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# Mechanical Characterization of Welded API X70 Steel Exposed to Air and Seawater: A review

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**Abstract-** A review of the mechanical characterization carried out on welded API X70 steel, and other related steels are presented in this paper. The major problems facing pipeline network are failures demonstrated in form of leaks, ageing, ruptures and explosions. However, corrosion-induced failure also occurs in pipelines that are installed in harsh environments such as seawater. The research works under review considered the welded joints of the API X70 pipelines to be a more critical region than the base metal. The mechanical properties of the welds examined include tensile strength, hardness, and Charpy impact absorbed energy. The experimental methods used to characterize the work that are reviewed include scanning electron microscope (SEM), X-ray diffraction and electron backscatter diffraction (EBSD) and ThermoARL optical emission spectroscopic analysis. Welding technique such as submerged arc welding (SAW) and Manual metal arc (MMA) and parameters used in producing welds are also discussed briefly. Discussion of seawater environment is also presented. It is important to mention that most of the works reported in the literature are those that considered weldments that are exposed to ambient air while just a few considered welds exposed to the corrosive environment such as seawater. Therefore, this review concludes with the need for more research to determine more empirical data on the effect of seawater on mechanical properties of welded API X70.

**Keywords:** Pipeline; Failure; Corrosion; Weld; HAZ

## 1. Introduction

Pipelines used for the transport of natural resources such as oil and gas are installed in various service environments some of which present enormous challenges as the pipelines experience severe environmental degradation and eventual failure resulting to heavy losses [1]. The pipeline industry has shown an increasing demand for increasingly larger pipe diameters, higher operating pressures and diversity of products transported. This leads to the use of higher strength steel grades to avoid large wall thicknesses [2]. High strength X70 grade steel (indicating minimum 70.3ksi/483MPa yield strength) was introduced to the pipeline industry, and the development of the grade X70 started about 30 years ago along with the introduction of thermo-mechanical (TM) rolling practices [3]. Current pipeline materials in the world market are often regulated according to the American Petroleum Institute's (API) standard 5L. The main design considerations outlined in API-5L are based on alloy chemistry and tensile strength. The chemical compositions of the X-grade steels are fairly simple, with maximum limits on C, Mn, S, P and other elements such as niobium and vanadium [4]. The variations in strength (e.g., between X70 and X80) do not result primarily from variations in alloy composition, but from variations in the processing route of the steel [4]. TM processing allows the yield strength of the



pipe steels to be tailored through combinations of grain refinement, precipitation hardening (micro-alloying) and phase formation [5]. The risk associated with the pipeline regarding the safety of people, damage to the environment and loss of income has been a major concern to pipeline integrity managers. Previous research works have established that in most cases, failure of pipeline starts at welds [6], [7], [8]. It is therefore important to determine the quality of the weld, and as such, the mechanical properties of the weld need to be investigated for better understanding. Various mechanical related tests which include Charpy test, hardness test, tensile test, compressive test, microstructural analysis, and spectroscopic analysis could be used to characterize the mechanical properties of weldments. In this paper, review literature on the investigation of the mechanical properties of welded API X70 pipeline steel in air and seawater environments is presented.

## 2. Failure in pipelines

Researchers have conducted some studies on the causes of pipeline failures in the oil and gas industry [9], [7]. Discussions on the failure of the pipeline are quite broad, the fact due to several sources of failures that are associated with pipelines. Achebe et al., [7] stated that the causes of pipeline failure include outside force damage 27%, mechanically induced 40%, operator error 6%, others 25%, and lastly control problems 2%. But the discussion here is primarily restricted to mechanically induced failure arising from the metallurgical/mechanical properties of the pipeline material and most importantly welded joints. Strength, hardness, toughness, plasticity, brittleness, ductility and malleability are mechanical properties used as measurements of how metals behave under a load [8]. These properties are described in terms of the types of force or stress that the metal must withstand and how these are resisted. Common types of external stresses experienced by pipelines as illustrated in figure 1(a-f) are compression, tension, shear, impact, or a combination of these stresses, such as fatigue [9].

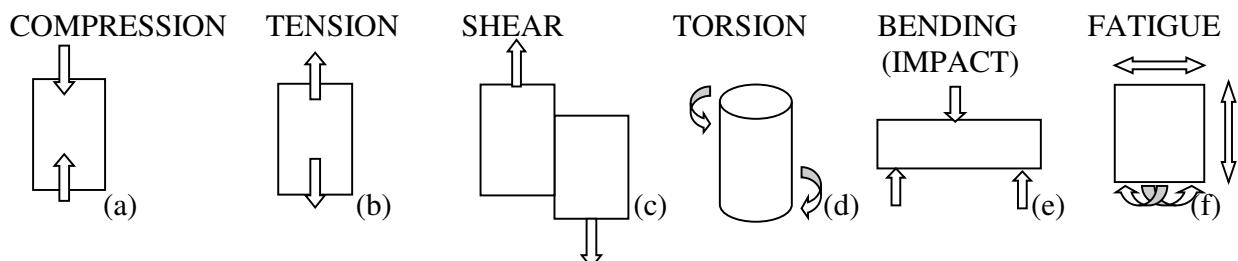


Fig. 1: Schematic of types of external stresses experienced by pipelines [9]

## 3. Chemical composition and mechanical properties of X70 pipeline steel

Idokoh [5] studied the microstructure and mechanical properties of welds in steel pipeline and discovered that the hardness was highest in the weld bead, a bit lower in the base metal and lowest in the heat affected zone. In this study, a higher density of voids was observed at the top of the weld bead than in the middle. It was also demonstrated that large grains and dislocation density in heat affected zone is related to the high susceptibility of the steel weld to fail under tensile load. Aliu [10] investigated the mechanical and microstructural properties of welded joint of Nigerian National Petroleum Corporation pipelines and observed that the Pipeline was made of High Strength Low Alloy (HSLA-A105) steel. At the end of the investigations, it was concluded that inadequate mechanical tests and lack of microstructural examination of the

welded joints before installations were possible sources of pipeline failures. Omale et al., [11] studied the evolution of microstructure, texture and mechanical properties of API X70 steel pipeline after different thermomechanical treatments using a combination of X-ray diffraction and electron backscatter diffraction (EBSD). The investigations revealed that different microstructure consisting of polygonal ferrite, bainite, coarse and fine acicular ferrite grains were obtained with centre line segregation traversing through and parallel to the rolling direction. EBSD investigations confirmed that both dynamic recovery and partial recrystallization occurred during hot rolling requiring further annealing for a more homogenous grain structure. It was also observed that after accelerated cooling, the fast cooling rate and low temperature interruption allows the formation of more bainite, which in turn increased the tensile strength of the steel. The tensile and impact properties of X70 steels pipeline exposed to wet hydrogen sulphide (H<sub>2</sub>S) environments were investigated by Pengyan et al. [12], through corrosion and mechanical testing. The results suggested that the Charpy absorbed energy, tensile strength and reduction in area of X70 steel decreased after H<sub>2</sub>S corrosion. When hydrogen was released, Charpy absorbed energy and reduction in the area exhibited a certain recovery. Fractography of the tensile and impact specimens showed mixed ductile–brittle failure after corrosion and hydrogen release. Fractured regions with brittle features diminished after the release of hydrogen. Hydrogen was closely associated with mechanical property degradation and fracture features.

Leonardo et al. [13] investigated the microstructure and mechanical properties of two API steels for iron ore pipelines. A chemical analysis of X70 steel was performed using a Thermo ARL optical emission spectrometer, and the microstructure was observed by a JEOL scanning electron microscope (SEM). The chemical composition of the X70 steel used for the experiment is presented in Table 1.

Table 1: Chemical composition of API-5L X70 steel (wt%)

C	Si	S	P	Mn	Ni
0.109	0.239	0.004	0.023	1.536	0.011
Cr	Cu	Al	Ti	Nb	V
0.024	0.011	0.026	0.016	0.045	0.045

The SEM micrograph of X70 steel revealed the presence of polygonal ferrite/pearlite banding (pancake type), an occurrence in hot-rolled, low alloy steels and a ferritic grain size. The presence of a small volumetric fraction of bainite / degenerated pearlite and the absence of acicular ferrite in X70 steel was also noted. The results of the tensile, impact and hardness tests showed yield strength of 586MPa, the ultimate tensile strength of 640MPa, a total elongation of 38%, Rockwell hardness A, HR<sub>A</sub> 65, and Charpy impact absorbed the energy of 184J.

### **3.1 Effect of welding techniques and weld parameters in pipeline steels**

The welding technique used in producing welds play very vital roles in controlling the occurrence of welding imperfections. Several welding methods exist but there is need to review the methods that are frequently used in producing steel pipeline. Loureiro [14] suggested that submerged arc welding (SAW) is used extensively in industries to join metals for the manufacture of pipes of different diameters and lengths. In this work, response surface methodology (RSM) technique of design of experiment (DOE) has been applied for the selection of the optimum input variables.

Dearden [15] suggested that in submerged arc welding process parameters play a significant role in determining the quality of a weld. So for such applications, optimum welding process parameters must be selected providing desired weld properties. In the work; beads were taken on 15mm thick plate by varying heat input and wire feed rate. Prediction equations were developed for penetration, reinforcement height and width using the multi-regression method and artificial neural networks; a comparative study of both techniques has also been performed.

Loureiro [14] suggested that in submerged arc welding (SAW), selection of appropriate values of process variables is essential to control heat-affected zone (HAZ) dimensions coupled with the required bead size and quality ensuring a predictable and reproducible weld bead. In the investigation, mathematical models were developed to study the effects of process variables and heat input on various metallurgical aspects; width of the HAZ, weld interface, grain growth and grain refinement regions of the HAZ. From the study, it was concluded that heat input and wire feed rate have positive effects, but welding speed has a negative impact on all HAZ characteristics. Width of grain growth and grain refinement zones increased but weld interface decreased with an increase in arc voltage.

Ito and Bessyo [16] analysed the influence of welding heat input on the mechanical properties of weld joints using heat input from 2.5 to 4.0 kJ/mm for submerged arc welded of duplex steel. The study revealed that the heat input from 2.5 up to 4.0 kJ/mm has no adverse influence on the mechanical properties of the joints in submerged arc welding of duplex steels.

Hosseini et al [17] used the digital image processing techniques to assess the heat-affected zone of submerged arc welding of structural steel plates through the analysis of the grain structure. It was concluded from the study that HAZ in submerged arc welding was of relatively less size due to 10% less grain growth.

### 3.2 Seawater Environment

Seawater, or salt water, is water from a sea or ocean. On average, seawater in the world's oceans has a salinity of about 3.5% (35 g/L), this means that every kilogram (roughly one litre by volume) of seawater has approximately 35 grams of dissolved salts - predominantly sodium (Na<sup>+</sup>) and chloride (Cl<sup>-</sup>) ions, average density at the surface is 1.025 kg/L [18]. The presence of dissolved salts mainly NaCl makes seawater one of the most corrosive and most abundant naturally occurring electrolytes. The highly corrosive nature of the seawater is reflected by the fact that most of the common structural metals and alloys are attacked by these dissolved salts and aerated water under varying levels of turbulent flow conditions [19, 25]. Seawater is denser than both freshwater and distilled water (density 1.0 kg/L at 4 °C (39 °F) because the dissolved salts increase the mass by a more significant proportion than the volume. The freezing point of seawater decreases as salt concentration increases. At typical salinity, it freezes at about -2 °C (28 °F) [20]. The coldest seawater ever recorded (in a liquid state) was in 2010, in a stream under an Antarctic glacier, and measured -2.6 °C (27.3 °F) [20]. Joyde et al. [18] stated that Seawater pH is typically limited to a range between 7.5 and 8.4. However, there is no universally accepted reference pH-scale for seawater, and the difference between measurements based on different reference scales may be up to 0.14 units [21].

According to Saleh and Malik [20], the seawater environments can be divided into five zones namely: subsoil, continuously submerged, tidal, splash zone above high tidal and atmospheric zone. The same authors observed in their studies that the corrosion behaviour of metals and alloys differ from one zone to another. In splash zone, the stainless steels usually have

satisfactory performance while the carbon and low alloy steels do not. Anderson and Rose [22] had found that the austenitic grades performed much better than martensitic and ferritic grades. The Ni, Cu and P alloyed steels were found to be much more resistant than carbon steel in splash zone [23]. Also, it was found that Mn, P and Al had a measurable influence on corrosion rates of low carbon steels under tidal exposure. After five years exposure test it was found that the rate of attack in splash zone was much higher than the atmosphere and deep submerged zones [24]. The approved composition for standard seawater prepared with 41.953 grams of sea salt with enough distilled water to yield on liter artificial seawater is as presented in Table 2.

Table 2: ASTM D114 standard composition for substitute seawater

Sodium Chloride	NaCl	58.49%
Magnesium Chloride	MgCl <sub>2</sub> -6H <sub>2</sub> O	26.46%
Sodium Sulfate	Na <sub>2</sub> SO <sub>4</sub>	9.7%
Calcium Chloride	CaCl <sub>2</sub>	2.765%
Potassium Chloride	KCl	1.645%
Sodium Bicarbonate	NaHCO <sub>3</sub>	0.477%
Potassium Bromide	KBr	0.238%
Boric Acid	H <sub>3</sub> BO <sub>3</sub>	0.071%
Strontium Chloride	SrCl <sub>2</sub> -6H <sub>2</sub> O	0.095%
Sodium Fluoride	NaF	0.007%

Note: (1) Density of Seawater equals 1.025 at 15°C; (2) pH adjusted to 8.2 using 0.1N solution of sodium hydroxide or hydrochloric acid (ASTM D114- 2013)

The American Society for Testing and Materials has put up a standard for seawater conditions for many uses including accelerated corrosion studies, oceanographic research, ocean instrument calibration and chemical testing. ASTM D114 is the updated standard “sea salt” which is used in the preparation of substitute/artificial ocean water.

#### 4. Conclusions

The following conclusions are drawn from this work:

1. Welds and corrosion are critical points of consideration in terms of design and initial fabrication and any subsequent repair during the life of a pipeline;
2. Welded joints are more susceptible to failure than the parent material due to the effect of welding on the mechanical properties of the weld and heat affected zone;
3. Installations of pipelines in corrosive environment require an understanding of the corrosion performance of such new weldments, which may be used in the marine environments. Generally, if the corrosion mitigation measures are correctly applied and proper inspection and maintenance adhered to, then welds should not pose any increased risk of corrosion failure, but owners of the steel pipeline must understand the potential issues associated with welds and likelihood of corrosion in the event of coating failure at welds;
4. In optimising maintenance strategies, it is essential therefore to determine with more empirical data the rate at which corrosion degrades the mechanical properties of welded joints of API X70 pipeline in corrosive environment (sea water).

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