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Misorientation, grain boundary, texture and recrystallization study in X90 hot bend related to mechanical properties

Liang Wang[a], Bin Wang[b,*], Peishan Zhou[a]

[a] School of Engineering, Southwest Petroleum University, Nanchong 637800, China
[b] School of Materials Science and Engineering, Southwest Petroleum University, Chengdu 610500, China

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ABSTRACT

In the present study, electron backscattering diffraction (EBSD) was used to study the relationship between misorientation, grain boundary, texture, recrystallization and the mechanical properties for API (American Petroleum Institute) X90 hot induction bend. The experimental results show that the yield strength of the parent pipe is 748 MPa, while it reduced about 40 MPa after hot induction bending. The strength in the inner arc side is similar along the longitudinal and transverse direction, but it is anisotropic in the outer arc side. The texture of {113} < 110 > components and {112} < 110 > components are the main reason for anisotropy. After hot induction bending, the deformed and elongated grains exist in the bend zone of X90 bend, and the sub-grain boundaries exist in the grains. The grains in the neutral axis are equiaxed and without lath-like structure and sub-structure. A large fraction of lath bainite (LB) boundaries and Σ3 boundaries in the outer arc side resulted in a high strength and low impact toughness. Moreover, the deformed region and the recrystallization region have the same tendency for the tested specimens, the neutral axis of X90 bend has a lower stored energy in the grains that could resist the cracks propagation effectively.

1. Introduction

As consumption of energy is increasing worldwide, there is a large demand to transport oil and gas by large diameter, high strength thick-walled pipeline at higher operating pressures to increase the capacity and reduce the cost of transportation. It is known that the increase in the yield strength will decrease the fracture toughness and formability, and then cause difficulties in forming (e.g. bending). Therefore, high strength combined with toughness and formability are the primary requirements of the pipeline steel industry [1,2]. American Petroleum Institute (API) X90 as the third generation of pipeline steel, its high uniform elongation and low yield ratio improve the material fracture capacity and pipeline safety significantly [3–5].

Addition of microalloying elements and thermos-mechanical control processing (TMCP) plays an important role in the high strength pipeline steel. Microalloyed elements addition such as Mn, Nb, V, Ti, Cr, Ni, Mo in pipeline steels obtain the desired microstructure and mechanical properties [6]. Microalloying elements, such as Ti and Nb form fine carbide and carbonitride precipitates during TMCP of high grade pipeline steels, which enhances the strength of the steel. Sufficiently uniform dispersed particles containing the microalloying elements, Nb, Ti, or V, have been found to inhibit austenite grain growth effectively [7]. Moreover, the fine-grained microstructure obtained via TMCP, provides high strength-toughness combination [8,9].

Hot induction bending, not only is an effective measure to still maintain high strength and toughness, low yield ratio of large diameter, high-strength thick-walled pipeline steel after bending forming, but also it is the main way to form the bend with large bending angle and small bending radius [10]. The heating temperature in hot induction bending is generally above Ac3, which is higher than the phase transition temperature. The microstructure of the pipeline provides high strength to the pipeline such as acicular ferrite(AF) (or bainite ferrite(BF)), granular bainite(GB), polygonal ferrite(PF), which turns into austenite, and the microalloying elements Nb, V, Ti fine carbide and carbonitride precipitates dissolved. An appropriate heating temperature can avoid coarse grains formed in the heating process. The higher the heating temperature, the grain size of bainite ferrite increases significantly, even become a large bainite structure that crosses the entire austenite grain boundary, which decrease the toughness. However, when the heating temperature is lower, the polygonal ferrite appears in the steel, which improve the toughness and reduce the strength, significantly. Of course, an appropriate re-cooling speed will eventually form the small sub-structure and multi-phase structure, and the solid elements such as C, Mn will supersaturate the solid solution in the microstructure that

* Corresponding author.
E-mail address: liangw1989@163.com (B. Wang).

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optimize the strength and toughness. If the re-cooling speed is improper, the good strength-toughness combination obtained by TMCP would decrease, even occurs the failure problem caused by cracks or micro-cracks when there is an inherent shear stress. The right heating temperature and the right re-cooling speed is the guarantee of good strength-toughness combination. S.H. Mousavi Anijdan et al. [11,12] have reported that cool deformation greatly improves the strength of microalloyed steels, and strain-induced transformation (SIT) of retained austenite in microalloyed steels, to be a significant factor for strengthening due to the deformation in ferrite.

The double effect of re-heating and deformation during the hot induction bending process, which influence the microstructure and mechanical properties of high strength wall-thick pipeline steel obtained by TMCP observably. Microstructure and mechanical properties in high grade pipeline steel depends on the hot induction bending processing parameters such as heating temperature, bending angle, tempering temperature [13–18]. According to the earlier study, the microstructure and mechanical properties of ×90 bend different positions is variant [19]. In addition, the texture during TMCP and the effect on mechanical properties are well reported [20–24]. Hot induction bending also affect the texture, and in spite of few earlier efforts, the effect of hot induction bending on the development of texture in ×90 bend is unclear.

At present, the hot induction bending process for API X70, X80 pipeline steel have been studied maturely, especially the effect on the microstructure and mechanical properties. The aim of this study is to improve and promote the research of hot induction bending for X90 pipeline steel through electron backscatter diffraction(EBSD) analysis. The grain misorientation, grain boundary distribution, grain size, texture, recrystallization and the mechanical properties in API X90 bend obtained from hot induction bending, and the relationship among the bending processing, microstructure and mechanical properties for X90 bend is established.

2. Experimental

2.1. Materials

The pipe was selected as parent pipe in this study is submerged-arc welded pipe with the dimension of Ø1219 × 26.4 mm, and the microalloyed pipeline steel was manufactured by TMCP to obtain yield strength of 748 MPa and tensile strength of 847 MPa (API X90). The chemical composition of the experimental steel is listed in Table 1. The steel is low in carbon content and rich in microalloying elements, primarily contains Nb-Mo in X90 pipeline steel. The alloy contained 0.065%C, 1.82%Mn, and 0.426% Mo, microalloyed with Nb+V+Ti (less than 0.1%). Microalloying elements such as Nb, V and Ti precipitate in the ferrite matrix and on the dislocations, which refine grain and provide high strength. On the other hand, alloy additions such as Cr, Cu, Ni are added to facilitate the corrosion resistance when in the severe corrosive environment. The carbon equivalent (CEV) of the steel is 0.21, the low CEV not only improves the ductility and formability but also enhances the weldability and toughness [24].

2.2. Hot induction bending process

According to CEV of experimental steel, the Ac3 temperature (930 °C) was calculated by Thermo-calc software. The hot induction bending process such as the heating temperature, pushing velocity, and tempering temperature for X90 pipeline steel shown in Table 2.

The schematic diagram for hot bending process is shown in Fig. 1(a). For X90 pipeline steel, Medium frequency induction heating was performed on the experimental parent pipe to 1000 °C that is higher than Ac3 temperature. Austenitizing the microstructure of X90 pipe at this temperature can be plastic deformed under the pushing force. In order to guarantee the mechanical properties of bend after hot induction bending, water cooling online in the heating is necessary at the same time. Temper heat treatment at 560 °C is to eliminate the residual stress after bending forming to obtain a good strength-toughness combination. The position of neutral axis and weld joint is shown in Fig. 1(b). To reduce cracking risk, the weld joint is 45° from the horizontal. After bending, the wall-thickness of the outer arc side is thinner, and that the wall-thickness of the inner side increases, the wall-thickness of the neutral axis is nearly the same.

2.3. Mechanical properties

The mechanical properties test specimens were machined in different positions from the bend zone, namely from the outer arc side, inner arc side, and from the neutral axis position, as shown in Fig. 2. The standard tensile specimen with the diameter of 12.5 mm and gauge length of 50 mm were machined according to ASTM E8M specification, and the tensile tests were carried out on the SHT 4605 testing machine at room temperature with a low strain rate of $5 \times 10^{-4}\,s^{-1}$. The impact toughness was measured using Charpy V notch specimens (10 mm × 10 mm × 55 mm) that were prepared according to ASTM standard E23. The impact tests were performed using JB-500B impact testing machine at −10 °C.

2.4. EBSD analysis

The electron backscatter diffraction (EBSD) experiments were performed on FEI NANO SEM 430 equipped with a HKL Oxford® camera using Channel 5 software. The positions of specimens are the same with that of mechanical properties tests. The specimens were electropolished 20 s at room temperature with the electrolytic solution of 650 ml alcohol, 100 ml chlorate, and 50 ml distilled water. A step size of 0.15 µm was used to construct the EBSD maps, over 60 µm × 60 µm microstructure area. In the EBSD measurements, the grains, the texture, and the recrystallization distribution in the specimens were analyzed.

3. Results and discussion

3.1. Mechanical properties

The corresponding tensile tests results are summarized in Fig. 3. The yield strength of X90 parent pipe is 748 MPa with the tensile strength of 847 MPa, and yield ratio of 0.88. After hot induction bending, the yield strength, tensile strength and yield ratio in the outer arc side along the longitudinal is 750 MPa, 848 MP and 0.88, respectively, and the elongation is 21%. But in the outer arc side along the transverse direction, it is 703 MPa, 796 MP and 0.88, respectively, and the elongation is 20%. The yield strength and tensile strength along the longitudinal direction are higher than that along the transverse direction. Nevertheless, the yield strength and tensile strength of the inner arc side are similar along

Table 1
Chemical composition of X90 pipeline steel (wt%).

	C	Mn	Si	Nb	V	Ti	Cu	Cr	Mo	Ni	B
X90	0.065	1.82	0.281	0.044	0.018	0.013	0.148	0.022	0.426	0.375	0.0007

CEV = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B = 0.21.