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Investigation of Impact Toughness of SMAW, GMAW and FCAW of API X60 Pipeline Steel

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Abstract- This research work investigates the impact of different welding processes i.e., Shield metal arc welding (SMAW), Gas metal arc welding (GMAW), and Flux core arc welding (FCAW) technique on the fracture toughness of API X60 pipeline steel. Utilizing Charpy V-notch (CVN) testing, the impact toughness of the base metal (BM), heat-affected zone (HAZ), and weld zone (WZ) was measured across a range of temperatures from -196°C to 20°C. The analysis reveals that different welding methods and the heat input associated with each significantly affect the fracture properties of the steel. The SMAW process shows the most considerable decrease in energy absorption in the HAZ, especially at lower temperatures, indicating a significant impact on the material's toughness. Conversely, GMAW demonstrates the lowest reduction and the highest increase in toughness in the HAZ and WZ, respectively, making it a superior method in maintaining material integrity during welding. The FCAW method exhibited a moderate and variable behavior in toughness changes, suggesting its intermediate effectiveness. The study further identifies that the chemical composition of the welding electrodes, particularly those containing nickel has a crucial part in enhancing the toughness of the welded zones. Additionally, it underscores the importance of understanding the microstructural changes induced by varying heat inputs, which directly influence the fracture behavior and lifespan of pipeline steels under low-temperature conditions. These findings are essential for improving welding practices and material selection in an ensuring safer, and economical transportation solutions for hydrocarbons over long distances.

Keywords- Impact toughness, CVN, SMAW, GMAW, FCAW, BM, WZ, HAZ.

I. INTRODUCTION

In regions like Asia, North America, and Europe, the demand for natural gas and other hydrocarbon products will remain substantial over the coming decades. To economically gather oil and gas, reserves are often located in remote locations away from communities and in harsh environments. Therefore, it is necessary to rapidly develop economical transportation methods. The installation of high-pressure transmission pipeline networks for transporting natural gas and oil products is a practical solution. From both technical and financial perspectives, using of pipes of high strength low ally steel (HSLA) is particularly crucial for the transmission of natural gas to remote areas[1].

It is important to carefully consider the effects of welding on the heat affected zone (HAZ) and weld zone (WZ) to ensure safe use of these high strength pipes. The key advantages include excellent weldability, high strength, and toughness [2].

Due to conditional weldability, HSLA steels usually require extra steps to achieve optimum joint properties. The current demand for welded structures has led to substantial increases in the application of HSLA steels. Utilizing these steels as an alternative to conventional structural steels offers numerous benefits. However, welding affects the properties of HSLA steels due to their highly tailored chemical composition and microstructure. An appropriate welding technique is the fundamental prerequisite for preserving material properties and microstructure post-welding [3].

The Lan et al. examined the microstructural changes and properties of different zone with three different heat input values using submerged arc welding (SAW) on HSLA steels. The main objective was to investigate the impact of microstructural features on the impact toughness of the weld metal and HAZ, in order to identify the fracture micro mechanisms and enhance the welding technology [4]. Similarly, results presented by Sadeghian et al. show that specimens subjected to low heat input fractured brittlely, while those subjected to higher heat input value exhibited higher impact toughness than the BM[5].

Pipelines in the oil and gas sector are often fabricated using the SMAW technique, commonly referred to as stick welding. This technique remains the most widely used procedure worldwide. SMAW involves the use of a metal coated in shielding materials as a consumable electrode. Despite its benefits, SMAW has significant drawbacks that make other welding techniques a better choice in some situations. Since SMAW is a manual operation, it requires operators with extensive training and also necessitates additional cleanup, generates waste materials, and has a greater possibility of welding errors. When compared to continuous wire-fed operations like GMAW and FCAW, SMAW is comparatively less productive and has higher operational costs[6].

GMAW utilizes an electrode wire that has no flux covering and provides a continuous supply of wire. The welding machine is equipped with shielding gas to protect the welding area from the atmosphere and other reactive gases. Shielding gases such as helium (He), argon (Ar), or a mix of the two are used. For the stabilization of the arc, the non-reactive gas is mixed with 2-5% of O_2 gas or 5-20% of CO_2 gas. The energy source is derived from either direct current or alternating current, which is obtained from a power plant. The Flux Core Arc Welding process involves the use of a tubular continuous electrode wire which creates shielding gas upon melting, and the rest of the process and equipment are similar to the GMAW process. Adopting an automated and semi-automated process results in significant improvements in terms of cost and production [7].

The welding area undergoes property changes during the welding process. These changes negatively impact the metallurgical and mechanical properties of the materials. Additionally, these changes cause internal stresses that may affect the toughness of the welded metal. Also due to the thermal gradient during welding, the microstructure of these zones i.e., BM, HAZ, and WZ is affected, which subsequently impacts the material's toughness. The fracture properties of pipelines operating in low-temperature conditions are significantly influenced by temperature. In applications where a continuous load is applied, cracks originate from the HAZ and propagate into the surrounding material. Therefore, it is vital to gain a deeper understanding of the fracture characteristics of these steels at low temperatures to accurately estimate their lifespans [8]. The Charpy test, widely used to determine the impact toughness of materials, is conducted on either pre-cracked or notched samples, with the absorbed energy plotted against testing temperatures [9].

This research provides a comparative analysis of the impact toughness of API X60 steel when subjected to different welding processes, specifically SMAW, GMAW, and FCAW, across a range of temperatures The objective of this study to evaluate most sound welding technique by assessing the impact toughness variations caused by different welding processes in different zone for API X60 steel and their implications for pipeline integrity under adverse conditions.

II. MATERIALS AND METHODOLOGY

The investigated material was an API X60 steel pipe with a diameter of 12″ and wall thickness of 0.35″ (Figure 1).

Figure 1.Welded pipe of API x60

The CVN specimens were prepared according to the specifications of ASTM E23 and were tested using a Brooks impact testing machine at GIK Institute. The samples were taken from different parts of the welded section, including the BM, HAZ, and WZ. The dimensions of the CVN specimens are given in Figure 2. The sample had a length of 55 mm, a width of 10 mm, and a thickness corresponding to the pipes. The V-notch has a depth of 2 mm and a radius of 0.25 mm.

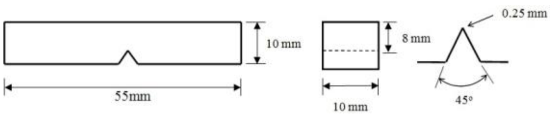

Figure 2. Dimension of Charpy V-notch specimens

The tests were conducted at -196°C, -40°C, -20°C, 0°C, and 20°C. Specimens were allowed to stabilize at the target temperature for 10 minutes. The test sample was positioned on the Brook impact testing machine, and the pendulum was released to strike the specimens once each temperature was achieved. The machine gauge recorded the amount of energy absorbed by the specimen upon breaking [10-11].

Figure 3. Charpy V-notch specimens

Figure 4. Charpy Testing Machine

III. RESULTS AND DISCUSSION

The chemical composition was analyzed using Spectro optical emission spectrometer at Heavy Industry Taxila.

Table 1. Chemical Composition of the API X60 Steel

Element Content (wt.%)									
Fe	C	Si	Mn	V	Nb	Ti	Cr	P	S
98.2	0.092	0.174	1.28	0.024	0.046	0.02	0.022	0.007	0.012

The composition of high-strength steel typically includes carbon ranging from 0.07%-0.12%, manganese up 2%, and small percentages of niobium, vanadium, and titanium in different combinations. Other elements that might be present include silicon and chromium. Microalloying elements are added to attain a finer grain structure or to favor dispersion strengthening by precipitation. Small amounts of sulfur and phosphorus are deliberately added to enhance both the machinability and strength of the steel[12]. In terms of the impact toughness of the HAZ and WZ under various welding procedures, these microalloying components can significantly affect fracture behavior and microstructural changes. Due to their grain-refining properties, niobium, vanadium, and titanium help maintain a finer grain structure in the HAZ, prevent excessive grain growth during heat treatments, and welding by pinning the grain boundaries. This leads to finer grains, which improve yield strength and toughness due to the Hall-Petch effect. The elements form carbides, carbonitrides, and other precipitates to enhance dispersion strengthening. The uniform distribution of these microalloying precipitates prevents dislocation movement in the steel matrix, increasing its strength and hardness without compromising ductility, and lowers the ductile-to-brittle transition temperature through precipitation strengthening, thus improving fracture toughness at lower temperatures. This leads to increased resistance to brittle fracture and enhanced toughness, particularly in environments where impact toughness is of utmost importance. These elements also promote microstructural stability during welding, even at high temperatures and varied cooling rates. This stability prevents the formation of coarse grains or excessive martensite or bainite, thereby preserving the integrity of the weld [13-14].

The graph shown in Figure 5 illustrates the comparison of the average impact energy absorbed by the BM, HAZ, and weldWZ during SMAW. The welded region exhibited a greater capacity to absorb impact energy than the base metal and HAZ across all temperatures. As depicted in the graph presented in Figure 7, when the heat input is low, the impact toughness of the HAZ exhibits low values. As the heat input increases, the impact toughness shows an upward trend until it attains a certain value, as shown in Figure 6, after which it displays a subsequent downward trend, as indicated in Figure 5. Steel subjected to GMAW heat input exhibits significantly increased impact toughness values. The GMAW welding technique exhibited the least reduction in impact toughness and the highest increase in impact toughness values at the HAZ and WZ, respectively, across all temperatures while the FCAW graphs shows least toughness match among other process. The differences in the amount of energy absorbed in the BM, HAZ, and WZ can be attributed to the effect of the welding heat input rate and thermal gradient. These factors result in microstructural changes which consequently influence the fracture behavior of the steel.

In the current investigation, the average heat inputs for SMAW, GMAW, and FCAW are 2.34 kJ/mm, 2.13 kJ/mm, and 1.91 kJ/mm, respectively. Hyun-Seop Shin et al. performed a similar study wherein they established a correlation between the characteristics of the HAZ and the heat input applied during the welding process. They suggested that the morphology variation of ferrite within the HAZ of SMAW and FCAW joints can be attributed to variations in heat input. Furthermore, they concluded that the formation of acicular ferrite can be controlled through thermal input. An increase in heat input leads to a reduction in the amount of acicular ferrite due to a slower cooling rate, while a reduction in heat input results in a faster cooling rate, thus leading to an increase in the amount of acicular ferrite. Additionally, increased heat input results in a coarser microstructure.[15].

Winarto et al. investigated the role of nickel on toughness. It was found that the filler material used for welding can affect material properties due to changes in the composition of the weldment [16]. Hyun-Seop Shin et al. reported that the FCAW weld metal exhibits higher toughness at low temperatures than SMAW, due to its increased nickel content in the electrode. The GMAW procedure yielded the most significant improvement in impact toughness within the weld zone, while displaying the least reduction in impact energy within the HAZ[17].

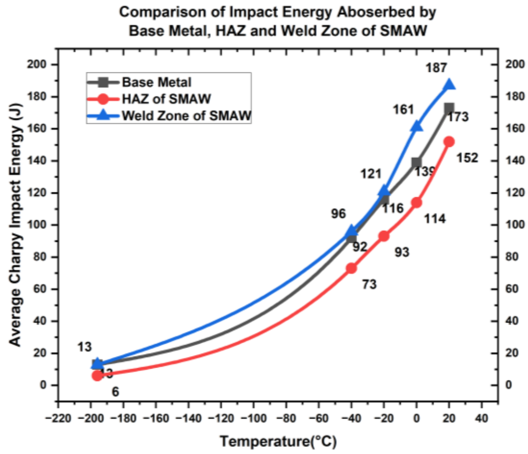

Figure 5. Comparison of Impact energy absorbed by BM, HAZ &WZ of SMAW.

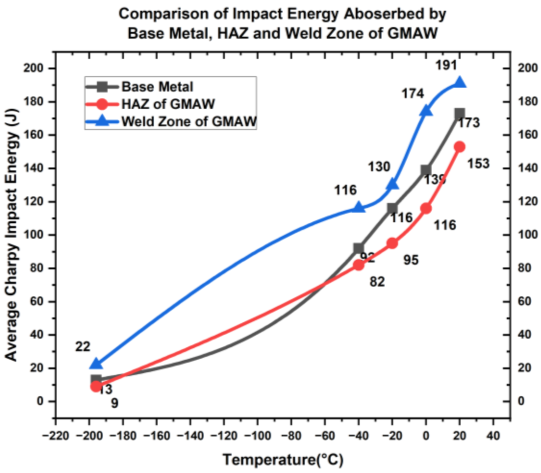

Figure 6. Comparison of Impact energy absorbed by BM, HAZ & WZ of GMAW.

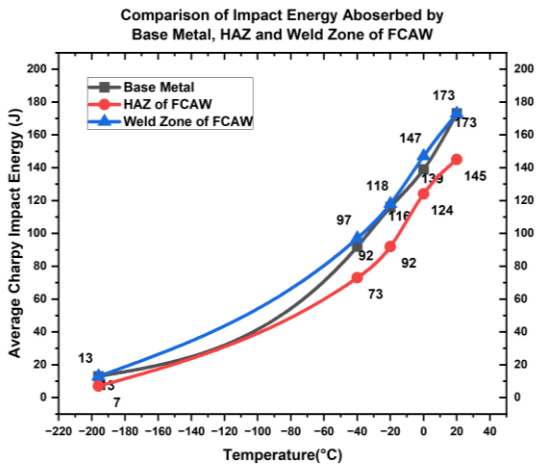

Figure 7. Comparison of Impact energy absorbed by BM, HAZ& WZ of FCAW.

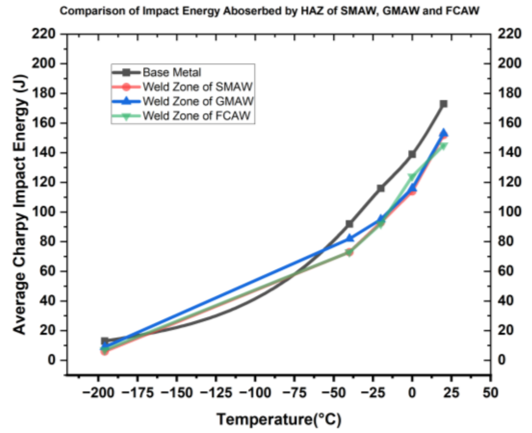

Figure 8. Comparison of Impact energy absorbed by HAZ of SMAW, GMAW and FCAW w.r.t BM.

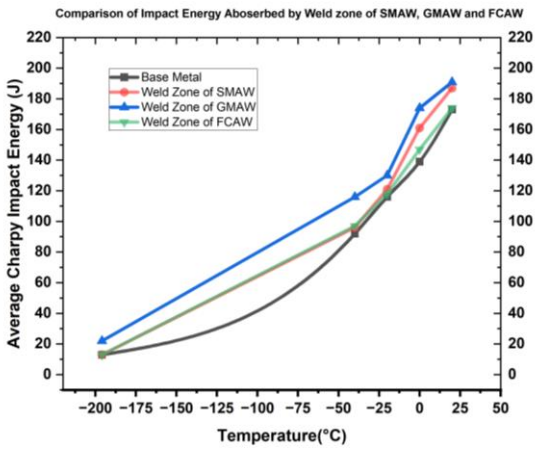

Figure 9. Comparison of impact energy absorbed by WZ of SMAW, GMAW and FCAW w.r.t BM.

The Table 2, Table 3, and Table 4 provide the percentage difference in energy absorption for SMAW, GMAW, and FCAW respectively. The most significant negative difference in energy absorption between the HAZ of SMAW and the base metal occurs at lower temperatures. The difference become narrower as the transition is made from lower temperatures to higher temperatures. The WZ of SMAW exhibits the lowest positive percentage difference in energy absorption compared to the base metal.

Table 2. Percentage difference of HAZ and WZ of SMAW w.r.t. to base metal

SMAW					
Temperature	**-196°C**	**-40°C**	**-20°C**	**0°C**	**20°C**
HAZ (%)	51.30	20.65	16.90	4.78	12.33
WZ (%)	2.53	4.70	4.29	15.55	7.89

Table 3 shows the percentage difference of energy between the HAZ and the weld zone of GMAW process as compared to the BM. The WZ exhibits the most positive percentage difference in energy absorbed while the HAZ of GMAW shows the lowest percentage difference in energy absorbed.

Table 3. Percentage difference of HAZ and WZ of GMAW w.r.t. to base metal

GMAW					
Temperature	**-196°C**	**-40°C**	**-20°C**	**0°C**	**20°C**
HAZ (%)	-30.76	-10.51	-18.05	-16.50	-11.75
WZ (%)	69.23	25.71	11.45	25.12	10.20

On the other hand, the percentage difference in energy absorbed by the WZ and HAZ of FCAW shows in Table 4 does not exhibit any specific pattern. It exhibits intermediate behavior in comparison to SMAW and GMAW.

Table 4. Percentage difference of HAZ and WZ of FCAW w.r.t. to base metal

FCAW					
Temperature	**-196°C**	**-40°C**	**-20°C**	**0°C**	**20°C**
HAZ (%)	-44.50	-20.65	-21.20	-11.24	-15.99
WZ (%)	8.33	5.06	1.14	5.50	0.38

Similarly, Egene et al. investigated the impact toughness behavior of grade X70 pipeline steel using the CVN test. Specimens from the base metal and weld zone were subjected to impact testing over a temperature range from -160°C to 20°C, with increments of 20°C. The weld metal exhibited higher energy absorption compared to the base metal across all measured temperatures. Additionally, they suggested that the sensitivity of the V-notch and temperature could significantly influence fracture toughness[18].

S. Capula et al. investigate the CVN toughness of API X52 seamless unwelded pipeline steel at temperature ranges from -100°C to 100°C and in different directional orientations of the pipeline. All directions exhibit similar CVN values, with a slight reduction in the transverse-longitudinal (T-L) direction. The material exhibits brittle behavior at -100°C with CVN values approximately 39 J, transitions between -100°C and 50°C with values increasing to 239-253 J, and shows ductile behavior beyond 50°C with maximum values of 278-334 J. They suggested that the presence of elongated ferrite and pearlite grain has major effects on toughness. In the transition and upper temperature shelves, fracture surface observations revealed fibrous fractures with dimples and cleavage facets at lower temperatures. This comprehensive study emphasizes the impact of microstructure and temperature on the mechanical properties of pipeline steels in various orientations 19].

Golisch, G. et al. investigated the effect of hydrogen (H) on the toughness of welded tube using CVN tests. They suggest that hydrogen absorption during welding could potentially lead to a reduction in CVN values. A NACE TM0177 solution saturated with H2S was used for hydrogen charging at room temperature for six hours. CVN impact toughness was measured at 0°C, -10°C, and -20°C. No hydrogen was found in the uncharged standard specimens. The findings showed that the BM had higher CVN toughness than the spiral welded specimen, but hydrogen-charged specimens experienced a significant decrease in toughness across all temperatures evaluated. BM CVN values reached up to 314 J and 229 J for uncharged charged sample respectively. Moreover, CVN values for weld specimen reached 153 J and 68 J for uncharged and charged specimen respectively. The investigation shows that hydrogen charging significantly reduces the impact toughness of the welded zone [20].

IV. CONCLUSIONS

The present study investigates the CVN impact toughness of x60 pipeline steel welded using SMAW, GMAW and FCAW.

- The impact toughness shows an increasing trend up to a particular limit as the heat input increases, after which it begins to decrease. In addition to the welding method, the heat input has a substantial impact on the impact toughness of API X60 steel.
- The results suggest that the WZ absorbed more energy compared to the BM, whereas the HAZ absorbed a lower amount of energy across temperatures. These results indicate that the materials experience a loss of their properties during welding due to the thermal gradient.
- The lowtemperature impact toughness of API X60 steel is substantially influenced by its chemical composition. Welding electrodes that include nickel exhibit enhanced impact toughness compared to other electrodes.
- The HAZ of SMAW exhibits the most substantial decrease in energy absorption compared to the BM, particularly at lower temperatures.
- TheGMAW process showed the lowest reduction in impact toughness and the highest increase in impact toughness values at the HAZ and WZ respectively, at all temperatures.
- However, the percentage difference in energy absorbed by the WZ and HAZ of FCAW, as shown in Table 4, does not demonstrate a clear trend. It exhibits a moderate level of behavior when compared to SMAW and GMAW, which shows the least toughness mismatch compared to other processes

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