

This chapter cover literature survey for the presented thesis. First chapter has briefly covered the pipeline steels and related issues. The literature survey was started with the weldability of the pipeline steels. The significance of flux constituents was discussed for various properties. Further, effect of flux on weld bead and weldment characterization has been discussed along with effect of hydrogen. Finally, some fundamentals of fracture mechanics have been discussed along with finite element method used for the research work.

2.1 WELDABILITY OF PIPELINE STEELS

Modern high-strength low-alloy (HSLA) steels are made by means of careful alloying (e.g., aluminum, titanium, vanadium, niobium) and controlled thermomechanical processing, resulting in fine-grained ferrite with high strength, toughness, and resistance to hydrogen-induced cracking. Acicular ferrite, which forms on particular oxides or borides after cooling, has better characteristics than other ferrite varieties. The carbon equivalent (CE) is a crucial quantity in steel design that determines hardenability and crack sensitivity. By combining the effects of numerous alloying components into a single number, CE directs material selection and process changes, assuring optimal welding performance and reducing cracking risks in varied steel grades (API 5L, 2004; Olson et al., 1993). Carbon equivalent can be estimated using equation (2.1) given by IIW, and equation (2.2) given by (Ito, 1968).

$$CE_{IIW} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15} \quad (2.1)$$

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad (2.2)$$

P_{cm} value is used when C weight % is less than 0.12.

2.2 FLUX COATINGS CONSTITUENTS AND ITS SIGNIFICANCE

2.2.1 The Wettability and structural properties of flux

The calcium fluoride-based flux systems are used in welding consumables and electroslog remelting. The thermophysical and physicochemical properties of the flux have a significant effect on the weld. The chemical composition of the slag affects the surface tension, viscosity, density, etc., (Mills et al., 1981). Kim et al. investigated the wettability of $TiO_2 - MnO - SiO_2 - Al_2O_3$ based quaternary welding flux systems. The effect of TiO_2/SiO_2 and SiO_2/Al_2O_3 were investigated on the wettability attributes. The interfacial tension between slag metal was found to be affected by both free oxygen (O^{2-}) and non-bridged oxygen (O^-) (Kim et al., 2016). Zhang et al. reported the structure-related model to predict the surface tension $CaO - SiO_2 - Al_2O_3 - FeO - Fe_2O_3$. The content of oxygen was characterized by spectral analysis. Surface tension was found to be in better agreement with Tanaka's model (Zhang et al., 2022).

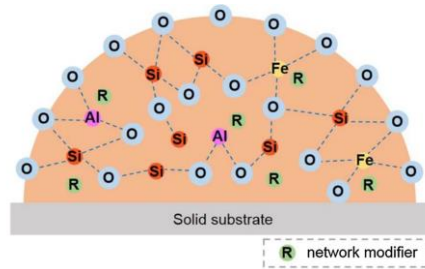


Figure 2. 1: Schematic representation of the local network structure in the $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3\text{-FeO-Fe}_2\text{O}_3$ system's surface layer and bulk phase (Zhang et al., 2022)

Sharma et al. investigated the flux systems $\text{CaO} - \text{CaF}_2 - \text{SiO}_2 - \text{Al}_2\text{O}_3$ and $\text{MgO} - \text{TiO}_2 - \text{SiO}_2 - \text{Al}_2\text{O}_3$ based submerged arc welding fluxes. The contact angle, spread area, work of adhesion, and surface tension were estimated, and the influence of different flux ratios was reported (Sharma, et al., 2020b, 2020a). Researchers have investigated the influence of structural properties on the wetting behavior of $\text{CaO} - \text{SiO}_2 - \text{Al}_2\text{O}_3$ based mold flux. The study concluded that the increase in $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio slightly increases the contact angle and interfacial tension. Whereas an increase in $\text{CaO}/\text{Al}_2\text{O}_3$ the ratio decreases the contact angle and interfacial tension (Wang et al., 2019). High-temperature wettability studies for glass metal joints reveal that the wetting of borosilicate glass on SS 304 was better than the low-carbon steel and copper substrate (Joshi et al., 2018). High-temperature wettability study of the fluxes revealed that the contact angle is influenced by the binary interaction of CaO-SiO_2 , CaO-CaF_2 , and $\text{CaF}_2\text{-SiO}_2$ (Khan et al., 2020). Mills et al. suggested corrected optical basicity (Λ^{corr}) over (NBO/T) ratio to correlate the degree of polymerization of the melts from the structure. The (NBO/T) is non-bridging oxygen per tetrahedron. The Optical basicity is the ability of the oxide to release a negative charge. The Λ^{corr} provides a measure of the O^0 , O^- and O^{2-} concentrations present in the melt. The main advantage to use Λ^{corr} is that it also applies to the non-silicate fluxes (Mills, 1993). Kim et al. have investigated the microstructural changes with corrected optical basicity and reported that with $\Lambda^{\text{corr}} = 0.62$ substantial grain coarsening occurs, which results in reduced strength. This work also concluded that the simple structural units containing TiO_2 resulted in higher heat transfer. The deficiency of complex structures such as $[\text{AlO}_4]^{5-}$ and $[\text{SiO}_4]^{4-}$ occurs with the addition of TiO_2 (Kim et al., 2018). The role of CaF_2 in submerged arc welding fluxes. The increase in CaF_2 leads to depolymerization of the flux structure (Tian et al., 2022). Wang et al. studied the influence of replacing CaO with BaO on the viscosity and structure of $\text{CaO} - \text{BaO} - \text{SiO}_2 - \text{MgO} - \text{Al}_2\text{O}_3$ slag system. Replacing CaO with BaO increases the viscosity due to an increase in the degree of polymerization. The Raman analysis revealed that the ratio of Q^3/Q^2 (Q^i , i is the number of bridging oxygen O^0 in $[\text{SiO}_4]$ –tetrahedral unit) and NBO/Si decreases with the addition of BaO (Wang et al., 2018). Choi et al. investigated the sulfide capacity of Al_2O_3 -bearing slag strongly depended on the stability of sulfide ions and basicity. The driving force for the sulfide capacity was free oxygen (O^{2-}) rather than its role in the stabilization of slag structure in the Al_2O_3 rich region (Choi et al., 2018). Wang et al. studied the viscosity and structure of $\text{MnO} - \text{SiO}_2 - \text{MgO}(-\text{Al}_2\text{O}_3)$ with varying Al_2O_3 . The study indicated that the viscosity decreases and then increases with the increase of Al_2O_3 content from 0 to 25 mass pct. The degree of polymerization increases with the enhancement of $(Q^2 + Q^3 + \text{Al} - \text{O}^0)/(Q^0 + Q^1 + \text{Al} - \text{O}^-)$ (Wang et al., 2022). From the literature, it can be deduced that the weld quality depends on the flux properties. The variation of flux composition plays an important role in the structural properties. Welding electrode coating properties are dependent on the structural properties which in turn affect the wetting attributes of molten slag.

2.2.2 Thermophysical and physicochemical behavior

Du Plessis et al. reported the role of welding flux in the diffusible hydrogen content. Fluoride additions was found to reduce diffusible hydrogen. Micaceous iron addition in flux reduces diffusible hydrogen content (Du Plessis et al., 2008). The extreme vertices design approach was utilized for mixture designing of welding flux. Using regression analysis, effect of flux on mechanical property and diffusible hydrogen content were discussed (Jindal et al., 2013).

Previous studies have shown that the welding fluxes affects the element transfer from filler to weld pool. Bhandari et al. formulated fluxes for SMAW electrode coating in austenitic stainless steel, and the fluxes' roles were correlated with element transfer and mechanical properties. The developed $\text{CaO} - \text{CaF}_2 - \text{TiO}_2 - \text{SiO}_2$ based SMAW electrode flux for 309L filler and reported element transfer behaviour as the flux composition changed. Mahajan et al. investigated the role of $\text{CaO} - \text{CaF}_2 - \text{SiO}_2 - \text{Al}_2\text{O}_3$ based flux for FM-182 nickel electrode on element transfer behaviour. The study also discussed the role of flux on microstructural and microhardness properties (Bhandari et al., 2016; Khan et al., 2021; Mahajan et al., 2021). Calcite reduces hydrogen and produces clean welds, but too much calcite results in a poor bead appearance. The flux composition ratio governs slag detachability, which is a fundamental requirement for any weld. Carbonates of flux constituents such as BaO , Na_2O , CaO , and MgO are added; these carbonates influence the microstructure and mechanical properties of the weld (Wang et al., 2018). To reduce the flux melting temperature, fluxes for SAW and SMAW were designed and developed using a ternary phase diagram. Thermogravimetric analysis (TGA), differential scanning calorimeter (DSC), and hot disk technique were used to investigate the fluxes' thermophysical and physicochemical properties (Kumar et al., 2022a; Sharma et al., 2020b, 2020a). During welding, SMAW electrode flux generates shielding gas and slag, which protect the weld, despite the fact that the minerals used for flux contain moisture, crystallization water, and volatile compounds, which are responsible for the increase in diffusible hydrogen. Thermally stable flux compounds experience less weight loss and enthalpy change, resulting in less volatile compound release. Thermal constants like thermal conductivity and thermal diffusivity are affected by the composition, porosity, and moisture content of the material (Santhosh et al., 2021; Suleiman et al., 2020). The hot disk technique used to measure thermal constants was discovered to vary with composition. Increased thermal diffusivity and conductivity results in uniform heat distribution across the coating, allowing for easy coating detachment from the filler while heating.

There has been a lot of research done on how welding input parameters like welding current, arc voltage, and speed affect metallurgical and mechanical properties. More understanding is required to comprehend the nature of flux. The flux designed for critical section must produce clean weld with less dissolved oxygen, hydrogen and nitrogen, this problem is usually addressed with utilization of high basicity index flux. The mineral oxides used for flux generally contain calcite (CaO), witherite (BaO) which are basic, and rutile (TiO_2), alumina (Al_2O_3) and silica (SiO_2) which are acidic. Previous research suggests use of fluor spar (CaF_2) reduces dissolved hydrogen, which is a major concern of pipeline industry, and use of witherite promotes acicular ferrite in the weld, which is a favorable microstructure. So, design and development of $\text{CaF}_2 - \text{CaO} - \text{Al}_2\text{O}_3 - \text{BaO}$ based flux was selected, and SiO_2 , TiO_2 , ferroalloys, binder, iron powder was kept constant.

The extreme vertices design approach is used in this work to design the SMAW electrode coating fluxes. Previous research indicates that an extreme vertices design approach is extremely useful in experiments involving mixtures (Khan et al., 2020; Mahajan et al., 2019). TGA gives the weight change and DSC gives the enthalpy change of the flux while heating at a constant rate. The hot disk technique is used to determine thermal conductivity, diffusivity, and specific heat.

2.3 EFFECT OF FLUX ON WELD PROPERTIES

During the process of welding, the flux coating undergoes detachment and melting, resulting in the production of slag. This slag then interacts with the molten metal. The quantities of nitrogen, oxygen, and inclusions that are dissolved are influenced by the interactions between the slag and the metal during the welding process (Chai et al., 1982). The basicity index can be mathematically expressed as the proportion of basic constituents to acidic constituents, and this measurement is directly associated with the oxygen concentration (Kou, 2003; Natalie et al., 1986). Omiogbemi et al. developed SMAW electrode coatings with basicity indexes of 2.40 and 0.40 for welding duplex stainless steel. This study addressed the mechanical and corrosion properties of the welded structure (Omiogbemi et al., 2022). The impact of welding flux composition on microstructure and alloying elements in submerged arc welding of high-strength low-alloy steel

(HSLA) has been investigated, $\text{CaF}_2 - \text{CaO} - \text{SiO}_2$ system flux and examined its chemical behavior in relation to weld chemistry (Dallam et al., 1985). The effect of different carbonates in electrode coating, study concluded that BaCO_3 produces finer acicular morphology and improves mechanical properties (Chang et al., 2008). Singh et al., investigated the role of CaF_2 , FeMn, and NiO additions on element transfer and found that impact strength was correlated with the oxygen potential of the slag (Singh et al., 2016).

Bang et al. examined how wire flux combinations affect element transport and mechanical properties in submerged arc welding. Element transfer quantity (Δ) between weld pool and slag was calculated to assess loss or gain. The study indicated that basic fluxes reduced oxygen concentration, lowering weld manganese (Mn) and carbon (C) (Bang et al., 2009). The element transfer behaviour of $\text{CaF}_2 - \text{TiO}_2$ and $\text{CaO} - \text{SiO}_2 - \text{MnO}$ fused fluxes for the purpose of welding EH36 shipbuilding steel was studied. The findings indicate that the presence of TiO_2 enhances the acquisition of oxygen and concurrently results in the depletion of Mn through a deoxidation reaction (Zhang et al., 2020). The process of element transfer was shown to be notably influenced by the equilibrium between slag-metal and gas-slag-metal, as reported in the study by (Zhang et al., 2021). Researchers have employed a mixture design technique to investigate the predictability and modeling of element transfers, specifically oxygen, manganese, silicon, and sulfur, through the utilization of statistical design of mixture trials (Kanjilal et al., 2006). Prior studies have demonstrated that the presence of welding fluxes has an impact on the transportation of elements from the filler material to the weld pool. The study established a connection between the functions of these fluxes and the transport of elements, as well as the resulting mechanical qualities (Bhandari et al., 2016). The objective of previous research was to establish a correlation between the roles played by these minerals and the behaviour of element transfer (Khan et al., 2021; Sharma et al., 2019).

In addition to facilitating the passage of elements to the weld pool, it is expected that SMAW fluxes demonstrate arc stability and the capacity to detach slag as their key requirements. The detachability of slag is influenced by the ratio of its constituents in the fluxes. Study indicated that optimal slag detachability was achieved when the ratio of $\text{CaO} : \text{CaF}_2 : \text{SiO}_2$ was 1.7:1.8:1 (Wang et al., 2016). Pamnani et al., investigated the effects of the welding process on microstructure and Charpy impact. According to the study (Pamnani et al., 2016), weld joint impact toughness increased with smaller inclusion sizes and a lower number of inclusions. The microstructures of nickel-containing weld metals and discovered that increasing the proportion of nickel in the alloy increases the acicular ferrite (AF) phase while decreasing the grain boundary ferrite (GBF) phase within the weld metals. The number of austenite islands and brittle martensite increases as the amount of nickel (Ni) in the weld metal increases (Fakheri et al., 2020). Bhole et al. investigated the toughness and microstructure of X70 Ni and Mo element powders during submerged arc welding. Mo enhances weld metal granular bainite and acicular ferrite while decreasing secondary phase and GBF (Bhole et al., 2006).

Weld improvement research has mostly focused on non-metallic inclusions, alloying, flux development, and welding process development (Hariprasath et al., 2022; Pamnani et al., 2016; Sharma et al., 2020b). The previous investigations have suggested that the cellulosic electrode weld results in higher high dissolved hydrogen than the basic electrode weld, preheating and postheating were suggested to avoid cracking (Hanzaei et al., 2018). The fluxes can be used to customize different microstructures and inclusions. The study of the flux involves multiple factors such as slag detachability, arc stability, spatter, wetting behavior, thermophysical-physicochemical properties, dissolved oxygen and nitrogen content (Bhandari et al., 2016; Khan et al., 2021). The impact of Ni content on the microstructure of E7018-G weld metal in SMAW. The Ni ~1.2 wt.% increases the area fraction of acicular ferrite from 32% to 62%, at the expense of polygonal, Widmanstätten, and grain boundary ferrite (Figure 2.2). This microstructure change improves the mechanical characteristics and corrosion resistance of the weld metal (Mosallaei et al., 2021).

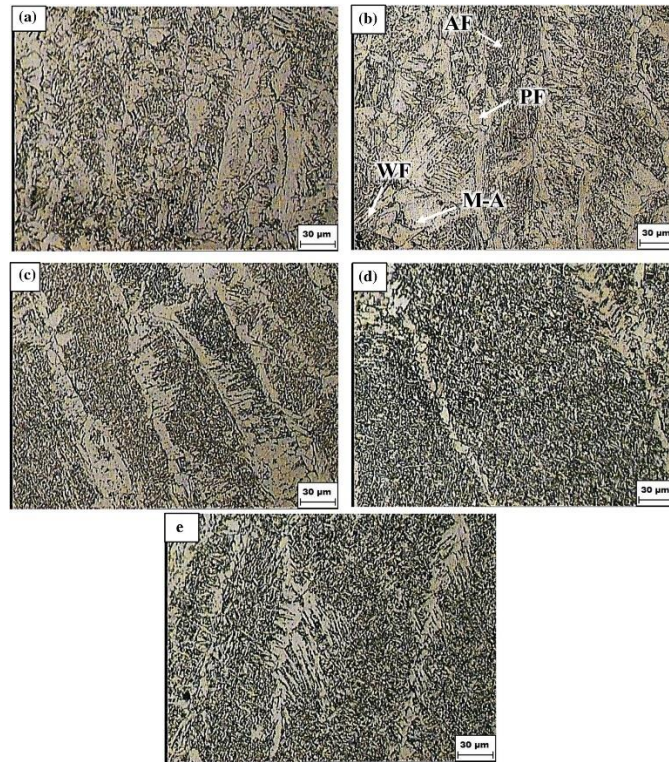


Figure 2.2: Optical microstructure of as-welded zone in the weld metal. (a) E7018G-0, (b) E7018G-0.6, (c) E7018G-0.8, (d) E7018G-1.2, (e) E7018G-1.7 (Mosallae et al., 2021).

The weld metal containing Ni 2.91 wt.% had a homogenous microstructure dominated by acicular ferrite (AF). This microstructure adds to higher corrosion resistance (Fakheri et al., 2020). Bhole et al., found that Mo and Ni addition to weld promotes an acicular ferrite microstructure, enhancing impact toughness. Nickel Ni and Mo reduce grain-boundary ferrite, increasing toughness. Toughness was optimized with 77% AF and 0.881 wt.% Mo in the WM. The study also observed centerline cracking tendency with Ni 3.75 % (Bhole et al., 2006). So, from the above discussion, it can be observed that the role benefits of Ni are conditional for the low alloy steel welds.

The study by Wang et al., shows that increasing Ti content in X70 steel weld metals changes the major phases of inclusions, shifting from (Mn-Al-Si-O) compounds to spinel and pseudobrookite solid solutions. Spinel, largely consisting of MnTi_2O_4 , enriches Mn in inclusions, resulting in Mn-depleted zones in the matrix. This encourages the formation of intragranular acicular ferrite (AF), which considerably increases weld metal toughness (Wang et al., 2021). Small additions of Ti to submerged arc welded API 5L-X65 steel create fine oxide inclusions (about 2 μm) that act as nucleation sites for acicular ferrite. This inclusion size encourages the production of acicular ferrite (Beidokhti et al., 2015).

2.4 EFFECT OF HYDROGEN ON WELD

The previous research on the hydrogen effect has been carried out for X65, X70, X80 base metals. Some studies suggested that weld metal (WM) in X65 steel pipeline weldments is more susceptible to hydrogen embrittlement (HE) and hydrogen-induced cracking (HIC) than HAZ and base metal. Microstructural characteristics such as Ti-rich inclusions, martensite/austenite components, and previous austenite grain boundaries (PAGBs) promote hydrogen-related damage in the weld, making it more susceptible (Zhang et al., 2024). In an investigation by Latifi et al., compared to E7010-G and E7018 electrode weld metals, hydrogen embrittlement considerably affects X65 steel's plasticity. Hydrogen directly enhances steel and weld metal hardness by up to 12%, with pearlite/ferrite contacts making the base metal more sensitive to

hydrogen-induced flaws. With its acicular ferritic microstructure, E7010-G weld metal has increased hydrogen diffusivity and more reversible hydrogen traps (Latifi V. et al., 2017). It is evident that the investigation of the weld, and HAZ is in the initial phase so conclusive remarks cannot be made. There has been negligible research on the weld by SMAW for X70 steel. The study shows that regardless of the benefits of friction stir welding of API 5L X70 pipeline steel, weldment still faces issues due to hydrogen embrittlement (Giarola et al., 2021). Figure 2.3 shows the effect on different charging conditions on the stress strain behavior of pipeline steel.

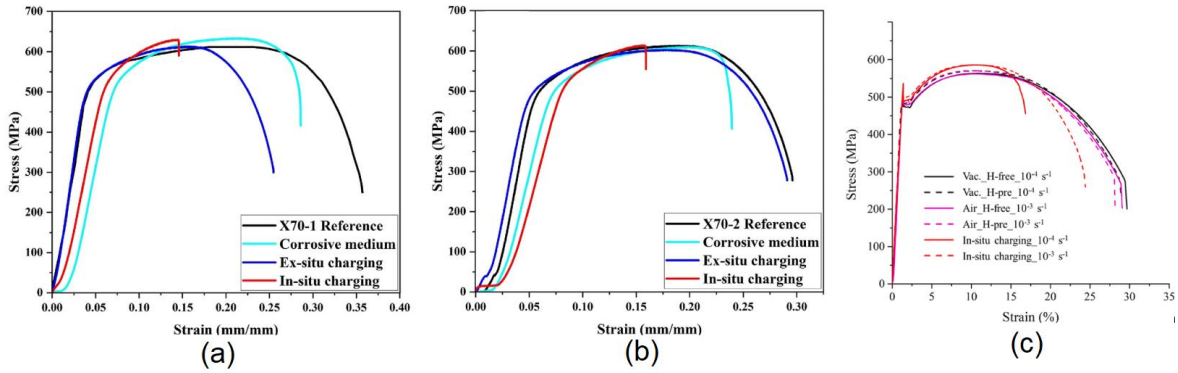


Figure 2.3: Stress strain curve under different environmental condition (a) (b) (Yadav et al., 2023) (c) (Wang et al., 2022)

Figure 2.4 depicts SEM images of the X70-1 and X70-2 steel fracture sites under different conditions. Both steels show ductile failure in air, with dimples caused by microplastic deformation. Ex-situ hydrogen charge resulted in a combination of ductile and brittle fractures, with smaller dimples indicating lower ductility due to the hydrogen-enhanced localized plasticity. The fracture surfaces of in-situ charged X70 steels are largely cleavage facets, indicating brittle fracture and the highest hydrogen embrittlement index with minimal elongation. X70-2 features more dimples than X70-1, which indicates somewhat better ductility under in-situ charging circumstances (Yadav et al., 2023).

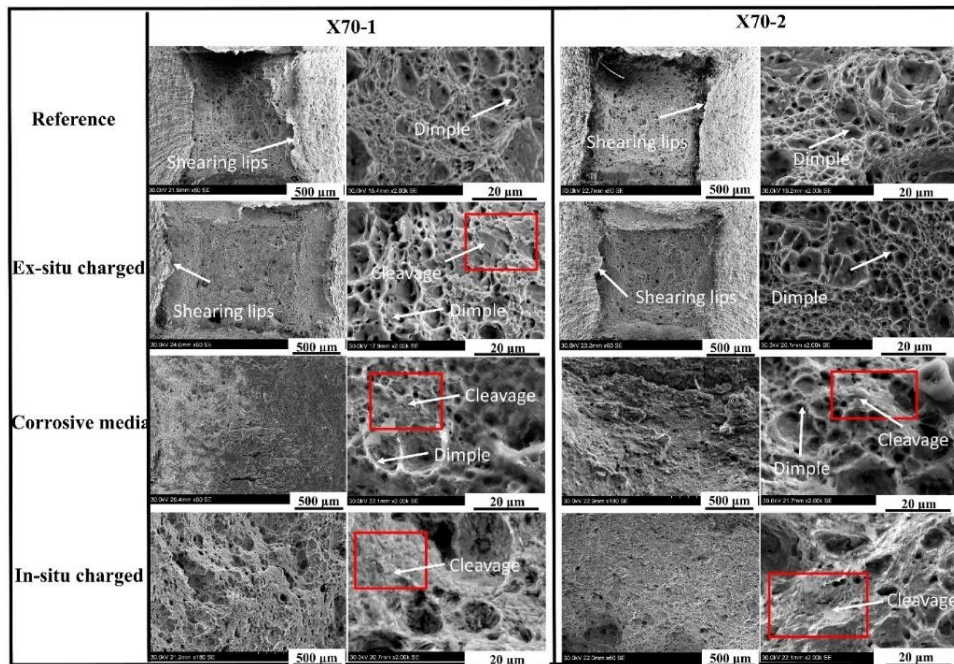


Figure 2.4: Fractography of tensile specimens under different environment (Yadav et al., 2023)

2.5 FRACTURE MECHANICS AND FINITE ELEMENT ANALYSIS

2.5.1 Introduction to pipeline fracture

Pipelines across long distances face difficult geological and corrosive conditions (Pourazizi et al., 2020). Complex stress states in these pipelines can cause catastrophic failures. In case of an accident, the pipeline steel generally undergoes ductile mode of fracture. Elastic-plastic fracture mechanics requires two factors to account for extensive plastic deformation near the crack tip, while linear elastic fracture mechanics assumes a small plastic deformation zone (Dieter et al., 1976). The pipeline ductile fracture properties can be explained using elastic-plastic fracture mechanism. Pipeline steel integrity is often assessed using Mode I fracture or opening mode. Full-scale pipeline testing is expensive and time-consuming for testing structural integrity (Park et al., 2018; Pavankumar et al., 2005). Testing smaller specimens is an option, however fracture toughness value is conservative from laboratory components to full-scale systems. Finite element simulations utilizing local ductile damage models have helped solve this problem (Pavankumar et al., 2005). The testing of fracture toughness using compact tension (CT), and single edge notch bend (SENB) test is common, and standardized (ASTM E1820). The variation in the initial crack length with respect to the specimen width a_0/W results in-plane constraints conditions. Similarly, variation in specimen thickness B results in out-of-plane constraints conditions. The rationale for utilizing deeply cracked specimens is to create conditions that facilitate crack growth under high crack-tip constraint with minimal-scale plastic deformation. Nevertheless, numerous real-world crack-like defects are generally surface cracks that develop during service operations, exposure to harsh environments, or welding processes (Chiesa et al., 2001).

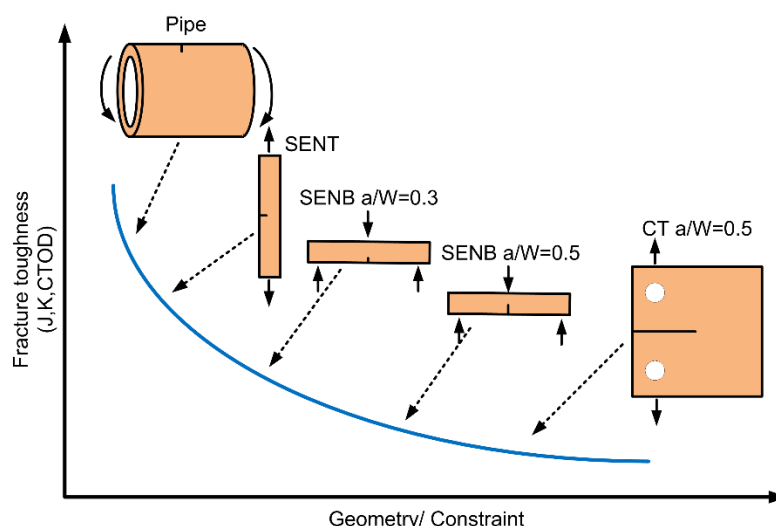


Figure 2.5: Effect of fracture specimen geometry on fracture toughness (Chiesa et al., 2001).

Structural components that are susceptible to such defects include girth welds in high-pressure piping systems. These crack configurations often undergo low crack-tip stress triaxiality, which markedly contrasts with the conditions observed in deeply cracked specimens. The use of single edge notch tension (SENT) test can resolve this issue of fracture toughness conservatism from high stress triaxiality (Chiesa et al., 2001; Qiang et al., 2019). The quantification of constraint of small fracture toughness specimen has been studied (Zhu et al., 2009). (Park, et al., 2017) discusses SENT testing procedure developed by CANMET materials. This method employs a single-specimen test approach, utilizing an unloading-compliance technique to estimate crack size and the J-integral. The technical review (Zhu et al., 2017) highlights the growing interest in fracture toughness testing using clamped SENT specimens. They provide an overview of existing approaches, including the CANMET procedure, BS 8571 standard, ExxonMobil method, and DNV practice, while also discussing recent advancements in these methodologies. It was observed that the SENT test method is still in development whereas, SENB and CT specimen testing have been standardized. The fracture toughness is usually measured using J integral and

CTOD value with respect to crack growth. The fracture toughness J integral and CTOD are related (Sarzosa et al., 2015). Researchers have investigated the ductile fracture of X70, weld, effect of notch acuity, and loading conditions (Park et al., 2017; Park et al., 2017; Park et al., 2015)

Finite element analysis (FEA) of fracture tests can help to understand the mechanics of the fracture behavior resulting in further development. Paredes et al. demonstrated the calibration of phenomenological Mohr-Coulomb model fracture criterion for X70 steel that can effectively predict the initiation of stable crack growth (Paredes et al., 2016). Study on 16MND5 steel, focusing on quantifying constraint effects through finite element analysis. Their work determined constraint-dependent R-curves and initiation fracture toughness (Liu et al., 2021). The Gurson-Tvergaard-Needleman (GTN) model is one of the popular micromechanics based ductile damage model initially developed by Gurson in 1977 and later improved by Tvergaard and Needleman (Chu et al., 1980; Gurson, 1977; Tvergaard, 1981; Tvergaard et al., 1984). It comprises nine constitutive parameters associated with the micro-ductile fracture mechanism. Setting these parameters is difficult and time-consuming. Some scholars have noted issues with these parameters' non-uniqueness (Kiran et al., 2014; Zhang et al., 2000). The GTN model is a damage model which when coupled with J2 plastic flow theory, becomes a robust method to analyze fracture scenarios incorporating void nucleation, growth and fracture. The fracture toughness test requires crack growth along with J integral or CTOD values to produce R curves. As discussed earlier that the pipeline cracks are mostly mode I type, which has no shear consideration, therefore GTN model becomes a powerful tool for fracture analysis of pipeline steel.

The parameter identification strategy has been studied by various researchers. Some researchers have identified void volume fraction parameters using extensive metallographic investigation (Batisse et al., 1987; Chhibber et al., 2012; Kumar et al., 2022). This approach can provide material realistic values although some tuning of the parameters might be required. Inverse approach followed by Fratini et al., utilized a statistical method for parameters identification. Inverse identification approach is a powerful and easy tool to tune the GTN parameter to fit the material response such as load-displacement curve from tensile test (Fratini et al., 1996). Abbasi et al., have used response surface methodology to identify the forming limit diagram for material IF steel (Abbasi et al., 2012). Gholipour et al., has also employed response surface methodology to fit tensile test curves of SAE 1010 steel with different stress states (Gholipour et al., 2019). Some recent investigations have also employed machine learning models to identify these parameters (Chen et al., 2021; Shafaie et al., 2022).

2.5.2 Classification of fracture mechanics

Fracture mechanics focuses on the analysis of cracks, crack-like imperfections, and the mechanical behavior of the affected structures. It considers factors such as flaw size, characteristics, loading conditions, component geometry, and toughness properties to evaluate a flawed component's resistance to fracture. Linear elastic fracture mechanics is applied to brittle materials or when plastic effects at the crack tip are negligible (small-scale yielding), while elastic-plastic fracture mechanics is used for ductile materials or when plasticity effects are significant. The fracture mechanics can broadly be classified as Linear Elastic Fracture Mechanics (LEFM) and Elastic Plastic Fracture Mechanics (EPFM)

The foundational principles of linear elastic fracture mechanics were established by (Griffith, 1921), who introduced the concept of a critical stress required for failure. In Fig. 2.6, a sheet with an initial crack length, a , subjected to a tensile stress, σ , is shown. The stress near the crack tip exceeds the average stress of σ . This elevated stress causes significant strain in the material near the crack tip, eventually leading to failure and allowing the crack to propagate forward (Anderson et al., 2005).

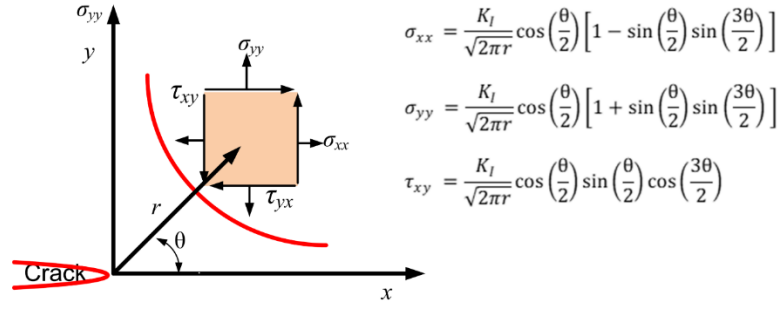


Figure 2.6: stress near the crack tip in an elastic material

If the material behaved in a purely linear elastic manner up to the point of fracture, the stress ahead of the crack would be.

$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \quad (1.1)$$

where r is the distance from the crack tip and K_I , called stress intensity factor, is related to the applied stress.

Stress-intensity factors K_I , K_{II} , K_{III} in accordance with the crack loading mode (Figure 2.7)

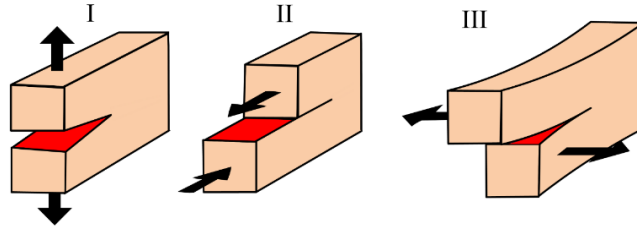


Figure 2. 7: Mode I, mode II, and mode III type of deformation

These are used to assess the fracture toughness of most materials based on linear elastic fracture theory. Specifically, K_I governs the crack tip deformation and fracture under the assumption of 'small scale yielding,' which occurs when the plastic deformation zone near the crack tip is much smaller than the crack length (a). Under this condition, the stress outside the yielding zone can be accurately approximated by equation "

$$K_I = \sigma \sqrt{\pi a \beta} \quad (1.2)$$

K_I = stress intensity factor ($\text{MPa}\sqrt{\text{m}}$)

σ = applied stress (MPa)

a = crack length (m)

β = dimensionless factor depending on crack length and specimen geometry

In the late 1940s, Irwin and Orowan built upon Griffith's work and attempted to apply his theory to ductile materials like steels. Specifically, they introduced a term for plastic deformation, in the form of plastic work, into Griffith's surface energy, thereby defining the fracture energy and adjusting the critical stress for fracture. When the applied load does work (i.e., causes displacement) and the crack area changes, the elastic energy of the body changes according to the following expression

$$dU = Pd\Delta - GdA \quad (1.3)$$

where U is the elastic energy, P is the force, Δ is the displacement, G is the energy release rate and A is the area of the crack.

The fracture energy Γ is a small portion of the work done by the applied force, which is absorbed by inelastic processes such as bond breaking and plastic deformation, that is

$$Pd\Delta = dU + \Gamma dA \quad (1.4)$$

This definition of fracture energy is independent of the specific microscopic processes, whether bond breaking or plasticity.

The strain energy release rate, G , represents the decrease in elastic energy as the crack grows per unit area (it is also referred to as the crack driving force) (Zehnder, 2007). A fracture criterion based on the energy approach is then given by $G \geq \Gamma$, where G is the available energy release rate. For small-scale yielding, plane strain condition, the energy release rate G is related to K_I for small-scale yielding, plane strain condition:

$$G = \frac{K_I^2}{E} \times \begin{cases} 1 & \text{(plane stress)} \\ (1 - \nu^2) & \text{(plane strain)} \end{cases} \quad (1.5)$$

where E is Young's modulus

Since the stress state ahead of a crack tip is three-dimensional, the shape of the plastic zone is not necessarily circular and must be determined using an appropriate yield criterion. The Tresca or von Mises criteria are typically applied. The equations highlight significant differences in the size and shape of the mode I plastic zones under plane-stress and plane-strain conditions (Figure 2.8).

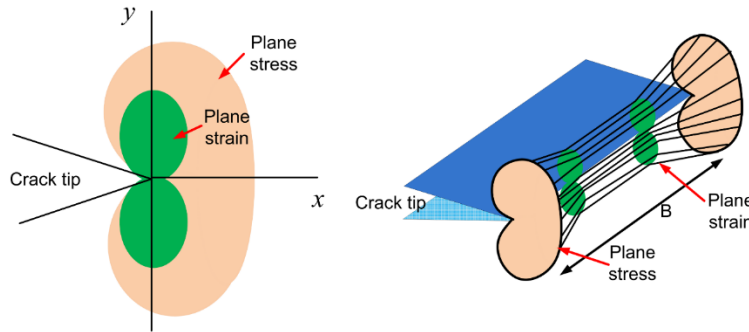


Figure 2.8: Plane stress and plane strain zone along the thickness (Wang, 1996)

2.5.3 J-integral

The J-integral, introduced by Rice in 1968, is a contour integral used as a fracture parameter in nonlinear elastic materials. Its mathematical formulation is expressed as follows:

$$J = \int \left(W dy - T_i \frac{\partial u_i}{\partial x} ds \right) \quad (1.6)$$

where $W = \int_0^{\epsilon_{ij}} \sigma_{ij} \epsilon_{ij}$ is strain energy density, $T_i = \sigma_{ij} n_j$ is traction vector, u_i denotes the component of displacement vector, and ds is an infinitesimal length element along the contour Γ . Here, n is unit normal vector to the contour Γ , and σ_{ij} and ϵ_{ij} are stress and strain tensors, respectively (see Figure 2.9) (Rice, 1968).

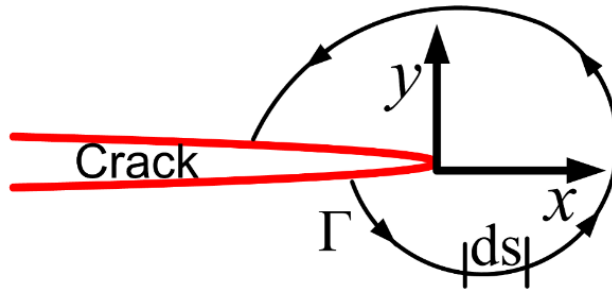


Figure 2.9: Arbitrary J integral contour path around the crack surface

2.5.4 Gurson-Tvergaard-Needleman Model

Gurson (Gurson, 1977) presented a computational cell with spherical voids embedded in a perfect plastic material matrix. This approach laid the groundwork for understanding the behavior of porous ductile materials by introducing a microscopic yield criterion. Tvergaard and Needleman (Tvergaard et al., 1984) improved the model by including void interaction parameters q_1, q_2 , and q_3 through bifurcation and localization investigations, which allow for micro-void interaction. They also changed the Gurson yield potential (Φ) to include the void volume fraction (f^*). This comprehensive model, known as the GTN model (Equation (4.12)), incorporates void interlinking and addresses micro-void coalescence.

$$\Phi = \left(\frac{\sigma_e}{\sigma_M}\right)^2 + 2f^*q_1 \cosh\left(q_2 \frac{3\sigma_h}{2\sigma_M}\right) - (1 + q_3f^{*2}) = 0 \quad (4.12)$$

where σ_h = hydrostatic stress, σ_M = tensile flow strength, σ_e = effective von-Mises stress, and f^* = effective void volume fraction. Equation (4.13) shows effective void volume fraction.

$$f^*(f) = \begin{cases} f & \text{for } f \leq f_c \\ f_c + \frac{(f_u^* - f)}{(f_f - f_c)}(f - f_c) & \text{for } f > f_c \end{cases} \quad (4.13)$$

where f_c = critical void volume fraction, f_f = final void volume fraction and f_u^* = effective ultimate void volume fraction.

The material is regarded as having an initial void volume fraction (f_o). The void volume fraction changes as the material deforms, as new micro-voids form and existing micro-voids increase. Thus, the net rate of change can be calculated as the sum of the void nucleation rate and the growth rate of existing microvoids.

$$\dot{f} = \dot{f}_{growth} + \dot{f}_{nucleation} \quad (4.14)$$

The presence of voids results in compressible macroscopic behavior, despite the matrix being regarded as plastically incompressible. Decohesion and the cracking of inclusions and second phase particles are the main contributors to void nucleation in ductile solids. The phenomenon of void nucleation exhibits non-homogeneity as a result of the uneven distribution of inclusions or second phase particles, along with the complexities inherent in the microstructure. Chu and Needleman proposed nucleation criteria based on plastic-strain control (Chu et al., 1980).

$$\dot{f}_{nucleation} = A\dot{\epsilon}_M^p \quad (4.15)$$

Where $\dot{\epsilon}_M^p$ equivalent plastic strain rate, A presents the relationship between the void nucleation rate and the equivalent plastic strain of the matrix. Equation (4.16) shows the evolution law for void volume change in plastic strain-controlled nucleation.

$$\dot{f} = (1 - f)\dot{\epsilon}_{kk}^p + \frac{f_N}{s_N\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{\epsilon_M^p - \epsilon_N}{s_N}\right)^2\right\} \dot{\epsilon}_M^p \quad (4.16)$$

where $\dot{\epsilon}_{kk}^p$ = volume dilation rate, ϵ_M^p = equivalent plastic strain, ϵ_N = mean strain for void nucleation with a standard deviation of s_N , and f_N is the void volume fraction of nucleating voids.

Thus, the GTN model has nine parameters:

- q_1, q_2, q_3 : Constitutive parameters
- f_o : Initial void volume fraction
- f_N, ϵ_N, s_N : Void nucleation parameters
- f_c : Critical void volume fraction
- f_f : Final void volume fraction parameter

The GTN model is implemented in Abaqus/Explicit finite element analysis software as porous metal plasticity. In the Abaqus implementation relative density is $(1 - f_o)$ is taken as input.

The GTN model is a damage model which when coupled with J2 plastic flow theory, becomes a robust method to analyze fracture scenarios incorporating void nucleation, growth and fracture. Figure 2.10 (a) shows the evolution of void around inclusions during crack growth, and (b) shows computational cell model for finite element analysis.

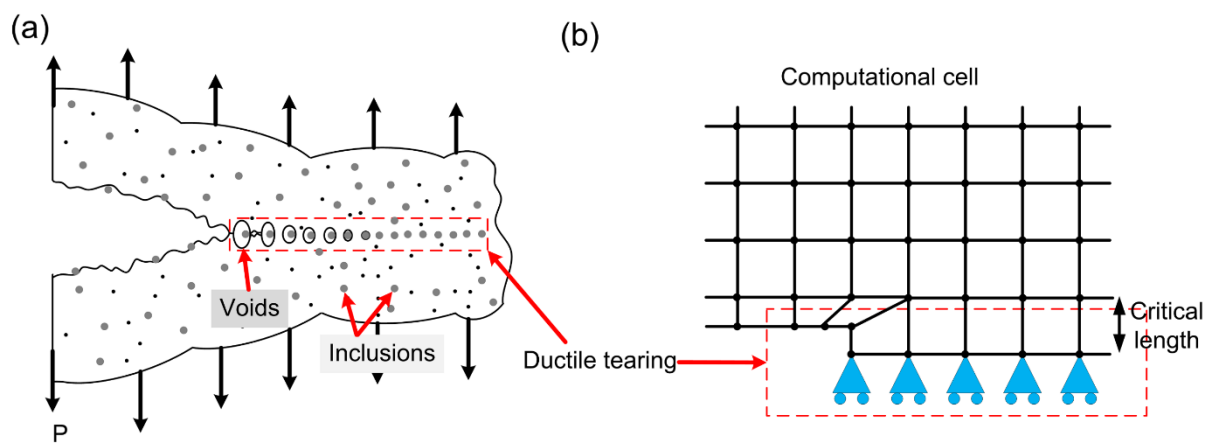


Figure 2.10: (a) Schematic of ductile crack growth (Ruggieri, 2012) (b) computational cell model