The Effect of Quenchants on the Mechanical Properties of Scrap Carbon Steel on Welded Joints by Manual Metal Arc Welding Process

Kwabena Offeh Gyimah[a], Gladys Perpetual Awudi[b], Emmanuel Akanvariba[a], Ebenezer B. Owusu[b]

[a]Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED), Ghana
[b]Southern Alberta Institute of Technology, Canada [b]University of Nottingham, UK

DOI: 10.29322/IJSRP.12.04.2022.p12428
http://dx.doi.org/10.29322/IJSRP.12.04.2022.p12428

Paper Received Date: 26th March 2022
Paper Acceptance Date: 11th April 2022
Paper Publication Date: 18th April 2022

Abstract: The effects of quenching medium on the mechanical properties of scrap and new carbon steel welded joints were investigated. Using flux coated electrodes AWS/SFA 5.1 E-6013, the welding was carried out at 100 A at welding speed of 1.52 mm/s and a constant arc voltage of 21 V with root gap and root face kept at 3 mm each. Three quenching media were used namely water, air and engine oil. Tensile, impact and Vicker's hardness tests were conducted on the welded joints to determine the effect of cooling rate on materials' mechanical properties. With the Ultimate Tensile strength, it was observed that the new sample had higher tensile strength compared to the scrap sample. The differences in the ultimate tensile strength were 38.91 %, 38.40 % and 42.75 % for water cooled, air cooled and oil cooled respectively. Also, the new sample had higher elasticity values than the scrap sample with 31.95 %, 64.88 % and 46.78 % differences in Young's modulus for water cooled, air cooled and oil cooled respectively. However, it was observed that the scrap sample had greater impact energy than the new sample. The difference in the impact energies were recorded as 54.55 %, 32.14 % and 35.78 % for water cooled, air cooled and oil cooled respectively in favour of the scrap samples.

1. Introduction

The greatest challenge for the steel and scrap processing industry to obtain long term sustainable steel recycling is perhaps the question of scrap quality and the need to avoid quality losses when recycling steel. As the share of steel produced from ore has increased in the last decade, accumulation of tramp elements has not been an issue of high importance recently, but it is an issue that has to be tackled in the future [1]. Some steel products are principally sourced via the primary route mainly because the steel specifications require low residual elements and this can be achieved most cost-effectively using more primary material. In most cases, scrap with a low amount of residual elements commands a higher market price owing to the ease of processing through the recycling routes [1].

Welding is a very vital process in production due to the high joint efficiency, flexibility, simple set up and the low cost of fabrication. It is an efficient, reliable and economical process [2, 3]. Sound welded joints are vital in any construction sector, and if there should be any failures, it can be very dangerous. Hence, standards must be taken seriously with keen interest in precision quality. This can be achieved if we can control mainly the heat input and effects that the cooling rate has on the welded joint [4].

Solidification cracking becomes a more serious problem when different materials and an increased welding speed are used for the high functionalization of the mechanical structure and to increase productivity [5]. Moreover, as the cooling rate increases, the residual stresses stored in the bulk material increases as well. The major influencing factors in the choice of the quenching medium are the kind of heat treatment, composition of steel, shape and size of parts [6, 7].

Application of quenching in steel manufacturing is done to obtain the desired mechanical properties such as, hardness, yield strength, and ductility [8]. The material properties are controlled by a quenching process in many industrial applications, e.g., in engine components for wear and durability, aircraft components for strength and fracture toughness, bicycle frames for strength, lightness and durability [8]

This research therefore seeks to consider the effect of cooling rate or choice of quenching medium on mechanical properties of recycled carbon steel welded joints.

2. Materials and Methods

2.1 Sample preparation

Two sets of three samples were used. One set consisted of scrap recycled carbon steel (SS) whereas the other, was steel fabricated from iron ore, here referred to as New Sample (NS). Samples preparation, welding and testing were conducted at the Tema Steel Works Company (TSWC) and the Kwame Nkrumah University of Science and Technology (KNUST) welding workshops and laboratories. Base samples of NS, obtained from TSWC and recycled NS samples from KNUST, were cut to size; 215 mm x 35 mm x 12 mm. Single V-edge preparation with 60 ^{o} included angle was made on the samples with root gap and root face kept at 3 mm each [9]. Welding of the different samples was performed at 1G welding position using the DC2013-T welder. Flux coated electrodes used for welding was AWS/SFA 5.1 E-6013 of 3.15mm diameter and 350mm long. A welding current of 100 amps was used by keeping the welding speed at 1.52 mm/s and a constant arc voltage of 21 V. Welding polarity was kept at DCEP. After welding, the weld reinforcement was ground and weld joint face made flat, using the Total TG1242306-2350W angle grinder. The welded joint samples were normalized at 780 ^{o}C for 1 hour and subsequently cooled in air, water and oil. Each medium was to cool two samples (one SS, one NS).

2.1.1 Material composition

Chemical analysis on both SS and NS carbon steel samples was done at Rider Steel Works in Tema, Ghana. The corresponding elemental composition for the analysis is presented in table 1.

Table 1 Chemical Analysis results of carbon steel base metal as-received and after welding

Sample ID		Chemical Composition / %						
		C	Si	Mn	P	S	Cr	Ni
SS	Unwelded	0.115	0.126	0.653	0.014	0.024	0.001	0.145
	Weldment	0.168	0.241	0.274	0.044	0.026	0.001	0.022
		V	Ti	Al	Cu	Co	Fe	Mo
	Unwelded	0.018	0.013	0.001	0.042	0.363	96.18	0.054
	Weldment	0.028	0.017	0.001	0.138	0.298	96.19	0.048
NS		C	Si	Mn	P	S	Cr	Ni
	Unwelded	0.164	0.038	0.323	0.033	0.044	0.001	0.132
	Weldment	0.087	0.225	0.21	0.038	0.033	0.249	0.213
		V	Ti	Al	Cu	Co	Fe	Mo
	Unwelded	0.021	0.013	0.033	0.055	0.274	96.74	0.043
	Weldment	0.011	0.02	0.001	0.147	0.29	96.19	0.057

2.2 Methods

2.2.1 Tensile testing

For tensile testing, sample was positioned in the PROETL: DI-CP/V2 2000KN computerized universal testing machine, with an extensometer connected to it. One end of the sample was secured firmly to the non-movable jaw while the other end was secured in the movable jaw of the universal tensile testing machine at room temperature. The load control knob was subsequently activated to apply a steady tensile load to each of the sample until the sample failed. With the aid of the load sensor attached to the test sample, the increasing tensile stresses were measured digitally. The extensometer recorded the corresponding changes in the length of the test sample due to the application of the tensile loads. Stress-strain graphs for each of the test on the sample were computed and displayed by the attached computer. The strain and yield Strength were also obtained using the same machine.

2.2.2 Hardness and impact testing

Vickers Hardness test was performed to determine the hardness of the sample. The pyramid diamond indenter was pushed at 30 points for an interval of 2 mm at the parent metal and 1.6 mm at the heat affected zone for each of the test sample, as shown in Fig. 1. An HSM55 PENDULUM digital impact testing machine (300J) was used to conduct the impact test. The impact is made using the pendulum raised to the required angle. When the pendulum hits the sample, it absorbs some energy from the impact of the pendulum and fails as shown in fig. 2 depending on its toughness and the energy absorbed is referred to as the impact energy which is recorded on the digital display. The impact strength is calculated as Impact Energy divided by Cross Sectional Area of the sample.

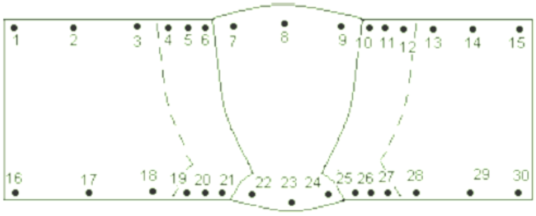

Figure 1. The Welded sample showing the 30 points at which the hardness measurement was made

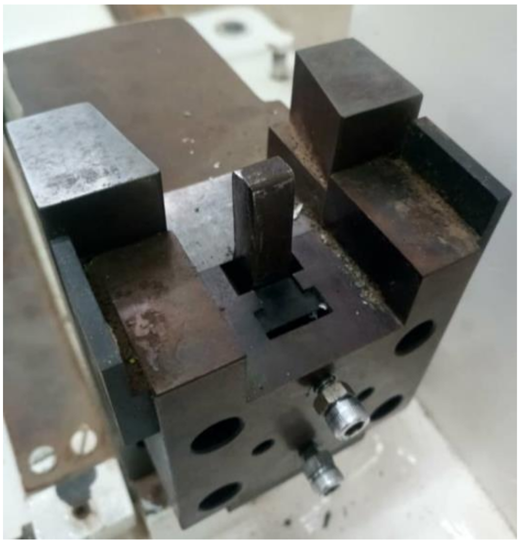

Figure 2a: Sample mounted on the Impact testing machine.

Figure 2b: Failure after impact Test

3. Results

3.1 Hardness test results

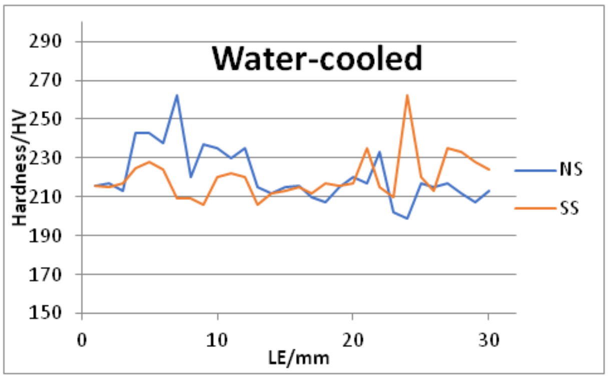

Fig 2: Vickers Hardness test results of water-cooled sample

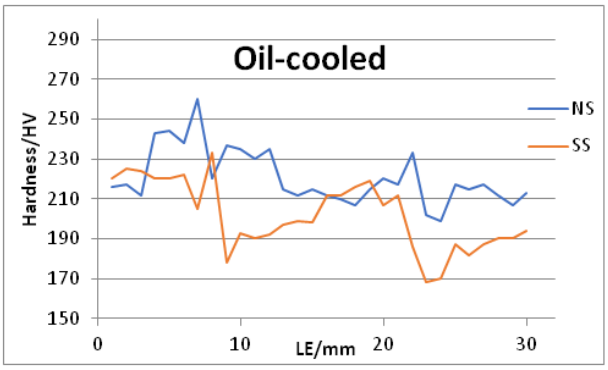

Fig 3: Vickers Hardness test results of oil-cooled sample

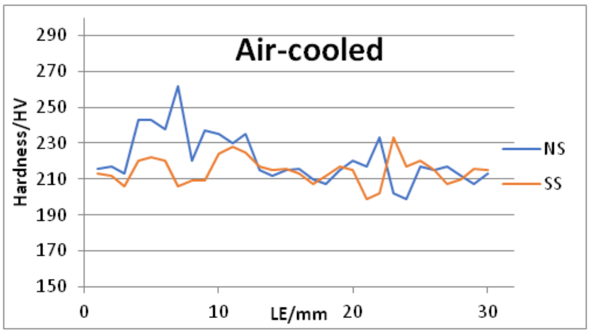

Fig 3: Vickers Hardness test results of air-cooled sample

The results of hardness test for all 6 samples are shown in figures 2, 3 and 4. Table 2 shows the average hardness values at the welded zone of samples cooled in water, air and oil respectively. Firstly, the average HV value at the weld zone for the water cooled new sample was 225.50 as compare to the average HV value at weld zone of 218.50 of the water cooled scrap sample indicating a hardness difference of 3.10%. At the heat affect zone the average HV values were 229.33 for the new sample and 224.17 for scrap sample indicating a hardness difference of 2.25%.

Secondly, the average HV value at weld zone for the oil cooled new sample was 225.17 as compared to 212.67 for the oil cooled scrap sample, indicating a hardness difference of 5.55%. At the heat affect zone the average HV values were 190.00 for the new sample and 157.50 for scrap sample indicating a hardness difference of 16.97%. Lastly, the average HV value at weld zone for the air-cooled new sample was 225.17 whereas that of the scrap sample was 190.00 indicating a hardness difference of 28.94%. At the heat affect zone the average HV values were 229.50 for the new sample and 216.67 for scrap sample indicating a hardness difference of 5.59%.

Table 2: Average Hardness Values at Weld Zone for water, air and oil cooled sample

Cooling medium	New		Scrap
Water	239.7		208.0
Air	239.7		208.0
Oil	239		205.3

3.2 TENSILE TEST

3.2.1 Tensile Test Results for 12mm New Sample (Water, Air and Oil Cooled)

The ultimate tensile strength for Air cooled new sample was 249.00 N/mm^2 as compared to the air cooled scrap sample which was 153.37 indicating a tensile strength difference of 38.40%. Again, the ultimate tensile strength for oil cooled new sample was 247.30 N/mm^{2}as compared to the oil cooled scrap sample which was 141.57 N/mm^{2}indicating a tensile strength difference of 42.75%. Also, the ultimate tensile strength for water cooled new sample was 249.20 N/mm^{2}as compared to the water cooled scrap sample which was 152.23N/mm^2 indicating a tensile strength difference of 38.91%.

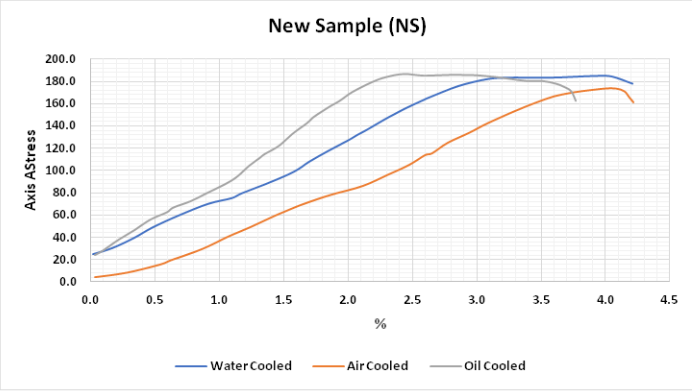

Fig 5: Stress-strain curve of 12mm New Sample (Water, Air and Oil Cooled)

Table 3: Summary of average tensile properties of 12 mm NS sample

Description	**Cooling medium**		
	Air	**Oil**	**Water**
Force max, kN	189.384	185.592	186.549
Tensile stress (Su/Rm), N/mm²	248.800	243.600	244.800
Yield stress (YS/Rt)(.5%), N/mm	68.100	80.500	83.700
t, %	0.500	0.500	0.500
Total elongation EI/(A), %	2.600	1.700	1.400
Youngs modulus E, kN/mm²	13.440	13.920	11.720

3.2.2 Tensile Test Results for 12mm Scrap Sample (Water, Air and Oil Cooled)

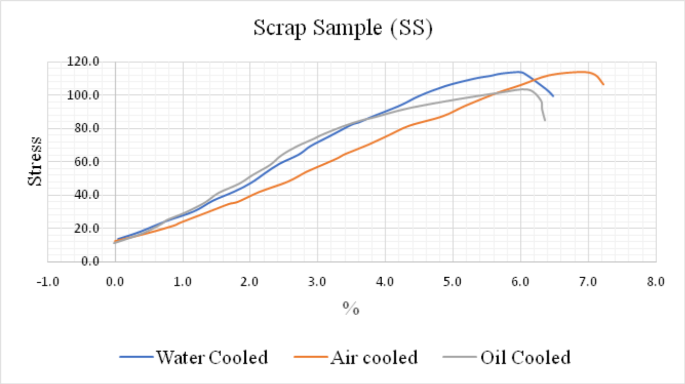

Fig. 5. Stress Strain Test for 12mm Scrap Sample (Water, Air and Oil Cooled)

Table 3: Summary of average tensile properties of 12 mm Scrap Sample

Description	**Cooling medium**		
	Air	**Oil**	**Water**
Force max, kN	116.562	107.876	116.059
Tensile stress (Su/Rm), N/mm²	277.500	256.800	276.300
Yield stress (YS/Rt)(.5%), N/mm²	43.200	49.300	47.600
t, %	0.500	0.500	0.500
Total elongation EI/(A), %	1.800	3.200	2.600
Youngs modulus E, kN/mm²	4.720	6.790	6.050

The Young modulus for the air cooled new sample was 13.44 kN/mm^{2}as compared to the air cooled scrap sample which was 4.72 kN/mm^2 indicating a young's modulus difference of 64.88%.Also, the young's modulus for the oil cooled new sample was 12.78 kN/mm^{2}as compared to the oil cooled scrap sample which was 6.79 kN/mm^2 indicating a young's modulus difference of 46.78%. Again, the young's modulus for the water cooled new sample was 8.89 kN/mm^{2}as compared to the water cooled scrap sample which was 6.05 kN/mm^2 indicating a young's modulus difference of 31.95%.

3.3 IMPACT TEST ANALYSIS

Table 4 and 5 show the results from the impact test of test sample obtained from the digital measuring scale attached to the impact test machine. The machine recorded the impact energy absorbed by the sample until it failed.

Table 4 Impact Energy and Impact Strength of the 12 mm New Sample

Parameters	**Cooling medium**		
	Water	**Air**	**Oil**
Impact Energy (J)	4.0	7.6	7.0
Impact strength (J/cm²)	5.1	9.5	5.1

Table 5 Impact Energy and Impact Strength of the 12 mm Scrap Sample

Parameters	**Cooling medium**		
	Water	**Air**	**Oil**
Impact Energy (J)	8.8	11.2	10.9
Impact strength (J/cm²)	11	14	13.6

It was observed from tables 4 and 5 that the air cooled sample absorbed more impact energy (new – 7.6 J, scrap – 11.2 J) than both the oil (new – 7.0 J, scrap – 10.9 J) and water (new – 4.0 J, scrap – 8.8 J) cooled sample. This means that the air cooled sample is tougher than the oil and water cooled sample. However, comparing the new and the scrap sample, it was observed that the air cooled scrap sample was tougher than the new sample with impact energies of 11.2 J for the scrap sample and 7.6 J for the new sample. The difference in toughness was 32.14 %. This projects that there is a higher effect of cooling rate and cooling medium on the impact strength of new low carbon steel as compared with scrap low carbon steel which agrees with the findings of Ghosh et al on the Effect of cooling rate on structure and properties of an ultra-low carbon steel [10].

The average impact energy for the water cooled new sample was 4 J with a correspondent impact strength 5.1 J/cm^2 as compared to the water cooled scrap sample with 8.8 J impact energy and 11.0 J/cm^2 impact strength. The difference in impact energy was 54.55 % in favour of the scrap sample. Secondly, the average impact energy for the air cooled new sample was 7.6 J with a correspondent impact strength of 9.5 J/cm^2 as compared to the air cooled scrap sample which was 11.2 J with correspondent impact strength 14.0 J/cm^2 indicating an impact energy difference of 32.14 % in favour of the scrap sample. Thirdly, the average impact energy for the oil cooled new sample was 7.0 J with a correspondent impact strength of 5.1 J/cm^2 as compared to the oil cooled scrap sample which was 10.9 J with correspondent impact strength 13.6 J/cm^2 indicating an impact energy difference of 35.78 % in favour of the scrap sample.

4. Conclusion

From the results obtained and the analysis carried out, it can be concluded that the cooling rates and media adversely affected the welded joints produced by the Manual Metal Arc Welding Process. They also affected the mechanical properties of the low carbon steel metals. Considering the hardness of both new and scrap carbon steels at the weld zone after the welding and heat treatment processes, (water cooled, air cooled and oil cooled), the new samples were harder than the scrap samples by 3.10 %, 5.55 % and 28.94 % respectively. At the heat affected zone the difference in hardness values were 2.25 %, 16.97 % and 5.59 % for water cooled, air cooled and oil cooled samples respectively. With the Ultimate Tensile strength, it was observed that the new sample had higher tensile strength compared to the scrap sample. The differences in the ultimate tensile strength were 38.91 %, 38.40 % and 42.75 % for water cooled, air cooled and oil cooled respectively. Also, the new sample had higher elasticity values than the scrap sample with 31.95 %, 64.88 % and 46.78 % differences in Young's modulus for water cooled, air cooled and oil cooled respectively. However, it was observed that the scrap sample had greater impact energy than the new sample. The difference in the impact energies were recorded as 54.55 %, 32.14 % and 35.78 % for water cooled, air cooled and oil cooled respectively in favour of the scrap samples.

References

1. Broadbent, C., *Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy.* The International Journal of Life Cycle Assessment, 2016. **21**(11): p. 1658-1665.
2. Rassizadehghani, J., S. Raygan, and M. Askari, *Comparison of the quenching capacities of hot salt and oil baths.* Metal Science and Heat Treatment, 2006. **48**(5): p. 193-198.
3. Momoh, I., et al., *Investigating the Mechanical Properties of post weld heat treated 0.33% C low alloy steel.* International Journal of Science and Technology, 2013. **2**(6): p. 433-437.
4. Chryssolouris, G., *Manufacturing systems: theory and practice*. 2013: Springer Science & Business Media.
5. Lippold, J.C., S.D. Kiser, and J.N. DuPont, *Welding metallurgy and weldability of nickel-base alloys*. 2011: John Wiley & Sons.
6. Odusote, J.K., T.K. Ajiboye, and A.B. Rabiu, *Evaluation of mechanical properties of medium carbon steel quenched in water and oil.* AU Journal of Technology, 2012. **15**(4).
7. Senthilkumar, T. and T.K. Ajiboye, *Effect of heat treatment processes on the mechanical properties of medium carbon steel.* Journal of Minerals & Materials Characterization & Engineering, 2012. **11**(2): p. 143-152.
8. Dewangan, S., S. Behera, and M.K. Chowrasia, *Comparative analysis into mechanical properties and microstructural attributes of quenched and tempered 0.2%-C steel.* World Journal of Engineering, 2020.
9. Ikumapayi, O., et al. *Effects of quenchants on impact strength of single-vee butt welded joint of mild steel*. in *IOP Conference Series: Materials Science and Engineering*. 2018. IOP Publishing.
10. Ghosh, A., et al., *Effect of cooling rate on structure and properties of an ultra-low carbon HSLA-100 grade steel.* Materials Characterization, 2006. **56**(1): p. 59-65.

AUTHORS

First Author – Kwabena Offeh Gyimah, BSc, MSc, PhD, Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development, Ghana (email: kofege127@gmail.com)

Second Author – Gladys Perpetual Awudi, BSc, MPhil, Southern Alberta Institute of Technology (email: awudipep@gmail.com).

Third Author – Emmanuel Akanvariba, BSc, Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development, Ghana (email: emmanuelakanvariba@ymail.com)

Fourth Author – Ebenezer B. Owusu, BSc, MSc, University of Nottingham, UK (email: ebowus@gmail.com)

Correspondence Author – Kwabena Offeh Gyimah, kofege127@gmail.com, kogyimah@aamusted.edu.gh, contact number: +233(0) 55 40 28 614