254.53 MPa for water quenched samples; 229.18 MPa, 236.72 MPa, and 248.63 MPa for oil quenched samples. Similar trend was observed for the UTS for unquenched, water quenched and oil quenched mild steel samples. All the data obtained from this research is indicative of the behaviour of steel in the different media and to the divers areas of application it will be well suited for.

5. Conclusion

Mild steel and its alloys are the main materials in the industry either as construction materials or as the raw materials for manufacturing process of a product. However, due to material degradation with the environment when in contact with corrosion mediums, it leads to reduction of its life span and this have adverse effects on the mechanical, chemical and physical properties of the material. The results obtained from the heat treatment and the quenching methods shows the effect of this processes on the corrosion resistant capabilities of the samples, with the strength and the hardness properties. The oxidation behaviour of the mild steel samples was influenced by the two quenching media. The material experienced weight loss in both quenching media but less when compared with the untreated or as received sample. The quenched materials provide some form of corrosion protection to the materials which was not enough to stop the corrosion activity but could only slow down the corrosion propagation. It was also observed that the heat treatment and subsequent water and oil quenched samples influenced the mechanical properties of the mild steel by improving its tensile and hardness strength. The data obtained from the research for water quenched hardness of 34.6 HRA, 35.9 HRA, 38.4 HRA; and oil quenched hardness of 32.3 HRA, 34.2 HRA, 36.8 HRA, is an indication that the quenched samples can find use in application areas that require high strength, cyclic, dynamic or static loading with sufficient corrosion resistant capabilities. However, the application implication with respect to increased cost and efforts needed can be categorized into direct cost, allocated cost, capitalized cost and general/ administrative cost, all these plays crucial role in determining total cost arising from the heat treatment procedure, quenching and testing. Direct costs are those directly associated with the equipment or equipment grouping for which the costs per hour of operation are being determined which also includes the energy and water cost. The allocated costs are a series of smaller costs that are assigned to quenchant costs includes the cost of additive quench materials such as water, oil etc and repairs/maintenance services used to maintain the equipment. Capitalized costs are the annualized costs based on the purchase price of the equipment and all related expenses that are capitalized and directly related to the equipment. The general and administrative costs include everything else not directly assigned, including the cost of administrative, supervisory function, all indirect personnel with related benefit costs, building cost, building maintenance and general utilities. All the associated costs listed are vital in order to have a heat treated material that will be applicable in different areas of application while making the process or procedure cost effective. The combined total cost of all the procedures involved in the heat treatment, quenching and testing is relatively less expensive but proper care and control of the process is crucial to achieve a material of a very high standard that conforms to international standard guidelines/ practice in the final mechanical property improvement of the mild steel.

6. Acknowledgement

This research was supported by both Covenant University (CU) and Universiti Malaysia Perlis (UniMAP).

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