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Effect of Ni content on the microstructure and mechanical properties of weld metal with both-side submerged arc welding technique

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ABSTRACT

The effects of nickel (Ni) content on the mechanical properties and microstructure evolution in the weld metals of commercial K65 oil and gas pipeline steel were studied. Increase Ni content could significantly improve the strength and low temperature impact toughness (−40 °C and −60 °C) of the weld metal. The above influences of Ni were attributed to the formation of predominant acicular ferrite (AF), at the expense of grain boundary ferrite (GBF), ferrite side plates (FSP) and martensite/austenite (M/A) constituent in weld metal. EBSD results indicated that GBF keeps K-S or N-W relations only with the prior austensite grain that belongs to one side of the grain boundary and the variants belong to the same bain group which always forms low angle boundary. Moreover, the retained austenite as one part of M/A constituent was mainly found in the weld metal with lower Ni content. It indicated that the transformation process could be promoted more completely by the increase of Ni content. The mechanism of the toughness improvement brought by Ni increasing was ascribed to the relatively uniform transformation to final microstructure, which reduces the appearance of GBF and M/A constituents.

1. Introduction

With the development of oil and gas exploitation, the pipeline construction is gradually transferred to the deep sea and polar regions. Thus, the low temperature performance of steel materials has been put forward higher requirements. For example, in Russia, the longitudinally submerged arc welded (LSAW) pipeline in the Bovanenkovo–Ukhta project [1] was recently constructed with K65 steel (the highest grade of the Russian natural gas pipeline), which is similar in specifications and yield strength requirement (550 MPa grade) to API X80 but has a stricter low temperature toughness value of 60 J/cm^2 at −40 °C (compared to −20 °C for API X80 grade [2,3]) due to the extreme Arctic environment. The extreme requirement for low temperature toughness of weld joint has been a great challenge. In addition, the low temperature toughness of the weld metal (WM) has been asked a governing parameter in the overall toughness performance of the pipeline optimal.

Previous studies [4–6] suggested that there are two major approaches to improve the low temperature toughness of weld metal. One is to use different types of fluxes and the other is to change the WM composition either by applying newer filler materials or metal power additions in WM. Well known, as an alloy element that is beneficial to both strength and toughness [7], Ni has been widely adopted in weld metal to attain desirable mechanical properties through increased hardenability. It can stabilize austenite grain and lower the ferrite transformation temperature. An increase of 1% in Ni content will lower the ferrite transformation temperature by 15 °C, according to Pickering's results [8]. So a certain addition of Ni can help suppress the formation of coarse grain boundary ferrite (GBF) in the weld metal, which can enhance the mechanical properties of the weld metal [9,10]. However, there is no general agreement regarding the content of Ni in WM. Kim [11] suggested that the WM toughness can be increased markedly by an increase of Ni content. Nevertheless, Wang [12] and Taylor [13]showed that the benefit from Ni is conditional as discussed in reference [14,15]. Keehan [14] found that the critical point of the Ni content depended on the Mn content. If the critical point was exceeded, −40 °C impact energy could be reduced significantly. Evans [15] pointed out that the addition of Ni could increase the AF fraction in weld metal when Mn content was below 1.0 wt%. While, if Mn content was higher (about 1.4 wt%), the weld toughness reduced when the Ni content was > 2.25 wt%. Therefore, it is difficult to clarify the influence of Ni in the weld metal. In addition, previous studies are mainly focused on the morphology analysis. There are less studies focused on the crystallography from the point of transformation, though the

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Table 1
Chemical composition of weld metals (wt.%) and Ac_3 and Ac_1 temperature (°C)

Sample	C	Si	Mn	Mo	Ni	Cr	Cu	V	Nb	Ti	B	Al	Ac_1	Ac_3
BM	0.06	0.19	1.66	0.22	0.37	0.22	0.13	0.05	0.06	0.017	0.002	0.024	708	823
WM-1	0.06	0.22	1.66	0.14	0.93	0.15	0.10	0.03	0.03	0.018	0.002	0.017	699	811
WM-2	0.06	0.21	1.60	0.13	1.19	0.15	0.12	0.03	0.03	0.014	0.001	0.017	694	806
WM-3	0.06	0.22	1.60	0.13	1.45	0.16	0.13	0.03	0.03	0.014	0.001	0.018	689	802

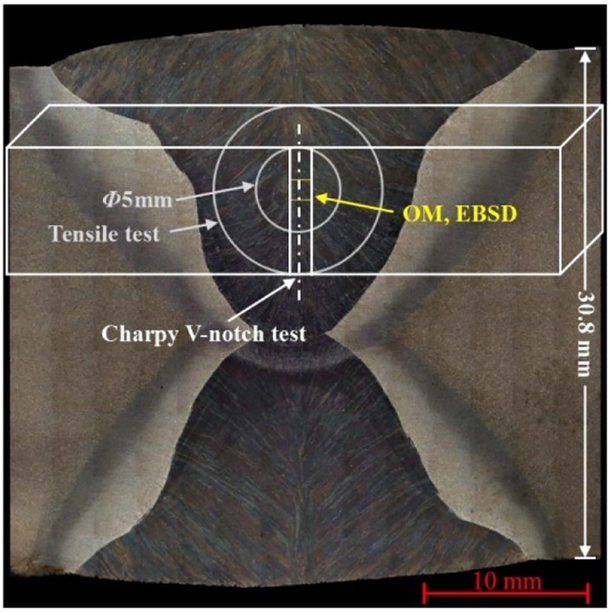

Fig. 1. Location of the measurement of mechanical properties in the test specimens.

microstructure is crystalline-like. In this paper, the relationships of the Ni content and the proportion of transformation products, average size, crystallographic information and completeness degree of transformation are explored. The results obtained here will help to provide a fuller understanding of Ni′s effects on the microstructure and properties and will be helpful in the chemistry designation of welding materials.

2. Materials and methods

The base metal was commercial K65 oil and gas pipeline steel with a 1420 mm outer diameter and a 30.8 mm wall thickness. The 30.8 mm thick plate was welded with the both-side submerged arc welding technique with four wires, which significantly increases the productivity and lowers heat input [16,17]. Before welding, the gas pipeline was preheated to 100–150 °C. The filler material whose composition is inherited to the weld metals was Mn-Ni-Mo alloy welding wire with different Ni content. Numerous work emphasized on the effect of heat input on the impact toughness of weld metals has suggested that the medium heat input was the most beneficial ones to toughness. For these considerations, the heat input was set as 60 kJ/cm and the interpass temperature was 80 °C. The compositions of the weld metals are listed in Table 1, and the weld metals are referred as sample WM-1, WM-2 and WM-3, respectively, with the increase of Ni content. In addition, the knowledge of criticaltemperaturesAc_3 and $Ac_1$for the γ phase is needed. They were calculated using Andrews' equations [18] (Eqs. (1) and (2)) for both of them were the most practical equations and were also shown in Table 1.

$$Ac_3 = 910 - 203\sqrt{C} - 15.2Ni + 44.7Si + 104V + 31.5Mo + 13.1W \tag{1}$$

$$Ac_1 = 723 - 10.7Mn - 13.9Ni + 29Si + 16.9Cr + 290As + 6.38W \tag{2}$$

After welding, an optical macrograph of the weld joint was shown in Fig. 1. The sampled regions for measurement of mechanical properties and observation of microstructure were also depicted in Fig. 1. Tensile properties were measured at room temperature (25 °C) using standard tensile samples machined to 5 mm diameter and 25 mm gauge length. The extension rate was$2.5 \times 10^{-3}\,s^{-1}$.Charpy V-notch (CVN) specimens were machined according to the ASTM E23 standard (55 mm × 10 mm × 10 mm, V-notch position as shown in Fig. 1), and all impact tests were performed at −40 °C and −60 °C.

The specimens were mechanically polished using standard metallographic procedures and etched with 3% nital for optical microscopy (OM) observation. LePera etchant [19](a solution of 1 g sodium metabisulfite in 100 ml water mixed with 4 g of picric acid dissolved in 100 ml of water) was used to reveal the M/A constituents. EBSD was used to display the crystallographic information with increase Ni content. The samples were electro polished using the solution (glycerol: perchloric acid: alcohol = 0.5: 1: 8.5). EBSD data was obtained by orientation imaging microscopy (OIM) under the following conditions: acceleration voltage, 20 kV; working distance, 15.2 mm; tilt angle, 70°; step size, 0.2 μm. Channel 5 software from Oxford-HKL was used for post-processing orientation data. Pole figure programs developed by Matlab were used for benchmarking structure's orientation relationship and performing the detailed crystallographic analysis. To characterize the M/A constituent, transmission electron microscopy (TEM) was carried out using 3 mm disks that were twin-jet electro polished in and electrolyte of 10% perchloric acid and 90% ethanol. The examinations were performed using aJEM-2010 TEM(JEOL, Tokyo, Japan) with 200 kV.

3. Results and discussions

3.1. Mechanical properties

Table 2 shows the mechanical properties of all the three weld

Table 2
Mechanical properties of weld metals.

Sample	Yield strength (MPa)	Tensile strength (MPa)	Total elongation (%)	−40 °C impact energy (J/cm^2)				−60 °C impact energy (J/cm^2)			
				1	2	3	Average	1	2	3	Average
WM-1	570 ± 5	708 ± 9	19.3 ± 0.9	138	114	102	118 ± 18	69	124	118	104 ± 30
WM-2	583 ± 14	723 ± 40	17.8 ± 2.8	129	93	100	107 ± 19	118	58	108	95 ± 32
WM-3	606 ± 13	722 ± 45	18.7 ± 2.9	169	154	181	168 ± 13	134	151	142	142 ± 8