Materials Science & Engineering A 615 (2014) 436–446

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Study of microstructural evolution and strength–toughness mechanism of heavy-wall induction bend pipe

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ARTICLE INFO

Article history:
Received 30 June 2014
Received in revised form
28 July 2014
Accepted 29 July 2014
Available online 6 August 2014

Keywords:
Induction bend pipe
Microstructure
Dislocation
Toughness
Microcrack propagation

ABSTRACT

The induction bending and subsequent tempering process has recently been proven to be an optimal technological route for the manufacture of bend pipe with a better combination of strength and toughness. In this work, high temperature quenching followed by tempering treatment from 500 °C to 700 °C has been applied to heavy-wall bend pipe steel produced by the ultra fast cooling technology. The evolutions of microstructure and dislocation were characterized by means of an optical microscope, the positron annihilation technique (PAT), SEM, TEM, XRD and EBSD. Microstructure observations showed that fine and homogenous M/A islands as well as dislocation packages in a quasi-polygonal ferrite (QPF) matrix after tempering at 600–650 °C generated an optimal combination of strength and toughness. At higher tempering temperature, the yield strength decreased dramatically; however, the impact toughness still remained at a high value of more than 300 J. Dislocation analysis by means of TEM, EBSD and PAT suggested that the decrease and pile-up of dislocation could provide better toughness and tempering stability. EBSD analysis indicated that the average misorientation angle enlarged and the effective grain size diminished with the tempering temperature increasing, and these caused more energy cost during the microcrack propagation process with subsequent improvement in impact toughness. Microcracks mainly originated from the interfaces between ferrite matrix and M/A islands. The ring-type join-up of microcracks and the large number of branches formed during the propagation process effectively improved the toughness. All these results benefit the cost-effective commercialization of heavy-wall induction bend pipe with high performance.

1. Introduction

In the long-distance transportation of oil and gas, pipeline transmission dominates because of its high safety, high efficiency and low cost. Meanwhile, there is an increasing demand for transporting oil and gas by pipeline at high operating pressure in an attempt to increase the capacity [1]. This requires the use of high strength parent steel, which allows wall thickness to be significantly reduced and consequent reduction in weight [2]. It is well known that the microstructure depends on alloy chemistry and thermo-mechanical processing. During the production of pipeline steels, the thermo-mechanical control process is the preferred route due to the resulting fine-grained and desirable microstructure. However, regarding higher strength steel grades and/or heavy-wall thickness pipe designed for long-distance transportation pipeline projects, the conventional laminar cooling system cannot meet the requirements for producing a hot rolled plate [3]. On account of low cooling capacity of the laminar cooling system, more alloy elements, for instance Mo, are usually needed to achieve the desired hardenability, which will not only lead to increasing the alloying cost, but also cause problems such as microstructural nonuniformity, higher hardness and poor welding performance. In particular, for the heavy-wall thickness pipeline steels, insufficient cooling capacity by the laminar cooling system yields instability of comprehensive performance. Therefore, cooling has become the bottleneck for developing and commercializing heavy-wall thickness pipeline steels. In this context, an ultra fast cooling (UFC) device has been developed as the available method for producing hot rolled products with high performance and low cost [4]. In the process of pipeline steel, a UFC device can achieve 2–5 times cooling rate higher than that of a regular laminar cooling device [5]. This advanced technology presents the advantages of increasing the strength and reducing alloy addition levels through the strengthening contribution by finer and uniform carbonitrides as a result of high undercooling degree during the UFC process.

Confronted with the persistent development of oil and gas pipeline project, bend pipes, as important fittings for changing

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http://dx.doi.org/10.1016/j.msea.2014.07.101
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transportation directions of oil and gas, present a huge demand. Approximately 30–40% of the pipes are bent in the construction of a pipeline project [6]. Cold bending is preferred, because it can be performed in the field. When the bend radius is small, it is necessary to apply a hot bending process, which applies localized induction heating and fast water cooling on the pipe body. This process allows the microstructure to be significantly changed with consequent variations in mechanical properties, especially the yield strength, resulting in the mechanical property below the standard requirement [7]. And most of the invalidation accidents are related to the quality of bends. The manufacturing process of bends is one of the key technologies directly affecting the safety of a pipeline. In order to guarantee the safety, subsequent tempering heat treatment after induction bending is usually required to obtain excellent comprehensive mechanical properties, and the final quality and performance of bend pipe greatly depend on the tempering process.

Published studies [6–11] about induction bend pipe mostly focused on the choice of the manufacturing process and the mechanical variation of different sampling locations around the pipe circumference in the corresponding process. Wang et al. [1] introduced a new alloy system for the induction bend pipe based on the chemical composition of commercial X80 steel. There are few finished papers concerning the mechanism of toughness and strength during the manufacturing process of bend pipe, especially for low-cost parent steel produced by UFC technology. In the present work, the heat treatment process in the manufacturing process of induction bend pipe has been stimulated. The microstructural evolution is discussed in details. More efforts are made to understand the relationship between strength–toughness and dislocation, misorientation angle, effective grain size as well as microcrack propagation. These research findings have been utilized to cost effectively commercialize heavy-wall induction bend pipe with high performance.

2. Experimental

2.1. Material and process

The materials investigated are X80 grade parent steel designed for induction bend pipe. The parent steel, with a thickness of 22 mm, is produced by thermo-mechanical controlled rolling via UFC technology. The chemical composition of the investigated steel is shown in Table 1. The carbon equivalent (CE) value is 0.445, with both weldability and hardenability considered. Kondo [12] suggested that the higher CE of induction bend pipe was beneficial to increasing hardenability and minimizing the yield strength loss during quenching. The equilibrium transformation temperatures Ae3 and Ae1 calculated using Thermo-Calc software are 843 °C and 712 °C, respectively. The specimens with dimensions of 12 mm × 12 mm × 75 mm for heat treatments were cut from the middle of the tested plates along wall thickness direction, and separated from the transverse direction. The details of the heat treatment process used in this study are described in Fig. 1.

2.2. Microstructural investigation

Samples for metallographic analysis were prepared by wire cut electrical discharge machining, mechanical grinding, polishing and then etched with 4% nital. The microstructures before and after heat treatments were investigated by an optical microscope (OM) and a Zeiss Auriga field emission scanning electron microscope (FE-SEM). To evaluate the microstructural characteristics of the metallographic samples, the color tint-etching method was employed with LePera agentia (equal portions of solutions: 1% aqueous sodium metabisulfite and 4% Picral) [13–16]. The volume fractions of individual microstructural constituents were determined by the Image Pro-Plus 6.0 software. Fractographic examination of tensile and impact specimens was performed to obtain a better understanding of the microscopic fracture mechanism. For further microstructural analysis, transmission electron microscopy (TEM) observation was carried out on thin foils which were prepared by cutting thin wafers from small coupons and grinding them to 60–70 μm. Discs of about 3 mm diameter were punched from the wafers and electropolished using a solution of 4% perchloric acid in alcohol kept below −20 °C by liquid nitrogen. These foils were examined by a JEM-2100(HR) TEM operated at 200 kV. Besides, the positron annihilation technique (PAT) was used to analyze the change in dislocation density. A fast–slow positron annihilation lifetime spectrometer was applied to measure positron annihilation lifetime of the specimens tempered at different temperatures.

Electron back scatter diffraction (EBSD) analysis was performed under the condition of tilt angle 70° and step size 0.2 μm in order to study effective grain size and grain misorientation. The data were post-processed with Channel 5 software provided by Oxford HKL Technology®. Local misorientation was used to evaluate small local strain gradients in the material. The local misorientation distribution component calculated the average misorientation between every pixel and its surrounding pixels, and assigned the mean value to that pixel. In the present study, 8 neighbors were used in this calculation and misorientations of over 5° were discarded. Because the magnitude of local misorientation correlated well with the density of dislocations and local strain, the

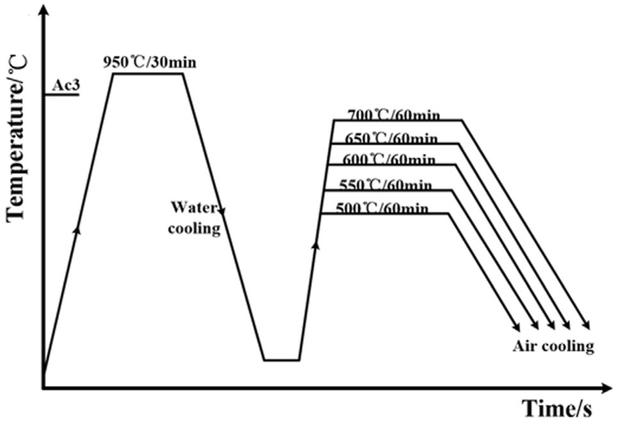

Fig. 1. A diagrammatic sketch of the heat treatment process.

Table 1
Chemical composition of the investigated steel (wt%).

C	Si	Mn	P	S	Nb+V+Ti	Cr+Mo	CE_{IIW}[a]	CE_{Pcm}[b]
0.04–0.07	0.1–0.3	1.5–2.0	≤ 0.020	≤ 0.005	≤ 0.10	≤ 0.50	0.445	0.177

[a] $CE_{IIW} = C + Mn/6 + (Mo + Cr + V)/5 + (Cu + Ni)/15$.
[b] $CE_{Pcm} = C + Si/30 + (Mn + Cr + Cu)/20 + Mo/15 + Ni/60 + V/10 + 5B$.