Mass Production of High Strength Linepipe with Low Surface Hardness for Severe Sour Service

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Abstract:

Based on the accident of severe sour service pipeline due to SSC caused by surface hardness, high strength UOE pipe manufacturing method for linepipe with low surface hardness for severe sour services was established aiming at the improvement of SSC resistance property of TMCP steel, with countermeasures for both quality control (QC) and quality assurance (QA). The commercial production was completed after obtaining the Customer mill approval. As a QC countermeasure, granular bainite main structure of low hardness was introduced in the whole surface by cooling rate control, and temperature control and surface hardness inspection in the whole surface of steel plate were implemented as a QA countermeasure. This paper presents our achievements of mass production of Grade X60 UOE pipe for linepipe with low surface hardness for severe sour services. The manufactured pipes showed excellent SSC resistance property from both surface hardness inspection results of all plates and SSC tests results of the pipes.

1. Introduction

In pipelines for natural gas transportation, larger diameter and higher strength are being promoted to improve transportation efficiency. In general, steel materials produced by the thermo-mechanical control process (TMCP) are used for linepipe from the viewpoints of production cost and field weldability. When natural gas containing hydrogen sulfide (H_2S) is to be transported, the required performance of the linepipe includes sufficient resistance against hydrogen induced cracking (HIC) and sulfide stress corrosion cracking (SSC) in addition to strength and toughness. Therefore, inclusions and segregation of the steel plates used as high-strength sour line pipe materials, which cause HIC, must be reduced as far as possible, and a fine bainite structure is required in the microstructure so that strength, toughness and HIC resistance are compatible[1,2]. However, it has been reported that SSC susceptibility increases as the hardness of steel materials increases[3,4], and for this reason, the upper limit value of hardness for the linepipe used in sour gas environments is regulated[5]. After an accident due to SSC in a sour gas pipeline in 2013, there were moves to reevaluate the SSC resistant performance of linepipe using steel plates manufactured by TMCP[6–8]. The supplementary specification S-616[9] prepared by the International Association of Oil & Gas Producers (IOGP) states that the surface hardness at a position 0.25 mm from the surface is to be measured with a lower load. API 5L is promoting standardization of surface hardness testing for sour linepipes under low pH environments, if required by a customer, and demand for sour linepipes with low surface hardness requirements is considered likely to expand.

Technological innovation of TMCP steel has greatly advanced as a result of application of an accelerated cooling process after plate rolling, and high strength and high toughness have become possible in thick steel plates by applying higher cooling rates[10–12]. Generally, accelerated cooling is a process in which a steel plate is cooled with water from the steel surface, and the cooling rate of the surface layer having a thickness of 0.5 mm or less is faster than that of the center of thickness. As a result, there is a possibility that parts called hard spots, where the surface layer hardness increases locally, may be occur in TMPC steel, and the relation-

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ship between this hard spot phenomenon and SSC has been discussed[6,7]. In order to minimize the risk of SSC in plates produced by TMCP, higher cooling control technology is required to suppress the generation of hard spots and ensure a uniform surface hardness distribution in the whole steel plate.

In 2011, the plate mill at JFE Steel's West Japan Works (Fukuyama Area) installed the controlled cooling technology *Super*-OLAC™-A, which enables uniform cooling and high-precision control of the cooling rate, and has applied this technology to a wide variety of high-performance steel plates and linepipe steel plates[11]. High strength linepipe with low surface hardness for severe sour service, in which the surface hardness is reduced over the entire surface of the steel plate by forming a soft granular bainite structure in the surface layer, was also developed by applying the *Super*-OLAC-A[13].

As quality assurance for hard spots, a steel plate surface hardness measuring device was introduced, together with temperature control of the whole plate surface before accelerated cooling device, and a surface hardness inspection system for the whole plate surface was established, and prior approval of the mill by customers was obtained.

This paper describes the production technology for high strength linepipe with low surface hardness for severe sour service from the respective viewpoints of quality control (QC) and quality assurance (QA), and reports the record of mass production of Grade X60 UOE linepipe with low surface hardness for severe sour service.

2. Production Technology of High Strength Linepipe with Low Surface Hardness for Severe Sour Service

2.1 Quality Control (QC) Countermeasures

In the material design of linepipe for sour service, there is an upper limit of hardness, as defined in the NACE/ISO 15156-2 standard, in order to avoid SSC. The upper hardness limit of 250 HV10 is defined for carbon steel and low alloy steel. API 5 L specifies that the hardness is to be 250 HV10 or less at 1.5 mm from the inner and outer surfaces of the pipe. On the other hand, since the SSC accidents caused by the surface hardness of sour pipeline in recent years, it has become difficult to measure the surface hardness of linepipe steel manufactured by TMCP under the conventional load of 10 kgf from the viewpoint of the indentation size. Therefore, measurement under a low load of 0.5 kgf is described in IOGP S-616[9].

In JFE Steel, in order to reduce the hardness of the surface layer of sour linepipe, the cooling rate at the surface layer of the material steel plates was controlled to 50°C/s or less over the entire surface of the steel plate by using the *Super*-OLAC-A cooling technology, which enables higher control of the cooling rate, and a soft granular bainite structure was obtained as the surface structure. As a result, steel plates for sour linepipe with reduced surface hardness were produced while continuing to secure high strength[13].

2.2 Quality Assurance (QA) Countermeasures

2.2.1 Temperature control by full scan surface thermometer

Figure 1 shows the layout of the steel plate entry side of the *Super*-OLAC-A, a proprietary accelerated cooling system developed by JFE Steel for plate manufacturing. As a QA countermeasure for obtaining a granular bainite-based microstructure in the entire steel plate surface, an automatic monitoring system was established, in which an full scan surface thermometer was installed on the entry side of the accelerated cooling facility, and cooling start at over the Ar_3 point was guaranteed for the entire steel plate surface.

2.2.2 Hardness assurance by introducing steel plate surface hardness measuring equipment

A new nondestructive inspection technology was also developed and introduced for quality assurance for hard spots in the steel surface layer. This section describes the principle of the new nondestructive inspection technology. It was generally known that the mechanical properties of steel display a correlation with electromagnetic properties[14–15]. For example, it has been reported that the shape of the BH curve, which shows the relationship between the magnetic field and magnetic flux density, changes depending on the mechanical properties of the steel, such as its hardness[16–17].

Focusing on this phenomenon, the new inspection equipment measures the eddy current signal using a

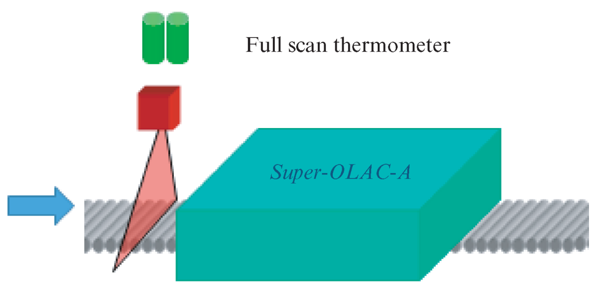

Fig. 1 Arrangement of thermometer in front of *Super*-OLAC™-A

sensor consisting of a yoke and coil to evaluate hardness. The measured eddy current signal is analyzed, and the hardness value is calculated. Specifically, as shown in **Fig. 2**, a signal in which a low-frequency signal and a high-frequency signal are superimposed is applied to the drive coil of the sensor to generate a magnetic field, and the changes in the magnetic field depending on the electromagnetic characteristics are measured by the receiving coil. Multiple features are extracted from the obtained measurement signal, and hardness is evaluated by using an evaluation model based on the relationship between the hardness and electromagnetic features, which is constructed beforehand. Although there are many hard spot detectors that use electromagnetic methods to inspect hard spots[17–19], JFE developed a new technology that can evaluate hardness more accurately by using an evaluation model constructed based on the relationship between multiple electromagnetic features and the hardness and texture of steel plate surface layers.

Photo 1 shows a steel plate being inspected for hard spot detection. The newly-developed inspection equipment is a trolley-type device used in manual inspections. A holder that houses a plurality of sensors for measuring eddy current signals is arranged at the tip of the trolley. Each sensor housed in the holder is designed to be grounded to the inspection surface and move around the area independently, measuring changes in the magnetic field as it moves smoothly on the steel surface.

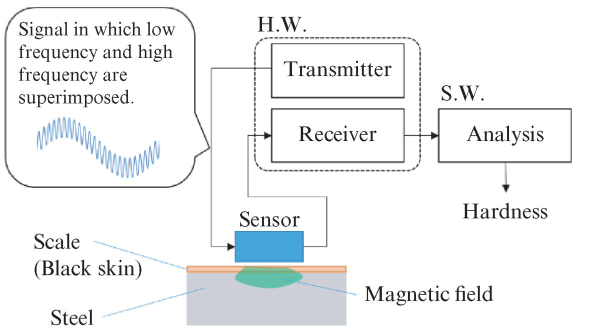

Fig. 2 Method of surface hardness evaluation

Photo 1 Surface hardness inspection

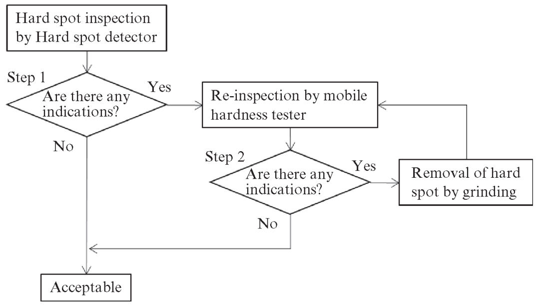

Fig. 3 Flow chart of surface hardness inspection

The probability of detection (POD) of the results of inspections of steel plates with hard spots of various sizes prepared by laser hardening when using the trolley-type surface inspection device was analyzed. POD analysis is a means for statistically evaluating the defect detection rate of inspection systems, and evaluates the minimum detectable defect size based on the 95% confidence level. The results confirmed that the new device has performance sufficient to detect hard spots with sizes over about 16 mm × 16 mm.

A flow chart of the surface hardness inspection process is shown in **Fig. 3**. The surface of the steel plate is inspected by using the trolley-type surface inspection device. If no hard spots are detected, the plate is determined to be non-defective. On the other hand, if a hard spot is detected, the hardness at the hard spot indication area is evaluated by using a contact-type portable hardness tester (e.g., repulsion type). If the measurement values show that there is no hard spot, the product is deemed to have passed the test, but if a hard spot is confirmed, the hard spot is removed by grinding with a grinder. The QA system was established to enable inspections based on the flow chart shown in Fig. 3.

3. Production of Sour Linepipe with Low Surface Hardness for Severe Sour Service

3.1 Record of Steel Plate Surface Hardness Inspections

Over 50 000 tons of X60 class sour linepipe with strict surface hardness specifications were mass-produced. **Table 1** shows the results of surface hardness

Table 1 Record of hard spot inspection on steel plate surface

Step	Inspection content	Result
1	Detect rate of hard spot by hard spot inspection equipment	0.4%
2	Reject rate of hard spot by mobile hardness tester	0%

testing of the steel plate material. The hard spot detection rate by the steel plate surface hardness measuring device was only 0.4%, and no hard spots exceeding the acceptance criteria were found in the surface hardness test by the contact-type portable hardness tester.

3.2 Production Record of UOE Steel Pipe

Hardness tests of the manufactured UOE steel pipes were carried out at the inner surface, which will be in contact with the product fluid. Inner surface hardness tests at 0.25 mm under the inner surface were carried out at the 3, 6 and 9 o'clock positions in the circumferential direction of the steel pipe. **Figure 4** shows the inner surface hardness test results. The inner surface hardness is 235 HV0.5 or less and sufficiently satisfies the requirement of Max. 240 HV0.5.

In addition, the four-point bend type SSC test according to the NACE TM0316 standard[20] was carried out in the production tests, and the SSC resistant property of the manufactured pipe was evaluated in a large-scale test. Test specimens were taken from the inner surface layer of the base metal at 3 and 6 o'clock from the seam weld. The conditions and results of the SSC test are shown in **Table 2** and **Table 3**, respectively.

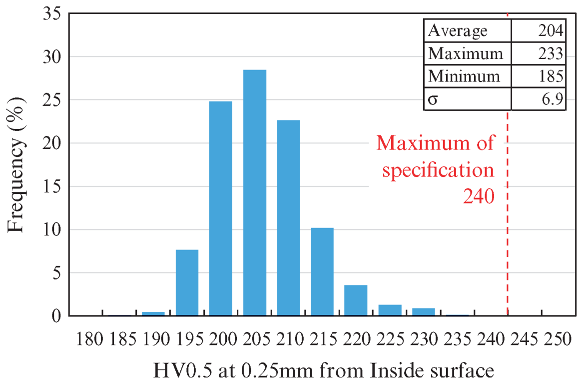

Fig. 4 Test record of hardness test on inside surface of steel pipe

Table 2 Condition of four point bend type SSC test

Test solution (NACE TM0177[21])	pH (Ini./Fin.)	Partial pressure (bar)		Duration (hr)
		H_2S	CO_2	
Solution A	2.6-2.8/4.0	1	-	720

Table 3 Record of four point bend type SSC test on inside surface of steel pipe

Test position	Number of tested specimens	Test result
Pipe body	312	No SSC
Pipe weld	156	No SSC
Total	468	No SSC

The manufactured steel pipe displayed excellent SSC resistance performance without occurrence of SSC in a mass-production test of a total of 468 specimens.

4. Conclusion

In order to achieve SSC resistance performance in TMCP steel, a manufacturing method for high strength UOE pipes for linepipe with low surface hardness for severe sour service was established, including countermeasures for both quality control (QC) and quality assurance (QA). After prior mill approval by customers, large-scale commercial production was completed successfully.

(1) As a QC countermeasure for the steel plate material for sour linepipe, a low hardness granular bainite main structure was induced in the whole surface of the plates by high-precision cooling control utilizing JFE's *Super*-OLAC^{TM}-A.

(2) As QA countermeasures for low surface hardness, a full scan surface thermometer was installed at the inlet side of an accelerated cooling facility for temperature control of the entire plate surface, a steel plate surface layer hardness measuring device was introduced for surface hardness inspection of the entire plate surface, and a plate surface hardness assurance system was established.

(3) The X60 grade UOE steel for severe sour service pipe produced using the newly-established method showed excellent SSC resistance performance, as no occurrence of hard spots was detected in surface hardness inspections of any mass-produced plates, and occurrence of SSC was not recognized in a mass-production SSC test of the manufactured pipes.

In the future, it is expected that surface hardness inspection of sour line pipes used in low pH environment will be standardized according to requests from customers, and demand for sour line pipes with low surface hardness specifications will expand.

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