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TO INVESTIGATE THE EFFECT OF HEAT TREATMENT ON FRACTURE TOUGHNESS OF WELDED JOINTS

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Annealing as a post weld heat treatment (PWHT), increases toughness in the welding joints of medium carbon steel in the same way as it increases toughness of the non-welded medium carbon steel. Measurement of increase in toughness through PWHT is focus of the present research work. Welded samples of commercially available steel AISI-1035 have been used for the proposed evaluation. The samples welded by two different techniques namely oxyacetylene gas welding and manual metal arc welding, passed through annealing process along with non-welded samples for comparison of increase in toughness. Toughness measured by impact tests revealed the improvement, which in the order of increasing effects is in gas welded, electric welded and non-welded samples. The aim of the present research was to measure the improvement in fracture toughness through post weld heat treatment (annealing). It has been shown that toughness increases as the structural flaws decrease.

Keywords: Steel, Oxyacetylene welding, Electric arc welding, Annealing, Charpy impact test, Fracture toughness

1. Introduction

Steel welds widely used in the structures and industries, are being studied since a long time in order to improve its toughness and strength requirements. The welded joints typically have ferritic microstructure. Toughness of a welded joint can be improved by shaping the microstructure in such a way that it resists crack propagation. One such ferritic microstructure is acicular ferrite, which is a long needle like structure that inhibits the dislocation movement and hence increases the toughness of the welded joints. Toughness of welded joints is undermined by the presence of weld defects. The deleterious effects of weld defects is more pronounced in case of inferior welding process like oxyacetylene gas welding than superior welding techniques like electric welding methods. A study conducted earlier emphasizes the role of filler metal and base metal contents to avoid some of the weld defects and harmful effects of microstructures like grain boundary ferrite, side plate ferrite and martensite [1]. In an another study, during investigation of change in filler metal composition on the mechanical properties and microstructure of X65 steel, it was found that the microstructure of weld metal consists of three basic modifications of ferrite namely; acicular ferrite (AF), polygonal ferrite (PF), and Widmanstätten ferrite (WF) [2].

Post weld heat treatment (PWHT) improves toughness of welded joints. Heating to a temperature in a furnace for microstructural changes to take place, soaking and then controlled cooling to room temperature is required. Structures larger than furnace capacity are heat treated through local arrangements, which may result in overheating of some parts. ASME SA-542/SA-542M describe that when steel is overheated at its welded joints, the microstructure slightly modified due to overheating, did not impair the fracture properties [3]. The duration of heating however, influences the mechanical properties as observed during a study conducted earlier on isothermal annealing of 9Cr-Mo "CB2" steel and It was observed that heating at annealing temperature (625°C) for 10khr to 30khr causes thermal degradation of microstructure, adversely affecting the mechanical properties [4]. Increase in toughness can be measured through Charpy impact test. Dynamic tear testing uses larger sized specimens necessary to accommodate stress distribution and constraints while checking ductile to brittle transition temperature where results of Charpy impact tests are not sufficient as mentioned in a study conducted earlier on HSLA-65 steel welds used in ships in the Arctic conditions [5].

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Table 1. Chemical composition of AISI-1035 steel*.

C	Mn	Si	Cr	Fe
0.32%	0.66%	Traces ≤ 0.01%	0.47%	98.549%

* Reportedly AISI-1035 also contain 0.05% Sulphur and 0.04% Phosphorus

Table 2. Chemical composition of RG60 welding wire as reported.

%C	%Mn	%Si	%P	%S	%Cu	%Cr	%Ni	%Mo	%Al
0.15	0.90-1.40	0.1-0.35	0.035	0.035	0.30	0.20	0.30	0.20	0.02

Table 3. Chemical composition of deposition metal by E6013 as reported.

%C	%Mn	%Si	%S	%P
≤0.12	0.30-0.60	≤0.35	≤0.035	≤0.040

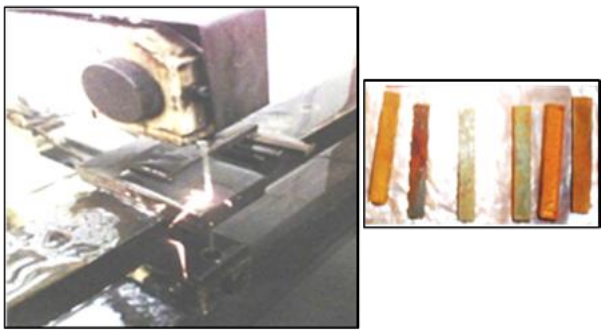
Present work focused on the increase in fracture toughness of steel (AISI-1035) commercially available on welded joints due to annealing (PWHT). Two welding techniques namely electric arc welding and oxyacetylene gas welding have been used for the proposed study. The objectives thus include study of effects in fracture toughness of heat-treated, non-heat treated of both welded and nonwelded steel samples. Charpy impact test is considered suitable for comparison of fracture toughness in the present work.

2. Experimental Process

The experimental process was commenced by first obtaining AISI-1035 steel plate sized 300 mm x 180 mm x12 mm (Length x Width x Thickness). The chemical composition of the selected metal AISI-1035 steel is given in Table 1.

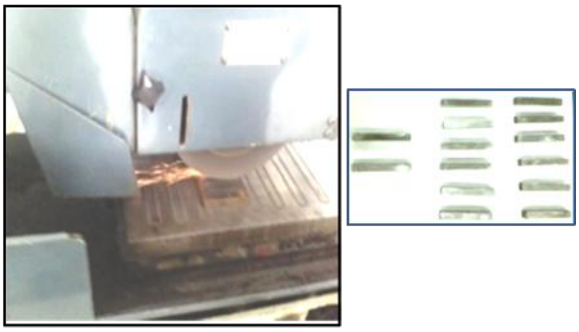
Above mentioned plate was cut into three equal parts, each of the size 240 mm x60 mm x12 mm for Gas welded, electric welded and non-welded plates. Further, the plates for gas and electric welded samples cut in longitudinal half, rejoined with gas and electric welding respectively. The gas welded plate was rejoined (V-butt) with the help of oxyacetylene gas welding using RG60 filler wire of composition given in Table 2. The electric welded plate rejoined (V-butt) with the help of electric arc welding using AWS-E6013 size Φ2.5 (3/32″) x300mm filler rod, composition is given in Table 3. The welded plates then cooled in still air after welding and each side of the plate ground for a flat surface finish. The size of the welded plate then ensured not to be less than 240 mm x 55 mm x 11 mm. The ASTM standard specimen (E23-2a) then prepared for experimentation.

Charpy impact specimens were cut from the gas welded plate, electric welded plate and non welded plate as per standard ASTM E23-2a [6], by using wire cutting machine as shown in Figure 1 and each specimen was ground for smooth surface finish and sized to 55 x 10 x 10 (mm) as shown in Figure 2. Thirty specimens i.e. ten specimens from each of these three plates were thus obtained.



(a) (b)

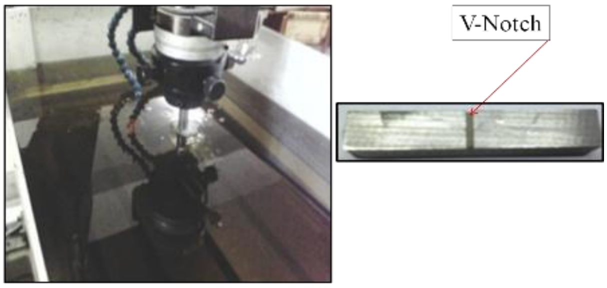
Figure 1. (a) Cutting of specimens from plate by wire cutting machine, (b) Specimens as prepared by the machine.



(a) (b)

Figure 2. (a) Surface finishing of the specimens on surface grinding machine, (b) Specimens prepared by the machine.

V notches were developed in the centre of each specimen with the help of EDM (electric discharge machine) as shown in Figure 3. The V notches of each specimen had depth of 0.25 mm, 45º sides' angle and 0.02 mm root radius.



(a) (b)

Figure 3. (a) Preparation of V grooves in the specimens by EDM, (b) V groove prepared in the specimen by the machine.

Five specimens of each type tested on Charpy Impact Test machine for fracture toughness without heat treatment therefore, these fifteen specimens were kept preserved for testing along with heat-treated specimens.

Next group of five specimens of each type i.e. non-welded, gas welded and electric arc welded specimens tested after heat treatment. Following heat treatment process adopted.

An electric furnace of heating capacity 1300ºC (2282ºF) made of Vecstar Ltd. has been used for annealing of specimens. Specimens and furnace interior cleaned properly before placing specimens in the furnace. Temperature for annealing of specimens calculated by keeping in view the fact that when steel is heated, its recrystallization or grain growth commences at its lower transformation temperature called A_1, and microstructure of steel is transformed to austenite phase above upper transformation temperature called as A_3. These temperature ranges depending upon constituents of steel can be predicted with the help of Grange empirical formulas with sufficient accuracy as following [7].

$$\text{Al (°F)} = 1333 - 25(\%Mn) + 40(\%Si) - 26(\%Ni) + 42(\%Cr) \quad (1)$$

$$\text{A3 (°F)} = 1570 - 323(\%C) - 25(\%Mn) + 80(\%Si) - 32(\%Ni) - 3(\%Cr) \quad (2)$$

Steel, when cooled slowly from austenite phase, converted to pearlite after crossing A_1 temperature range. The pearlite microstructure is tougher than the martensite phase formed when steel cooled quickly from austenite phase. Slow cooling also refines the microstructure of weld metal and improves its toughness by formation of acicular ferrite. Since annealing consists of heating the specimens a little more than upper transformation temperature, A_3 soaking for some time to allow uniform heating of complete specimens and slow / furnace cooling to room temperature therefore, A_3 temperature is calculated by using the Grange empirical formulas mentioned in equation (2) above as following.

Let A_3 temperature for gas welded specimens as A_{3G} , for electric welded specimens as A_{3E} and for non welded specimens as A_{3N} then,

For gas welded specimens, A_{3G}

$$A_{3G}\text{ (°F)} = 1570 - 323(\%C) - 25(\%Mn) - 3(\%Cr) - 32(\%Ni) + 80(\%Si)$$

$$A_{3G}\text{ (°F)} = 1570 - 323(0.15\%) - 25(1.40\%) - 3(0.20\%) - 32(0.30\%) + 80(0.35\%)$$

$$A_{3G}\text{ (°F)} = 1570-48.45-35-0.6-9.6+28$$

$$= 1504.35ºF\ [817.97ºC]$$

For electric arc welded specimens,A_{3E}

$$A_{3E}\text{ (°F)} = 1570 - 323(\%C) - 25(\%Mn) - 3(\%Cr) - 32(\%Ni) + 80(\%Si)$$

$$A_{3E}\text{ (°F)} = 1570 - 323(0.12\%) - 25(0.60\%) - 3(0\%) - 32(0\%) + 80(0.35\%)$$

$$A_{3E}\text{ (°F)} = 1570-38.76-15-0-0+28=1544.24ºF\ [840.13ºC]$$

For non-welded specimens, A_{3N}

$$A_{3N}\text{ (°F)} = 1570 - 323(\%C) - 25(\%Mn) - 3(\%Cr) - 32(\%Ni) + 80(\%Si)$$

Table 4. Upper transformation temperatures A_{3G} , A_{3E} and A_{3N}

Specimen Type	Upper Transformation Temperature, A_3
Oxyacetylene gas welded	A_{3G} = 1504.35ºF [817.97ºC]
Electric arc welded	A_{3E} = 1544.24ºF [840.13ºC]
Non-welded	A_{3N} = 1449.53ºF [787.52ºC]

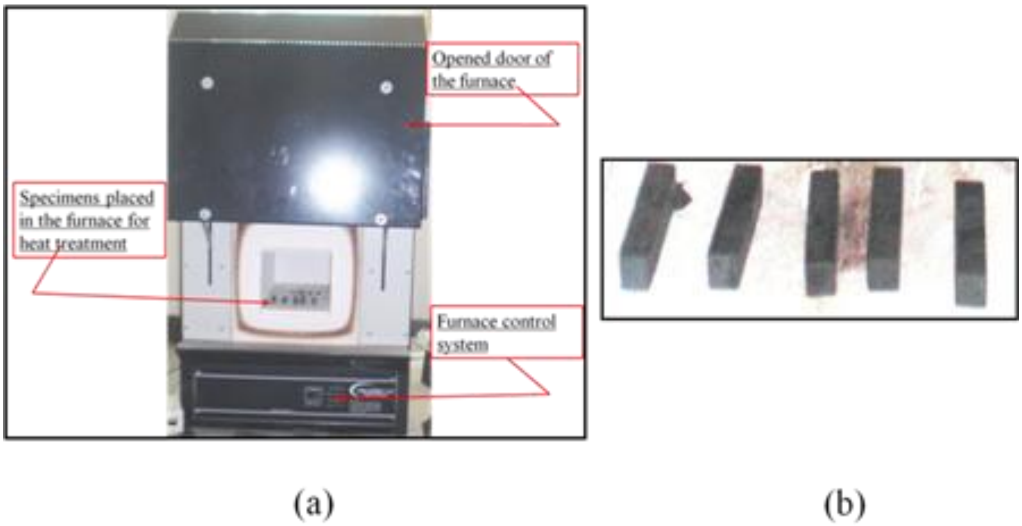


Figure 4. (a) Heat treatment of specimens in an electric furnace, (b) heat treated / annealed specimens.

A_{3N} (°F) = 1570 - 323(0.32%) - 25(0.66%) - 3(0.47%) - 32(0%) + 80(0.01%)

A_{3N} (°F) = 1570-103.36-16.5-1.41-0+0.80 = 1449.53ºF [787.52ºC]

A_{3G} , A_{3E} and A_{3N} temperatures calculated as above are summarized in Table 4.

It can be seen in the above Table 4 that maximum temperature required for annealing is for electric arc welded specimens,A_{3E} i.e. 1544.24ºF [840.13ºC]. If each type of specimen is heated according to its own upper transformation temperature then a doubt may exist regarding toughness values achieved at different annealing temperatures of different specimens and a true comparison may not be obtained; moreover, grains refinement is completely achieved by heating at little more than upper transformation temperature. Therefore, annealing temperature selected for all specimens was 1562ºF (850ºC) which is a little more than A_{3E} temperature but not too much for A_{3N} (the lowest temperature in the Table) that it could cause a burnt structure.

Full annealing was achieved by controlled cooling from upper transformation temperature 1562ºF (850ºC). After soaking specimens for two hours in the furnace, the cooling was done by lowering the temperature by 212ºF (100ºC) for each consecutive hour until the furnace reached the room temperature i.e. 69.8ºF (21ºC). Hence, slow furnace cooling achieved to complete the annealing process. The specimens examined after annealing. Color of the specimens turned grey but no heat treatment problems like warping, cracking or spalling were observed.

After heat treatment, the specimens were cleaned properly for carrying out Charpy impact tests along with non heat-treated specimens.

Charpy impact tests of all specimens including heat-treated and non-heat treated were carried out at room temperature i.e. 69.8ºF (21ºC), on Charpy impact testing machine. The machine was first checked for correct calibration (without any error) and then specimens were tested. The hammer was allowed to rise and locked at its topmost position (height, h_1) and accordingly dial indicator was placed at maximum energy indicating mark on the

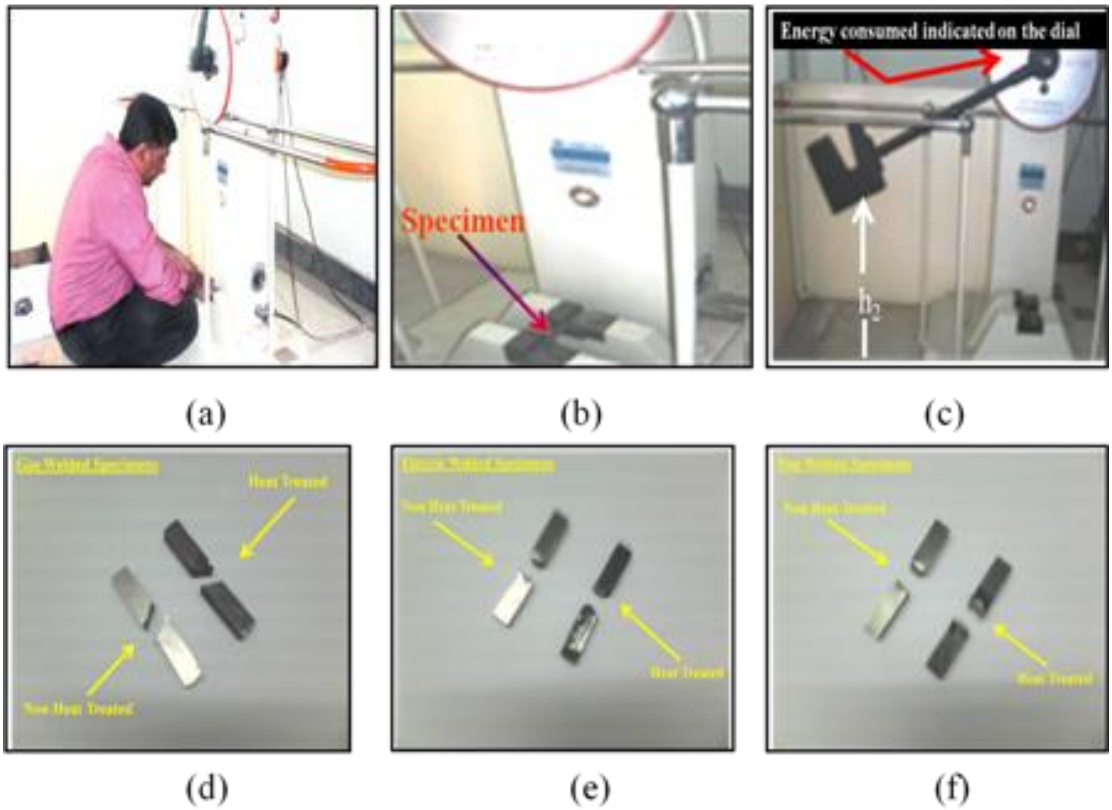


Figure 5. Specimens being tested for fracture toughness in Charpy impact test machine (a,b,c) & Fractured specimens (d,e,f).

dial i.e. 150 Joules in case of present experiment. Each specimen was carefully placed at its position and the hammer was allowed to fall freely and hit the specimen. Hammer broke the specimen on its way and rose to height, h_2 as shown in Fgure 5. Energy consumed during breaking of specimens is difference in heights i.e. h_1- h_2, which was read directly from the dial.

3. Results

All specimens were tested for fracture toughness by using the Charpy impact test machine as described above and the results tabulated in Table 5.

The results indicate minimum fracture toughness values for gas welded non heat treated specimens and increasing trend towards gas welded heat treated, electric welded non heat treated, electric welded heat treated, non welded non heat treated and maximum fracture toughness values for non-welded heat treated specimens which clearly indicates increase in fracture toughness due to heat treatment. Mode of fracture for gas-welded specimens is brittle along fusion line whereas for all other specimens, it is mixed mode fracture. Above results have been summarized in Table 6 and presented in Figure 6.

4. Discussion

From the test results summarized in Table 6 and Figure 6, it can be seen that impact energy is increased due to heat treatment, which confirms the increase in fracture toughness of steel weld metal after annealing. The percentage increase in fracture toughness of each type of specimens and comparative proportional increase in relation to other types of specimens is presented in Table 7 and diagrammatically expressed in Figures 7 and 8.

Metallurgical speaking, the weld metal microstructure becomes rich in acicular ferrite structure after heat treatment, which improves its fracture toughness. Acicular ferrite is a fine needle like grain structure, which provides maximum resistance to crack propagation. The formation of upper bainite, ferrite side plates and grain boundary ferrite in the weld metal is deleterious to its fracture toughness as these microstructures offer easy paths to crack propagation. Thus, acicular ferrite improves the weldmetal toughness. [9].

Table 5. Charpy impact test results (test location = weld metal, test temperature 69.8ºF (21ºC).

No.	Energy Absorbed in Joules (J)	Nature of Fracture by Appearance	Energy Absorbed by Selected Specimen (after discarding lowest and highest values) [8] in Joules (J)	Average Energy Absorbed in Joules (J)
Non Welded Non Heat Treated Specimens				
1.	92.2	Mixed mode	92.2	
2.	76	Mixed mode	76	
3.	100	Mixed mode	-	85.73
4.	89	Mixed mode	89	
5.	60	Mixed mode	-	
Non Welded Heat Treated Specimens - Annealed at 850ºC (1562ºF)				
1.	130	Mixed mode	-	
2.	105	Mixed mode	-	
3.	105	Mixed mode	105	113.20
4.	116	Mixed mode	116	
5.	118.6	Mixed mode	118.6	
Gas Welded Non Heat Treated Specimens				
1.	2.5	Brittle along fusion line	-	
2.	5	Brittle along fusion line	5	
3.	6	Brittle along fusion line	-	4.26
4.	5	Brittle along fusion line	5	
5.	2.8	Brittle along fusion line	2.8	
Gas Welded Heat Treated Specimens - Annealed at 850ºC (1562ºF)				
1.	4	Brittle along fusion line	4	
2.	3.2	Brittle along fusion line	-	
3.	11	Brittle along fusion line	-	8.03
4.	10	Brittle along fusion line	10	
5.	10.1	Brittle along fusion line	10.1	
Electric Welded Non Heat Treated Specimens				
1.	51	Mixed mode	-	
2.	66	Mixed mode	66	
3.	74.5	Mixed mode	74.5	67.23
4.	76	Mixed mode	-	
5.	61.2	Mixed mode	61.2	
Electric Welded Heat Treated Specimens - Annealed at 850ºC (1562ºF)				
1.	97.5	Mixed mode	97.5	
2.	97	Mixed mode	97	
3.	80	Mixed mode	80	91.50
4.	77	Mixed mode	-	
5.	98.6	Mixed mode	-	

Table 6. Summary of Charpy impact test results.

Type of Specimens		Nature of Fracture by Appearance	Average Energy Consumed, J(ft.lbf) (as per method in AWS D1.1/1.1M:2010) [8]
Non Welded Specimens	Non Heat Treated	Mixed Mode	85.73 (63.23)
	Heat Treated	Mixed Mode	113.20 (83.49)
Gas Welded Specimens	Non Heat Treated	Brittle along fusion line	4.26 (3.14)
	Heat Treated	Brittle along fusion line	8.03 (5.92)
Electric Welded Specimens	Non Heat Treated	Mixed Mode	67.23 (49.58)
	Heat Treated	Mixed Mode	91.50 (67.49)

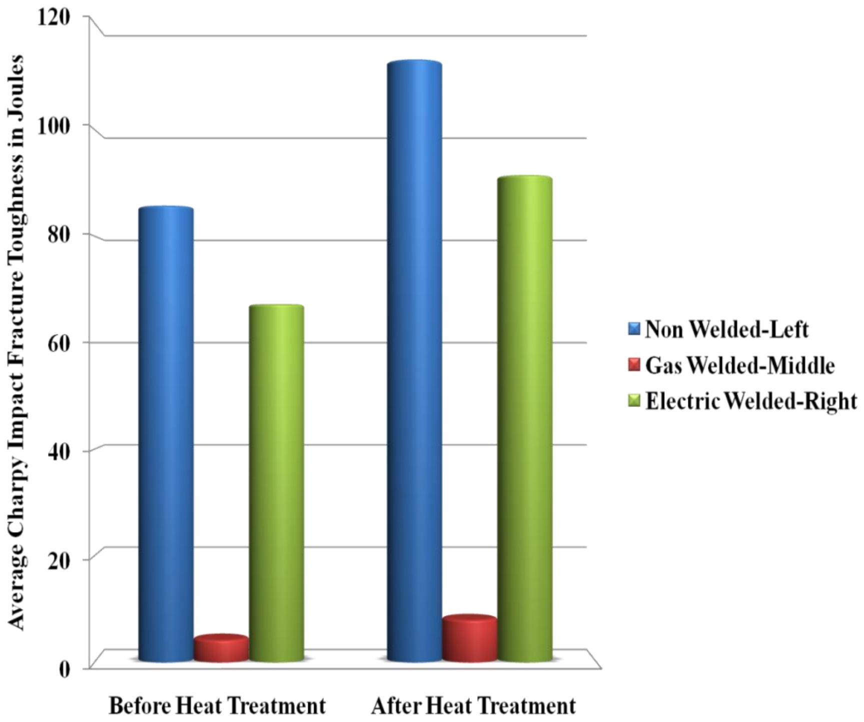


Figure 6. Comparison of fracture toughness before and after heat treatment

Table 7. Increase in impact energy and percentage increase due to heat treatment.

Type of Specimen	Impact Energy Increased Due To Heat Treatment J(ft.lbf)	Percentage Increase in Consumed Energy	Proportionate Increase in Toughness Percentage
Non Welded	27.47 (20.26)	32.04 %	49.49%
Gas Welded	3.77 (2.78)	88.50 %	6.79%
Electric Welded	24.27 (17.91)	36.10 %	43.72%

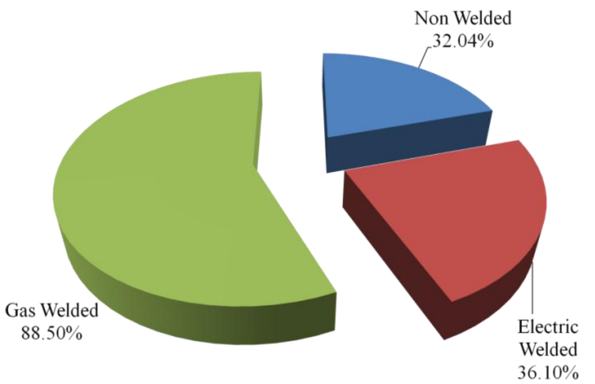


Figure 7. Percentage increase in toughness after heat treatment

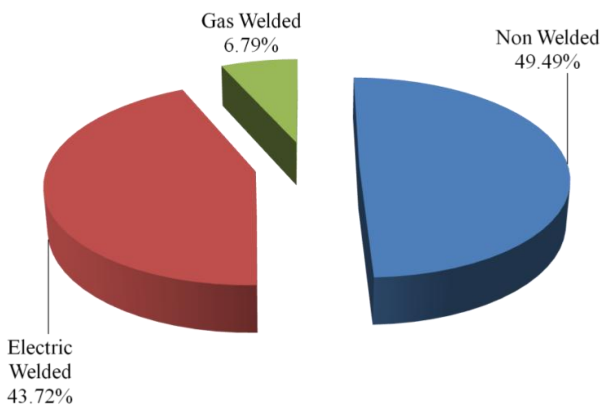


Figure 8. Proportionate increase in percentage of toughness after heat treatment.

Oxy acetylene gas welded specimens have shown very low toughness as compared to specimens welded with electric arc welding as well as non-welded specimens. This very low toughness of gas-welded specimens is due to comparatively low-grade welding technique, having weld defects. The lack of fusion in gas-welded specimens resulted fracture appearance as brittle along fusion line in contrast to mixed mode fracture of all other specimens.

5. Conclusion

Annealing improves the toughness of welded and non-welded samples of medium carbon steel. Through toughness measurement of heat treated welded and non-welded specimens, it is observed that increase in toughness depends on welding structural flaws and PWHT processes. It is evident that increase in toughness is more in non-welded samples as compared to electric arc welded and gas welded samples. The gas-welded samples have more flaws as compared to electric arc welded samples due to a low-grade welding technique**.** The impact test results obtained for different specimens of each type are consistent and hence self-validating. The outcome of experiments are useful for selection of material and welding method for a particular job keeping in view of technical and economical considerations. It is therefore, concluded that despite of any welding technique being used, the components should be properly heat treated after welding for improvement in toughness.

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