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Pandemic in the Rearview Mirror? Stay Safe, Feel Good and Continue Learning

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As we are observing the world rebound from a pandemic that has profoundly impacted almost every facet of life, it is quite obvious that what looks like a unique lifetime experience has left us knowing more about ourselves as individuals, members of communities, industry and the international community. I am saying this knowing that the economic consequences have been astounding; and in many cases unpresented. It is incumbent on us to recognize what such a pandemic has helped us discover in ourselves, which is a great deal of adaptability and resilience.

2020 was undeniably a tough year given the fall in world demand for hydrocarbons due to COVID-19 restrictions, and its subsequent impact on crude oil prices. Also, safety precautions have come with restrictions on social gatherings and travel, which were, and still are, essential aspects of our ability to conduct business. Our resilience was tested as we embraced this challenge and attended to our business needs. In this regard, I want to quote from Saudi Aramco's President & CEO, Mr. Amin H. Nasser's, 2021 New Year's Message that went out to all Saudi Aramco employees:

"In this most testing of years, the Aramco family became closer as one team. We can be proud too that despite the ongoing challenge and uncertainty caused by the COVID-19 pandemic, none of us gave up on the idea of a better future last year."

Saudi Aramco demonstrated social responsibility and its "employee of choice" motto by ensuring workforce safety through allowing many employees to work from home. Also, The pipeline industry's commitment to a safe and reliable supply of energy was tested, and the industry showed a great level of adaptability and resilience. As knowledge sharing is one essential component of the industry's effort toward maintaining a high level of excellence, industry members successfully enriched many events with high quality content. A record attendance was observed at the International Pipeline Conference (IPC 2020), which was held virtually for the first time. Key Technical Committee Workshops and Research Exchange Meetings were sponsored by Pipeline Research Council International (PRCI) in virtual settings as well. The current edition of this journal is coordinated with the virtual Pipeline Technology Conference, which will bring together a significant number of major pipeline stakeholders from across the industry.

I find myself thinking of Mr. Nasser's inspiring message for 2021 as I conclude with a message for our young pipeline professionals of the future. "If 2020 was a test of our endurance, I believe this coming year will be a test of our agility: our capacity to adapt and thrive in response to rapidly changing circumstances."

I presume that one major contributor to adaptability to change and ensuring resilience is knowledge sharing and collaboration. So seeing young pipeline professionals committing to publishing quality pipeline content will be a major indicator of the industry's ability to sustain excellence. In my home organization at Saudi Aramco, Pipelines, Distribution and Terminals (PD&T), we made sure that our recognition program promotes young professionals so they can take great strides toward becoming major contributors in the pipeline industry's publications. This has successfully impacted those professionals and enabled them to accelerate their technical maturity and professional development.

In conclusion, I wish all PTJ readers continued health and safety, and for PTC attendees to fully enjoy this vital event.

Yours,

Nader A. Al-Otaibi, Supervisor (A), RT Terminals Engr. Unit, Saudi Aramco

THIS ISSUE'S COMPLETE CONTENT

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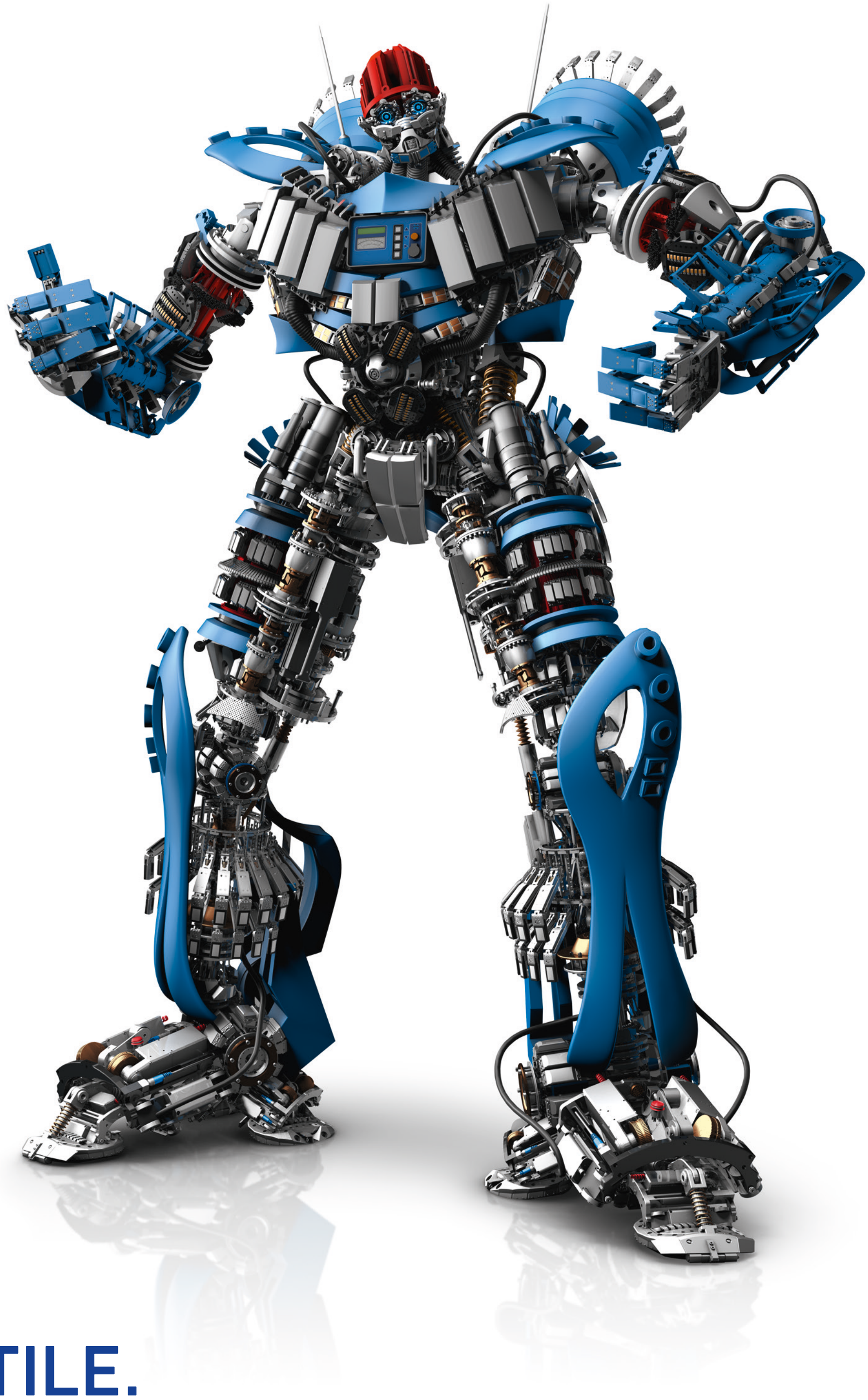

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16th Pipeline Technology Conference

Opportunities to Access the Benefits of High-Frequency Welded (HFW) Pipes for a Wider Scope of Oil and Gas Industry Applications

Dr. Timur Tadjiev; Dr. Pavel Stepanov; Dr. Holger Brauer; David Evans > Wood; JSC Vyksa Steel Works; Mannesmann Line Pipe GmbH; Tata Steel Europe

Abstract

In recent years, many papers have been published describing the advantages and disadvantages of the high-frequency welded (HFW) and seamless (SMLS) carbon and low-alloy steel (LAS) pipe manufacturing processes for the oil and gas industry. However, there are few published papers that compare these different manufacturing processes in a way that would give a clear guidance for design house engineers, operators, and installation contractors. Such guidance could improve the selection process of a cost-effective carbon and LAS pipe product (i.e., a SMLS or an HFW pipe) for specific size range (4.5 to 26´ (114.3 to 660mm) OD)), applications (e.g., subsea, onshore) and service conditions (e.g., design and material limitations). The intent of this paper is not to suggest SMLS pipes are not high-quality products, but to put forward the idea that more cost-competitive alternatives, such as HFW, could suit and meet the requirements of some scopes which fall within HFW's capabilities.

Wood successfully used HFW pipes on previous projects. This paper helps to re-evaluate the design approach, cost-effective choices, and intelligent use of available pipe manufacturing processes in favour of HFW pipes which can offer 10 to 30% cost saving over its SMLS equivalent, and a potential 20 to 30% reduction in manufacturing lead times. This paper also discusses the feasibility of using HFW pipes alongside their SMLS equivalent and reviews various HFW manufacturing processes. It has been shown that from a cost-efficiency and general project cost-savings standpoint, HFW pipe which is used either alongside or instead of the SMLS equivalent is a viable alternative solution with HFW continuing to grow its successful project delivery portfolio. It is proposed that HFW carbon and LAS pipe can be considered as a viable alternative solution to SMLS equivalent for a range of scopes that fall into its capability range.

1. INTRODUCTION

This paper presents a comparison between seamless (SMLS) carbon steel (CS) and low alloy steel (LAS) pipes (typical outside diameter (OD) range of 1 to 28´ (33.4 to 711.2mm) and high-frequency welded (HFW) CS and LAS pipes (typical OD range of 4.5 to 26´ (114.3 to 660mm). Submerged Arc Longitudinal Welded (SAWL) CS and LAS pipes (typical OD range of 16 to 56´ (406.4 to 1422.4mm) for UOE/JCOE processes) are not considered in the scope of this paper as they are generally a different size range (large diameter) solution compared to HFW and SMLS carbon and LAS pipes.

There is some reluctance within the oil and gas industry to use HFW pipes due to concerns about historic failures during hydrotest and in service. This paper has been written to assess the reliability and advantages of modern HFW pipes as compared to the SMLS equivalent and brings together the combined expertise and experience of many industry HFW leaders, considering the latest technology advances and developments as well as HFW pipe in service track record. There are now, however, several manufacturers with proven capability (track record) to produce high-quality and reliable HFW pipe which can offer significant advantages over SMLS equivalents which needs to be more widely recognised.

The intent of this paper is not to suggest SMLS pipes are not high-quality products, but to put forward the idea that more cost-competitive alternatives, such as HFW, could suit and meet the requirements of some of these scopes which fall within HFW's capabilities. We are facing challenging times in the oil and gas market and capital expenditure (CAPEX) savings (typical industry norms are costs up to 10 to 30%, lead times up to 20 to 30%) when using HFW pipes may make future projects economically viable. There has been an ongoing debate as to whether SMLS pipe has advantages in various applications compared to its HFW equivalent. This has resulted in several papers being published describing the advantages and disadvantages of these two pipe manufacturing processes for the oil and gas industry [1-5].

There have also been several publications which examined the technological aspects related to the manufacturing process of HFW and SMLS pipes separately without comparing their advantages for the consumer or the comparative associated manufacturing costs [1-3, 6].

A large-scale comparative study of the properties of the HFW pipe and its SMLS equivalent would be useful to rank and distinguish applications from the standpoint of making efficient use of the various pipe designs in the oil and gas sector.

This paper will only review certain comparative aspects of HFW and SMLS pipes to provide evidence showing HFW and SMLS pipes could be an equally reliable option operationally provided the manufacturing process and the intended pipe application are appropriately selected, qualified, and followed. It will also refer to the opinions of research institutions and end-user engineering organisations regarding the quality of HFW and SMLS pipes.

There is no doubt that both HFW and SMLS pipes have their advantages and disadvantages depending on the specific application; these include manufacturing costs, size constraints (e.g., wall thickness (WT)), design considerations (e.g., extreme low temperature), material constraints (severe sour service), installation costs.

The recent market challenges have resulted in cost-efficiency (price advantages) becoming a priority when selecting and using available pipe manufacturing processes. Consequently, certain engineering requirements have become optimised, including HFW pipes becoming prioritised over their SMLS equivalent, given that the price of HFW pipes can be 10 to 30% lower, and lead times 20 to 30% shorter than those of similar SMLS solutions. These savings, however, depend on pipe size, grade, and technical requirements. There is a spot for SMLS where HFW cannot compete and vice versa due to the available size ranges.

Therefore, it appears expedient from the cost-efficiency standpoint to consider expanding the application scope of HFW pipe with respect to the SMLS equivalent provided the operational reliability of oil and gas export and in-field pipelines can be maintained.

2. HFW AND SMLS PIPE MANUFACTURING PROCESSES

2.1 HFW PIPES

ERW is the overarching family term which includes low-frequency welding (LFW) and high-frequency welding (HFW) processes. HFW, in this paper, refers to the high-frequency induction (HFI) (contact free) and high-frequency conduction (HFC) (with contact shoes) welding processes with current frequencies ≥ 70kHz. Although ERW is the overarching family term, in this paper it is used to refer to LFW, not including HFW process, implying the lack of 'high frequency' (current frequencies ≥ 70kHz) associated with the HFW processes. Figure 1 summarises the hierarchy of the processes in question.

An advantage of the HFI process over that of HFC is the elimination of the potential to produce arc strikes if contact

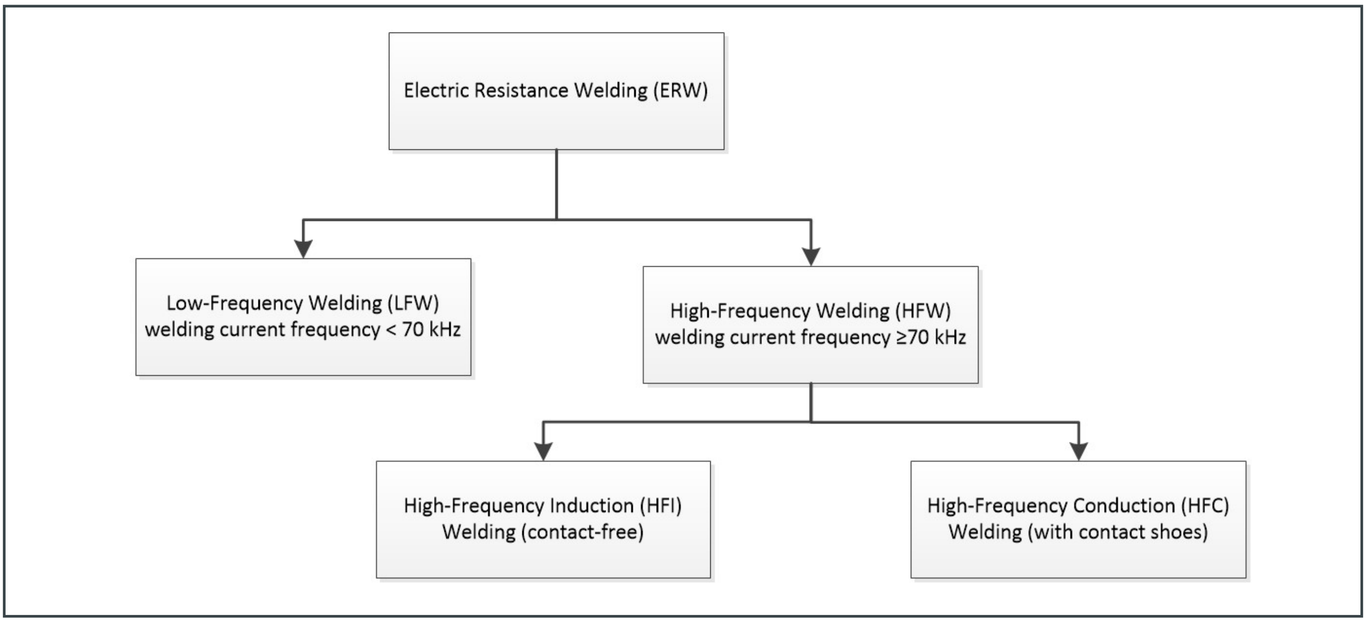

Figure 1: ERW process family

shoes disengage with the pipe surface because of movement, geometry, or setup. As pipe wall thickness increases and higher power is required for the process this becomes more of a concern for HFC. The effect of frequency, however, often overlooks the cumulative role of the process on the quality of the weld and cannot be considered exclusively. There are several factors collectively involved in achieving high-quality HFW production, these relate to the manufacturing equipment in use, the setup of said equipment and the material being welded. It can be said, however, that the use of higher frequency generally produces shallower skin depths and lower frequency produces deeper skin depths. One consequence is that higher frequencies can result in lower power requirements and a reduced sensitivity to process parameter variations. Using higher power for thick pipes may cause deposition of the contact shoe material to the pipe/weld itself if contact is not properly adjusted. This could lead to a reduction in weld quality.

Modern manufacturers tend to use the HFW method, whereas historically many manufacturers used the LFW method. HFW has benefits over LFW in that the heating of the strip edge occurs differently, leading to better control of the resultant weld. With HFW, most of the heating occurs before the strip edges come together, the heat is concentrated on the faces of the strip edge and the maximum temperature achieved is higher than that of the LFW process. This leads to a thin layer of molten material which is squeezed out along with any impurities. HFW allows for a higher net weld pressure than with LFW because the heated layer is so thin and backed up by colder and stiffer material. With the lower frequency LFW, more of the material is heated, whereas the higher frequency of HFW allows the heat to be more concentrated, leading to the higher and more concentrated temperature at the strip edge. An advanced HFW manufacturing facility includes an edging machine, a pipe-forming and welding mill, seam heat treatment equipment, a sizing mill, and a finishing area.

The layout of the process to make HFW pipe at the JSC VSW (part of OMK) plant is shown in Figure 2. HFW pipe-forming is a process whereby coil strip is continuously bent into round skelp and subsequently seam-welded using a single longitudinal seam without the use of filler metal.

For welding, the strip edges are heated using high-frequency current and subsequently compressed together.

In addition, there is seam heat treatment equipment which helps improve the quality of the weld. Seam weld heat treatment improves weld microstructure, making it more uniform with a finer grain, whilst also tempering back any hard faces.

Figure 3 shows the heat treatment of two seam-welded microstructure samples of API SPEC 5L X70 (L485) steel. The samples were subjected to two types of heat treatment: quenching at 990°C, followed by tempering at 780°C as well as normalising at 960°C. The desirable microstructures shown are indicative of material which exhibits low-temperature mechanical properties and improved weld corrosion resistance.

Typically, post-weld heat treatment (PWHT) of the longitudinal weld seam is required in HFW pipes to rectify the microstructure generated during the welding process. Full-body heat treatment of a pipe is only performed where

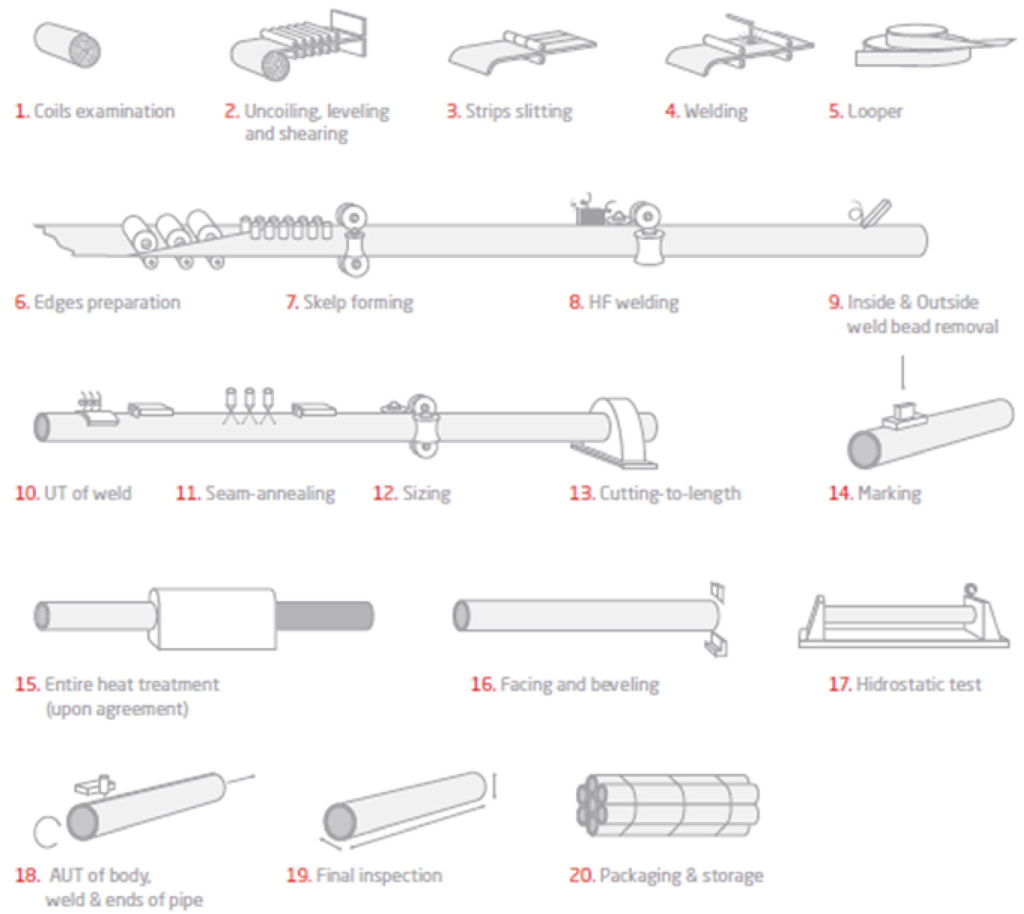

Figure 2: HFW pipe manufacturing process layout (courtesy of JSC VSW (part of OMK))

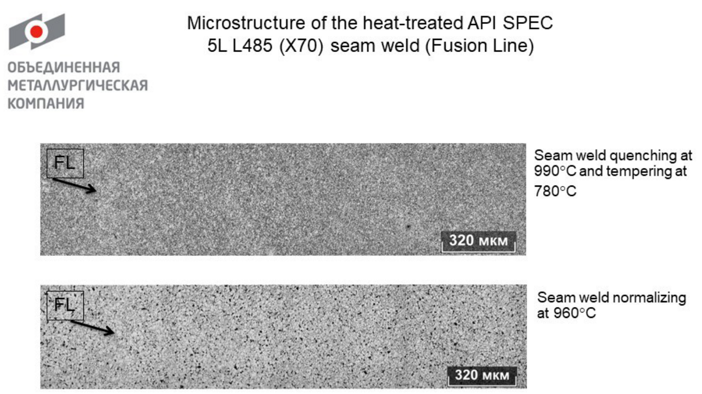

Figure 3: Effect of seam weld heat treatment on API SPEC 5L L485 (X70) HFW pipe (courtesy of JSC VSW (part of OMK))

needed or specified. The application of full-body heat treatment is primarily considered for stress-relieving purposes and not for the improvement of the weld properties. Typically, when performing mandatory full-body heat treatment in specific cases of API SPEC 5CT pipes used for drilling, as well as for some process pipe specifications (e.g., ASTM A333). Mannesmann Line Pipe GmbH and Tata Steel Europe perform full-body heat treatment, e.g., FBN (full-body normalised) or Q&T (quenching and tempering). Full-body pipe heat treatment (FBN or Q&T) provides oil and gas line pipe with enhanced corrosion and low-temperature properties as well as higher strength pipe of grades up to K65 (X80) and higher-grade casing from different types of steel.

Table 1. HFW Pipe international Code Requirements

Requirements	OD, " (mm)	WT, " (mm)	Steel Grade	Application
API SPEC 5L/ ISO 3183/ DNVGL-ST-F101	4.5 to 26 (114.3 to 660)	0.16 to 1 (3.17 to 25.4)	A 25 (L175) to (L555) (X80)	Transportation of liquid hydrocarbons, hydrocarbon gas, water

Table 1: HFW Pipe international Code Requirements

Table 1 lists the principal international code requirements relating to pipes for HFW manufacturers. Please note the wide range of steels used to make line and structural pipe.

At the present time, HFW pipes are manufactured and widely used globally for oil and gas production and transportation, as well as in civil and industrial construction.

A review of the market indicates that HFW pipe has just as many applications globally as its SMLS equivalent. Manufacturing capabilities and applications for HFW pipe will grow, given the vast improvement in quality and broader scope [2, 4].

HFW pipe is manufactured with state-of-the-art engineering practices, assuring high product quality and the capability to make a product that meets the stringent requirements of the global markets.

Suppliers of HFW seam-welded pipes are well recognised in the oil and gas industry, some of which are: Tata Steel Europe, Mannesmann Line Pipe GmbH and JSC VSW (part of OMK), the list given here is not extensive.

Some examples of HFW manufacturers and their capabilities are listed below. The nature of the HFW product and industry means that an individual HFW pipe mill will manufacture a product specific to that mill, and each mill will have its own advantages and disadvantages.

JSC VSW (part of OMK) manufactures small and medium-sized carbon and LAS pipe using HFW for use in oil and gas lines with ODs ranging from 2.4 to 21" (60.3 to 530mm) and wall thickness of up to 0.157 to 0.5" (4 to 12.7mm), with steel grades up to API SPEC 5L X70 (L485). Pipes are formed from coil manufactured in-house at JSC VSW (part of OMK) at the integrated casting and rolling facilities. For offshore subsea pipes, JSC VSW's (part of OMK) capabilities are currently limited to -40°C Charpy V-notch (CVN) testing in the weld fusion line (WFL) +/-2.5mm for CS and LAS. The following requirements are fulfilled for sour service: stress corrosion cracking (SSC) 0.72 Specified Minimum Yield Strength (SMYS) based on National Association of Corrosion Engineers (NACE) TM0177, solution A testing; hydrogen-induced cracking (HIC) Crack Length Ratio (CLR)<6%, Crack Thickness Ratio (CTR)<3% NACE TM0284, sol. A.

Mannesmann Line Pipe GmbH manufactures small and medium-sized carbon and LAS pipe using HFW for use in oil and gas lines with ODs ranging from 4.5 to 24´ (114.3 to 610mm) and wall thicknesses up to 0.26 to 1´ (3.2 to 25.4mm) with steel grades up to API SPEC 5L X80 (L555). For offshore subsea pipes, Mannesmann Line Pipe GmbH's capabilities are currently limited to -20°C CVN testing in the WFL +/-2.5mm for CS and LAS. Mannesmann is also keen to support clients with project-specific requirements, e.g., HIC testing for sour service, assuming the mill can meet their requirements, the appropriate steel can then be ordered.

Tata Steel Europe manufactures small and medium-sized carbon and LAS pipe using HFW for use in oil and gas lines with OD ranging from 8 to 20´ (219.1 to 508mm) and in wall thicknesses up to 0.197 to 0.688´ (5 to 17.5mm), with steel grades up to API SPEC 5L X80 (L555). This is based on a fully integrated steel and coil internal route, enabling targeted investment upstream and downstream to drive performance. For offshore subsea pipes (including strained and aged testing for reel lay installation), Tata Steel Europe's capabilities are currently limited to -20°C CVN testing in the WFL +/-2.5mm for CS and LAS and to -50°C for onshore for CS and LAS. At Tata Steel Europe, sour performance is available but dependent on specific project requirements. Further developments are ongoing.

Figures 4a, 4b and 4c show the HFW product range for line pipe and casing being offered by JSC VSW (part of OMK), Mannesmann Line Pipe GmbH and Tata Steel Europe respectively for oil and gas industry. Typical industry capabilities for HFW CS and LAS pipes are OD ranges of 2.4 to 26" (60.3 to 660mm) and wall thicknesses of 0.126 to 1" (3.2 to 25.4mm).

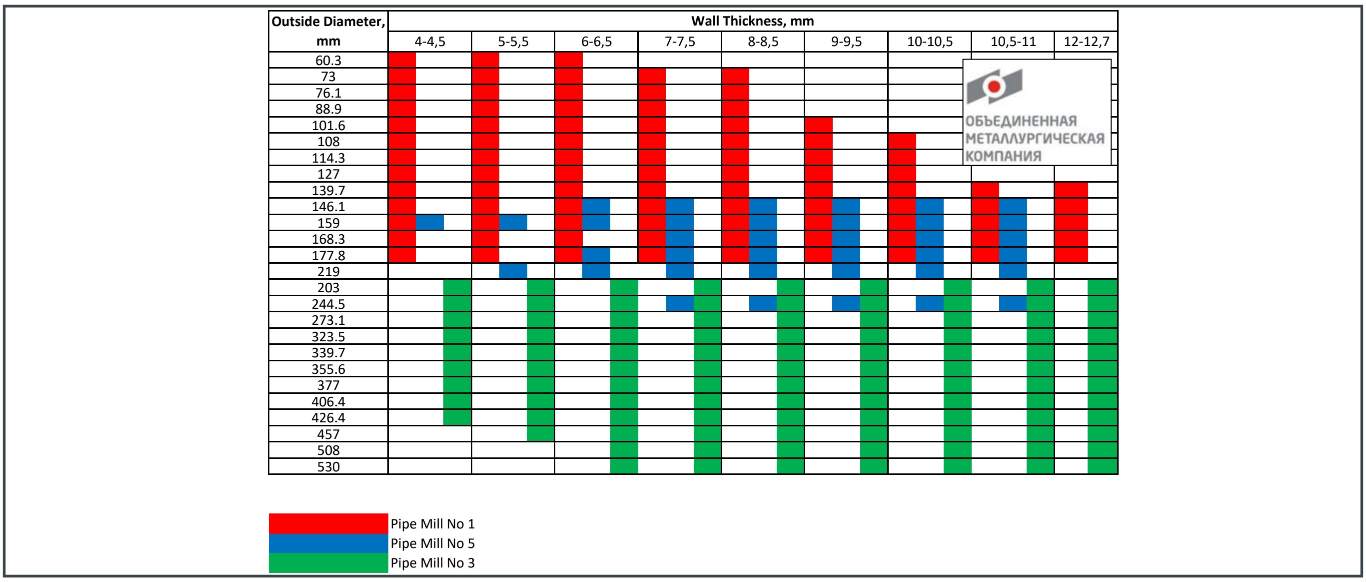

Figure 4a: Current HFW pipe product offering by JSC VSW (courtesy of JSC VSW (part of OMK))

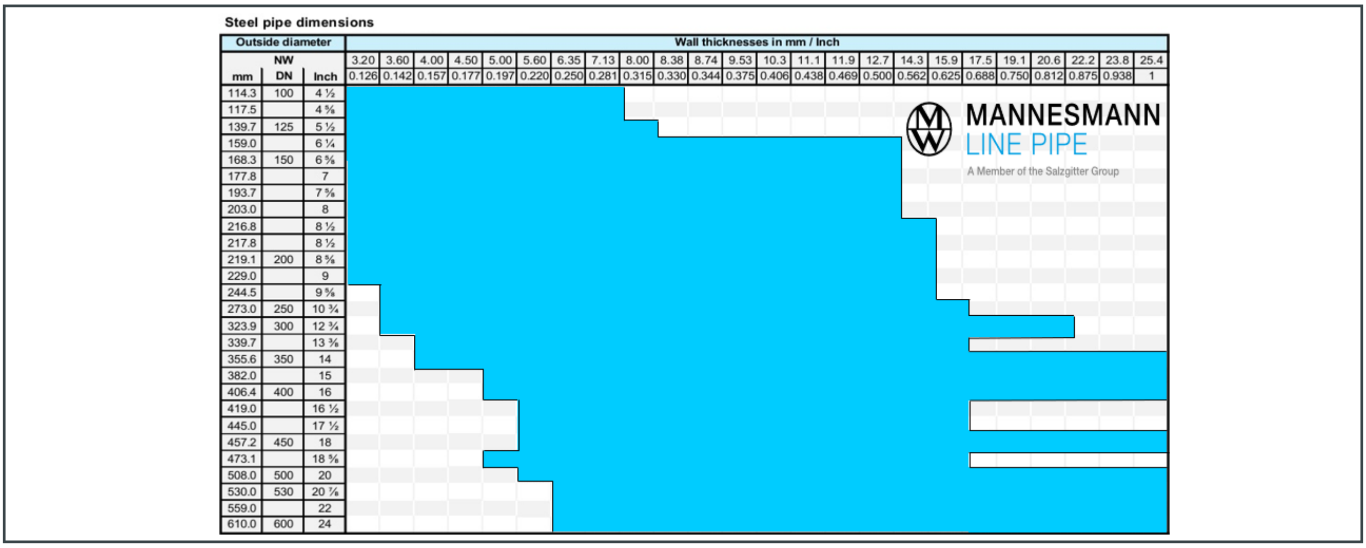

Figure 4b: Current HFW pipe product offering by Mannesmann Line Pipe GmbH (courtesy of Mannesmann Line Pipe GmbH)

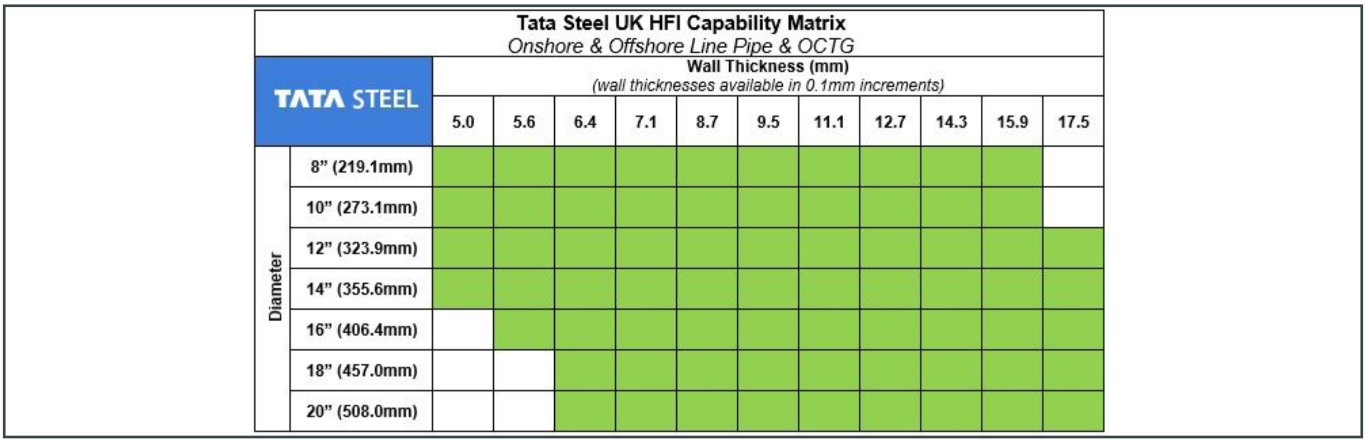

Figure 4c: Current HFW pipe product offering by Tata Steel Europe (courtesy of Tata Steel Europe, UK)

2.2 SMLS PIPES

A large body of evidence demonstrates that the SMLS pipe produced by various manufacturers meets the most stringent operational reliability requirements [1-3, 8, 9] of the industry.

A wide variety of SMLS pipe mills have predetermined methods and equipment that are used in their manufacturing processes. At the same time, each pipe mill produces a range of pipes in the most efficient manner. This paper does not intend to present detailed SMLS pipe manufacturing processes.

Currently, there are various manufacturing processes of SMLS pipes such as:

- Mannesmann Brothers: The pierce and pilger rolling process for OD from 60 to 660mm and WT from 3 to 125mm
- Stiefel: The plug rolling process or 'automatic mill' for OD from 60 to 406mm and WT from 3 to 40mm
- H. Ehrhardt: The continuous mandrel rolling process (for OD from 21 to 178mm and WT from 2 to 25mm), push bench process (for OD from 50 to 170mm and WT from 3 to 18mm), pierce and draw process (for OD from 200 to 1450mm and WT from 20 to 270mm)
- W.J. Assel: Tube extrusion process (for OD from 60 to 120mm and WT from 3 to 15mm), cross-rolling process (for OD from 60 to 250mm and WT from 4 to 15mm)
- S.E. Diescher: For OD from 60 to 168mm and WT from 4 to 30mm

Preference is given to the following modern high-performance processes:

- Continuous mandrel rolling process and the push bench process in the size range of 21 to 178mm OD
- Multistand plugmill (MPM) with controlled floating mandrel bar and the plug mill process in the size range of 140 to 406mm OD and the cross-roll piercing and pilger rolling process in the size range from 250 to 660mm OD.

Aside from these defined size range limits, many SMLS pipe mills also operate on varying dimensional ranges.

3. DISCUSSION

Every type of pipe, whether HFW or SMLS, has advantages and disadvantages. The intent of this paper is not to suggest SMLS pipes are not high-quality products, but to put forward the idea that more cost-competitive alternatives, such as HFW, could suit and meet the requirements of some of these scopes which fall within HFW's capabilities. Advantages and disadvantages of both SMLS and HFW, are reviewed below in detail.

3.1 SMLS PIPES

The high strength of SMLS pipes, coupled with the ability to make wall thickness of up to 60mm makes SMLS pipes the only choice for a wide range of lines with extreme service conditions (e.g., extreme low temperature, high H2S (sour service), extreme high pressure), as well as certain load-bearing and support structures.

SMLS pipes have been successfully used in construction for a long time. There are well-known instances where SMLS pipe is used to manufacture frames, steel trusses, supports, etc.

However, a review of SMLS manufacturing processes also demonstrates that SMLS pipes are not immune to the type of body defects which affect pipes' mechanical capability and operational reliability. Defects in SMLS pipe bodies, originated during hot rolling in continuous rolling mills, could theoretically be classified as steelmaking defects, rolling defects, and finishing defects, which also include those made during heat treatment [9, 10]. Studies have demonstrated that 80% of identified defects came from the quality of the billet and only 20% from the rolling process [9].

The primary steel manufacturing defects in SMLS pipes could include OD and internal diameter (ID) scabbing resulting from blisters, slag, and segregation inclusions which are formed during hot rolling.

Pipe defects with non-metallic inclusions may impact pipe performance significantly. Given the high degree of non-metallic contamination, the macrostructure of the pipes from these heats could potentially exhibit areas with residual cast structures. These residual cast structures are typically around 2 to 3mm from the surface of pipes. This results in a structural and chemical heterogeneity in the metallic structure and, under certain conditions, could be conducive to the initiation and development of failures for various reasons associated with service conditions [11].

The primary type of limitation with SMLS pipes resulting from the billets being heated could be elevated wall thickness variation. Other types of defects potentially could result from metal under or overheating which adversely affects billet press piercing (under-rolling). Metal hot spots can result in defects that cannot be corrected. The principal defects potentially resulting from the press-piercing operation are those caused by the condition of either the billet or the tooling. Tool marks or imprints on the outside surface of the shell may subsequently develop into rolling laps.

Undercut can be another surface defect whose shape and location depend on the shell twisting angle while the genesis is associated with the condition of the tooling. During subsequent rolling, undercuts can transform into rolling laps. To prevent these defects, worn-out guides and mandrels must be replaced on a regular basis which potentially results in additional costs and, in the final analysis, affects the price of the final product.

Defects made during the rolling process in the continuous and the extraction/sizing mills also have to do with the condition of the tooling and the forming processes at these stages. The most common defect with SMLS pipes is in the form of long protrusions on the outside surface, usually described as ridges or whiskers, can be created when the rolling profile overflows with the material being formed, the metal finds its way in between rolls. If ridges are made in the initial mill stands, subsequent stands may roll them out into laps, or the pipe may fail along the ridge. Depending on the condition of the rolls and the shape of the rolling profile, pipes may become undercut. Misconfiguration of the continuous mill and misco-ordination of the forming speeds in the various stands may result in such defects as washboard and pigeonholes. Through tears, otherwise known as pigeonholes, could be potentially created by non-uniform metal plasticity around the pipe perimeter as the shell coils, or improper roll calibration causing unacceptable stresses in the metal being formed. Pipe OD cracks could also be created by continuous mill misconfiguration, e.g., excessive reduction in the first stands (insufficient clearance between rolls and oversized shell) which creates significantly non-uniform metal deformation which, in turn, causes the metal to crack.

Guide marks, gouges, roll marks, OD and ID dents can all be created as rolls wear out and as bits of metal become attached to them; generally caused by dry or non-uniformly lubricated mandrels, failed coating and/or mill misconfiguration. The 'orange peel' pattern surface defect can be an imprint of a network of thermal cracks on the surface of the continuous mill rolls.

One of the disadvantages of a longitudinal pipe no-mandrel rolling process is that pipe ends can become hooked with the length of the hook being equal to the distance between the mill stands.

The above SMLS defects may significantly impact operational reliability performance and result in local defects under certain circumstances.

Local defect propagation, as a result of adverse service conditions, may create local and extensive structural failures such as crack-like defects to propagate past critical defects [8, 11]. However, imperfections and variability can be managed to acceptable limits through material/process controls and effective non-destructive testing (NDT). In this way, SMLS line pipe is widely available and accepted for the most challenging designs (e.g., strain-based design, reel lay installation) with the imperfections having no significant effect on integrity; integrity is often dominated by the butt weld quality which applies equally to HFW and SMLS line pipe.

SMLS pipe is manufactured in a wide range of sizes comparable to that of HFW pipe. At the same time, the wall thickness potential of a SMLS pipe is much greater than that of an HFW pipe and can be as high as 60mm, whereas HFW pipes mostly have a wall thickness limit of less than 1´ (25.4mm). There are, however, facilities capable of manufacturing HFW pipe with a wall thickness of up to and including 1´ (25.4mm).

Typically, the cost to produce SMLS pipes is greater because SMLS pipe has a much higher energy component during manufacture due to the furnaces that must be used at different points in the process.

SMLS piercers and rolling mills are extremely sophisticated engineering systems requiring continuous process monitoring. The need to maintain equipment functionality and process stability requires the use of complex engineering systems and techniques whose overhead cost is included in the final cost of the manufactured product.

In addition, there are several challenges in the SMLS manufacturing process that do not yet have standard engineering solutions. Firstly, SMLS pipes normally have inferior surface quality to other pipe manufacturing methods, primarily with the ID, resulting from the use of a mandrel. There is also difficulty with obtaining uniform mechanical properties in the pipe material. Small instabilities in the manufacturing process associated with the heating, hot forming, and cooling operations may result in reduced pipe performance.

3.2 HFW PIPES

Due to the sheer quantity of pipe required to construct oil and gas pipelines, HFW pipe can be an attractive alternative option to SMLS equivalents from the perspective of cost-efficiency, lead times and several technical considerations, e.g., lower ovality, narrower tolerances, etc. (for further details, see Table 2).

For HFW pipes, stable material properties are derived from the properties of the coils which are more easily and consistently achieved at contemporary casting and rolling facilities as demonstrated in this paper using the case of the JSC VSW (part of OMK) integrated casting and rolling facility.

There are various methods to assess the suitability of pipes for use under high-strain conditions. According to relevant standards, properties such as uniform elongation shall be monitored during pipe manufacturing. In addition, mechanical properties after full-scale bend testing (simulating the strain conditions during laying) should be verified. HFW pipes have tighter OD and wall thickness dimensional manufacturing accuracy than for SMLS products; this can offer potential material savings of up to 15%, when compared to equivalent SMLS product. Uniform roundness and low ovality/out-of-roundness of HFW pipes are important factors in understanding collapse behaviour, strain-based designs under multiaxial loads and reel lay installations [12-15]. Additionally, there is uniform distribution of mechanical properties of HFW pipes [16]. This is a factor of importance for procurement and welding operations associated with pipeline construction and reel lay installation.

It has been shown that the relatively limited range of wall thicknesses offered by HFW pipe is not a defining characteristic that would prevent the use of these pipes in pipeline and structural demands. Market evaluations for HFW demonstrate capabilities of ODs up to 26´ (660mm) and WTs of between 0.126´ and 1´ (3 and 25.4mm). Thicker walled product up to 25.4mm is regularly supplied for welded construction and engineering applications.

The nature of manufacturing from coil and the thickness control on strip for HFW generally means final pipe wall thickness does not need to be a standard API gauge, whereas SMLS generally does, i.e., tighter WT tolerances of HFW pipes mean that a lower nominal WT value can be targeted and the absolute minimum WT value for SMLS is still achieved, meaning thinner walls and further cost savings.

Current experience demonstrates that a weld is not a constraint on HFW pipes. Whilst the seam weld can show some degradation affected by loss of alloying elements, inclusions, etc., the state-of-the-art seam heat treatment or weld line annealing (WLA) and a full-body heat (FBH) treatment process (where applicable) produce complete microstructure uniformity. The metallographic analysis shows the weld structure is indistinguishable from that of the base metal. Consequently, the location of where the weld used to be had to be marked for engineering and lab analysis purposes. Otherwise, it may not be identifiable following heat treatment without specific targeted metallography.

The high quality of factory welding followed by heat treatment (WLA, FBT) results in the weld and the base metal having similar strength and toughness. There is a significant cost-saving when using HFW pipe as opposed to SMLS equivalent, given the higher quality assured by the above factors.

A performance comparison of HFW and SMLS pipes demonstrates, first and foremost, a much higher OD and wall thickness tolerance accuracy in HFW pipes compared to SMLS equivalents. This is a significant advantage, enabling effective use of HFW pipe in pipelines and structures by optimising welding processes, times, construction cost-efficiency, and in the case of fatigue sensitive applications where ID mismatch tolerance (hi-lo) must be tightly controlled, SMLS pipe ends may require counterboring to achieve the required joint fit-up.

The remainder of the performance properties affecting pipeline operational reliability (strength, failure resistance) are very similar for both HFW and SMLS pipes. In practical terms, provided the HFW weld is as strong as the base metal, [7] they are the same.

Consequently, the cost-efficiency becomes of paramount importance under these circumstances. As stated, SMLS pipe can be 10 to 30% more expensive than HFW. This suggests HFW equivalents make them capable of replacing SMLS pipe, with everything else being equal.

Range testing of pipes for PAO GAZPROM was performed at the OAO VNIIST field test range (Figure 5) confirming the high performance of the HFW pipe. Three joints of full-size HFW 168.3 x 7.3mm casing, of grade API SPEC 5CT (this grade can be compared to API SPEC 5L L485 (X70), were subjected to the testing with the weld at 12, 6, and 3 or 9 o'clock positions. The objective of the test was to evaluate the pipes' performance under complex loads. Metal performance under combined load, two-axis loading, tension with bending, buckling behaviour, etc., is known to be significantly inferior to that under single-axis loading which is predominantly used to evaluate base metal and weld mechanical performance [8, 10, 17]. The pipes were made of coil steel produced at the integrated casting and rolling facility. The test applied a combined load, internal pressure with bending, tension with bending and internal pressure. The pipe was equipped with special 150mm cylindrical-machined end caps which had undergone ultrasonic inspection. The end caps were seam-welded to the pipe using contractor's technology.

The finding approved by PAO Gazprom-VNIIGAZ stated that the deformation properties demonstrated in all three tests indicate that the HFW pipe metal and structure have high plasticity properties. Testing showed that the performance of the weld is at least equal to that of the base metal. The testing confirmed the JSC VSW (part of OMK) HFW pipes' high degree of resistance and performance under the combined effect of maximum excessive internal loads and high bending forces. Thus, it has been experimentally proven that JSC VSW (part of OMK) pipe can be used to implement strain-based designs. Using this promising method to design pipelines helps reduce the pipe wall thickness, optimise pipeline construction and operation costs without compromising performance.

Figure 5: HFW combined load test (courtesy of JSC VSW (part of OMK))

92km (16000 ton) of 12¾" OD with 11.13 WT mm DNVGL 450 SD (supplementary enhanced dimensional requirements) (equivalent of X65 API SPEC 5L L450) HFW pipes manufactured by Mannesmann Line Pipe GmbH were installed using S-lay installation method (Figure 6) for the project 'Hejre' in 2014 in the North Sea/Denmark. The customer was Saipem UK and the end-user was Dong Energy.

A paper produced by TechnipFMC [18] highlights the typical challenges faced by low-temperature reel lay installed HFW pipes, as well as some of the other key parameters relating to HFW pipe manufacturing. It concludes that the advances in both technology and understanding of HFW pipe production have driven the large capability development in HFW pipes.

An example of reel lay installation HFW pipe is shown on Figure 7. More than 460km of HFW pipe manufactured by Tata Steel Europe has been installed using reel lay construction methods.

The above case studies present that HFW pipes have been successfully used for S-lay and reel lay installation methods.

As with SMLS equivalent, the scope of HFW pipe's final applications and specifications achieved is highly dependent on the quality of manufacturing operations.

For true pipeline integrity a stable welding operation is essential, only achieved by a deep understanding of the welding process and tightly controlling its parameters. It is this process control which has allowed confidence to build amongst operators, contractors and pipeline engineering teams leading to the specification and use of HFW line pipe where SMLS was previously the only option.

Like SMLS equivalents, HFW pipe can suffer from defects if the process control is not correctly managed, and so it is essential when considering an HFW product, that the pipe mill has this in place, and this is likewise the same for the hot strip mill supplying the coil.

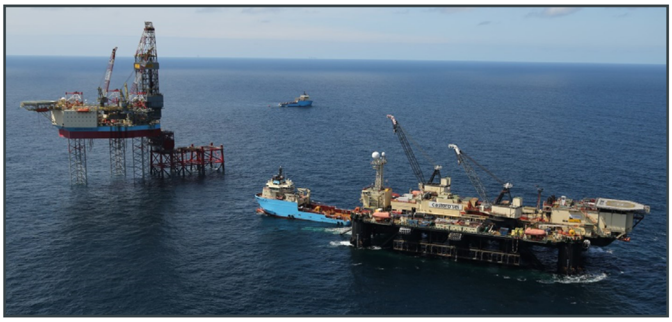

Figure 6: HFW S-lay installation onto seabed (Courtesy of Mannesmann Line Pipe GmbH)

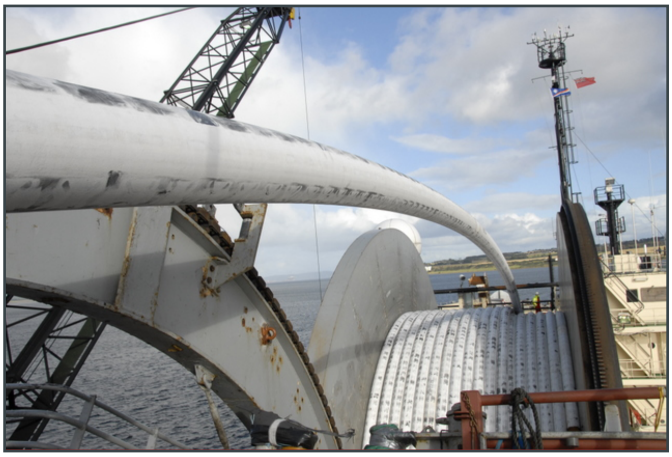

Figure 7: HFW reel lay installation onto seabed (courtesy of Tata Steel Europe)

The final quality of the pipe should not be as a result of testing, but rather the testing, e.g. CVN in the WFL +/- 2.5mm, crack tip opening displacement test (CTOD), NDT, weld macrographs etc., should all confirm the process control has worked. Some HFW manufacturers have over many decades developed and finely tuned their welding and heat treatment procedures to consistently achieve high weld integrity. These procedures are continuously reviewed and developed further to achieve, for example, new capabilities such as size increases, wall thicknesses increases, sour service applications and higher grades. The continuous improvements also lead to greater manufacturing yields driving product confidence and performance.

Welding is carried out in accordance with mill instructions which detail of all the required parameters which must be set and monitored to achieve a sound weld for the product being rolled. This includes settings for weld speed and temperature, geometry of the strip edges as they are presented at the welding vee, expected weld line geometry and annealing requirements. Each of these is discussed in further detail in the sections below.

Like with the SMLS process, in HFW processes, any instability in the control of the welding parameters, pipe strip and weld geometry, or heat treatment operations may result in reduced pipe performance.

3.2.1 HFW PIPE WELDING PARAMETERS

The welding speed and temperature are closely monitored and recorded using calibrated pyrometers and encoders. Large changes in power output can be an indication of non-optimum welding conditions and welding must stop whilst this is investigated. Without tightly controlling the weld speed and temperature weldline performance can deteriorate with a higher possibility of weld defects in the form of increased non-metallic inclusions in the weld, and in extreme cases a lack of weldline fusion. Traditionally, monitoring of the HFW welding operation was carried out visually during production. However, the latest technologies have enabled automated, real-time monitoring of welding parameters. The welding parameters to be used are the result of process validation over many years. Ensuring that these aims are achieved is paramount to the integrity of the weld.

Previous failures of HFW have been associated with automated ultrasonic testing (AUT) missing defects by not tracking the weld seam since it is narrow and not always clearly visible. It is important to ensure accurate tracking of the seam by the AUT probes. It should be noted that there have been advances in AUT technology including the introduction of rotary probes which make it more robust against imprecise probe positioning. It is essential for the AUT procedures to be fully qualified and validated.

3.2.2 HFW PIPE STRIP AND WELD GEOMETRY

The strip edges should have the necessary dimensional accuracy and profile to facilitate reliable welding. This is achieved by milling rather than shearing of strip.

Due to the nature of the welding process, presentation of the strip edges as they pass through the induction coil and into the welding vee is a critical factor in the weld quality. Closely monitoring and controlling this within tight tolerances is essential to achieving a sound, consistent weld. Having edges that are correctly profiled with the correct skelp gap ensures proper heating of the strip edges which in turn leads to a good quality weld. There is also a need to ensure that the strip edges are positioned at the same height during the whole of the heating and welding procedure, so that misalignment of the weld area is avoided. Strip geometry is monitored in several ways, including measurement of the formed strip prior to the induction coil, as well as measurements post weld and analysis of routine macrographs at set intervals. These checks allow monitoring of not only the ingoing strip conditions but also the weld achieved as a result of analysing the macrograph. Proper control of strip geometry allows the avoidance of potential issues such as non-metallic inclusions in the bond line, offset edges, and skewed or swerved weld lines. Inconsistent toughness through the weld wall thickness is a possible defect if the edges are not presented and squeezed perfectly square, e.g., the ID and OD not coming together at the same time, as the leading edge will heat prematurely.

3.2.3 HFW PIPE HEAT TREATMENT

PWHT of the longitudinal seam weld or WLA is required in HFW welded pipes to rectify the microstructure generated during the welding process. HFW welding produces a structure harder and more brittle than the base material. The aim of PWHT of the longitudinal seam weld (WLA) and weld area is to create smooth mechanical properties (tensile, toughness) and transition between the base material and the specification, respectively. As a result of extensive research and development work coupled with process validation, the optimum seam annealing parameters have been defined and are used in order to achieve low temperature impact performance. Temperatures are monitored using a series of calibrated pyrometers and penetration is confirmed by means of a macrograph taken post annealing. The results of this routine analysis allow for minor adjustments to the process to be made to ensure proper penetration and alignment. The frequency of checks ensures that potential issues can be detected before they pose a risk to weld integrity. Furthermore, the alignment of the annealing heads to the bond line must be closely controlled at all times.

3.2.4 HFW PIPE SURFACE IMEPERFECTIONS

Whilst HFW pipe offers far superior surface quality to SMLS due to the hot-rolled feed stock, surface imperfections are still possible, with the extreme case of an under-thick wall, or challenging surfaces for coating. The feedstock supplier manufacturing the coil must therefore have processes in place to prevent this happening.

4. CONCLUSIONS

Available HFW pipe manufacturing procedures have been developed to overcome historical issues and improve HFW

Description	HFW Pipes	SMLS Pipes
Cost	Typical industry norms are costs up to 10 to 30% lower total cost through the supply chain and with significant savings downstream. Note: There is a spot for SMLS where HFW cannot compete and vice versa.	Can be 10 to 30% more expensive. Note: There is a spot for SMLS where HFW cannot compete and vice versa.
Lead time	20 to 30% shorter (larger manufacturing base).	20 to 30% longer (fewer manufacturers of SMLS pipes than welded pipes).
Seam weld flaw	In poorly managed mills with lack of proven capability there are risks associated with Presents risk of seam weld poor seam weld properties or serious crack-like defects. However, this risk is well managed by some mills with the proven capability and strong quality management.	Not applicable.
Parent material defects	The rolled strip normally has low levels of minor imperfections.	The size of imperfections is typically higher than the strip of HFW line pipe. However, this can be managed to acceptable levels by control of manufacturing process and NDT.
Dimensional control: wall thickness consistency (eccentricity)	Consistent (as manufactured from coil which are subject to tight tolerance control). Final pipe wall thickness does not need to be a standard API SPEC 5L gauge meaning thinner walls and further material cost savings.	Inconsistent (wall thickness tolerance across length is +/- 12.5% as per API SPEC 5L). Final pipe wall thickness needs to be a standard API SPEC 5L gauge, meaning
	Limited to API SPEC 5L OD.	sometimes it is thicker than required due to the gauge 'jump'. Has a wider variety of OD available (tooling is generally cheaper for SMLS to have additional OD sizes and the oil country tubular goods (OCTG) sizes mean that there are generally more options for ODs).
Dimensional control: roundness and ovality	More predictable and precise shapes, in terms of roundness and ovality (depends on the type and accuracy in the last forming step, e.g., calibration stands or multi-roller straightening machine.	Depends on the type and accuracy in the last forming step, e.g., calibration stands or multi-roller straightening machine.
Uniform mechanical properties	Stable material properties devolve from the properties of the coils that are much more easily achieved. Weld seam is a point of mechanical property variance. Forming of coils can lead to localised strains which may be relieved by applying a stress relieving heat treatment.	Any small instability in the manufacturing process (heating, hot forming, and cooling operations) may result in reduced pipe performance, or considerable non-uniformity in the mechanical and corrosion resistance of the pipe metal over the length of the pipe.
Wall thickness range	Narrower range (up to and including 1" (25.4mm). WT does not need to be a standard API gauge.	Wider range (up to and including 2.4" (60mm). WT needs to be a standard API gauge.
Pipe length capability	18m + lengths available for non-full body heat treated (24.4m max). 12.2m max lengths available for full-body heat treated.	Typically, 12.2m but longer lengths up to 18m are available. For higher WTs and ODs some suppliers offer pipe lengths below 12.2m.
Total weight of line pipe	Lighter (due to consistent wall thickness across the welded pipes). However, if factor applied to HFW in case of collapse resistance a heavier WT for HFW would be required.	Heavier (due to inconsistent wall thickness across the welded pipes).
Low temperature capability	For subsea, typically down to -20°C, although -40°C capability exists. Real-time monitoring of weld-seam and full body heat-treatment give the best potential for low-temperature capability. Developments are still being carried out to expand the limitation.	Better capabilities as compared to HFW due to absence of the weld area. Typically, -40°C are achievable.

Description	HFW Pipes	SMLS Pipes
Sour service (H_2S) limitation	Application of real-time weld monitoring and full-body heat treatment is a necessity to ensure that there are not issues with NACE TM0177, solution A and NACE TM0284, solution A. Developments are still being carried out to expand the limitation.	Can be used with higher partial pressure levels of H_2S as compared to HFW.
Line pipe fabrication	Reduction in number of shop/field welds/coating joints by manufacturing and coating pipes in 24.4m rather than 12.2m. Better fit-up, less weld repairs, no need for rotation apart from offsetting of HFW weld.	Limited due to typical average size of 12.2m.
Reel lay installation	Tighter dimensional control, OD, and manufacturing accuracy. HFW pipes when reel lay installed are more malleable/flexible product over SMLS and less prone to buckling. Increased lay installation rates due to optimised dimensional tolerances. Note: Limited for reel lay installation up to 20".	Less dimensional control, OD, and manufacturing accuracy, therefore, potentially thicker pipe to be reel lay installed. Note: Limited for reel lay installation up to 20". SMLS typically achieves better yield to tensile (Y/T) ratio and uniform elongation and so SMLS reelability is demonstrated with less work (also, most reelability assessment models are based on SMLS so it has taken time to adapt these models to HFW and recognise its advantages).
Pipe matching	Higher uniformity of girth welds.	May require counterboring to achieve the required joint fit-up.

Table 2: Advantages and disadvantages of HFW and SMLS pipes

pipe usability. Unfortunately, many of these accomplishments have been overlooked because the SMLS method is traditionally the 'known, understood and desirable' option. In a more buoyant market there was potentially less desire to seek incremental efficiencies. The recent market slowdown and advances in HFW manufacturing technology should now make it an even more attractive option in the oil and gas sector.

A review of the manufacturing processes, the studies completed as well as testing outcomes enable us to make the following specific conclusions:

- HFW pipes have the advantage of being made from coil assuring tighter dimensional control, especially wall thickness distribution, but also increased stability and homogeneity of mechanical properties
- HFW manufacturers can produce very high quality pipes provided the correct level of manufacturing control is enabled through manufacturing technologies, particularly on welding, heat treatment and NDT testing
- On average, SMLS pipe can contribute 10 to 30% greater total cost through the supply chain than its HFW equivalent, however the downstream benefits of HFW can accrue much greater efficiencies and total project cost savings
- As production methods are much quicker, HFW pipes could potentially save up to 20 to 30% on lead times and as a result reduce overall project costs
- A comparative review of the manufacturing processes, pipe makers' research, and performance evaluation of HFW pipes by end-users confirms that HFW pipes have now become a more viable option
- Field testing of pipes and pipe structures demonstrate HFW pipes' high resistance in the face of combined and cyclic loads and experimentally showed that in oil and gas applications such pipes have enough strength and plasticity margin to assure the required performance.

Table 2 summarises the above conclusion as well as other advantages and disadvantages of HFW and SMLS pipes.

Seam welding with HFW of carbon and LAS is now a very well-established manufacturing process; many mills have proven track records in reliably and consistently delivering high quality pipe products.

Even setting aside the highlighted 10 to 30% cost-efficiency at the design stage, taking into consideration other service conditions e.g., application limitation such as extreme low temperature or high partial pressure of H2S, etc., using HFW pipes instead of the SMLS equivalent could potentially save 20 to 30% lead time and therefore overall project costs. For the list of project portfolios, please contact appropriate HFW pipe manufacturers.

Previous seam weld failures of HFW carbon and LAS line pipes have deterred projects from selecting it in the past with preference towards the SMLS equivalent. However, over the past 20 years several manufactures have demonstrated their capability (track record) to produce high-quality reliable HFW pipe. In recognition of this, HFW carbon and LAS line pipe should only be procured from pipe mills with the necessary technology and proven capability (track record) to meet the specific project requirements. For each project, the purchaser should always audit the mills quality assurance/quality control (QA/QC), steel quality, reliability of process control/monitoring and NDT. It is important to ensure that these requirements are clearly specified and confirmed by sufficient independent inspection of the critical stages to mitigate seam weld failure.

It is proposed that HFW CS and LAS pipe can be considered as a viable alternative solution to SMLS equivalent for a range of scopes that fall into its capability range.

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Application of Pipeline QRA Methodologies to Hydrogen Pipelines in Support of the Transition to a Decarbonised Future

Adnan Aslam, Nigel Curson > Penspen

Abstract

Hydrogen is expected to play a key role in the decarbonised future of energy. For hydrogen distribution, pipelines are seen the main method for mass transport of hydrogen gas. To support the evaluation of risk related to hydrogen pipelines, a revised QRA methodology is presented based on currently available and industry accepted guidance related to natural gas. The QRA approach is primarily taken from HSE UK's MISHAP methodology [1]. The base methodology is reviewed and modifications suggested to adapt it for use with hydrogen gas transport. Compared to natural gas, it was found that the escape distances (based on the degree of heat flux) for hydrogen was lower. However, as for the overall risk, for both individual and societal, the case with hydrogen was more severe. This was driven by the increased ignition probability of hydrogen. The approach may be used as part of the review and appraisal process of hydrogen projects.

1. INTRODUCTION

As the energy transition gathers pace on the backdrop of increasing concern around climate change and need to decarbonise, the use of hydrogen as an energy source is seen as a key enabler. The case for hydrogen has been assessed for some years and now firm steps are being taken to make the hydrogen economy a reality. Various pilot schemes around the world have completed or in progress, such as HyNet, Acorn Hydrogen and H21 in the UK. As part of the hydrogen economy, its transportation via pipelines is expected to play key role to connect the supply side with end-point users.

To facilitate onshore pipeline developments, a Quantitative Risk Assessment (QRA) is widely used in natural gas and liquid pipeline transportation. Introducing hydrogen as an alternative fuel, its transportation via pipelines could be as a mixture with natural gas or pure hydrogen. The latter may require new pipelines primarily owing to issues of steel embrittlement, although this is still an area of ongoing research. In both cases, to support the evaluation of hydrogen pipeline transport, a QRA methodology is presented. The primary source is HSE UK's MISHAP [1] methodology for which Penspen have an in-house software tool for pipeline QRA assessments. The MISHAP approach is discussed in this paper with modifications for use with hydrogen based on latest industry literature.

It is noted hydrogen pipeline transport is relatively less understood with various research activities currently underway or planned, such as consequence modelling (specifically jet fire models for hydrogen-methane mixtures). Further maturity in the understanding of hydrogen transport, either as a mixture or on its own, is expected to affect QRA methodologies. This paper presents a robust methodology to support concept project evaluation based on state-of-the-art techniques and knowledge.

2. THE QRA PROCESS

The use of QRA for onshore pipelines is standard practice in the UK and elsewhere. The general methodology is well established in industry to identify and manage risks. Figure 1 shows a typical QRA process with the key steps.

3. INPUT DATA

Most of the input parameters can be used directly as with the case with natural gas; this includes pipeline size, coatings, terrain etc. However, there are a few parameters that are affected by the introduction of hydrogen and are discussed below.

3.1 PIPELINE PRESSURE

The operating pressure is a key input parameter for a QRA. The energy density by volume of hydrogen is approximately a third of that for natural gas. However, hydrogen's density is ~8 times lower meaning its flow rate (for the same pressure drop) is higher – see Table 1. It can be shown the net result is a small reduction in energy transported via hydrogen [8] [9]. Thus, based on an energy transport basis, the operating pressure is similar to that of current natural gas pipelines. There are other possible reasons where the pressure could be different; most likely the pressure would be reduced to counter the risk of embrittlement (which would need to be balanced with a consequent reduction in transported energy).

3.2 PIPELINE MATERIAL

The main concern from transporting hydrogen in steel in pipelines is embrittlement. This is a known failure mechanism, primarily from experience with "sour" hydrocarbons

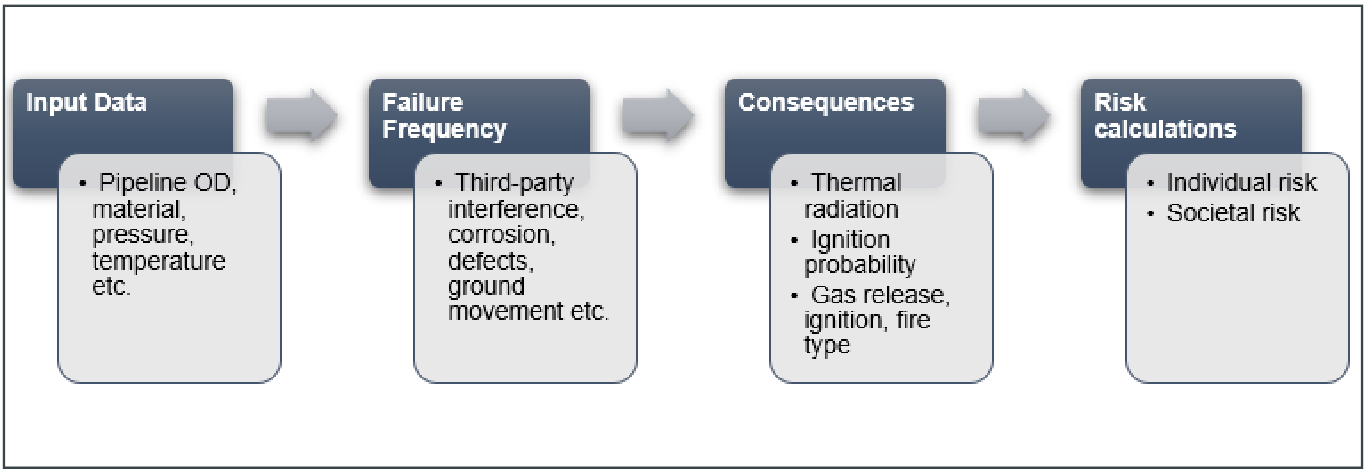

Figure 1: Typical QRA Process

containing high hydrogen sulphide content. Causes of embrittlement are mainly related to the pipeline material and operating conditions, including hydrogen concentration. Embrittlement is characterised by a loss of ductility due to hydrogen diffusion into surface flaws resulting in increased sensitivity to fatigue. It is a time-dependent phenomenon with failure occurring at stress levels well below the yield limit [5] [10]. Higher pressures increase the risk of embrittlement. A combination of steel grade and operating pressure can be suitably selected for safer operation. If using existing pipelines, the material is a given and so the pressure may need to be reduced if embrittlement is found to be a potential issue. Embrittlement is more pronounced in higher strength steels. Indeed, the design of existing hydrogen pipelines is based on steel with low yield strengths and with low carbon and manganese content [10].

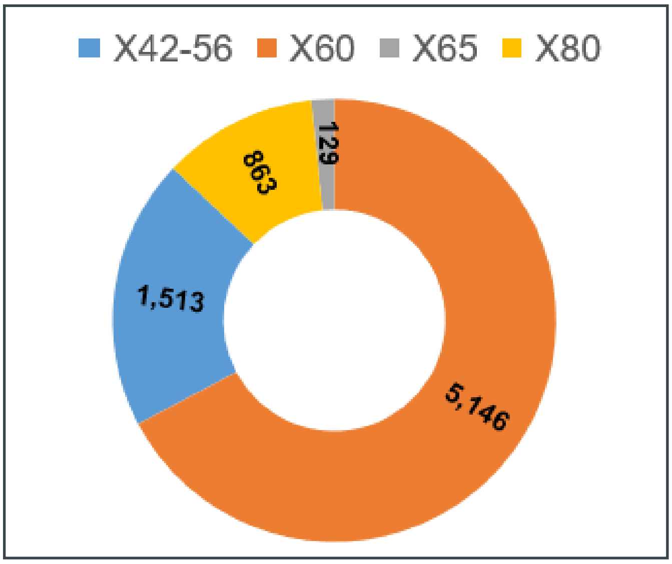

Figure 2: UK NTS Breakdown by Steel Grade (in km)

Figure 2 presents a summary of the UK NTS pipeline by steel grade [11]. This shows 89% of the NTS network is steel grade X60 or lower. 90% of the network operates between 70-80bar.

Based on limited research data, for a hydrogen-natural gas mixture with 25% molar volume of hydrogen embrittlement for X70 steel was not observed [2]. The QRA methodology presented herein assumes embrittlement is not a likely failure mechanism (whether in an existing pipeline or, in the case of new pipeline, it is suitably designed for) and should be used with low strength steel grades (assumed to be X60 or lower).

3.3 PRODUCT

A comparison of key parameters for methane and hydrogen is presented in see Table 1. Of note, particularly for a QRA, is the increased flammability range, ignition energy and the heat of combustion. The wider flammability range and significantly lower minimum ignition energy combine to make hydrogen more hazardous. The ignition energy at the lower flammability limit is similar to that of methane, however, this rapidly reduces with increasing hydrogen concentration. Hydrogen has been reported to ignite even from unintended small static electricity discharge [10].

4. FAILURE FREQUENCY

Pipeline failure statistics, mainly for hydrocarbon transport, are well documented with various databases available; UKOPA being the main one for the UK [17]. There remains inherent uncertainty in the use of these statistics particularly for higher grade materials for which the available historical data is relatively sparse. Even with available data due care is required in its use for QRAs, with engineering judgment often used to make appropriate assumptions for the particular pipeline being assessed.

Parameter	Units	Methane	Hydrogen
Gas properties			
Molecular Mass	g/mol	16.04	2.016
Heat of Combustion (lower heating value)	kJ/kg	50,000	119,960
Higher Heating Value	kJ/m^3	39,800	12,700
Specific Heat Ratio	-	1.31	1.41
Combustion properties			
Stoichiometric Fuel Volume Fraction	%	9.5	29.5
Adiabatic Flame Temperature	K	2226	2380
Flammability limits	% vol.	5-15	4-75
Minimum Ignition Temperature	K	905	845
Minimum Ignition Energy	J	33×10^{-5}	2×10^{-5}

Table 1: Methane & Hydrogen Properties

Source	3rd Party	Internal Corrosion	External Corrosion	Material – Construction	Cracking – SCC	Natural Causes, Geotechnical	Other - Unknown
EGIG	48%	0.5%	13%	17%	2.5%	8%	11%
UKOPA	22%	1%	20%	28%	16%	5%	8%
DOT-PRCI	43%	16%	14%	8%	1%	10%	8%
TRANSPERTO	67%	0%	33%	0%	9%	0%	0%

Table 2: Failure Statistics for Gas Pipelines [13]

For hydrogen, given only a small number of hydrogen pipelines around the world exist, the available data is insufficient for direct use. The total estimated length of hydrogen pipelines is less than 0.1% of that for natural gas pipelines. Though there is some data for hydrogen failures, the majority of these are in process plants [12], and as such not directly applicable for transmission pipelines.

A closer examination of pipeline failure statistics indicates the main source of failure is due to third-party interaction [13]. This threat is, generally, equally applicable irrespective of the transported medium. For the QRA calculation the assumption is to use the same failure statistics as for natural gas pipelines. It represents a suitable risk level to facilitate concept evaluation of hydrogen pipelines. The main concern with hydrogen being injected into existing steel pipelines designed for natural gas is material embrittlement and leakages. For new pipelines designed for hydrogen specifically, these concerns are assumed to be adequately addressed through design. Whilst the potential increased risk is acknowledged; this can be addressed on a case-by-case basis, depending on hydrogen concentration, pipeline history, mitigation measures etc.

5. CONSEQUENCE

The HSE MISHAP guidance has the following key components for consequence analyses [1]:

- Gas release modelling (LOSSP model for gases)
- Fireballs
- Jet fire models

5.1 GAS RELEASE

The gas release model (LOSSP) is considered appropriate for hydrogen gas. A comparison of the gas release rate for methane and hydrogen is shown in Figure 3. Owing to the reduced density of hydrogen, the release rate is approximately one-third that of methane.

5.2 FIREBALLS

The MISHAP fireball model (“FBALL”) [1] is considered adequate for use with hydrogen. The surface emissive power (SEP) and the substance-specific A-factor (which relates the radius of the fireball to its mass) are suitable selected

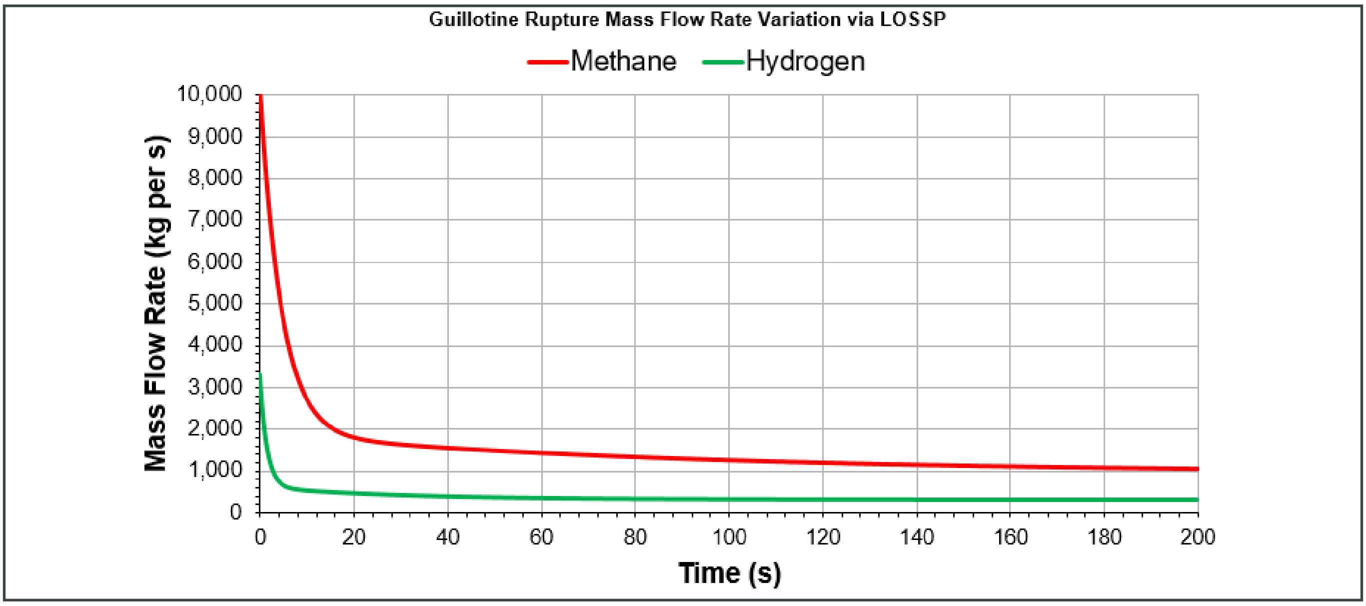

Figure 3: Mass Flow Rate Comparison – Full Bore Rupture (ID = 0.7m, 70 bar)

Parameter	Methane	Hydrogen [6]
Combustion efficiency factor	0.35	
Emissivity factor	0.20	0.15
Release decay factor	0.33	0.24

12345678jhbgfcdxsyrdtfghj

for hydrogen. The SEP value is not well defined for hydrogen based on a literature search and so the same value as for natural gas has been conservatively used in the model from the MISHAP guidance [1]. The "A-factor" is also not well defined in literature, although a value of 7.93 is quoted from a previous study [18], which has been adopted in the hydrogen model. It is noted that the fireball risk, compared to a jet fire, is relatively lower.

5.3 JET FIRES

There are two main jet fire models in MISHAP12 [1]; one specifically for natural gas ("PIPEFIRE") and another for "other substances" ("JIF/MAJ3D"), though it is not stated whether this includes hydrogen. This is based on Chamberlain's flame model, which employs a multi-point radiation source approach. The ASME B31.12 code for hydrogen piping and pipelines [14], presents an alternative methodology for jet fire radiation, which collapses the heat emitters into a single point emitter at ground level [6]. The methodology is the same as their natural gas model, found in ASME B31.8S [15], however it has been specifically adapted for hydrogen [7]. A comparison between the ASME and HSE MISHAP JIF/MAJ3D model for hydrogen was performed, which showed the ASME model as more conservative. Given the uncertainty with hydrogen using the ASME model was adopted to determine the jet fire heat flux, whilst the remaining methodology follows MISHAP guidance (for thermal dosage limits etc.).

The ASME model is based on a study by the Gas Research Institute (GRI) [6], which was subsequently updated for other gases [7], from which the "potential impact radius" formula quoted in ASME B31.12 [14] and ASME B31.8S [15] is taken from. The heat flux, I, from a jet fire flame from the ASME model is calculated as shown in Calculation 1.

As part of the update for hydrogen, additional considerations for the combustion, release decay and emissivity factors were made [7]. Table 3 presents a comparison of these factors for methane and hydrogen.

ASME B31.8S [15] and ASME B31.12 [14] provide an equation for the "Potential Impact Radius" (PIR), which is based on the above formulation. The equation is setup to give the radius at the 1% fatality dosage (15.8kW/m2). The equations as presented in the codes are shown in Calculation 2.

$$I = \frac{\eta . X_g . Q_{eff} . H_c}{4\pi r^2}$$

Where:

$\eta = combustion\ efficiency\ factor$

$X_g = emmissivity\ factor$

$H_c = heat\ of\ combustion\ in\ [kJ/kg]$

$r = horizontal\ distance\ from\ source\ to\ target\ [m]$

$Q_{eff} = gas\ release\ rate\ in\ [kg/s] = 2\lambda C_d \frac{\pi d^2}{4} p \frac{\varphi}{a_0}$

$\lambda = release\ decay\ factor$

$C_d = Gas\ discharge\ ratio$

$d = hole\ diameter [m]$

$\varphi = flow\ factor = \gamma \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$

$where\ \gamma = specific\ heat\ ratio$

$a_0 = sonic\ velocity\ [m/s]$

Calculation 1: Jet fire heat flux

$Methane\ (B31.8S\ [15])$ $\quad r = 0.69\sqrt{pd^2}$

$Hydrogen\ (B31.12\ [14])$ $\quad r = 0.47\sqrt{pd^2}$

$r = radius\ of\ impact\ (ft)$

$p = pipeline\ segment\ maximum\ allowable\ operating\ pressure\ (psig)$

$d = diameter\ of\ pipeline\ (in)$

Calculation 2: ASME B31.8S and ASME B31.12 equation

From theses equations, for the same diameter and pressure the implication is an approximate 30% reduction in the PIR value for pure hydrogen compared to methane (for a 20% hydrogen-natural gas mixture, there is <3% difference compared to methane). This comparison is presented to illustrate the difference based on existing codes. However, the proposed Penspen QRA methodology uses the thermal dosage limits as per HSE MISHAP guidance [1] and MISHAP is used for methane/natural gas – comparison presented in the case study.

5.4 IGNITION PROBABILITY

Compared to natural gas, hydrogen is significantly more flammable requiring a considerably lower ignition energy; approximately 1/15th of the natural gas value – see Table 1. Within the HSE MISHAP methodology there are 3 event trees presented; one for natural gas and two for other substances primarily based on the minimum ignition energy (MIE) [1].

- Natural gas;
- R12 substances with MIE < 0.2 mJ; and,
- R12 substances with MIE ≥ 0.2 mJ.

Hydrogen is included in the R12 substances with a low MIE. However, this tree has flashfire as a possible consequence, which given hydrogen is intrinsically buoyant flash fires are not applicable and so this event tree does not directly apply [4]. Furthermore, within the R12 substance family, there are other substances with much higher MIE and may not capture the increased ignition potential of hydrogen. For the QRA an adapted version of the MISHAP event tree for R12 low MIE is used where flashfire is discounted and the ignition probability increased to reflect hydrogen's higher flammability. The currently available guidance for hydrogen is not fully defined in literature and is an area of ongoing research. As part of the NaturalHy project, this aspect was assessed experimentally [20]; it was found that the probability of ignition is related to the equivalent ratio (a measure of the actual air/fuel ratio versus a stoichiometric reaction) and the energy level of the source. A degree of engineering judgment is required for use within a QRA framework. This is further discussed in the case study.

6. RISK

To compute the individual and societal risk, the methodology of MISHAP is used [1], which is incorporated in the software. This includes the various dosage limits for which safety distances are computed and resulting individual and societal risk curves. The approach is generic and unaffected by the transported medium.

7. CASE STUDY

An example using the aforementioned methodology is presented. The following cases were considered:

- Full rupture with pure methane using HSE MISHAP methodology [1] throughout; 2 diameters were considered; 157mm & 700mm.
- Full rupture with pure hydrogen using the ASME approach for jet fire modelling as detailed above, with remainder based on HSE MISHAP [1], also with the same 2 diameters.

Summary of the key input parameters is shown in Table 4, which are common to both the methane and hydrogen scenarios. Table 5 presents a summary of the release rate results comparison for a full-bore rupture using HSE MISHAP LOSSP methodology. In addition, results from the MISHAP FBALL for the fireball modelling is also presented, along with percentage differences. Due to the light nature of hydrogen the release rate is significantly lower, which also drives the fireball characteristics, mainly the view factor which is a function of fireball flame radius.

Parameter	Units	Value
Operating Pressure	barg	71
Operating Temperature	°C	15
Pipeline Inner Diameter	mm (inch)	157 (6) & 700 (28)
Material Grade	-	X46
Land Type	-	Rural
Landslide Potential	-	Low
Pipeline Condition	-	Buried (no slabbing)

Table 4: Case Study – Input Parameters

ID (mm)	Contents	Release Rate (kg/s)		Fireball Mass (t)	Radius (m)	Duration (s)
		Initial	Steady-State			
157	Methane (100%)	523	73	1.3	33	5
	Hydrogen (100%)	170	24	0.2	23	4
	% difference	-67%	-67%	-86%	-31%	-31%
700	Methane (100%)	10,376	2,341	72.8	127	20
	Hydrogen (100%)	3,366	758	11.5	90	14
	% difference	-68%	-68%	-84%	-29%	-29%

Table 5: Release Rates & Fireball Modelling – Results Comparison

ID [mm]	Contents	Spontaneous Ignition (m)	Piloted Ignition (m)	Standard Escape (m)	Vulnerable Escape (m)
157	Methane (100%)	35	53	15	57
	Hydrogen (100%)	28	37	13	30
	% difference	-20%	-31%	-15%	-48%
700	Methane (100%)	131	215	119	349
	Hydrogen (100%)	124	164	104	204
	% difference	-5%	-24%	-13%	-42%

Table 6: Safety Distances from a Jet Fire – Results Comparison

Figure 4 show the heat flux comparison for methane and hydrogen using MISHAP FBALL. As indicated very close the pipeline the heat flux from hydrogen is slightly higher but then decreases beyond a distance of around 75m for the pipeline case considered.

Table 6 presents a comparison of the escape distances, which are typically assessed in MISHAP. Note these are not safe distances but rather distances from which escape is possible in the absence of any available shelter. The results show a reduction for the pure hydrogen case for both the smaller and larger pipeline size. This is primarily driven by the reduced heat flux with hydrogen.

Figure 5 presents a spatial comparison of the standard escape distance for a pipeline segment in a rural setting. To fully assess the safety distance, the risk has to be calculated which is typically performed for an individual and society. The methodology used for this is as per HSE MISHAP.

Figure 6 presents the results for the individual risk for all four cases considered. The risk closer to the pipeline is higher for the hydrogen case. This is primarily driven by the increased ignition probability (built into the event tree). Further away from the pipeline, the risk from hydrogen reduces compared to methane, which reflects the reduced heat flux from hydrogen. The zero-risk distance for the 0.7m ID case for methane is 263m, whilst for hydrogen it is 165m, a reduction of 37%. The results for the small diameter (0.16m ID) are also presented, but the differences are less pronounced; 28% reduction in the zero-risk distance but only a relatively small increase in risk closer to the pipeline.

Figure 7 presents the societal risk results against the IGEM TD1 criteria [19]. For the 0.7m ID cases, the societal risk from methane marginally exceeds the IGEM TD1 criteria, whilst for hydrogen the risk is even higher, which is again driven by the significantly higher ignition probability assumed in the event tree. (Note: the intention here is not to determine the absolute risk level to assess mitigations but rather to explore the differences.) The assumed ignition probability was 60% more (probability of all events resulting in a fire) for hydrogen to account for the lower mini-

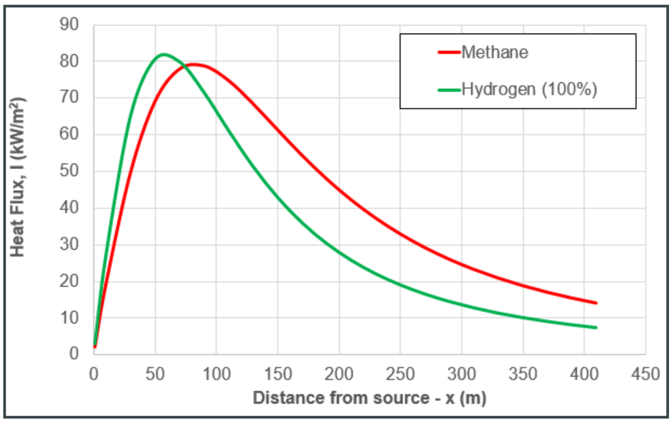

Figure 4. Fireball Heat Flux Comparison (MISHAP FBALL) (ID = 0.7m, 70 bar)

Figure 5: Standard Escape Distance – Methane (red) vs Hydrogen (green) (ID = 0.7m, 70 bar)

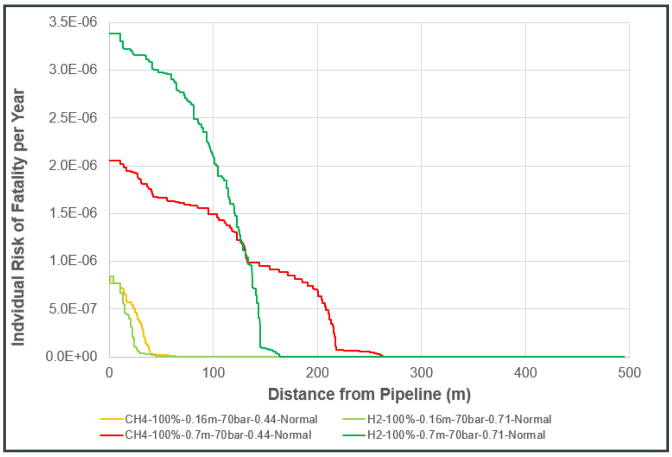

Figure 6: Individual Risk Results

mum ignition energy and increased flammability range. This value is considered conservative, however as noted before it is a function of other factors, such as input energy, and as such would need to be reviewed and assessed on a case-by-case basis. For the small diameter pipeline, the risk for hydrogen is in fact lower than that of methane (ignition probability the same for both diameters).

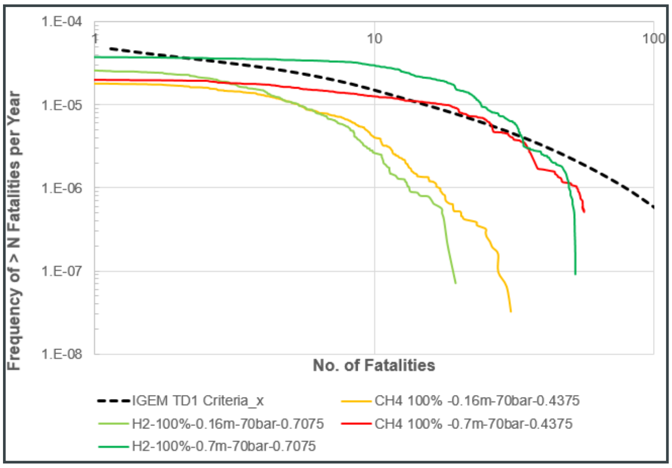

Figure 7: Societal Risk Results

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8. CONCLUSIONS

A revised QRA methodology, based on the HSE MISHAP guidance, is presented for use with hydrogen pipeline assessments. The main amendment to the MISHAP guidance was made for the jet fire model for which an alternative single-source model used in the ASME codes is adopted. The results show an approximate 30% reduction in the escape distances for hydrogen transport, which is due to the reduced heat flux. However, the significantly higher ignition probability results in an increased individual risk with hydrogen. The results showed an increased individual risk close to the pipeline with hydrogen, but the risk reduces faster compared to methane resulting in a lower risk further away from the pipeline. Though there is also an increased societal risk, it was only found for the larger diameter pipeline considered. Thus, the increase ignition probability of hydrogen is a key factor to be assessed and its value should be selected with due care.
As acknowledged, various elements are currently being researched further to better define use with hydrogen pipeline QRAs. The methodology presented provides a robust basis for QRAs of hydrogen pipelines based on existing and accepted industry guidance.

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Ductile fracture propagation control in modern high strength steel pipeline for transportation of high pressure natural gas with H2 and CO2 contents: arrest requirements evaluation by numerical tool and full-scale testing verification

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Abstract

One of the most severe accidents which could occur in a gas transmission pipeline involves the linepipe wall failure and subsequent fracture initiation, which may evolve in a long running fracture propagation if the material toughness properties are not adequate. The most acknowledged approach for ductile fracture propagation assessment is the Battelle Two-Curve Method (BTCM), which has been developed in the '70s for gas transmission pipelines, validated against hundreds of experimental tests over the last decades and now incorporated in international standards and recommendations such as ISO, API and DNV-GL.

RINA, on behalf of Sinopec Petroleum Engineering Corp. (SPE), performed a full-scale burst test in the framework of the Xinjiang Coal-to-Gas Delivery Pipeline Project on a pipeline transporting coal gas containing H2 and CO2 impurities. In addition, a state-of-the-art tool has been developed which applies the BTCM and provides valuable inputs for pipeline design engineers in terms of minimum material toughness for having an arrest, as a function of initial pressure and temperature, gas composition, pipeline geometry and material grade.

The present paper shows the theoretical and experimental activities carried out on ductile fracture arrest topic and the main software features. Software predictive capabilities are discussed together with suggestions on proper correction factor to apply for different pipeline scenarios.

1. ABBREVIATIONS AND ACRONYMS

- BTCM: Battelle Two-Curve Method Battelle
- CATC: Crack Arrest Toughness Calculation model
- CVN: Charpy V-Notch
- DWTT: Drop-Weight Tear Test
- FSBT: Full-Scale Burst Test
- GERG: European Gas Research Group
- HSAW: Helical Sub-merged Arc Welded
- LSAW: Longitudinal Sub-merged Arc Welded
- OD: Outer Diameter
- PICPRO®: PIpe Crack PROpagation code
- REFPROP: REFerence Fluid PROPerties code
- SMYS: Specified Minimum Yield Strength
- SPE: Sinopec Petroleum Engineering Corporation
- TP: Pressure Transducer
- TW: Timing Wire
- WT: Wall Thickness
- UT: Ultrasound Testing

2. PROJECT BACKGROUND

The Xinjiang Coal-to-Gas Transmission Pipeline Project is an ambitious project led by SPE aimed at delivering gas from Xinjiang Uygur autonomous region to Zhejiang province through Guangdong by realizing an 8,000-kilometre main gas pipeline made by API 5L X80 grade steel, 48" outer diameter, 18.4-22 mm wall thickness linepipes. Among all the technical issues SPE is facing, one is specifically related to the nature of the transported gas. Being generated by coal gasification, the gas contains a few percentage of hydrogen (H2) and carbon dioxide (CO2) which might influence the capability of the linepipe material to arrest a propagating ductile fracture. For the present project, it has been envisaged that typical gas composition could include CO2 up to 4% and H2 up to 8%, for a gas total internal pressure up to 12 MPa.

3. DUCTILE FRACTURE PROPAGATION CONTROL

A propagating ductile fracture is driven by the energy released by the expansion of the internal fluid at the tip of and behind the fracture. During fracture propagation a large plastic deformation field takes place around the crack tip, leading to steel work hardening, as well as ovalisation and flattening of the pipe ahead of the crack tip. Under steady-state conditions, a ductile fracture propagates at a constant velocity governed by the balance between the local gas pressure and toughness of the steel. If the toughness lowers, the fracture speed increases, and new steady-state propagation conditions may be reached. If the toughness increases, the fracture speed drops down, with a new steady-state propagation condition possibly achieved. If the toughness is high enough, no steady-state propagation conditions can be reached and fracture slows down, turns in a spiral direction, and finally arrests. Figure 1 shows an example of fracture propagation that was arrested.

Figure 1: Example of ductile fracture propagation in a Rina test on a gas pipeline

Ductile fracture propagation, in case occurs, is usually controlled by specifying a minimum toughness of the linepipe material able to ensure a fracture arrest. Usually the minimum transverse upper-shelf Charpy V-notch impact energy is used and calculated according to a given model, the most used being the Battelle Two-Curve Model, BTCM ([1]), as also stated in Annex G of [2] and [3]. The BTCM considers the resistance to ductile fracture and driving force separately; the driving force is due to the gas decompression and is function of gas composition, temperature and internal pressure while the resistance force depends upon linepipe material and geometrical properties (Figure 2).

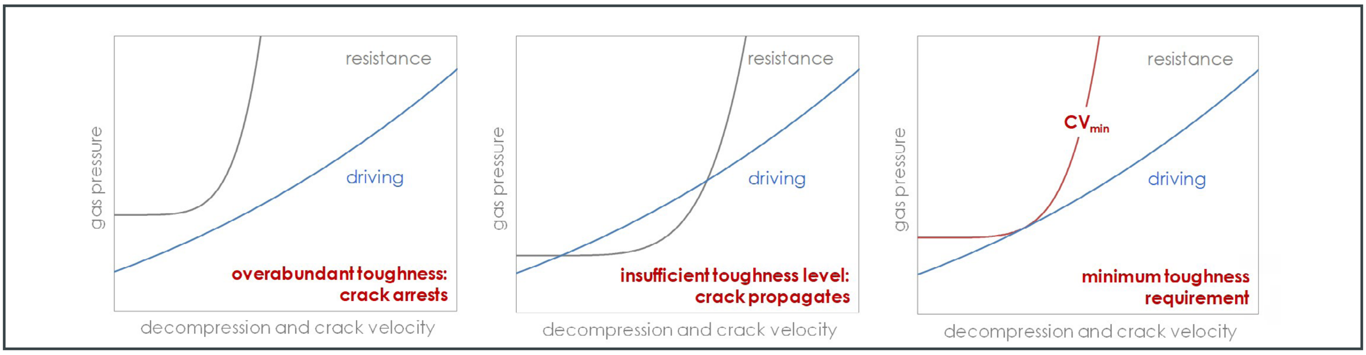

Figure 2: Illustration of the Battelle Two-Curve Model (BTCM) concept

The BTCM for controlling propagating ductile fractures has validity limited to welded pipes with hoop stress not greater than 80 percent of SMYS, gas pressure up to 12 MPa, line pipe grades not exceeding API 5L X80, and Charpy V-notch impact energy derived by this method not greater than 100 Joule (Annex G.9 of [2] and [3]); when the predicted arrest toughness is higher than 100 Joule, it is necessary to apply a proper correction factor involving specialist advice. In general, when outside the validation range, the material fracture behaviour should be evaluated or verified through experimental full-scale testing which is considered the most general approach applicable to pipeline design outside the existing experimental databases (Annex G.11 of [2] and [3]).

The transported fluid composition may significantly increase the applied driving force, so affecting fracture arrest ability. Therefore, it is important to evaluate the effect of fluid composition on its decompression in case a pipeline failure is envisaged.

In the project described in this paper, the majority of the fluid was methane with limited contents of H2 and CO2. Concerning small H2 content in the conveyed gas, it can be anticipated that it does not significantly affect the gas decompression curve for the gas composition envisaged in this project, and hence the driving force applied. However, H2 may affect material toughness, since it may cause H2-embrittlement of the linepipe steel. In carbon-steel pipeline the severity of the embrittlement in presence of gaseous hydrogen depends upon both gas pressure and steel microstructural features [4]. Embrittlement due to gaseous hydrogen transportation in carbon-steel materials has been studied revealing a fracture toughness decrease in presence of defects under both static and cyclic loads (see for instance [5] and [6]); material toughness resistance in presence of gaseous H2 may be assessed according to proper standards [7]. On the other hand, the CO2 presence in small quantities has been found to affect the gas decompression curve. In the following of the paper the effect of varying the amount of H2 and CO2 on fracture arrest ability is discussed.

Even though it is not the case of the project described here, for the sake of completeness it is important to briefly introduce the case of supercritical/liquid CO2 pipelines; compared to pipelines conveying natural gas where pressure reduces continuously during decompression, pipelines conveying CO2 will be exposed to a roughly constant critical pressure (plateau in the gas decompression curve) which implies a higher driving force applied (Figure 3), also depending on the remarkable effect of impurities combination. Standards like ISO 27193 [8] and DNVGL-RP-F104 [9] specify how to deal with fracture propagation control for CO2 pipelines, i.e. when the fluid transported is mainly CO2 possibly with impurities. The methodology for calculating the arrest pressure in CO2 pipelines should be validated through specific fracture arrest testing or by existing fracture testing database, with adequate safety consideration. In this regard, it should be considered that fracture propagation occurred in some tests on dense phase CO2-rich mixtures pipeline, even though the saturation pressure was below the predicted arrest pressure [9].

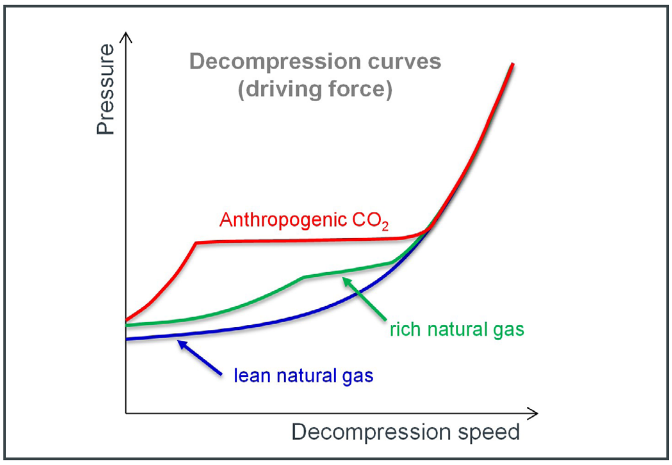

Figure 3: Example of different decompression curves for lean and rich natural gas, and anthropogenic CO2

4. DECOMPRESSION MODEL

The Xinjiang Coal-to-Gas Transmission Pipeline is not designed to transport 100% CO2 or H2, however their potential detrimental effect on gas decompression behaviour, particularly as far as CO2 content is concerned, shall be considered and experimentally validated.

In order to select the decompression model for the project, a literature survey has been performed, focused on pipeline transportation and Oil&Gas sector in general, to collect all the published experimental results from tests performed on pipeline conveying gas and CO2 mixtures (including two tests carried out by RINA [10]). The REFPROP code [11], (REFerence Fluid PROPerties) has been selected, which is developed and distributed by the National Institute for Standards and Technology (NIST) and implements the GERG 2008 equation [12]. REFPROP calculates the thermodynamic and transport properties of industrially relevant fluids and their mix, which can be used as main inputs for the decompression curve calculation. The chemical species that can be solved by REFPROP include CO2 and H2 as either pure fluids or mixed to various chemical compounds. Even though REFPROP may exhibit some limits in convergence when high O2 and N2 contents are present in the mixture, it is able to account for a large number of impurities among the ones typically present in anthropogenic CO2 mixtures. An additional advantage of using REFPROP is that it is continuously maintained by an independent institute (NIST) and is well accepted by the Oil&Gas industry.

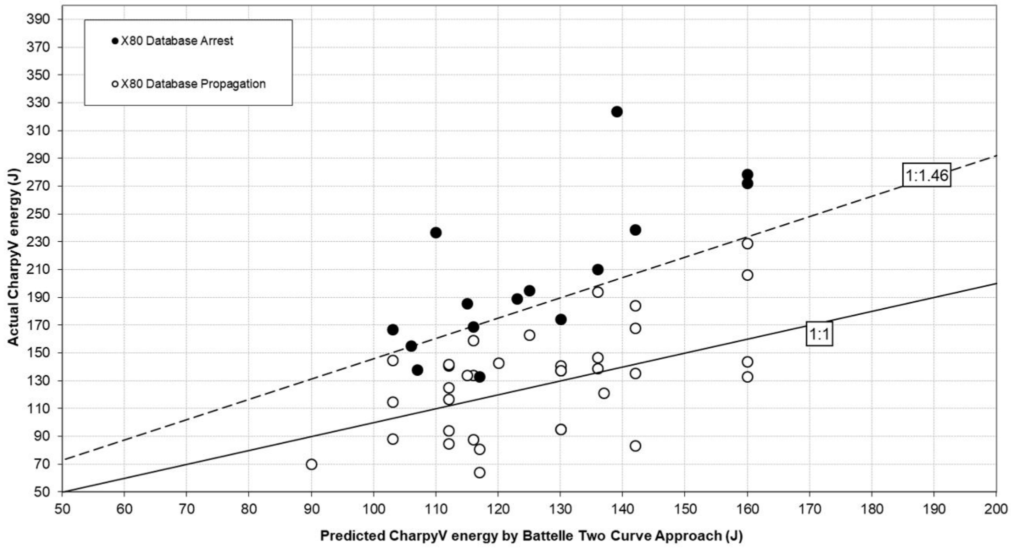

Figure 4: Actual and predicted Charpy V-notch energy for X80 past burst tests (excluding the test carried out for the present project and Russian tests [14])

5. EVALUATION OF THE BTCM CORRECTION FACTOR

As already mentioned, one of the most acknowledged methods to evaluate the minimum toughness requirement for having an arrest of a ductile fracture propagation is the BTCM; unfortunately, it has been validated within a specific range of testing conditions, and the present project falls outside the validation range due to gas composition, in particular for the presence of CO_2 and H_2.

An attempt of overcoming the inadequacy of the BTCM to properly predict the toughness requirements outside its range of validation consists in adopting an appropriate correction factor calibrated on the basis of past experimental experience and as close as possible to the situation being evaluated. The experimental results database of full-scale fracture propagation tests on large diameter (≥36") and high pressure X80 pipes were compared to BTCM predictions, [13]; it was seen that a multiplying factor of 1.43 applied to the predicted value was sufficient to ensure that no propagation points appeared below the propagation/arrest boundary. The correction factor was very recently updated to 1.46 after the execution of the most recent tests (see in the following) and is considered valid within the range of tests data considered; therefore it should be validated again if new conditions are envisaged outside the database limits.

In this regard, with the aim to verify and show the best correction factor for the project, the available results of ductile fracture propagation tests carried out on X80 linepipes have been collected and reported in Table 1, which does not include neither the test carried out for the present project nor the tests carried out in Russia [14] (Russian tests have not been included since no details are available about toughness properties of the single tested line pipes but just the average Charpy V-notch value of line pipes used in each test).

The minimum requested Charpy V-notch energy value predicted by the BTCM has been compared with the actual Charpy V-notch energy value. As it is evident from Figure 4, BTCM "as is" is proven not to achieve effectiveness in predicting the minimum arrest conditions for the X80 tested pipes. Indeed, pipe points lie well above the BTCM predictions (1:1 slope line) and a conservative correction factor can be identified in 1.46; applying such factor all the propagation pipes are in fact correctly predicted (no propagation mis-predictions) even if some arrests are mis-predicted as propagations (i.e. conservative mis-predictions). An attempt has been made to consider also Russian tests results: in this case the correction factor grows up to 1.65; such value should be considered with caution since published Russian tests data are not complete, as mentioned above.

Correction factor values given above (either 1.46 or 1.65, the latter if also Russian tests are considered), refer to X80 pipeline steels pressurized with different media (air, natural gas, rich gas).

6. CRACK ARREST CALCULATION SOFTWARE

As an outcome of the project, a crack arrest calculation software was developed. The software is able to deal with different pipeline geometries, steel grade and operating conditions in terms of temperature, pressure and gas composition, that is both pure gas and mixtures containing several species including CO_2 and H_2.

The software, named CATC (Crack Arrest Toughness Calculation model), is based upon the BTCM and makes use of GERG2008 equation for calculating the decompression curve starting from operating conditions and gas composition. Main outcome of CATC is the minimum Charpy V-notch energy value for arresting the ductile fracture propagation; both driving force and resistance curves can be plotted. In addition, the code allows considering different backfill conditions, that is null (air), soil and sea (marine) making use of specific soil coefficients [16]. A user-friendly graphical interface has been developed and, if needed, a report file can be automatically generated.

In this project, the CATC tool has been used to evaluate the minimum toughness BTCM requirements for arresting a potentially propagating ductile fracture along both LSAW and HSAW pipes considered for the full-scale propagation burst test (Table 3), which correspond to the tangency point between the driving force identified by the gas decompression curve and the resistance curve, as prescribed by the Battelle Two-Curve Model [1]. A gas mixture of 94% natural gas (99% methane), with 1% nitrogen, 2% carbon dioxide and 3% hydrogen (mol%) was used as pressurizing medium at a pressure of 12.0 MPa, that is in correspondence of a hoop stress of 397 MPa (0.72 SMYS), calculated for the HSAW pipes wall thickness. This was the gas composition used in the full-scale test described in the following of this paper. The calculation diagrams are provided in Figure 5, where is clear that, for the specific project conditions, the low CO2 percentage does not seriously affect the decompression curve, at least from an analytical perspective, as instead occurs with a plateau development for a 100% CO2 decompression.

CATC also allows the user to consider a specific correction factor, which for API X80 envisaged in this project is in the range of 1.46-1.65. Therefore, the minimum toughness requirements have also been corrected by using such correction factors: Table 2 reports the tool predictions in terms of "as is" values (i.e. without any correction) and corrected values. Looking at the table, test predictions indicate a rapid arrest in the initiation pipe / first pipes (after the initiation).

7. FULL SCALE BURST TEST AND SENSITIVITY ANALYSIS

As an outcome of the project, a crack arrest calculation software was developed. The software is able to deal with different pipeline geometries, steel grade and operating conditions in terms of temperature, pressure and gas composition, that is both pure gas and mixtures containing several species including CO2 and H2.

Number of X80 full scale tests	12 tests (6 tests carried out by RINA)
Number of X80 pipes involved	61 pipes
Pipe outer diameter	610 mm (24") to 1422 mm (56")
Pressurizing medium	Lean gas, air, rich gas
Charpy V-notch energy	65 Joule to 325 Joule
Pressure	9.35 to 18.52 MPa
Test date	Tests were carried out mainly in the '80s. Other tests were carried out end of '90s (RINA test [15]) and in 2007-2008
Type of pipes	All longitudinally welded (no spiral) pipes

Tbale 1: RINA X80 full scale burst tests database (excluding the test carried out for the present project and Russian tests [14])

Pipes	BTCM "as is" calculation	X80 correction factor (1.46-1.65 BTCM)
HSAW	117 J	171-193 J
LSAW	88 J	128-145 J

Table 2: BTCM predictions "as is" and "corrected"

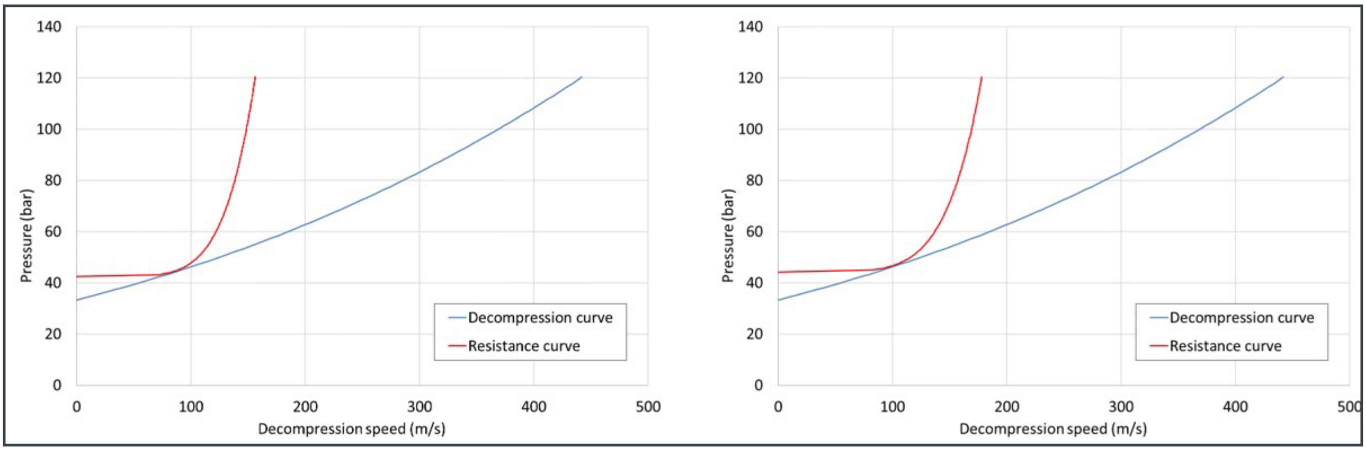

Figure 5: Battelle Two-Curve Model application to the west side (left) and east side line (right)

		SINOPEC - Full Scale Burst Test Nominal Outer Diameter: 48 inches; Nominal Wall Thickness: 22.0 mm LSAW, 18.4 mm HSAW Test pressure 12.0 Mpa										
Pipe ID		**W5**	**W4**	**W3**	**W2**	**W1**	**I**	**E1**	**E2**	**E3**	**E4**	**E5**
Pipe Type		HSAW	HSAW	HSAW	HSAW	HSAW	LSAW	LSAW	LSAW	LSAW	LSAW	LSAW
Actual test linepipe length (m)		8.93	9.70	10.69	10.67	10.74	8.63	10.66	10.55	9.55	10.72	10.71
$R_{t\ 0.5\%}$ (MPa)	*Source: pipe mill*	596	588	665	622	644	658	662	662	641	633	624
$R_{m\ 0.5\%}$ (MPa)	*Source: pipe mill*	701	668	733	682	706	769	770	768	709	704	701
$R_{t0.5}$ / R_m (MPa)	*Source: pipe mill*	0.85	0.88	0.91	0.91	0.91	0.86	0.86	0.86	0.90	0.90	0.89
CVN (J) @ +0°C or +10°C	*Source: pipe mill*	446	395	377	290	252	229	230	266	316	362	394
CVN (J) @ +10°C	*Source: Rina lab*	329	321	343	305	344	177	198	265	331	294	327
DWTT ave. total energy (J) @ +10°C	*Source: Rina lab*	11386	11225	11426	11688	11684	8514	7906	9028	13002	12834	13043
DWTT Shear Area (%)	*Source: Rina lab*	100	100	100	100	100	100	100	100	100	100	100

Table 3: Test layout and pipe properties

The software, named CATC (Crack Arrest Toughness Calculation model), is based upon the BTCM and makes use of GERG2008 equation for calculating the decompression curve starting from operating conditions and gas composition. Main outcome of CATC is the minimum Charpy V-notch energy value for arresting the ductile fracture propagation; both driving force and resistance curves can be plotted. In addition, the code allows considering different backfill conditions, that is null (air), soil and sea (marine) making use of specific soil coefficients [16]. A user-friendly graphical interface has been developed and, if needed, a report file can be automatically generated.

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7. FULL SCALE BURST TEST AND SENSITIVITY ANALYSIS

In order to determine the capability of the linepipes selected for the project to arrest a ductile fracture propagation, a full scale burst test has been carried out on 48" outer diameter API 5L X80 grade steel pipes, wall thickness 18.4-22mm, pressurized at 12 MPa using a gas mixture representative of coal-to-gas.

The test has been carried out using pipes manufactured by different Chinese producers; in particular, the test section was made of 11 pipes (1 initiation pipe and 10 test pipes) for a total length of 111.5 m (Table 3). The west test side was made of helical welded pipes (HSAW), 18.4 mm wall thickness, whereas east test side was made of longitudinal welded pipes (LSAW), 22 mm wall thickness; also, the initiation pipe was longitudinal welded.

The selection of pipes was carried out with the aim to identify pipes with low, medium and high toughness values in order to have a test layout as much as possible with a classic telescopic toughness variation, i.e. increasing from the initiation pipe towards the two ends of the test line. Actually, it was unfeasible to find out pipes produced having the requested characteristics of very low toughness for the initiation/propagation pipes. Nonetheless, the test pipes selection is quite representative of current production available in the Chinese market.

Figure 6: Test line fully instrumented

Figure 7: Test onset after 2sec (left) and 9sec (right)

Test pipes were laid in the trench, girth welded and fully instrumented (Figure 6) in order to measure fracture speed, pressure onset and decay during the test, gas and pipe wall temperature, elastic and plastic deformation (on selected pipes). In addition, in order to evaluate the consequences of the burst and subsequent gas combustion in the environment, a set of blast pressure and thermal heating transducers were placed in the surroundings.

Once instrumented, the test line was fully buried. Then it was pressurized with the target gas mixture up to 12.0 MPa, and the day of the test fracture was initiated by means of an explosive shaped charge located on the upper generatrix of the initiator (onset) pipe (Figure 7). The pipe wall temperature (around +15°C) was high enough to ensure the fully ductile fracture propagation on pipe material.

The fracture was regularly injected and propagated on the upper pipe generatrix at a very high speed along both directions, sustained by the driving force ensured by the gas decompression at and behind the crack tip. The velocity of the crack propagating during the test has been evaluated through proper electrified wires (named “timing wires”) installed along the line. According to the position of each timing wire along the test line and the time at which its rupture occurred, the local speed has been calculated (see Figure 8). Due to the very high crack speed level, which is typical of burst testing of high-grade steel pipes (especially in the first pipe), small fluctuations in the wires’ rupture time led to high scatter in the crack speed data. As apparent, a light disturbance is still present in the plot which is not to be related to any effective crack speed fluctuation but results from a mathematical elaboration of scattered raw data. To obtain a more meaningful and realistic speed trend, a best estimate has been carried out and results presented in the plot as a black continuous line.

The fracture propagated in the initiation pipe and arrested on first pipes on both west side (pipe W1) and east side (pipe E1), in agreement with the CATC model prediction. Despite some scatter in the toughness values of these two pipes, it can be stated that the experimental behaviour was in agreement with predictions obtained for X80 linepipe steels (using correction factors in 1.46 - 1.65 range). Both arrests presented the typical spiralization path; in particular, the arrest on HSAW W1 pipe was not affected by the presence of the helical weld. The analysis of the fracture surfaces revealed that fracture propagation was fully ductile on all of the fractured pipes (Figure 9).

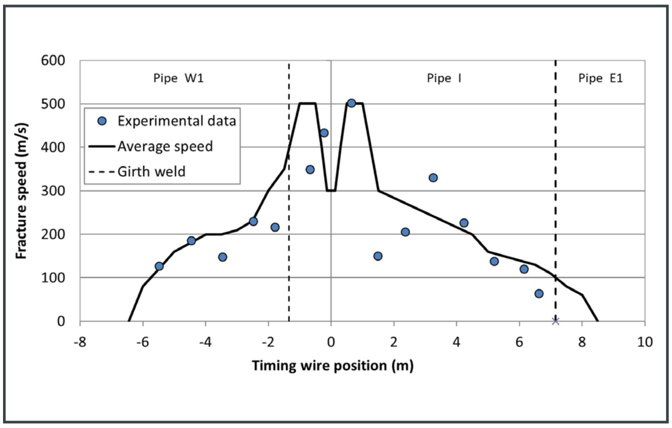

Figure 8: Full-scale burst test crack speed diagram

Figure 9: Overall view of the fractured line

Looking at the test data, it was found that the gas decompression behaviour predicted by REFPROP through the GERG-2008 equation followed well the experimental results gathered through pressure transducers (see an example in Figure 10 for the pressure transducer No. 5 installed on the west side).

Furthermore, a sensitivity analysis has been carried out by simulating the full-scale test through the Rina proprietary tool PICPRO® (PIpe Crack PROpagation), which is able to model a ductile fracture propagation in buried or unburied gas pipelines ([17], [18]). The gas composition influence upon fracture propagation was investigated to evaluate whether small changes in CO2 and H2 amount could affect the gas decompression and, consequently, the arrest ability of the pipes in the project conditions.

In our simulation by using the CATC tool implementing the GERG-2008 equation, the gases with a higher percentage of light components (such as H2) exhibited a faster decompression curve (i.e. lower pressure at the same decompression velocity), whereas gases with higher percentage of heavy components (such as CO2) showed a slower decompression curve (i.e. higher pressure at the same decompression velocity). Those decompression curves have then been used in the PICPRO® simulations, whose results are shown in Figure 11 for seven different compositions. The black dashed line represents the simulation of the full-scale test, i.e. with the actual gas composition used in the test: among the cases accounted for in the analyses, the gas composition leading to the most severe fracture propagation has been found to be that with CH4=92%, H2=3%, CO2=4%, N2=1%, and such behavior can be ascribed to the higher CO2 percentage. It should be observed that in none of the examined cases, the fracture was predicted to reach pipes W2 or E2. Therefore, W1 and E1 pipes had toughness values high enough to arrest fracture propagation in all the cases under examination.

8. CONCLUSIONS

One of the most challenging technical topics faced in the Xinjiang Coal-to-Gas Transmission Pipeline Project is related to the nature of the transported gas. Being generated by coal gasification, gas contains a small percentage of hydrogen (H2) and carbon dioxide (CO2) which might influence the capability of the linepipe material to arrest a propagating ductile fracture.

RINA, on behalf of SPE, performed a full-scale burst test on selected Chinese X80 linepipes reproducing the project operating conditions, demonstrating that toughness properties of the selected linepipes were good enough to arrest the fracture in short distance. More in general, the full-scale burst test has demonstrated that pipes available in current Chinese production selected by SPE for testing were able to arrest a propagating ductile fracture occurring at the project operating conditions.

In addition, RINA developed for SPE a state-of-the-art software (named CATC) which applies the Battelle Two-

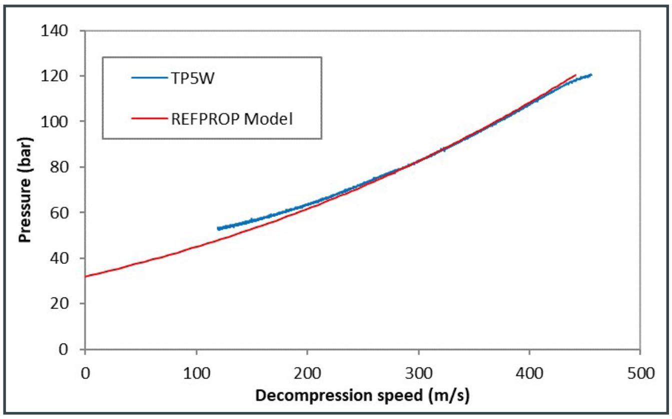

Figure 10: Experimental-to-theoretical decompression curves comparison

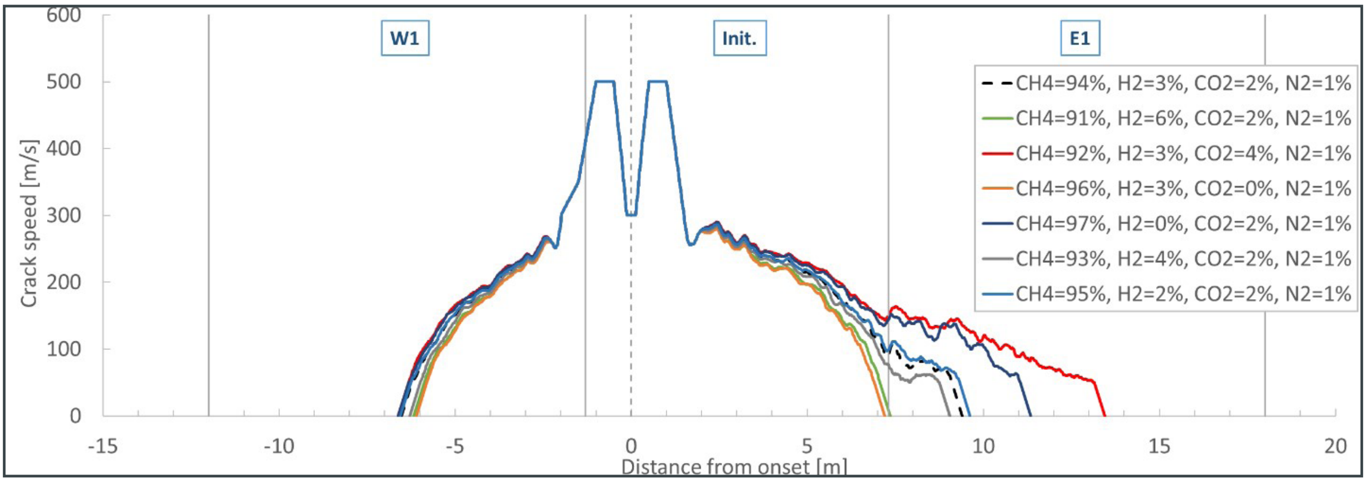

Figure 11: Crack speed dependence on gas composition (expressed in mol%) as calculated by RINA's PICPRO® software

Curve Model and provides valuable inputs for pipeline design engineers in terms of minimum material toughness for having an arrest, as a function of initial pressure and temperature, gas composition, pipeline geometry and material grade. The software has been applied in this project to evaluate the gas decompression curve and the minimum linepipes toughness requirements to achieve a ductile fracture arrest. In addition a sensitivity analysis varying the gas composition has been performed by jointly using CATC and RINA's PICPRO® software (the latter being a Finite Element Model able to simulate a full scale burst test), the results indicated that even for the worst case considered (92% CH_4, 3% H_2, 4% CO_2, 1% N_2) the selected pipes are able to arrest the ductile propagating fracture.The test has been performed in presence of 3 mol% H_2 in dry gas composition. It has not been found any material embrittlement after the observation of post-test fracture surfaces, that resulted fully ductile. However, it is worth remarking that the test performed in this project is not intended to evaluate the effect of the hydrogen on an existing crack in presence of either static or cycling tension loading, and the effect of the hydrogen on mechanical properties, such as potential reduction of tensile resistance, ductility or upper-shelf energy. These issues are worth a specific study and specialist advise.

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Qualification of High-Strength Linepipes for Hydrogen Transportation based on ASME B31.12 Code

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Abstract

A number of CPW manufactured HFW and SAWL pipes were tested for fracture toughness properties in high pressure 100% hydrogen environment. All tests were performed in RINA laboratory, following a developed test procedure based on code ASME B31.12 Option B (qualification of the material threshold stress intensity factor KIH).
Testing involved API 5L grades of quality X60M to X70M, with a hydrogen test pressure of 80bar and varying applied stress intensity factors 110-145 MPa·√m.

Following a test exposure of 1000h, all parent material, weld and HAZ specimens presented an excellent resistance to hydrogen embrittlement showing no measurable crack propagation from the fatigue pre-crack front.
Based on the results, a KIH value of 55 MPa·√m and above was established in all cases, fulfilling the minimum qualification criteria of ASME B31.12 Option B

1. INTRODUCTION

Hydrogen is the most environmentally friendly carrier of energy: when consumed it solely emits water. Energy carrier means that its potential role has similarities with that of electricity. Both hydrogen and electricity can be produced by means of various energy sources and technologies. Both are versatile and can be used in many different applications. No greenhouse gases, particulates, sulfur oxides or ground level ozone are produced from the use of either hydrogen or electricity [1].

Conversely, hydrogen can be produced in an environmentally sustainable way by using only water and energy. This excellent energy solution requires however currently costly electrolysis equipment and is accompanied by a substantial energy loss during the extraction process. Nevertheless, also under this aspect, R&D efforts are producing important results with more efficient and cost effective electrolyzers available in the near future [2].

Consequently, hydrogen is currently enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly; in July 2020, EU Commission adopted a new dedicated strategy on hydrogen in Europe: the strategy explores actions to support the production and use of clean hydrogen, focusing in particular on the mainstreaming of renewable hydrogen. The strategy highlights a condition for a widespread use of hydrogen as an energy carrier in the EU is the availability of energy infrastructure for connecting supply and demand, and this can be done in a cost effective way via pipeline. Hydrogen offers ways to decarbonize a range of sectors, as well as helps improve air quality and strengthen energy security. Although hydrogen can be produced from a wide variety of fuels, its greatest potential lies in assisting with variable output from renewables, like solar photovoltaics and wind, whose availability is not always well matched with demand. As a result, hydrogen is one of the leading options for long term storing of converted electricity.

The production of hydrogen from renewables can be achieved at lower cost in regions with abundant solar and wind resources. For large volumes and long distances, transportation via pipelines to large energy consumers is the most financially attractive alternative [3] [4]. Additionally, blending hydrogen into natural gas has been proposed as a mean of delivering pure hydrogen to markets, by using separation and purification technologies downstream in order to extract hydrogen from the natural gas-H2 blend close to the point of end use [5]. Blending hydrogen would provide a boost to hydrogen supply technologies without incurring the investment costs and risks of developing new hydrogen transmission and distribution infrastructure. [1].

The recent interest in developing a hydrogen-based energy economy resulted to the need for hydrogen compatible materials to the forefront, especially dealing with the effect of Hydrogen Embrittlement (HE). HE is the degradation of the mechanical properties of a metal, most frequently manifested by the emergence of low energy fracture mechanism when exposed to hydrogen.

The phenomenon of HE has been recognized since 1875 [6] and has been extensively studied. While the fundamental mechanism behind HE is a matter of continuous investigation from the scientific community, the amount of data on the effect of hydrogen on mechanical properties of different metals and alloys made the standardization of appropriate materials possible, for a number of applications involving gaseous and liquid hydrogen systems. [7].

2. STATUS OF CARBON STEEL HYDROGEN LINEPIPES

The transport of gaseous hydrogen through pipelines has been realized by use of mild carbon steel for almost a century and it is estimated that there are over 4,500 km of hydrogen linepipes in operation worldwide [8]. Typically, hydrogen linepipes are designed to transport gas over only short distances, from the production facility to the end user. Many such applications operate with a very good safety record but at maximum pressures which are considerably less than the ones that would be required for long-distance pipeline transmission of hydrogen [9]. In addition, typical pipeline size is 300mm or less, manufactured with X52 or lower strength steels [10] and in comparison to natural gas, H2 pipelines normally operate at relatively conservative conditions.

However, owing to the low volumetric energy density of hydrogen (0.0108 MJ/L) in comparison to natural gas (0.0364 MJ/L) and the forecasted expansive utilization of renewable energy sources mentioned in section 1, it will be necessary to transmit hydrogen at high pressures using large size pipelines in order to be financially competitive. The combination of high pressure and large size pipe demands the use of higher strength steels.

The advantages of specifying a higher grade line pipe for transportation of hydrogen or hydrogen-gas mixtures can be substantial: According to independent analysis [11], for a baseline scenario using a 24'' HFW longitudinal pipe operating at 1,500psi (10.34MPa), the use of X70 material can result into cost savings up to 31% relative to the use of X52.

The amount of published results on the effect of hydrogen to the mechanical properties of higher grade API line pipe steels under high pressure is rapidly increasing and results of systematic work have been presented by NIST and Sandia National Laboratories. According to published work [10] [12], a number of toughness tests on API carbon steels have shown that the absolute fracture toughness remained high under high pressure hydrogen conditions, even though it was lower than respective measurements in air or inert gas. In addition, a comprehensive testing program to determine fatigue crack growth rate of pipeline steels in pressurized hydrogen gas verified no change in FCGR (Fatigue Crack Growth Rate) with increasing yield strength up to X100 [13].

K. Xu [10], reviewed a number of published results for carbon steels up to X70 and 10.3MPa test pressure when tested under static loading condition and no subcritical crack extension was exhibited under various loading conditions. The same report presents also a number of rising load method fracture toughness KJC tests for micro alloyed steels up to X80 in 6.9MPa H2 where the measured fracture toughness was found above to be 95 MPa·m1/2 in all cases. San Marchi et al [12] [14] reported also fracture toughness values in the range of 80 to 100 MPa·m1/2 using a rising load test method in high pressure gaseous hydrogen (5.5 and 21MPa) for two X60 and X80 pipeline steels.

In comparison to plain carbon ferritic steels, API 5L steels of higher grade typically contain additional alloying elements, such as small quantities of niobium and titanium. These "microalloying" additions as well as processing by thermomechanical rolling provide a combination of elevated strength with excellent low temperature fracture toughness. In metallurgical terms, many modern higher grade API 5L steels utilise a ferrite/bainite or ferrite/acicular ferrite microstructure to attain these properties. The lower pearlite volume fraction of these steels is considered to provide enhanced hydrogen resistance, an effect obtained by reducing the amount of H2-trapping sites i.e. the interfaces between microstructural constituents [15] [16].

3. APPLICABLE STANDARDS AND PRACTICES

There is a limited number of standards that can be used for material qualification for pipeline gaseous hydrogen transportation:

- International European standardization bodies are working in revising EN 1594, EN 16348 and EN 12732 in order to consider H2 and H2NG mixtures also.
- EIGA (European Industrial Gases Association) published a document (IGC Doc 121/14) which recommends maximum steel grade to be used and suggests testing to be carried out, but with not specific instructions on how to qualify the material.
- ASME B31.12 is a US standard for material qualification for use with H2 and H2NG mixtures. Two basic approaches are adopted: Design Option A and B, that are briefly described hereinafter.

It is worth highlighting EIGA report makes specific suggestions to limit the effects of hydrogen embrittlement on materials, such as appropriate material classes, compositional and strength limits, and suggests appropriate testing methods, but is a recommended practice and not a standard. At the same time, new ISO standards under revision are expected to follow the ASME B31.12 approach for the material qualification of pipelines for high pressure gaseous hydrogen transportation; ASME B31.12 is now the most used standard for material qualification and can be expected to be the reference one also in the next future.

4. ASME B31.12 CODE

The ASME B31.12 Hydrogen Piping and Pipeline Code [17], has been initially published in 2008, in order to deal with design, construction, operation, and maintenance requirements for piping, pipelines, and distribution systems in hydrogen service. The B31.12 committee has developed two design methods that can be considered in conjunction with steel/piping specifications (i.e. API 5L PSL2) and acceptable manufacturing routes for welded pipes (HFW, SAWL or SAWH) [15].

The first (Option A) is prescriptive and similar to design processes contained in ASME B31.8 Natural Gas Pipeline Code. It considers the use of lower basic design factors, F, and a material performance derating factor, Hf, derived from pressure and tensile strength relationships.

The second (Option B) is performance based, using a fracture mechanics approach (on the basis of ASME Section VIII, Div. 3 - Alternative Rules for Construction of High Pressure Vessels). The qualification of the pipeline materials is performed by use of fracture mechanics and crack propagation testing that empowers the use of enhanced design factors and withdraws the limitations on pressure due to the use of the Hf derating factor.

In regards to the second design method, the code introduces additional requirements for pipe material, related to lower Phosphorus content (<=0.015%) and consideration of API 5L Annex G for CVN testing (Enhanced Ductile Fracture Propagation Properties). More specifically, the ASME B31.12 code requires that the threshold stress intensity factor for hydrogen-assisted cracking (denoted as KIH) should be measured according to ASME VIII [18] and ASTM E-1681 [19].

When designing a pipeline for hydrogen transportation, the benefits of compliance with ASME B31.12 Option B can be substantial. This is illustrated in Figure 1 for an API X60M grade: the design factor for Option B can be 72% of the specified yield strength for all applicable pressures up to

20.7 MPa (3,000 psi). On the contrary, the same design factor for Option A is limited to a maximum yield strength percentage of 43,7% or even lower, due to additional limitations of the material performance (Hf¬) factor when the design pressure approaches 3,000 psi (20.7MPa).

The latest version of ASME B31.12, specifies for Option B that fracture toughness qualification testing is required to validate the minimum threshold stress intensity factor (KIH) at the design pressure and 100% H2 concentration. The test on the pipes should be performed at the base metal, weld metal and heat affected zone positions, on three heats of the pipe material. It is highlighted that the tests qualify also other materials with similar chemical composition and tensile properties (Yield and Tensile Strength) up to 5% higher than the qualified ones. Therefore, samples should be selected from the upper end of the tensile properties distribution. The KIH value that qualifies the material in accordance with ASME B31.12 Option B is 50ksi·in1/2 (or 55 MPa·m1/2) unless otherwise specified by design analysis. It should be noted that the latest version of the ASME B31.12 code has removed the requirement to perform specific FCGR testing for the qualification of a hydrogen line pipe and generic curves are provided, applicable for all carbon steels in gaseous hydrogen up to 20.7 MPa (3,000 psi) service pressure.

5. FRACTURE TOUGHNESS QUALIFICATION TESTING

Aimed at validating the performance characteristics of high grade API 5L pipes in pressurized hydrogen, CPW organized a number of fracture toughness qualification (KIH) tests under the ASME B31.12 code Option B scheme, including both High Frequency Welded (HFW) and Longitudinal Submerged Arc Welded (SAWL) pipes. All tested pipe material is presented in Table 1. As presented in Figure

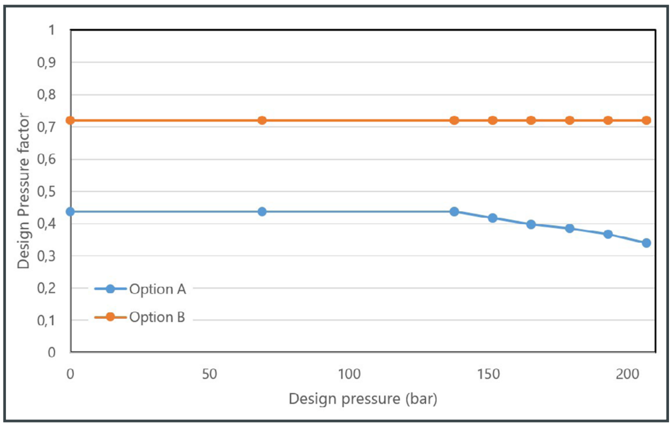

Figure 1: Design pressure factors for X60M for Option B vs Option A in areas characterized as Location Class 1, Division 2

2, the selected pipe dimensions for the HFW pipe, belong to the upper diameter and thickness segment of the 26" mill's product range. All the tests were carried out at room temperature (around +15°C).

6. PROCEDURE FOR KIH TESTING

ASME-based hydrogen material tests were performed in RINA Consulting – Centro Sviluppo Materiali SpA, an acknowledged European Company specialized in the development of new materials and in the performance assessment of materials and equipment in new operating windows; with regard to the subject, RINA has specific skills and laboratories specialized to evaluate materials and components performance in presence of gaseous hydrogen up to 1,000bar external pressure.

Fracture toughness testing protocol in pure hydrogen gaseous environment was determined in terms of KIH for all notch positions in compliance with ASTM E1681 [19]

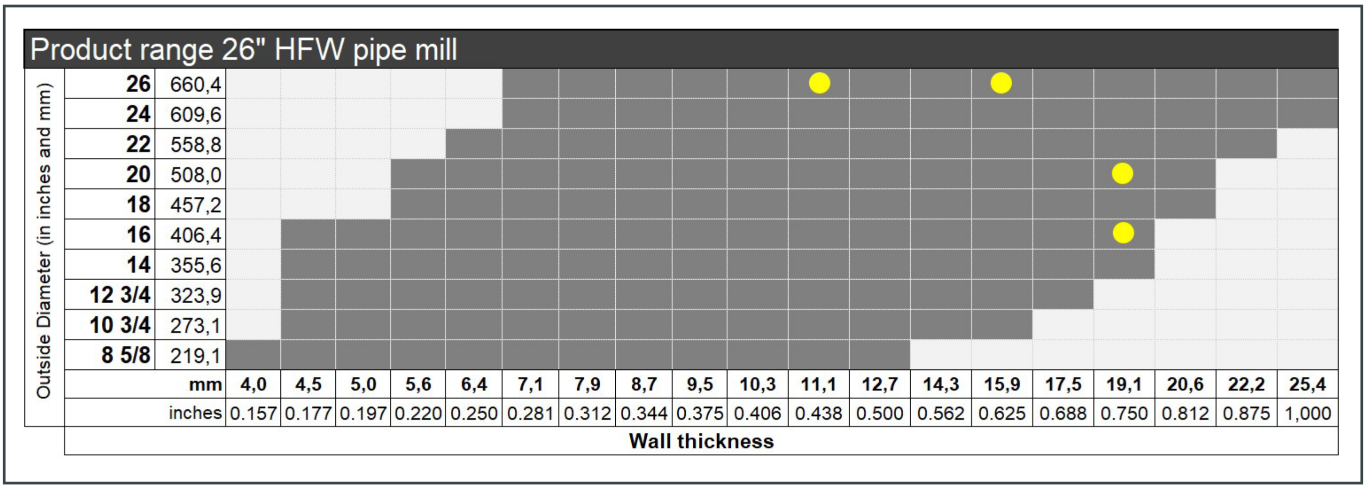

Figure 2: CPW HFW 26" mill product range (yellow points: tested pipes)

Pipe type	Service	OD	WT	Steel Grade	Tensile properties			Steel supplier	Test Pressure	Test Gas
					YS $R_{t0,5}$	*TS* R_m	CVN at -10°C			
		in.	mm		MPa	MPa	J		MPa	
HFW	Onshore	26"	15.9	L415 (X60M)	492	612	299	ArcelorMittal Bremen	8.0	100% H_2
HFW	Onshore	20"	19.1	L485 (X70M)	539	655	275			
HFW	Onshore	26"	11.1	L415 (X60M)	498	627	219			
HFW	Offshore, Reeling	16"	19.1	DNV 450PD (eq. X65MO)	524	605	265	ArcelorMittal Fos-sur-Mer		
SAWL	Onshore	32"	20.0	L485 (X70M)	496	614	284	Voestalpine Grobblech		

Table 1: Overview of CPW pipes tested for fracture toughness (KIH) in pressurized hydrogen

according to the constant displacement configuration, with the additional prescriptions of ASME B31.12 [17] and ASME BPVC Section VIII, Division 3 [18] [20].

The procedure for KIH fracture toughness testing is presented schematically in Figure 3.

Samples are machined in bolt-load compact configuration in compliance with the prescriptions of ASME E1681 [19] for the Modified bolt-Load, Compact Specimen; H/W=0.486, where W/B is 2:1 (Figure 4). No pipe flattening was applied prior to sample machining and the largest possible thickness was obtained depending on pipe curvature. In any case, the request of having at least 85% of the pipe nominal thickness was always satisfied.

The determination of the threshold stress intensity factor involves a specimen containing a machined notch, which is placed in base material and, for HFW pipes, in bond line or, for SAWL pipes in weld metal and Heat Affected Zone crossing the fusion line (Coarse Grain HAZ) at the maximum extent. This notch is extended by fatigue cracking under controlled conditions for maximum loading, especially for the final part of the crack growth. The fatigue precracked specimen is then placed in a glovebox filled with a nitrogen atmosphere, under very low oxygen and moisture levels as required per ASME code.

The specimen is then loaded by means of a bolt to the attainment of the target Crack Mouth Opening Displacement, established on the basis of the target stress intensity

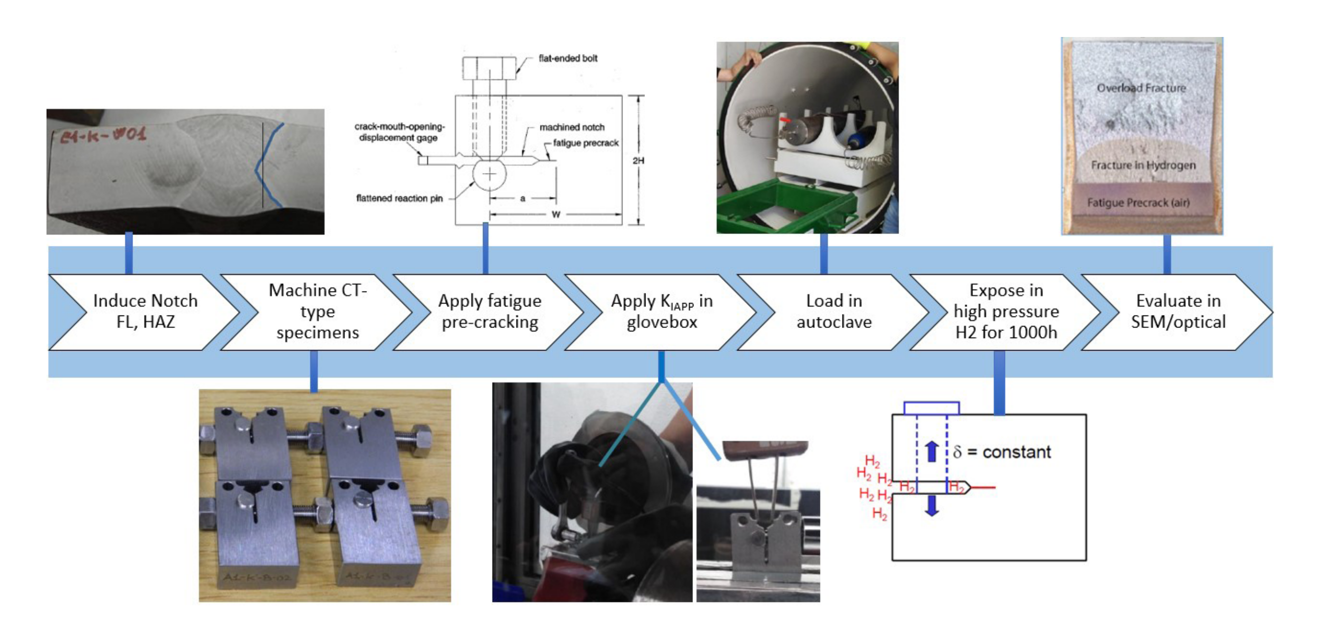

Figure 3: Outline of KIH testing procedure

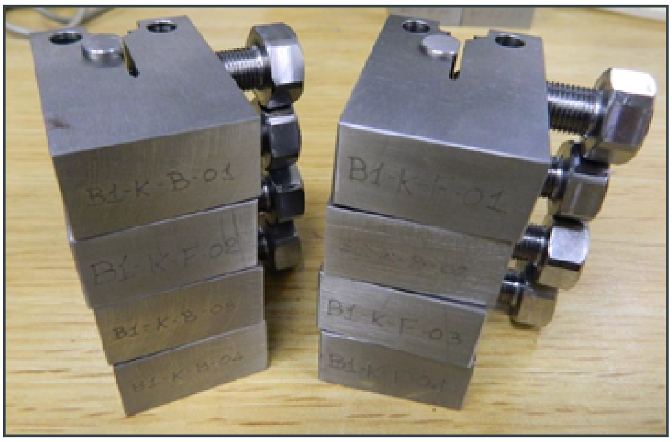

Figure 4: Compact tension specimens in RINA laboratory

KIAPP for plain strain conditions. According to the code, the applied KIAPP should be at least 1.6 times greater than the estimated KIH but not more than 180 ksi·√in (198 MPa·√m). After loading, the samples are put inside the test chamber which is sealed while still inside the glove box, preventing any contact of the loaded samples with atmosphere oxygen and moisture.

The test chamber is then charged with pure hydrogen gas at the target test pressure and maintained at this pressure for 1,000h. In this way, any fresh crack surface that is possibly generated by ductile tearing during bolt loading has never been exposed to oxygen or moisture and is hence prone to hydrogen permeation from the gaseous hydrogen environment.

After the specified test period, the specimen is examined to assess whether the initial fatigue crack did or did not grow. The specimens are heat tinted and broken open in liquid nitrogen. The fracture surface is then examined by optical observation and scanning electron microscope. Measurements of the crack front extent are taken in five positions and the average crack growth in hydrogen is calculated.

7. FRACTURE TOUGHNESS KIH TEST RESULTS AND EVALUATION

The results of all validated fracture toughness KIH tests are summarized in Table 2. Four samples per material/notch were prepared in order to obtain at least three valid results per position. According to KD-1047 clause of ASME code [18] for the constant displacement method, if the average measured crack growth does not exceed 0.01 in. (0.25mm) KIH is equal to 50% of KIAPP. Taking this clause into consideration, the KIAPP initial stress was selected to be at least double of the minimum threshold stress intensity value required by the code of 55 MPa·√m.

No hydrogen crack growth was noticed at any specimen after visual and SEM examination at high resolution. In all cases also the SEM micrographs highlighted a dimpled fracture surface in front of the fatigue pre-crack, extending a few microns (Figure 5). Presence of this surface represents an evidence of a newly generated surface, formed as a consequence of the load application by the bolt and serving as a site for hydrogen permeation during the hydrogen 1,000h exposure.

Pipe	Test item code	Diameter (inch)	Thickness (mm)	Grade	Specimen type	Test gas	Test pressure	Test duration	Crack plane orientation	Notch position	Applied initial stress intensity (K_{IAPP}) in MPa·m$^{1/2}$		Crack propagation after exposure	Min fracture toughness K_{IH} (=½·K_{IAPP})
							bar	hr			Min	Max		MPa·√m
HFW	A	20	15.9	L415M (X60M)	Bolt-load CT	100% H_2	80	1000	T-L	BL	109.4	143.1	No	55-72
HFW	A	20	15.9	L415M (X60M)	Bolt-load CT	100% H_2	80	1000	T-L	BM	109.9	144.6	No	55-72
HFW	B	20	19.05	L485M (X70M)	Bolt-load CT	100% H_2	80	1000	T-L	BL	120.7	121.4	No	60-61
HFW	B	20	19.05	L485M (X70M)	Bolt-load CT	100% H_2	80	1000	T-L	BM	115.7	118.2	No	58-59
HFW	C	26	11.1	L415M (X60M)	Bolt-load CT	100% H_2	80	1000	T-L	BL	110.0	137.9	No	55-69
HFW	C	26	11.1	L415M (X60M)	Bolt-load CT	100% H_2	80	1000	T-L	BM	110.2	138.5	No	55-69
HFW	D	16	19.1	450PD (X65MO)	Bolt-load CT	100% H_2	80	1000	T-L	BL	110.1	139.1	No	55-70
HFW	D	16	19.1	450PD (X65MO)	Bolt-load CT	100% H_2	80	1000	T-L	BM	110.1	124.7	No	55-62
SAWL	E	32	20	L485M (X70M)	Bolt-load CT	100% H_2	80	1000	T-L	HAZ	110.3	138.3	No	55-69
SAWL	E	32	20	L485M (X70M)	Bolt-load CT	100% H_2	80	1000	T-L	BM	110.2	138.8	No	55-69
SAWL	E	32	20	L485M (X70M)	Bolt-load CT	100% H_2	80	1000	T-L	WM	110.4	139.3	No	55-70

Table 2: Results of fracture toughness ASME KIH testing

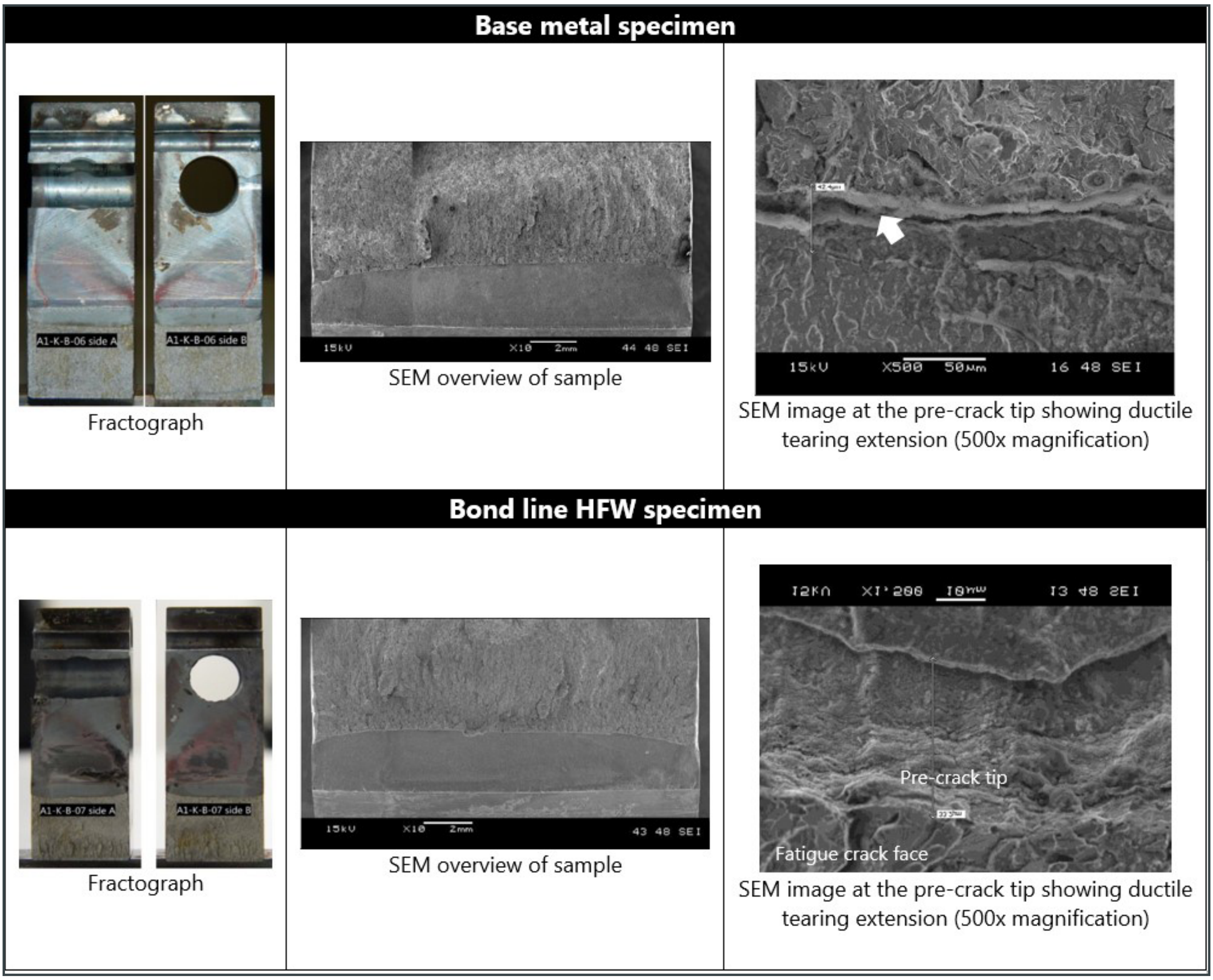

Figure 5: Visual and SEM examination of representative post-exposure examination results from the 26" x 15.9mm HFW test item

8. DISCUSSION

The excellent resistance of the tested pipes against hydrogen embrittlement was endorsed by the chemical analysis characteristics of the tested pipes (Table 3) as in all cases the steel quality was characterized by low carbon content and carbon equivalent (PCM) and high levels of cleanliness (very low P, S). In addition, the TMCP processed coils (or plates, for the case of the SAWL pipe) presented in all cases a fine polygonal or acicular ferrite microstructure with finely dispersed pearlite and no or minimal banding (Figure 6). Such characteristics in steel chemical composition and microstructure are in-line with the recommendations of the hydrogen linepipe code (Table 4). It has been documented that pipeline steels containing acicular ferrite microstructures present higher resistance to hydrogen damage compared to ferrite/pearlite microstructures due to reduced potential of hydrogen trapping sites at the interface between microstructural constituents [15] [21]. In addition, a fine ferrite grain microstructure with minimal banding can reduce the mobility of hydrogen, lower the diffusion coefficient and eventually enhance resistance to hydrogen embrittlement [16]. Lower carbon microstructures reduce also the probability of having high strained martensitic phases in the pipeline steel which have also been evaluated to increase susceptibility to hydrogen damage [22]. The test results presented in the current report seem also to be consistent with existing other published work, where the measured results surpassed the minimum ASME B31.12 value of 55 MPa·√m.

9. CONCLUSIONS

The certification of pipes for the transportation of pure gaseous hydrogen or H2/NG gas mixtures without additional design pressure limitations can be achieved, on the basis of pipe material's fracture resistance properties qualification following design "Option B" requirements of

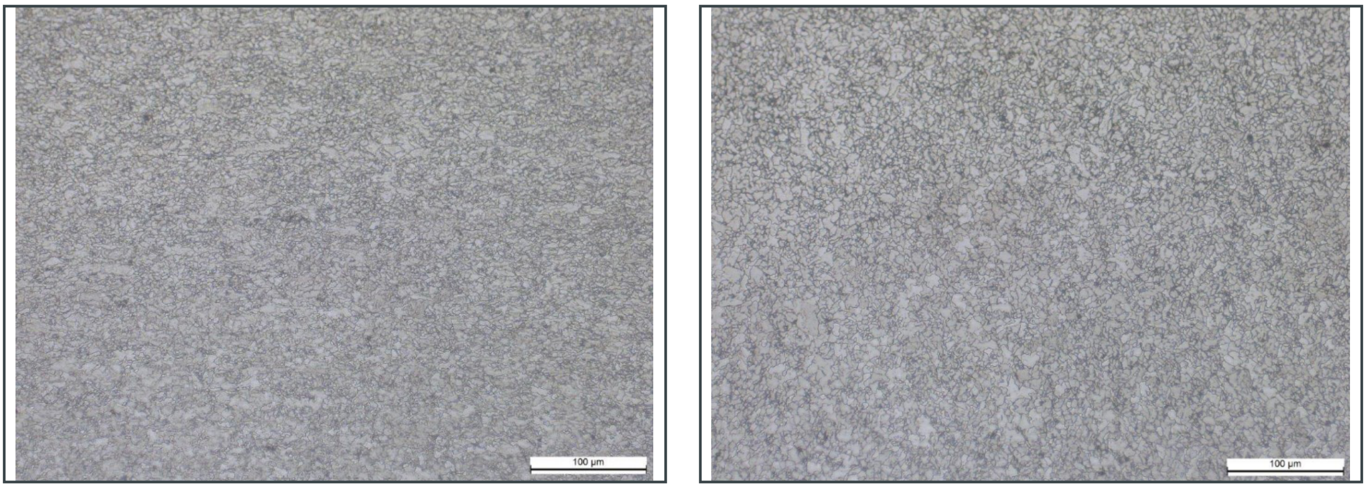

Figure 6: Representative micrographs of X70M HFW pipe on PM (left) and weld seam (right) presenting a fine polygonal ferrite microstructure. Etching: Nital 2%

Test item	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Nb	V	Ti	N	P_{CM}	IIW
A (X60M)	0.05	0.28	1.57	0.007	≤ 0.001	0.02	0.01	0.03	0.04	0.01	0.04	-	0.01	0.004	0.15	0.33
B (X70M)	0.05	0.31	1.67	0.010	≤ 0.001	0.02	0.01	0.26	0.03	0.01	0.05	-	0.02	0.004	0.15	0.35
C (X60M)	0.05	0.29	1.58	0.012	≤ 0.001	0.02	0.01	0.03	0.04	0.01	0.05	-	0.02	0.003	0.15	0.33
D (X65MO)	0.07	0.21	1.35	0.013	≤ 0.001	0.04	0.02	0.03	0.03	0.02	0.03	-	0.01	0.004	0.15	0.31
E (X70M)	0.06	0.25	1.56	0.010	≤ 0.001	0.08	0.09	0.09	0.04	0.01	0.04	-	0.01	0.007	0.16	0.36
Limit*	≤ 0.12	≤ 0.45	**	≤ 0.025	≤ 0.01						***	**	**		≤0.25	≤0.43

* According on API 5L PSL2
** Up to 1.70% depending on grade
*** Nb + V + Ti ≤ 0.15%

Table 3: Chemical analysis of tested pipes (% wt.)

Desired microstructure of polygonal and acicular ferrite TMCP made steel is recommended Phosphorus content ≤ 0.015% wt. Recommended Carbon content ≤ 0.07% wt. Recommended Carbon Equivalent (Pcm) ≤ 0.17% wt. Maximum UTS 110ksi (758MPa) Nb micro alloyed steel is recommended

Table 4: ASME B31.12 Option B & Appendix G: Steel chemistry requirements and recommendations.

code ASME B31.12. The respective qualification procedure, among other requirements, require primarily the long-term exposure of artificially pre-cracked specimens under high pressure 100% H2 conditions. Following the above qualification scheme, Corinth Pipeworks is currently progressing with an extensive R&D program for fracture toughness testing of HFW, SAWL (longitudinal) and SAWH (helical) pipes in high pressure hydrogen. All tests are accomplished in RINA, an acknowledged external European Company, highly experienced in hydrogen testing and fracture mechanics.

According to the up-to-date test results for HFW and SAWL pipes in grades up to L485M/X70M, all tested specimens in base metal, weld and HAZ (where applicable) positions demonstrated high resistance against hydrogen-assisted crack growth and the measured values for the KIH fracture toughness property were always higher than the minimum required value of 55 MPa·√m. Furthermore, the observed fracture mechanism does not pose any evidence of brittle or low-energy cracking phenomena. It has been therefore demonstrated that the requirements of the code for the pipe material are consistently feasible, thus certification of a higher grade line pipe for 100% hydrogen transportation using Option B can be provided. This certification can be the first step towards the efficient transportation of larger volumes of hydrogen through the steel pipeline network in the future.

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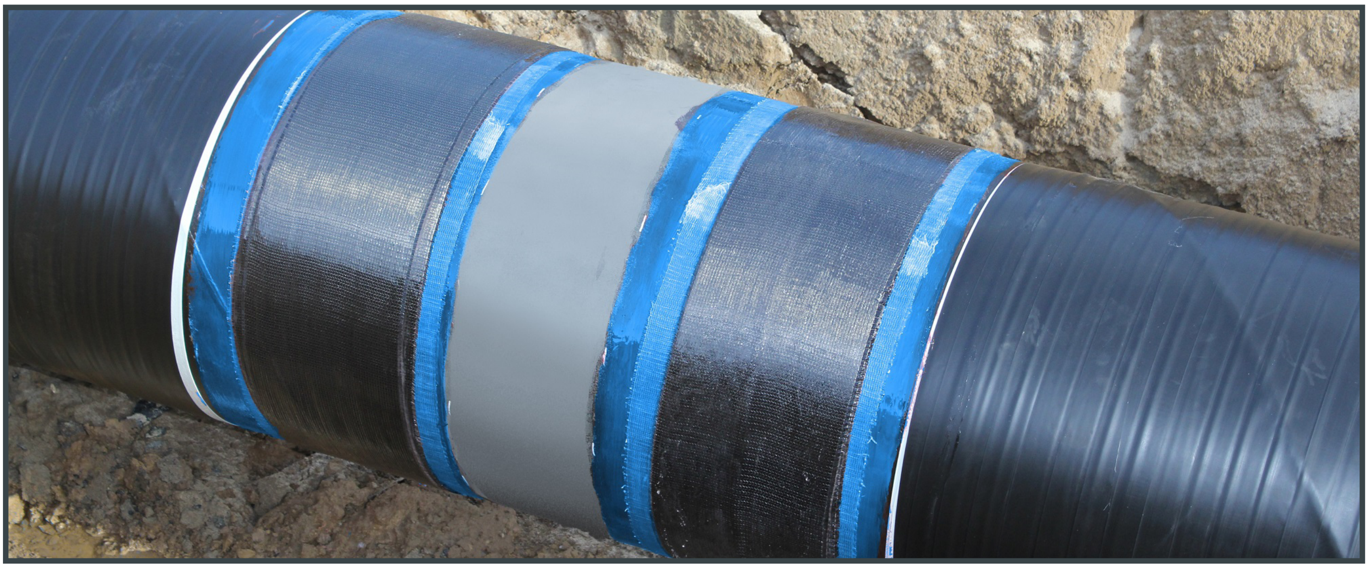

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www.premiercoatings.com/

RPR Technologies
Norway
www.rprtech.com/

Shawcor
United States
www.shawcor.com

Sulzer Mixpac
Switzerland
www.sulzer.com

TDC International
Switzerland
www.tdc-int.com

TIAL
Russia
www.tial.ru

TIB Chemicals
Germany
www.tib-chemicals.com

Construction

BIL - Federal German Construction Enquiry Portal
Germany
www.bil-leitungsauskunft.de

Herrenknecht
Germany
www.herrenknecht.com

IPLOCA - International Pipe Line & Offshore Contractors Association
Switzerland
www.iploca.com

Liderroll
Brasil
www.liderroll.com.br

LogIC
France
www.logic-sas.com

MAX STREICHER
Germany
www.streicher.de/en

Petro IT
Ireland
www.petroit.com

VACUWORX
Netherlands
www.vacuworx.com

Vintri Technologies
Canada
www.vintritech.com

Vlentec
Netherlands
www.vlentec.com

Construction Machinery

Maats
Netherlands
www.maats.com

Worldwide Group
Germany
www.worldwidemachinery.com

VIETZ
Germany
www.vietz.de

Engineering

ILF Consulting Engineers
Germany
www.ilf.com

KÖTTER Consulting Engineers
Germany
www.koetter-consulting.com

Inline Inspection

3P Services
Germany
www.3p-services.com

A.Hak Industrial Services
Netherlands
www.a-hak-is.com

Baker Hughes
United States
www.bakerhughes.com

Intero Integrity Services
Netherlands
www.intero-integrity.com/

Kontrolltechnik
Germany
www.kontrolltechnik.com

KTN AS
Norway
www.ktn.no

LIN SCAN
United Arab Emirates
www.linscaninspection.com

NDT Global
Germany
www.ndt-global.com

Pipesurvey International
Netherlands
www.pipesurveyinternational.com

PPSA - Pigging Products and Services Association
United Kingdom
www.ppsa-online.com

Romstar
Malaysia
www.romstargroup.com

Rosen
Switzerland
www.rosen-group.com

Ameterk – Division Creaform
Germany
www.creaform3d.com

Applus RTD
Germany
www.applusrtd.com

EMPIT
Germany
www.empit.com

INGU
Canada
www.inguc.com

Integrity Management

Metegrity
Canada
www.metegrity.com

Pipeline Innovations
United Kingdom
www.pipeline-innovations.com

Associated Technology Pipeline Ltd
United Kingdom
www.atpuk.co.uk

Leak Detection

Asel-Tech
Brazil
www.asel-tech.com

Atmos International
United Kingdom
www.atmosi.com

Entegra
United States
www.entegrasolutions.com

Fotech Solutions
United Kingdom
www.fotech.com

GOTTSBERG Leak Detection
Germany
www.leak-detection.de

Hifi Engineering
Canada
www.hifieng.com

MSA
Germany
www.MSAsafety.com/detection

OptaSense
United Kingdom
www.optasense.com

Pergam Suisse
Switzerland
www.pergam-suisse.ch

PermAlert
United States
www.permalert.com

sebaKMT
Germany
www.sebakmt.com

Prisma Photonics
Israel
www.prismaphotonics.com

PSI Software
Germany
www.psioilandgas.com

Materials

Vallourec
France
www.vallourec.com

SolAres (Solgeo / Aresys)
Italy
www.solaresweb.com

Monitoring

Airborne Technologies
Austria
www.airbornetechnologies.at

Krohne Messtechnik
Germany
www.krohne.com

PHOENIX CONTACT
Germany
www.phoenixcontact.de/prozess

SolSpec
United States
www.solspec.solutions

Operators

Transneft
Russia
www.en.transneft.ru/

OGE (Open Grid Europe)
Germany
www.oge.net

TRAPIL
France
www.trapil.com/en/

Qualification & Recruitment

YPPE - Young Pipeline Professionals Europe
International
www.yppeurope.org

Pump and Compressor Stations

TNO
The Netherlands
www.pulsim.tno.nl

Repair

CITADEL TECHNOLOGIES
United States
www.cittech.com

Clock Spring NRI
United States
www.clockspring.com

T.D. Williamson
United States
www.tdwilliamson.com

Research & Development

Pipeline Transport Institute (PTI LLC)
Russia
www.en.niitn.transneft.ru

Safety

DEHN & SÖHNE
Germany
www.dehn-international.com/en

HIMA
Germany
www.hima.de

Signage

Franken Plastik
Germany
www.frankenplastik.de/en

Surface Preparation

MONTI - Werkzeuge GmbH
Germany
www.monti.de

Trenchless Technologies

Bohrtec
Germany
www.bohrtec.com

GSTT - German Society for Trenchless Technology
Germany
www.gstt.de

Rädlinger Primus Line
Germany
www.primusline.com

Valves & Fittings

AUMA
Germany
www.auma.com

Zwick Armaturen
Germany
www.zwick-armaturen.de

Event Calendar		
16th Pipeline Technology Conference	15 - 18 March 2021	Online
5th Trenchless Romania - Conference & Exhibition	16 June 2021	Bucharest, Romania
AOP Investor Forum Paris 2021	17 - 18 June 2021	Paris, France

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