

The Consequences of cracks formed on the Oil and Gas Pipelines Weld Joints

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Abstract: Weld cracking is one of the main failure modes in oil and gas (O & G) pipelines. Cracks are the most severe of all weld defects and are unacceptable in most circumstances. A simple existing defect on the pipeline after welding can generate a catastrophic fracture. The major cause of a crack is when internal stresses exceed the strength of the weld metal, the base metal, or both. If undetected, the cracking defects can act as stress concentration sites which lead to premature failure via fatigue, as well as offer favourable sites for hydrogen assisted cracking and stress corrosion cracking. For welded metal products such as deep sea oil and gas transportation pipes, such defects heighten the risk of catastrophic in-service failures. Such failures can lead to devastating environmental, economic, and social damage. Knowing the basics behind why cracks happen, a welder can prevent those cracks from occurring in the first place. Using different literatures, this paper reviews on the consequences of cracks on the oil and gas pipelines weld joints focusing on favourable welding processes for pipeline manufacturing, causes and effects of various types of weld cracks. It further highlights the importance of inspection, maintenance and repair of weld joints cracks. Hence, the knowledge of weld joint cracks mechanisms for any person that deals with pipelines is very important.

Keywords: cracks, Oil and Gas, Pipelines, Welding, inspection, maintenance and repair.

I. INTRODUCTION

Today, most of the steel structures in engineering are fabricated by welding [1]. Welding is an integral part of the steel pipeline industry [2] and is considered as the primary joining method used in oil and gas pipelines [1, 3]. It has long been the most common and economical way of joining metals. The history of joining metals goes back several millennia; however, it wasn't until the 1920's that notable advances towards modern arc welding technology began [2]. However, the welded structures are often subjected to dynamic service loads [1].

Cracks that formed in and around the weld can be distinguished into two main categories, hot cracks and cold cracks. Cracks can also be formed in and near the weld during use and can be caused due to fatigue or corrosion. Cracks that are formed during

the cooling process at elevated temperatures and are usually solidification related are referred to as hot cracks. Cracks whose formation is delayed i.e those that occur after the weld metal has been cooled to room temperature are called cold cracks [4, 5].

Most forms of cracking result from the shrinkage strains that occur as the weld metal cools. If the contraction is restricted, the strains will induce residual stresses that cause cracking. There are two opposing forces: The stresses induced by the shrinkage of the metal and the surrounding rigidity of the base material. The shrinkage stresses increases as the volume of shrinking metal increases. Large weld size and deep penetrating welding procedures increase the shrinkage strains. The stresses induced by these strains will increase when higher strength filler metals and base materials are involved. With a higher yield strength, higher residual stresses will be present [5].

Residual stresses can be defined as those stresses that remain within a material after been manufactured, processed, heat treated or welded in the absence of external forces or thermal gradients. The magnitude of residual stresses must be known when the integrity of a structure is assessed. Mostly, surface tensile residual stresses are undesirable. Welding, is an examples of operations that generate surface tensile stresses. In almost every step of material processing residual stresses can be arise due to mechanical effects (generated by plastic deformation as a result of processes during production), thermal effects (generated as a result of heating or cooling processes), and chemical effects (generated by reaction such as precipitation or chemical surface treatment) [6, 7, 8].

Residual stresses are categorized based on the length scale over which they equilibrate. Type I which refers to macro residual stresses that develop in the body of a component on a scale larger than the grain size of the material. Type II are micro residual stresses found at the grain-size level, which vary on the scale of an individual grain. Such stresses may be expected to exist in single phase materials because of anisotropy behavior of each grain. They may also develop in multi-phase materials because of the different properties of the different phases. Type III is generated at the atomic level. They are micro residual stresses that exist within a grain, essentially as a result of the presence of dislocations

and other crystalline defects. Types II and III are often grouped together as micro stresses [6].

Every crack, regardless of its type or origin, weakens the structural integrity of the pipeline. There are many types of cracks, including Stress Corrosion Cracking (SCC), fatigue cracking, Hydrogen-induced Cracking (HIC) and Sulfide Stress Cracking (SSC). They occur in the base material of the pipe, in welds and in heat-affected zones (HAZ), and can develop from dents or other defects. Since each type exhibits distinct attributes and growth characteristics, accurate and timely crack detection is a major challenge [9].

This paper gives a review on the consequences of cracks formed on the O & G pipelines weld joints. It indicates the favourable welding processes for pipeline manufacturing. It presents the causes and effects of various types of weld cracks. It further highlights the importance of inspection, maintenance and repair of weld joints cracks.

II. PIPELINES MANUFACTURING

Pipelines play a very important role as a method of long-distance transportation of gases and liquids from their sources to the consuming centres [10, 11, 12, 13]. Pipelines are safest for transportation of oil and gas [10]. They are the main ‘arteries’ of the oil and gas business. Also they are critically important to most countries’ economies. They have a long history: pipelines have been used to transport liquids and gases for many years [14].

A. Historical Background

In the early 1860s, the oil was transported in wooden barrels on rivers by horse-drawn barges which was very dangerous because of weather, labour disputes, and often disrupted flow. The railway relieved this, but the oil was now controlled by the rail bosses and their worker i.e. the “teamsters”. Pipelines were an obvious solution to this transport problem, and the early oil workers were familiar with pipes: cast iron and wrought iron pipes of various diameters were in use around the producing wells from the start of the industry. The pipes were used as drive pipe, conductor, casing, tubing, and for conveyance of oil in and around the lease. Iron pipe had been in use since 1843, and short pipelines were in use in the USA to transport manufactured gas (gas obtained from coal). These pipelines often used cast iron pipe with bell-and-spigot joints sealed with rope or jute packing and molten lead. In 1861 to 1863 short cast iron oil lines were laid with associated pumps in the USA [14] which was soon after the drilling of the first commercial oil well in 1859 by “Colonel” Edwin Drake in Titusville, Pennsylvania [15, 16, 17]. For example, a short (1,000 feet) 2 inch diameter cast iron oil line successfully carried oil from a producing well to a field refinery in Pennsylvania. Unfortunately, the joints were soldered using lead,

which caused many to leak [14], but threaded joints, screwed together using tongs, were later to solve this problem [14, 16]. The pipelines were successful: a 2½ mile long (4km), 2 inch diameter pipeline was laid in 1863, and it moved 800 barrels (33,600 gallons) of oil per day. The threaded pieces of pipe were joined end-to-end by screwed collars. Many pipelines were laid in the latter half of the 1860's, [14, 18] displacing some 6000 teamsters who had relied on the wooden barrel. Most of these early pipelines were five or six inches in diameter (although pipe of 30” diameter was made in 1897), and laid ‘by hand’. Eight inches became the standard pipe size and remained so until the early 1930s, as it was the largest diameter that could function at the normal operating pressures of the times. [14].

The next big change in pipeline engineering was the building of long distance, large diameter pipelines: these were pioneered in the USA in the 1940s due to the energy demands of the Second World War. ‘Long’ pipelines had been built at the turn of the century; for example: In 1906 a 472mile (755km), 8in diameter pipeline was built from Oklahoma to Texas; similar length, small diameter (8 in to 12 in) lines were built in Baku at the same time; in 1912, a 170 mile (272km), 16” diameter manufactured gas pipeline was built in 86 days, in Bow Island, Canada to make it one of the longest pipelines in North America [14].

In 1941 oil industry executives began to plan the building of two pipelines: twenty-four inches in diameter, called the ‘Big Inch’, to transport crude oil; and another, twenty inches in diameter, called the ‘Little Big Inch’, to transport refined products. Big Inch was to travel 1400 miles (2240km): the longest pipeline ever built up to that date [14].

The Second World War also forced innovation in pipeline technology [14, 15]: in 1944, ‘Pluto’, the ‘Pipeline under the Ocean’ was commenced. This project was to construct undersea oil pipelines under the English Channel between England and France, to provide vital fuel from Britain to Allied forces in France. These small diameter (~75mm), cable pipelines eventually totaled 500 miles (800km), and delivered 1,000,000 gallons of fuel per day across the channel: an amazing feat. As the world emerged from the Second World War it was able to build high pressure, long distance, O & G pipelines. Indeed, during the 1950s and 1960s, thousands of miles of natural gas pipeline were constructed throughout the United States as the demand for this energy form increased [14, 15].

The 20th century saw many improvements in pipeline engineering like: from wrought iron to steel pipe; from brittle, low toughness iron to ductile, high toughness steel; from lap welds to submerged arc welds or seamless pipe; from low strength materials to high strength materials; from small diameter pipe to large diameter pipe; from low pressure operation to high pressure operation; from threaded joints to

welded joints; from horses and mules to tractors and trucks; from picks and shovels to ditching machines; from bare pipe to coated, cathodically-protected, pipe; from horse patrols to aerial surveillance; from simple above ground inspections, to sophisticated internal inspections using smart ‘pigs’; from oil pipelines, to oil, gas and product pipelines; from solely onshore construction to offshore and deep-water construction; from no standards and regulation, to benchmark standards and safety regulations; etc [14].

The oil and gas business today is big, and it is going to become bigger. Consider these facts: global oil demand will rise by about 1.6% per year, from 75 millions of barrels of oil per day (mb/d) in 2000 to 120 mb/d in 2030; demand for natural gas will rise more strongly than for any other fossil fuel: primary gas consumption will double between 2000 and 2030 [14].

For instance the length of gas pipelines in the United States (US) in 2013 reached 1,984,321 Km and length of pipelines transporting oil and petrochemicals– 240,711 Km. In Russia there is a developed network of pipeline transportation of natural gas, oil and petrochemicals: total length of main pipelines exceeds 200,000 Km and length of field pipelines reaches 400,000 Km. Total length of pipelines of various purposes in 120 world countries is, approximately, 3,500,000 Km [10, 11]. The diameter of Pipelines can be anywhere from 6 to 48 inches (15-120 cm) in diameter [19]. The pipeline system is one of the biggest engineering structures of 20th century [11].

The O & G pipelines are manufactured by using fusion welding processes and seamless pipe forming process. The commonly used welding processes are shielded metal arc welding (SMAW), submerged arc welding (SAW), gas metal arc welding (GMAW), and seamless pipe manufacturing [20].

B. Welding Processes

Shielded metal arc welding that was invented in 1880s used bare electrodes, however the subsequent developments led to the use of coated electrodes. This process is also known as stick electrode welding or coated electrode welding or manual metal arc welding (Fig. 1). The process uses coated electrodes of 2.5 to 6.35 mm diameter and 300 to 450 mm length held in an electrode holder. The coating on the electrodes burns along with metal of electrode and produces a denser smoke which covers and shields the weld pool and the tip of electrode from the ill effects of the atmospheric gases [20, 21]. Besides the chemical composition, the “coating ratio” (ratio between the external diameter of the coating and the rod) is one of the determining aspects of the electrode behavior [20, 22]. The process is very versatile and is used for welding in

all positions and all metals for which electrodes have been developed. Typical application of the process includes its extensive use by the industry for fabrication of ships, bridges, pressure vessels, welded pipes and structural works. However, as the process can be used in its manual mode only, it is slowly getting replaced by other welding processes for heavy fabrications where large quantity of metal deposit is needed [20, 21].

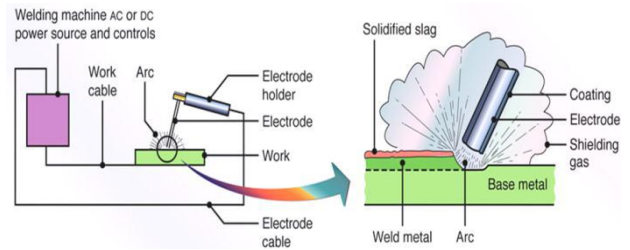


Fig. 1 Shielded Metal Arc Welding [23]

Submerged arc welding was first introduced in the early 1930s and developed to provide high-quality deposited weld metal at a high deposition rate. Today, SAW process is extensively used in weld joints in thick plates in nuclear reactors, pressure vessels, bridges, welded pipes, power generation, shipbuilding, offshore, and construction industries [20, 21, 24].

The demand for higher deposition rates and the failure to mechanize SMAW resulted in the development of SAW process. The process employs granular flux and a copper-coated wire in spooled form, thus making it possible to deposit long weld runs without interruption, using electrode wire diameter ranging between 2 to 10 mm. The granular flux is poured to cover the joint ahead of the electrode thus the electrode wire moves forward through the flux and the arc remains merged underneath it consequently eliminating the use of protective shielding glass for the eyes. The flux that melts due to the arc heat provides a blanket of slag on the deposited bead but peels off easily on cooling. The un-melted flux is collected by vacuum suction and is re-circulated. The process is mainly used in the down hand welding position [20, 21].

SAW is preferred over other methods of welding of pipes including fuel tanks because of its inherent qualities like easy control of process variables, high quality, deep penetration, smooth finish, capability to weld thicker sections and prevention of atmospheric contamination of weld pool. With the growing emphasis on the use of automated welding systems, SAW (Fig. 2) is employed in semiautomatic or automatic mode in industry where the automatic mode is more popular [20, 25].

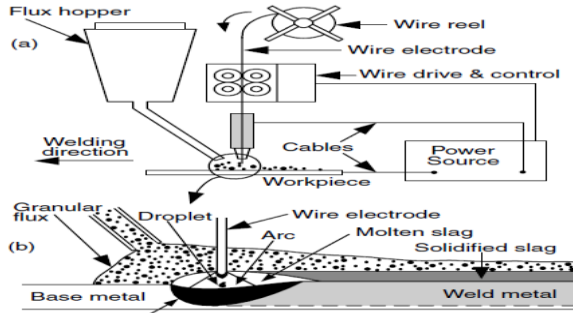


Fig. 2 Schematic illustration of the submerged arc welding process [2]

Gas metal arc welding was invented in 1940s and at present is the fastest growing welding process in the world. This process consumes wire of 0.8 to 2.4 mm diameter, and wound on a spool, and is fed at a preset speed through a welding torch provided with electrical connection and the shielding gas. Depending on the work material, different types of shielding gas may be used such as; argon, helium, carbon dioxide, hydrogen or their mixtures. When inert shielding gas is used, the process used is popularly known as MIG (Metal Inert Gas) welding and when CO₂ is used it is called MAG (Metal Active Gas) welding. GMAW is an all-position semi-automatic welding process though its automatic versions are also available [20, 21, 26, 27].

GMAW is an arc welding process that uses a plasma arc between a continuous, consumable filler-metal electrode and the weld pool. The high temperature plasma arc melts the electrode and forms a droplet at the electrode tip. The droplet is detached and transferred in the arc to the workpiece. A weld pool forms under the influences of the arc plasma and the periodical impingement of droplets. The formation of droplet, the transfer of droplet in the arc, and the dynamics of weld pool are governed by the balance of forces and the heat transfer inside the droplet or within the weld pool and the heat transferred from the arc plasma [20, 27, 28]. Due to its high productivity, the GMAW process (Fig. 3) has been the predominant welding method [20, 28]. The process can easily be applied to automatic welding in combination with robots and automatic welding equipment [24]. It is a very versatile process and can be used for welding all metals for which compatible filler wires have been developed. However, its typical applications include medium-gauge fabrication such as structural works, earth moving equipment, plate and box girders, fuel tanks, welded pipes, and automobile bodies [20, 21].

C. Seamless Pipes Manufacturing

Various hot rolling methods remain to be the most widely used methods of making seamless steel tubes. The development of technology of seamless tube production has a history of more than hundred years

long [29]. Seamless Pipes forming process (Fig. 4) uses hot rolled round bar billet of carbon steel or steel alloy.

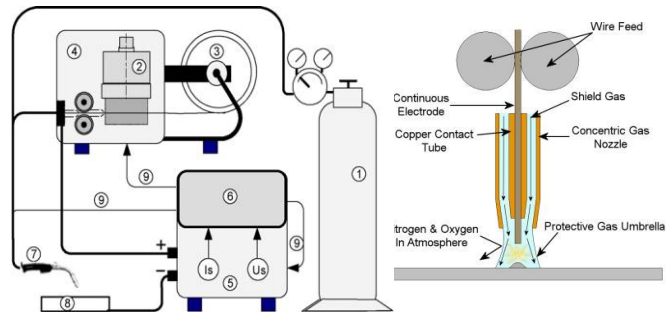


Fig. 3 Basic GMAW equipment. (1) Shielding gas; (2) DC motor and gear box; (3) welding electrode roll; (4) Wire feed unit; (5) Power source-GMAW; (6) control box; (7) welding gun; (8) workpiece; (9) control cable [30,31,32]

The billets are cut into suitable length depending on the required length of the finished tube. The billets are heated in a furnace at a temperature of 1200 °C to 1300 °C. Then the seamless tube is formed by drawing a solid billet over a piercer to create the hollow shell (mother blanks). These hollows are crimped at one end in hot condition and then they are air cooled.

The tubes are then surface treated (pickled, phosphate coated and lubricated) to facilitate the next process of tube drawing. Depending on the finished sizes required, the tubes are subjected to single, double or triple drawing. After every draw the tubes are annealed at a temperature of 750 °C. The tubes are then straightened and cleaned if necessary and before being cut to the exact size required. The finished tubes are tested for quality and they are marked and coated with rust preventive oil before being bundled and dispatched [33].

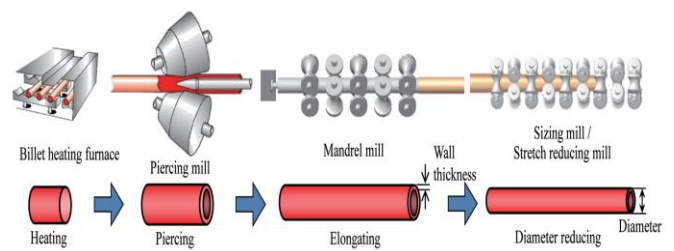


Fig. 4 Schematic illustration of seamless pipe production [34]

Then the seamless pipes can be joined together by using welding process where the circumferential weld joints are achieved. The convenience in an approach of this kind lies in the ability to use more productive welding processes (with the possibility of rotating the pipes), which would not be possible to use directly on board, under typical pipeline laying conditions. The fabrication system can use highly reliable mechanized GMAW circumferential systems extensively for the welding [35].

III. WELDING CRACKS ON OIL AND GAS PIPELINES

Every crack, regardless of its type or origin, weakens the structural integrity of the pipeline. There are many types of cracks, including Stress Corrosion Cracking (SCC), fatigue cracking, Hydrogen-induced Cracking (HIC) and Sulfide Stress Cracking (SSC). They occur in the base material of the pipe, in welds and in heat-affected zones (HAZ), and can develop from dents or other defects [14]. According to the American Society of Mechanical Engineers (ASME), causes of welding defects can be broken down as follows: 41% poor process conditions, 32% operator error, 12% wrong technique, 10% incorrect consumables, and 5% bad weld grooves [36].

A. Stress corrosion cracking (SCC)

Pipeline stress corrosion cracking (SCC) has been one of the vital threats to safety of pipeline operation. [37]. Metals and alloys subjected to tensile stresses and exposed to certain environmental conditions may develop cracks that would not occur in the absence of either of these controlling factors [38]. SCC is a particularly dangerous and potentially catastrophic mechanism that initiates slowly and can progress undetected at stresses well within engineering design limits and typical operating conditions [39].

Stress corrosion cracking (SCC) refers to crack propagation due to an anodic reaction at the crack tip. The crack propagates because the material at the crack tip is consumed by the corrosion reaction. In many cases, SCC occurs when there is little visible evidence of general corrosion on the metal surface, and is commonly associated with metals that exhibit substantial passivity [40]. In order for the crack to propagate by this mechanism, the corrosion rate at the crack tip must be much greater than the corrosion rate at the walls of the crack. If the crack faces and crack tip corrode at similar rates, the crack becomes blunt. Under conditions that are favourable to SCC, a passive film (usually an oxide) forms on the crack walls. This protective layer suppresses the corrosion reaction on the crack faces. High stresses at the crack tip cause the protective film to rupture locally, which exposes the metal surface to the electrolyte, resulting in crack propagation due to anodic dissolution [40].

Therefore, SCC in pipelines is a type of Environmentally Assisted Cracking (EAC). EAC is a generic term that describes the formation of cracks caused by various factors combined with the environment surrounding the pipeline. Together these determinants reduce the pressure carrying capacity of the pipe [12, 41].

Table 1 Different approaches of FCC Control [38]

Approaches of FCC Control		
Mechanical	Metallurgical	Environmental
Avoid stress concentration	Change alloy composition	Modify environment
Relieve fabrication stresses		Apply anodic or cathodic protection
Introduce surface compression stresses	Change alloy structure	Add inhibitor
Reduce operating stresses		Use organic coatings
Non-destructive testing implications for design	Use metallic or conversion coating	Modify temperature

B. Hydrogen Induced Cracking

Hydrogen-induced cracking (HIC) is a materials and corrosion-related problem that occurs in surface production systems. Steels used to construct sour-gas production facilities and flowlines may corrode from wet hydrogen sulfide (H₂S) gas in the production stream. The corrosion process generates hydrogen that may damage the steel, resulting in HIC and other forms of damage from hydrogen [42]. Weld metal hydrogen cracking is one of the defects in pipeline's welds which have caused hazardous incidents for many years [43]. HIC control and prevention are an important consideration in operating surface-facility equipment in a safe and efficient manner [42]. Some welding consumables have become available that meet the requirements for mechanical properties, such as strength and notch toughness, even for low temperature service. However, particular attention should be paid to preventing HIC, because in general, susceptibility to cracking tends to increase as the plate thickness and/or tensile strength increases [44]. Techniques to control or reduce the hydrogen entry are (1) water washing to reduce concentrations of H₂S, (2) treating with inhibitors to reduce corrosion and available hydrogen, and (3) lining the steel areas that are subject to corrosion with corrosion-resistant claddings like austenitic stainless steels [42].

C. Sulfide Stress Cracking (SSC)

Natural gas and oil inherently contain a certain amount of hydrogen sulphide (H₂S). In combination with increased temperatures and pressure in environments containing chloride, sulfide stress cracking (SSC) can occur. Typically these conditions occur in oil and gas extraction, predominantly off-shore [45].

The phenomenon of sulfide stress cracking (SSC) can result in catastrophic failures of pressurized equipment and piping, resulting in extensive damage, injuries and possible fatalities. Sulfide stress cracking was first identified as a serious problem in the oil industry in the late

1950's with the development of deeper sour reservoirs. The high strength materials required for these wells began to fail as a result of brittle fracture that was later identified as SSC [46].

Aqueous hydrogen sulfide (H₂S) in oil and gas production operations can result in many challenges. H₂S is a poisonous gas that can result in severe metal loss corrosion as well as catastrophic brittle fractures of pressurized equipment and piping. These brittle fractures to metallic structures can happen quickly, with little to no warning, or may take years of exposure to occur. Several variables can influence a material's likelihood or its resistance to cracking from exposure to hydrogen sulfide. The physical properties of the material, the chemical properties of the material, and the environment to which it is exposed all play an important role in determining whether a material is susceptible to SSC. Sulfide stress cracking, or SSC, is defined by NACE as the "Cracking of a metal under the combined action of tensile stress and corrosion in the presence of water and H₂S (a form of hydrogen stress cracking) [46].

SSC is very dependent on the composition, microstructure, strength, and the applied and residual stress levels of the steel. With the types of steel used in the refining industry, cracking is observed in the welds or heat-affected zones in the base material adjacent to welds. This is where high-strength/low-ductility microstructures may be present and can be identified by high hardness. Limiting hardness, therefore, is one practical method of reducing the susceptibility of a particular steel to SSC [47, 48]. Proper welding electrode selection and welding procedures will also minimise the hardness of welds and heat-affected zones. Nevertheless, it has been found that post weld heat treatment (PWHT) is necessary to minimise the susceptibility to SSC. PWHT serves two purposes: it tempers the microstructure and reduces the residual stresses [47].

D. Fatigue cracking

Fatigue cracking is a phenomenon that occurs in metals due to repeated load, which can lead to failure at loads considerably below the material's static strength [1, 48]. Welded structures such as offshore structures, pressure vessels and pipelines, are affected by fatigue loading [49]. It is estimated that approximately 80 - 90% of failures of machineries is caused by fatigue cracking originating in negligence and poor maintenance [48].

Microscopic investigations in the beginning of the 20th century have shown that fatigue crack nuclei start as invisible microcracks in slip bands. After more microscopic information on the growth of small cracks became available, it turned out that nucleation of microcracks generally occurs very early in the fatigue life. Indications were obtained that it may take place almost immediately if a cyclic stress above the fatigue limit is applied. After a microcrack has been nucleated, crack growth can

still be a slow and erratic process, due to effects of the microstructures, e.g. grain boundaries. However, after some microcrack growth has occurred away from the nucleation site, a more regular growth is observed. This is the beginning of the real crack growth period. Various steps in the fatigue life are indicated in Fig 4. The important point is that the fatigue life until failure consists of two periods: the crack initiation period and the crack growth period. Differentiating between the two periods is of great importance because several surface conditions do affect the initiation period, but have a negligible influence on the crack growth period [50].

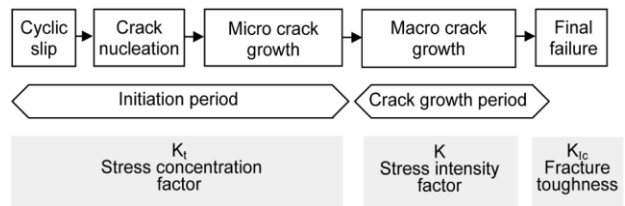


Fig. 5 Different phases of the fatigue life and relevant factors [50]

In most technical materials, a variety of inclusions can be present, such as impurities introduced during the melting production process of the alloys. Larger macroscopic inclusions are generally regarded as material defects which should not be present, for example slag streaks, weld defects, major porosities. Large defects have occasionally caused disastrous failures in service [50].

Premature fatigue failure is prevented by careful attention to detail at the design stage to ensure that cyclic stresses are sufficiently low to achieve the required endurance. Stress concentrations should be avoided where possible; a design with smooth 'flowing' lines is usually the optimum [51]. Select materials with high fracture toughness and slow crack growth; works done in controlled environment is usually better than in the field [52]. Proper filler metal selection and storage can also help to prevent costly weld cracking [53],

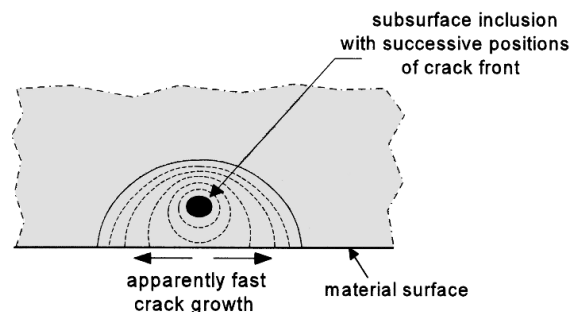


Fig. 6 Subsurface nucleation of fatigue crack at inclusion which suggests initial fast crack growth [50]

The weld cracks can be in different forms as shown in fig. 7.

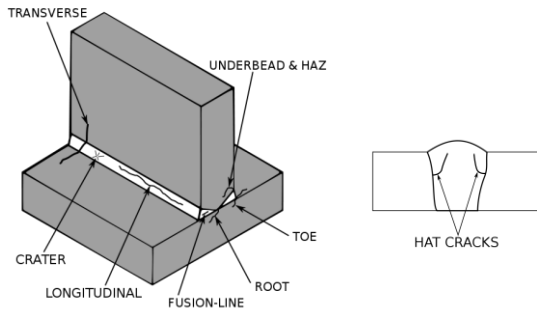


Fig. 7 Different forms of weld cracks [54]

IV. EFFECT OF CRACKS ON THE O & G PIPELINES

Cracks in any form are usually unacceptable discontinuities and are considered most detrimental to the performance of the weld [50]. The most dangerous defect is the occurrence of cracks [55]. Of all things that can go wrong with, weld cracks are the worst. That is why weldability assessment of a material is usually based on its cracking tendency during and after welding. A crack in a high pressure pipeline can literally race at the speed of sound for several kilometers from one pumping station to another. Cracks must therefore be never ignored, even if they are tiny ones [21]. A crack, by its nature, is sharp at its extremities and consequently acts as a stress concentration. The stress concentration effect of a crack is greater than that of most other discontinuities. Cracks have a tendency to propagate and can contribute to weld failure if subjected to stress in service. Cracks, regardless of size, are not normally permitted in weldments governed by most fabrication codes [56]. Data show that ruptures caused by weld cracks are a relatively common occurrence. The consequences of oil and gas pipelines rupture cause leakage of product that can be damage to soils, surface and ground water, air quality, vegetation, wildlife, and fish populations. Oil spills, are the most damaging. Pipeline spills can lead to direct loss of various species as a result of contaminated food intake, reduced respiratory functions, or ingestion of oily water [57]. Therefore, cracks are required to be removed, usually by grinding or gouging, and the excavation filled with sound weld metal [56].

V. OIL AND GAS PIPELINES INSPECTION

There are different methods used in the inspection of oil and gas pipelines as a whole including weld joints cracks, and their choice depends on the nature and location of the pipeline, as well as the motives of the assessment [10, 58]. On existing pipelines, there are three methods to detect the defect: field investigation programs (direct assessment), hydrostatic retesting, and in-line inspection (ILI) [12, 10].

A. Direct Assessment (DA)

As a part of condition monitoring programs, pipeline companies commonly use field investigation (DA) programs [10, 12]. DA is essentially a structured process approach that doesn't impede a pipeline operation [59]. The overall condition of the coatings and pipelines is assessed, and it is determined whether corrosion or crack is present on the system. Models are sometimes developed to predict the likelihood of the presence and severity of corrosion or cracking. This information is then used to prioritize the system for direct examination, hydrostatic testing, in-line inspection, recoating, or pipe replacement. Dig programs and the associated models are not generally considered as a replacement for hydrostatic testing as a means to ensure the integrity of a pipeline [10, 12].

B. Hydrostatic Testing

Hydrostatic testing is one of the quality-control measures used to ensure that installed pipeline systems are fit for service. Qualification of the individual components of the pipeline for the intended service is an integral part of the design process. Hydrotest loads are one of the loads a pipeline system experiences in its service life, and these loads are also considered in the design process [60]. Hydrostatic testing involves pressure testing the pipeline with water at a pressure that is higher than the operating pressure, typically 125% of the maximum operating pressure (MOP) of the pipeline. This is the most common method to ensure the integrity of a pipeline and establish a safe operating pressure, regardless of the types of flaws present in the pipeline. Any flaws that are larger than a critical size at the hydrostatic retest pressure are removed from the pipeline. However, subcritical flaws remain in the pipeline after a hydrostatic retest. If the defects are growing with time, as might be the case with corrosion, and cracking the pipeline is generally periodically retested to ensure integrity [10, 12].

C. In-line inspection (ILI) tools

They are also referred to as smart or intelligent devices known as PIGs, are devices that are propelled by the product in the pipeline and are used to detect and characterize metal loss caused by corrosion and cracking. There are two primary types of metal-loss ILI tools: magnetic flux leakage (MFL) tools and ultrasonic tools (UT) [61, 62].

Magnetic flux leakage tools. Among various pipeline inspection technology MFL inspection is the most widespread and perfect one. It has well Effect in ordinary defect detection, such as loss of metal [63]. MFL is the method which can detect cracks in both the axial and circumferential directions, although it is susceptible to the pipe wall and other factors [64]. They measure the change in magnetic flux lines produced by the defect and

produce a signal that can be correlated to the length and depth of a defect. The MFL tool can be used to inspect either liquid product pipelines or natural gas pipelines [10].

Ultrasonic tools (UT) utilize large arrays of ultrasonic transducers to send and receive sound waves (ultrasonic pulse) that travel through the wall thickness, permitting a detailed mapping of the pipe wall [12, 65]. Ultrasonic tools can indicate whether the wall loss is internal or external. Ultrasonic tools are typically used in product pipelines (those carrying crude oil, gasoline, and the like) since the product in the pipeline is used as the required couplant for the ultrasonic sensors. This tool can be used to inspect natural gas pipelines, but requires introducing a liquid (such as water) into the pipeline for an ultrasonic couplant [12]. Internal cleaning of the pipeline using special cleaning pigs has also been used primarily to ensure the required low levels of hydraulic resistance [10, 66].

VI. MAINTENANCE AND REPAIR OF OIL AND GAS PIPELINES

Oil and gas (O&G) pipelines are expensive assets that cross through both the ecologically sensitive and densely populated urban areas. If not well maintained, pipelines may fail with potentially significant consequences that could have long-term and irreversible impacts on the both natural and human environments [67]. The United States Department of Transportation reported more than 10,000 failures in O&G networks across the country which caused losses around six billion US dollars in the form of property damage, production losses, environmental impacts and human casualties. Therefore, to improve the reliability of infrastructure, planned maintenance is the integral activity [67]. Pipeline maintenance is important to ensure the integrity of the product network. It is extremely important that all pipelines are duly maintained to prevent damage to asset and environment. It is of the utmost importance that pipelines are kept close to their original installation conditions. This is achieved by routine maintenance which should be carried out to ensure safety of the product network, personnel and facility [68].

Welding onto a gas pipeline in active operation is a technique that is frequently employed in the repair, modification or extension of gas pipelines. This ‘in-service welding’ has significant economic advantages for the gas transmission or gas distribution industry since it avoids the costs of disrupting pipeline operation and secures continuity of supply to the customer. If in-service welding were not possible, sections of the pipeline would have to be sealed and degassed before any welding operation, and then purged prior to reinstatement. These are costly, wasteful and also environmentally damaging actions since methane is a ‘greenhouse gas’. In-

service welding is an essential part of hot-tapping, a technique which allows the establishment of a branch connection to a live pipeline. It is also important for pipeline maintenance such as the installation of sleeves around damaged sections. Direct deposition of weld-metal onto an active pipe has also been suggested as a way of replacing wall thickness lost through corrosion or local damage [68].

When a condition that could impair pipeline integrity is discovered, an operator may need to reduce the operating pressure until remediation can be implemented. The purpose of a pressure reduction is to provide a margin of safety beyond that present when the condition was first discovered. Pressure reduction is usually a temporary measure that is implemented until remediation is completed. Typically, the pressure is reduced to no more than 80% of what was first reported at the location [69].

Defects in pipelines may be repaired by a variety of methods. Those that have been commonly used by pipeline operators include: **Removal** of a section of pipe and replacement with new pipe; **Grinding** an anomaly to significantly reduce its effect as stress concentrator or site for crack initiation; **Reinforcing** a defective piece of pipe with an encircling sleeve; **Placing** a sealed pressure containment device (clamp or sleeve) over a defect, including one that is leaking; **Applying** a composite wrap over corrosion and blunt wall-loss defects; **Applying** deposited weld metal in a defect to fill it with new material; **Placing** a patch or sole (partial encirclement reinforcement device) over a defect; **Hot tapping** to remove a defect [69].

In multilayer welds, cracks occur most frequently in the first layer of the weld metal in the root zone of the weld joint. That is why so much attention is paid to making a good, solid first pass in a large joint. If cracks are found in the weldment by using a non-destructive testing method, the weld metal will have to be gouged or ground out and the weld remade. One method of avoiding or minimising cracking in and around welds is to heat the parent metal before welding. This reduces the tendency to form martensite in steels during cooling, and in the case of multipass welding it provides more extensive allotropic refinement of beads by the normalizing effect of heat of the succeeding passes [21].

Pipelines crack arrestors can also be installed at predetermined intervals along the pipeline, so that any propagating crack would be arrested at least within a few pipe lengths under the particular operating conditions, minimising harm to the environment and pipeline operation [70].

VII. CONCLUSIONS

Whether the result of poor parts fit-up, rapid cooling or a variety of possible contaminants from the atmosphere, base material or filler metal weld cracking carries with it significant consequences for any welding operation. Not only does this defect

adversely affect the integrity of the finished weldment, but it also requires significant time and money to rectify. In a best-case scenario, a welding operator must remove the weld crack by carbon arc gouging, grinding or other means and repair the weld, while in other instances the welded part must be completely rejected and scrapped. It has been noted that, stress concentration is the major drive mechanism of crack formation and propagation. If the internal stresses of the weld metal are greater than strength of weld metal, parent metal or both then the weldment is susceptible to crack formation. Every crack, regardless of its type or origin, weakens the structural integrity of the pipeline. A simple existing defect on the pipeline after welding can generate a catastrophic fracture, resulting in extensive damage, injuries and possible fatalities. Cracks in any form are usually unacceptable discontinuities and are considered most detrimental to the performance of the weld. The best defense against cracking, however, is proper pre- and post-weld heat treatments, along with general practices that minimize the exposure to hydrogen sources. Proper filler metal selection and storage can also help to prevent costly weld cracking. Proper selection of materials with high fracture toughness and slow crack growth is advised. Working in a controlled environment is usually better than in the field. However, here is the bottom line: weld cracking costs money, no matter what type it is. Fortunately, as with any part of the welding process, knowledge is the key to understanding the problem and to solving it.

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