Initiatives for Energy Transition in the Pipe and Tubular Sector

ISHIKAWA Nobuyuki[*1]　HIRATA Norimasa[*2]

Abstract:

Technologies for energy transition to hydrogen and CO_2 capture and storage (CCS) are being developed around the world to realize carbon neutrality. This paper briefly introduces the pipe and tubular products used in the hydrogen supply chain including CCS, and the development status of these products in JFE Steel.

1. Introduction

The energy transition from conventional fossil fuels to hydrogen and ammonia is indispensable for realizing a carbon neutral society. Development and demonstration projects for large-scale supply chains for these new forms of energy are being implemented in many countries. In Japan, many demonstration projects such as marine transportation of hydrogen produced in foreign countries and hydrogen mixed combustion power generation are in progress, with the aim of introducing hydrogen (including ammonia) on a scale of 12 million tons by 2040 and 20 million tons by 2050[1)]. Among the various types of hydrogen energy, so-called "green hydrogen" produced using renewable energy such as solar or wind power is thought to be an ideal energy solution. "Blue hydrogen" produced by reforming petroleum or natural gas, together with capture and storage of the CO_2 (CCS: Carbon Dioxide Capture and Storage) generated in the production process, is also considered to be very important for expansion of hydrogen energy. CCS and CCUS (Utilization) are important technologies that directly contribute to CO_2 emission reduction, and efforts to commercialize CCS are being promoted at several sites in Japan[2)].

JFE Steel has a long history of developing and manufacturing many steel pipe products required in the petroleum and natural gas field, contributing to a stable energy supply worldwide. However, for decarbonization by energy transition, new infrastructures will be required for transportation and storage of hydrogen and CO_2, and specific material properties such as resistance to hydrogen embrittlement and carbon dioxide corrosion are required in the pipe materials. **Figure 1** shows a schematic diagram of a hydrogen supply chain including CCUS and the required steel pipe materials. This paper outlines the challenges of JFE's steel pipe business in the new energy field represented by hydrogen and CCUS, focusing especially on the development status of these products.

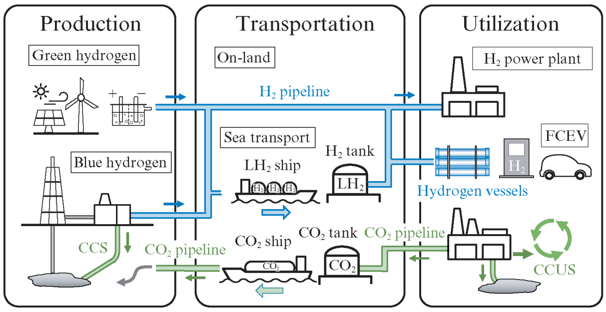

Fig. 1　Schematics of hydrogen supply chain including CCUS

2. Steel Pipe Products for Hydrogen Transport and Storage

2.1 Linepipe for Hydrogen Transportation

Ship transportation of liquid hydrogen is possible for mass transport of hydrogen from foreign countries to Japan, while pipeline transportation of high-pressure gaseous hydrogen is suitable for land transport. Small-scale hydrogen pipeline systems are operated in Japan using conventional pipe materials because the hydrogen pressure is less than 1 MPa and material degradation (hydrogen embrittlement) is not remarkable. However, high pressures over 1 MPa are necessary for large-volume transportation of hydrogen, and a remarkable

† Originally published in *JFE GIHO* No. 54 (Aug. 2024), p. 8–12

*1 Dr. Eng., Senior Management Staff, Plate Business Planning Dept., JFE Steel

*2 Senior Management Staff, Planning & Marketing Dept., Tubular Business Division, JFE Steel

decrease in the fracture property of linepipe steels is a concern under these conditions, because penetration of hydrogen into steel increases corresponding to the pressure[3].

ASME B31.12 "Hydrogen Pipeline and Piping" is an international standard for hydrogen pipelines. Linepipes of API (American Petroleum Institute) standard can be used, but integrity assessments using fracture toughness test and fatigue crack growth test data of the linepipe material are required for high-pressure transportation. **Figure 2** shows a schematic diagram of the integrity assessment specified in ASME B31.12. When a minute defect exists in the inner surface of a pipe, fatigue crack growth occurs by internal pressure fluctuation, and unstable fracture occurs at the point where the fracture driving force exceeds the material fracture toughness. JFE Steel investigated the compatibility of linepipe materials for hydrogen transportation and developed an optimum material design guideline. **Figure 3** shows the results of fatigue crack growth tests in high-pressure hydrogen of the base metal of UOE pipe (outer diameter: 914.4 mm, wall thickness: 28.6 mm) of API Grade X65. The fatigue crack growth rate in hydrogen is much higher than that in the air, but is slower than the reported values of conventional linepipe steels and the design curve specified in ASME B31.12. This is because a fine, homogeneous bainitic microstructure is obtained by appropriate alloy design and rolling and cooling control in the plate manufacturing process[4]. This UOE linepipe also has higher fracture toughness in hydrogen than conventional materials. **Figure 4** shows the fracture toughness test results of the same X65 linepipe in 21 MPa hydrogen. Although the fracture toughness of the heat affected zone (HAZ) and weld metal (WM) of the seam weld are lower than that of the base metal (BM), the value is sufficiently higher than the minimum fracture toughness (55 MPa√m) specified in ASME B31.12. The results of an analysis of an integrity assessment using the fracture toughness value in hydrogen for the HAZ showed that there is a sufficient safety margin even in case of a defect 25 mm in length and 3 mm in depth[5]. As described above, the reliability of hydrogen pipelines can be improved by using linepipes manufactured based on an appropriate material design.

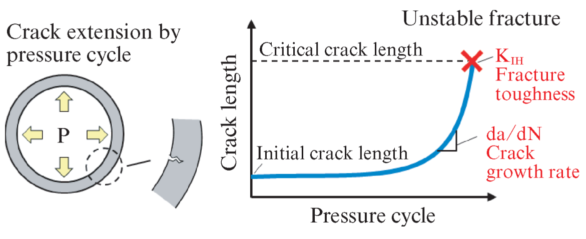

Fig. 2 Concept of integrity assessment of hydrogen pipeline

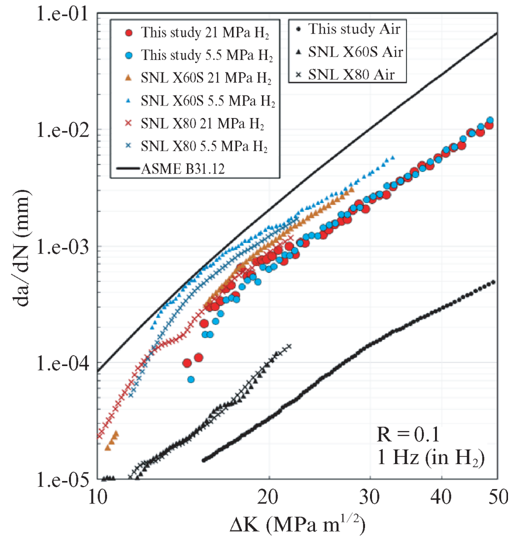

Fig. 3 Fatigue crack growth curves of X65 linepipe[3]

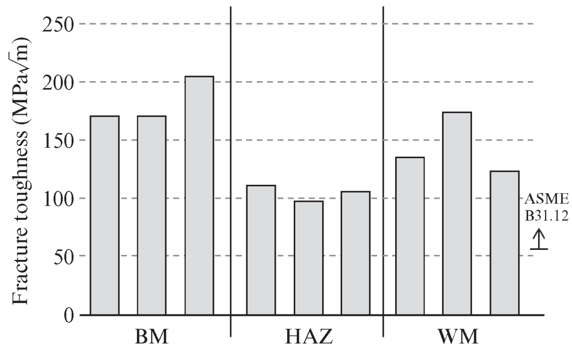

Fig. 4 Fracture toughness test results of X65 linepipe in hydrogen[3]

Electric resistance welded (ERW) pipes are widely used in pipelines. JFE Steel developed Mighty Seam™, which has improved weld seam reliability and is applied to pipelines in severe environments such as very low temperatures and deep water[6]. In Mighty Seam, in addition to optimization of the chemical composition and rolling conditions and optimization of ERW welding and seam heat treatment, stable seam weld properties are ensured by monitoring minute oxides formed in the weld over the whole length of the product by a phased array ultrasonic flaw detection technology. **Figure 5** shows the Charpy impact properties of the ERW weld. As a result of reduction of oxides in the ERW weld, Mighty Seam has a high absorbed energy equal to or higher than that of the base metal, and is expected to be applicable to high-pressure hydrogen pipelines. Studies of material compatibility with high-pressure hydrogen pipelines are being conducted in cooperation with the oil majors ExxonMobil Co. (U.S.A.) and TOTAL Energies Co. (France) in the "Cooperative Technology Development Grant Program

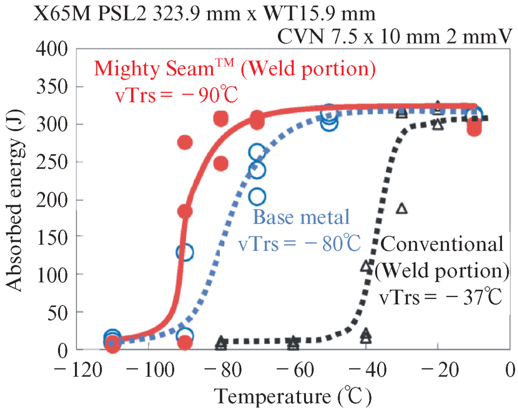

Fig. 5 Charpy impact property of ERW weld[6)]

between the Japan Foundation and DeepStar for Offshore Oil and Natural Gas"[7)].

2.2 Pressure Vessels for Hydrogen Refueling Stations

The number of fuel cell vehicles and hydrogen refueling stations in Japan is increasing steadily, and fuel cell buses have already been adopted, taking the opportunity of the Tokyo Olympic Games. Many types of fuel cell vehicles are also being developed. Since reducing the construction cost of hydrogen refueling stations is an important issue for expanding the use of fuel cell vehicles, JFE is developing low-cost pressure vessels for hydrogen refueling stations[8)]. JFE Steel and JFE Container jointly developed a Type 2 pressure vessel, which is made of seamless pipes with excellent resistance to hydrogen embrittlement with carbon fiber reinforced plastic (CFRP) wrapped around the cylindrical part. As advantages of this new vessel, it is possible to extend the life of the product in the high pressure range, reduce the manufacturing cost by adopting a straight structure, and simplify maintenance work[9,10)]. JFE Steel and JFE Container have also commercialized a large-capacity Type 1 pressure vessel (steel liner not using CFRP), which supports further cost reduction of hydrogen refueling stations. Together with the Type 2 pressure vessel, it is expected to contribute to expanding the number of hydrogen refueling stations.

3. Pipe Products for CO_2 Transportation and Storage

3.1 Linepipe for CO_2 Transportation

Carbon dioxide (CO_2) is a gas at normal temperature and pressure and becomes a solid (dry ice) at -79˚C, but it is liquefied at high pressure, as shown in **Fig. 7**. In pipeline transportation of CO_2, it is often transported in the liquid phase or as a supercritical

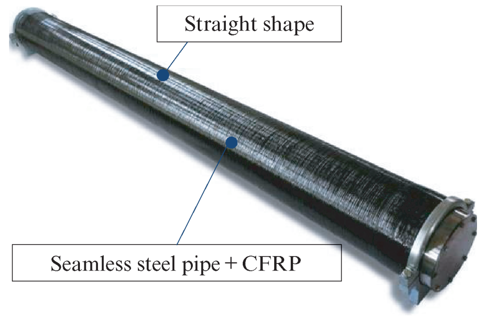

Fig. 6 Type 2 pressure vessel for hydrogen refilling station

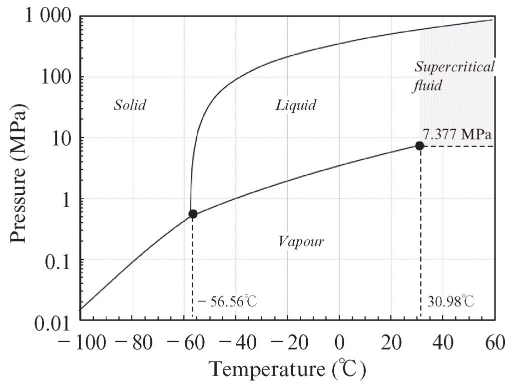

Fig. 7 Phase diagram of CO_2[13)]

fluid at a pressure under 10 MPa and temperature above ambient temperature. ISO 27913 "Carbon dioxide capture, transportation and geological storage - Pipeline transportation systems" and DNV-RP-F104 "Design and operation of carbon dioxide pipelines," specify the impurity compositions of the CO_2 stream and the materials to be used. In both standards, the water content is severely limited since the presence of liquid water in the CO_2 stream will cause so-called carbon dioxide corrosion[11)]. Under conditions without liquid water, carbon steel similar to that used in conventional gas pipelines can be used as the linepipe material.

One of the major threats to high-pressure gas pipelines is running ductile fracture, in which a crack that has formed as a result of some type of accident propagates over a long distance driven by the high pressure of the pipeline. If linepipe with appropriate material properties is used, the crack will arrest as the gas pressure decreases. However, in the case of high-pressure CO_2 (liquid phase or supercritical phase), a gas phase forms during depressurization, which hinders further depressurization, and the crack does not arrest, as can be seen from the phase diagram in Fig. 7. Many full-scale burst tests have been conducted to clarify the material properties required to prevent running ductile fracture in CO_2 pipelines[12)]. **Figure 8** shows the experimental results plotted on the design diagram specified

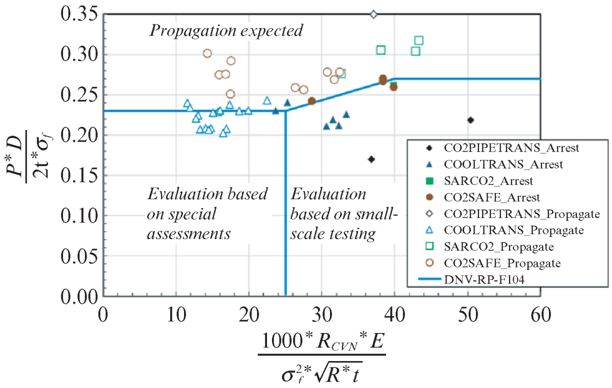

Fig. 8 CO_2 burst test results plotted on the DNV-RP-F104 diagram

in DNV-RP-F104, where P is the pressure at the crack tip (MPa), D is the outer diameter (mm), t is the wall thickness (mm), σ_f is the flow stress (average value of yield stress and tensile strength, MPa), R_{CVN} is the Charpy energy per cross-sectional area (J/mm^2), E is the Young's modulus (MPa) and R is the pipe radius (mm). Crack arrest occurs in the lower right region of the graph, and a material design based on the Charpy absorbed energy is possible in this region. For example, when the CO_2 pressure is 10 MPa in API X65 with an outer diameter of 610 mm and wall thickness of 19.1 mm, the required absorbed energy is more than 210 J, which is higher than that for ordinary gas pipelines. For higher grade linepipes over X70, demonstration tests using actual linepipes are required.

Pipeline transportation of CO_2 combined with CCS or CCUS has been investigated in Japan and other countries. For mass transportation, linepipes with higher strengths and larger diameters are required, but as can be seen from the DNV design diagram in Fig. 8, higher absorbed energy is also required. JFE Steel has developed a high strength linepipe with high absorbed energy by precise microstructure control in the plate manufacturing process[13]. **Tables 1** and **2** show the chemical composition and mechanical properties of the developed API X80 UOE linepipe, which exhibits an extremely high absorbed energy. This material design is applicable to linepipes of other grades, and various linepipes can be supplied for CO_2 pipelines.

3.2 Corrosion-Resistant Pipe for CO_2 Injection

The underground environment for oil and natural gas drilling is wet and may contain corrosive gases such as CO_2 and H_2S. Excellent corrosion resistance is required in oil well pipes used in such environments, and martensitic stainless steel is often applied. On the other hand, the CO_2 stream for CCS may contain impurities such as NO_X, SO_X, H_2 and O_2 originating from the recovery source, which may lead to a more severe corrosion environment. JFE Steel is investigating the effects of impurities on the corrosion resistance of martensitic stainless steel pipes in order to advance material development for CCS in view of cost reduction and shorter delivery time. **Figure 9** shows an example of the steel grades applied to JFE's high-Cr type corrosion-resistant oil well pipes from the viewpoints of CO_2 corrosion resistance and sour resistance (resistance to sulfide stress corrosion cracking, SSC)[14]. As a result, JFE-HP2–13CR-110 was adopted as the steel pipe for the CO_2 injection well at the Tomakomai CCS demonstration facility[15]. In the future, application in many CCS projects is expected.

Table 1 Chemical composition of API X80 linepipe[14]

C	Mn	Others	*Ceq*	*Pcm*
0.06	1.9	Si, Cr, Mo, Nb, Ti	0.45	0.18

$Ceq = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5$
$Pcm = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B$

Table 2 Mechanical properties of API X80 linepipe[14]

Grade	Tensile properties*1			Charpy test*2 at−5°C
	YS (MPa)	TS (MPa)	Y/T (%)	vE (J)
API X80	602	706	85	330

*1 API 5L. transvers direction
*2 ISO 148 (converted from ASTM A370) transverse direction

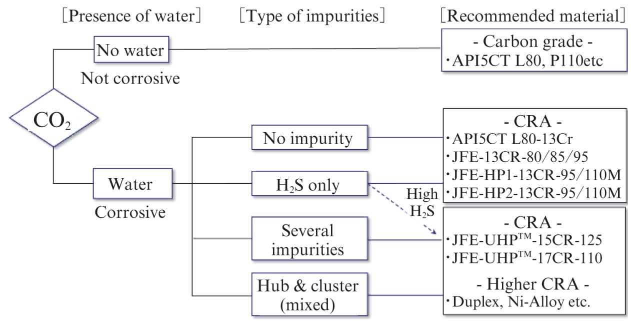

Fig. 9 Schematic illustration of JFE Steel's material selection for CO_2 injection tubing

4. Conclusion

This paper outlines the challenge of JFE Steel's steel pipe business in the new energy field represented by hydrogen, and especially the development status of steel pipe products. Many steel pipes will be required in hydrogen supply chains that include CCUS, and JFE Steel will contribute to realizing carbon neutrality by further promoting the development of these products.

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