Journal of Applied Science, Engineering and Technology (2016) vol. 16, issue 1:58 - 62

Effect of Post Welding Heat Treatment on the Mechanical Properties of Welds of AISI 1040 Medium Carbon Steel

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ABSTRACT

AISI 1040 steel is one of the grades of medium carbon steel of American standard and as such, is mostly being used in the industries. Again, when welding a piece of material, only the joint and surrounding area being welded (Heat Affected Zone, HAZ) is heated and cooled. This causes uneven expansion and cooling, and the piece begins to warp or distort at the point. Uncontrolled Distortion may lead to a serious dimensional defect/failure. In order to arrest this failure, Steps may be taken before, during, and after welding to minimize or control the effects of this heat distortion**.** Controlling the effects of heat distortion after welding forms the basis of this study. To this end, this work studied the effects of post welding heat treatments on the mechanical properties of welds of AISI 1040 medium carbon steel. Butt-welds of AISI 1040 medium carbon steel were prepared with the aid of electric arc welding and subsequently subjected to annealing, normalizing, hardening and tempering heat treatment processes. Finally, the welds were subjected to impact, tensile and Rockwell hardness tests. The results show that tempering improves the toughness of the steel at the HAZ. Normalizing refines the grain structure and relieve the internal stress, Annealing increases the ductility and softens the steel at the HAZ. Hardness and brittleness of the hardened and tempered pair increase while that of the normalized and annealed pair considerably reduced. The study recommends paired annealing and normalizing processes for welds of AISI 1040 medium carbon steel.

Keywords: AISI 1040 carbon steel**,** arc-welding**,** heat treatment and mechanical properties

1. Introduction

Post welding heat treatments have been carried out by various researchers due to its wide range of applications such as in ship building, automobile, aerospace industry, joining of beams in building and refineries. Heat treatment processes are used to produce changes in the metallurgical structure and the related material, structural, and surface texture properties of steel (Totten and Howes 1997). Heat treatment techniques include annealing, case hardening, precipitation strengthening, tempering and quenching. It is noteworthy that while the term heat treatment applies only to processes where the heating and cooling are done for the specific purpose of altering properties intentionally, heating and cooling often occur incidentally during other manufacturing processes such as hot forming or welding. Metallic materials consist of a microstructure of small crystals called "grains" or crystallites.

[1]The nature of the grains (i.e. grain size and composition) is one of the most effective factors that can determine the overall mechanical behavior of the metal. Heat treatment provides an efficient way to manipulate the properties of the metal by controlling rate of diffusion, and the rate of cooling within the microstructure. Past works relating to this area have been well documented. For instance, Roy et al. (2003) evaluated the enhancement of the fatigue resistance of welded transverse stiffeners and cover plate details by ultrasonic impact treatment (UIT) in 18 full-scale W27×129 rolled beam specimens. Fatigue tests were conducted under constant amplitude loading at various stress range levels and at two minimum stress levels simulating the effect of sustained load. The test specimens were investigated for fatigue crack initiation and propagation. Distributions of residual stresses adjacent to the weld toe were determined before and after the treatment. Test results indicated that UIT enhanced the fatigue performance of all treated details by improving the weld toe profile, changing microstructure and introducing beneficial compressive residual stresses at the treated weld toe. The treatment effectively elevated the fatigue crack growth threshold and the fatigue limit without changing the slope of the S–N curve. Also, the effects of a post-weld heat treatment on the fracture toughness and fatigue crack growth behavior of electron beam welds of an $\alpha + \beta$

Received: 19 February 2016; Revised: October 2016; Accepted: 11 November 2016
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titanium alloy, Ti–6.5Al–1.9Zr–0.25Si have been studied by Mohandas et al. (2001), they showed that welds in the stress-relieved condition exhibited poor fracture toughness due to poor energy absorbing capacity of the thin α and α' phases. Post-weld heat treatment which resulted in the decomposition of α' to α + β and the coarsening of intra-granular and inter-granular α resulted in improved toughness. This improvement in the toughness is related to improved ductility leading to crack blunting, crack path deviation at the thick intra-granular and inter-granular α phase. Fatigue crack growth resistance of welds was superior to the base metal in the α + β heat-treated condition. The superior crack growth resistance of the welds is due to the circular α microstructure which results in a tortuous crack path and possible crack closure arising from crack path tortuosity. Furthermore, the effect of the heat treatment conditions on the microstructure evolution in the iron base alloy strengthened by carbide precipitation was studied by Lothongkum et al., (2005). The Fe - 30.8Ni - 26.6Cr alloy, produced in the form of centrifugally cast tubes, was studied by means of scanning electron microscopy (SEM) after various heat treatment conditions. The obtained TTP diagram was established for the aging application and welding of this alloy. It can be summarized that the heat treatment conditions have a great effect on shape, size, dispersion and the location of the secondary carbides in the microstructures and could result in the different mechanical properties. The development of the weld microstructure in a dissimilar metal weld between two heat resistant steels, one ferritic and one martensitic during welding and post-weld heat treatments has been studied by Andersson (2005). The results show that the carbon depleted zone that develops near the weld metal in the lower alloyed steel depend on the formation and dissolution of the MzsCe-carbide. Variations of the weld parameters and the post-weld heat treatment affect the size and shape of this zone. The process has been successfully modeled by computer simulation. It was found that the applied stress influenced the grain growth process in the weld. As a result of the treatment the hardness of the material was found to be increased by 25 percent Munsi (2001). The effect of heat treatment on the mechanical properties of mild steel using samples of mild steel were annealed at a temperature of 100, 300 and 5000C and quenched in SAE 40 oil, some of this specimen were released as quenched while other were temper at temperature of 2000C. The heat treated mild steel rod were then subjected to tensile, impact and torsional test and the result of the test show that stress and ultimate decreases as both annealing and tempering temperature increases, the percentage elongation also increases as annealing and tempering temperature increases. Moreover, the impact energy and the breaking torque increases as the tempering and annealing temperature increases (Adebayo and Stephen, 2008). Spitsen et al. (2005) investigated the use of post-weld cold working process to improve fatigue strength of low carbon steel resistance spot welds. Comparisons of the mechanical properties and qualitative results between the as-resistance spot-welded specimens and the post-weld cold worked resistance spot-welded specimens have been made in this investigation. Fatigue testing was also conducted to evaluate the effect of post-weld cold working process on the fatigue characteristics of resistance spot welds. Results showed that a significant improvement in the fatigue strength has been achieved through the post-weld cold working process. Umoru (2008) studied the effect of lap joint and butt joint electric arc welding together with their post weld heat treatments, Stainless steel AISI 321 was used as base metal, the corrosion experiment was by the non-electrochemical technique and the analysis of the result was by corrosion rates determination in mils per year (mpy). The tar sand used for investigation was analyzed using energy dispersive x-ray analyzer (EDXA). The result indicated that the furnace cooled heat-treated lap joint welded stainless steel exhibited the least resistance in the tar sand environment, it can be concluded that butt-welding coupled with water quenching as a post-weld heat treatment should be adopted for the construction of tar sand digester. When welding a piece of metal; bigger and more level residual stresses can occur in weldment due to restraint by the parent metal during weld solidification. The stresses may be as high as the yield strength of material itself especially when combined with normal load stresses and these may exceed the design stresses (WTIA, 2003). Thus, investigating the effect of post weld heat treatment on the mechanical properties of welds cannot be over emphasized, this work therefore critically studied the effect of annealing, normalizing, hardening and tempering heat treatment processes on the mechanical properties of the welds of medium carbon steel AISI 1040.

2. Materials and Method

Medium carbon steel AISI 1040 was obtained from Owode Onirin in Ikorodu, Lagos state. The specimen is as shown in figure 1 and the chemical composition in table 1.

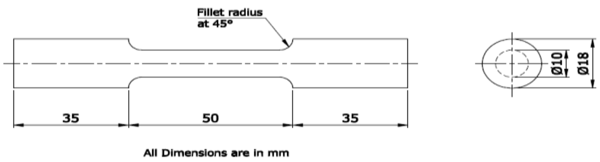

Figure 1: Test specimen for AISI1040 steel

The material was cut and grinded in to fifty samples of the following dimensions as shown in figure 1 using standard ASTM method for heat treatment. The samples were now washed in order to remove the organic substances on the surface. The samples were divided into twenty five pairs, each comprising two pieces of five sample groups. Each pair was butt-welded with the aid of electric arc welding. Each of the sample groups was labeled as sample group 1-5, sample groups 2, 3, 4 and 5 were subjected to normalizing, annealing, hardening and tempering post welding heat treatment at the metallurgy workshop, department of material science and engineering, obafemi awolowo university, Ile-Ife. For Normalizing, the sample groups 2 were austenitized in a muffle furnace at temperatures of 700, 675, 650, 640 and 630 ^{O}C and subsequently cooled in an open air for 60 minutes. After, sample groups 3 were annealed by heating the samples in a muffle furnace at temperatures of 700, 675, 650, 640 and 630 ^{O}C and subsequently cooled/held in the furnace for 60 minutes. Sample groups 3 were hardened by heating the sample group to 700, 675, 650, 640 and 630 ^{O}C) and rapidly cooled with cold water outside the furnace. Sample groups 4 were subjected to higher tempering temperatures of 700, 675, 650, 640 and 630 ^{O}C. Sample group 1 was however not subjected to any heat treatment process as it serves as control. Table 2 shows heat treatment procedure employed in the experiment. After the post weld heat treatment process, materials were subjected to engineering test in order to determine the effect of heat treatment on the mechanical properties of the material. Impact test was performed on samples 1 and 5, tensile test on samples 2, 3 and 1 and Rockwell hardness test on samples 4 and 1.

Table1: Chemical composition of AISI 1040

Medium carbon steel (AISI 1040)	
Alloying Element	Composition (%)
Carbon	0.39
Manganese	0.69
Phosphorus	0.03
Sulphur	0.04
Silicon	0.20

Table 2: Heat treatment procedure

Sample group	Heat treatment	Temp. range (^{O}C)	Time (min.)	Cooling medium
1	None	-	-	-
2	Normalizing	700, 675, 650, 640 and 630	60	Air
3	Annealing	700, 675, 650, 640 and 630	60	Furnace
4	Hardening	700, 675, 650, 640 and 630	60	Cold water
5	Tempering	400, 350, 300, 250 and 200	60	Air

3. Results and Discussion

3.1 Effect of tempering

Figure 2 shows the result of impact test after tempering process. The result shows that the higher the tempering temperature the higher the energy absorbed (toughness), this is due to the partial transformation of martensite back to pearlite (at high temperature) again thereby taking away some of the hardness but making the steel tougher. The as-welded pair 1 gives a low energy absorbing ability (45J) this is due to the welding process which induced stress in the heat affected zone (HAZ) thereby changing the original orientation of microscopic structure, which causes a reduction in the energy absorbing ability at the HAZ .

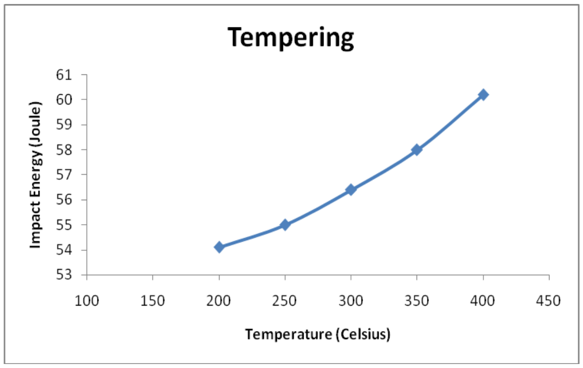

Fig. 2: Impact energy vs. Temperature (Tempering)

3.2 Effect of Annealing

Figure 3 shows the results of tensile test after Annealing. The result obtained from the tensile test shows that the percentage elongation increases with temperature for the annealed specimen this is due to the softening of the HAZ and the relieving of internal stress which is mainly due to the slow rate of cooling (furnace cool). The percentage elongation for the as-welded pair 1 at ambient temperature (30ºC) was found to be lower (1.3 %) compared to the annealed pair. This is due to the increased residual stress induced at the HAZ during the welding process which eventually overcame the yield stress of the medium carbon steel, thereby reducing the ability of the steel to resist the application force without rupture (Strength) also reducing its ability to be drawn out in tension without rupture (Ductility).

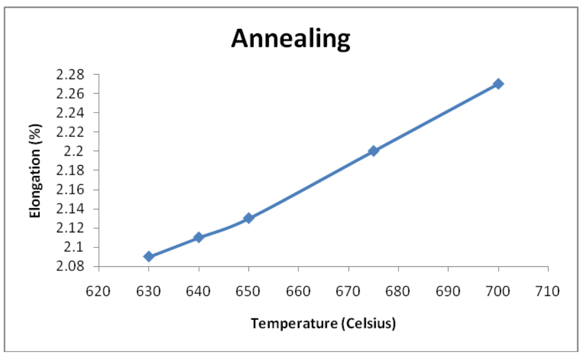

Fig.3: Elongation vs. temperature (Annealing)

3.3 Effect of Normalizing

Figure 4 shows result of tensile test after Normalizing heat treatment process. Similar trend was observed with the annealing heat treatment but with slight difference in percentage elongation. The result obtained from the tensile test shows that the percent elongation increases with temperature for the normalized specimen, this is due to the refinement of the grain structure and removal of residual strains generated during the welding process which helped to soften the HAZ and the relieving of internal stress which is mainly due to the slow rate of cooling (air cool). The percent elongation for the as-welded pair 1 at ambient temperature (30ºC) was found to be lower (1.3%) compared to the normalized pair this is due to the increased residual stress induce at the HAZ during the welding process which eventually overcame the yield stress of the medium carbon steel, thereby reducing the ability of the steel to resist the application force without rupture (Strength) also reducing its ability to be drawn out in tension without rupture (Ductility).

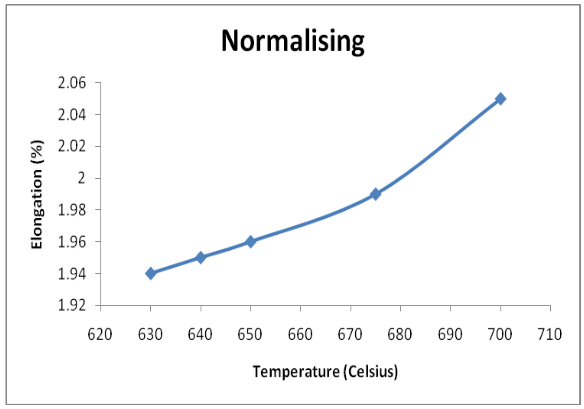

Fig 4: Elongation vs. temperature (Normalizing)

3.4 Effect of Hardening

Figure 5 shows result of hardness test after hardening post-weld heat treatment process. Result obtained from the Rockwell hardness test indicates that the As-welded pair 1 shows a considerable hardness due to the non-uniform distribution of the welding heat across the cross sectional area of the HAZ, causing non uniform cooling and coarse micro structure). Pair 4 shows a high hardness, this is due to the formation of martensite, a needle like structure (rapid cooling) at the HAZ, this is because when the metal was suddenly cooled it underwent a general contraction which is not uniform but occurs first at the outer surface and in the thin section of the HAZ.

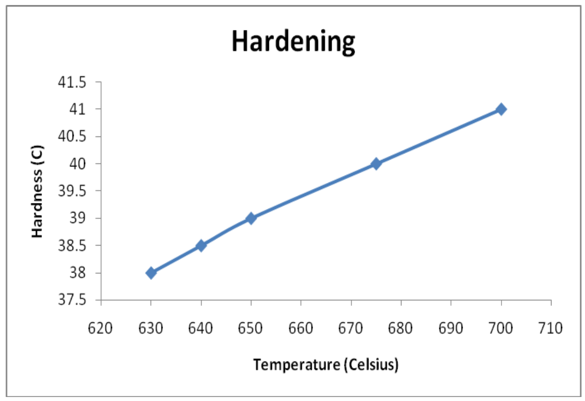

Fig. 5: Hardness vs. temperature (Hardening)

4. Conclusions

The effect of post welding heat treatments (normalizing, annealing, hardening and tempering) on the quality of electric arc welds of AISI 1040 medium carbon steel have been investigated. It is hereby concluded that the welding process generally results into distortion and induction of residual stress and strain in the welded pair which changes the original micro structure of the welded pair. The thermal distortion and residual stress induced by welding increases with thickness of the welded pair. The welding process leads to reduction in the strength, toughness and ductility of the as-welded pair 1 at the heat affected zone (HAZ) but with moderate increase in the hardness and brittleness. Tempering post welding heat treatment increases the toughness of the steel while reducing the hardness of the steel at the HAZ. Normalizing, annealing post welding heat treatment increases the strength and ductility of the steel at the HAZ. Hardness and brittleness of the hardened and tempered pair increase while that of the normalized and annealed pair was considerably reduced.

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