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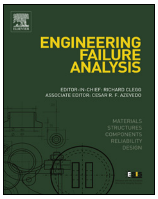

Role of cold rolled followed by annealing on improvement of hydrogen induced cracking resistance in pipeline steel

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ABSTRACT

In this study, we investigated the effect of cold rolled followed by annealing on hydrogen induced cracking susceptibility in an API X60 pipeline steel. To this, we carried out cold rolling on X60 steel up to 20%, 50% and 90% in thickness reduction to change the microstructure and texture of steel. Then, we annealed all specimens at 850 °C for 90 s. We studied all tested specimens by electron backscatter and X-ray diffraction techniques. EBSD results showed that the grain refinement process was properly done via cold rolling and annealing treatments in tested specimens. However, the dislocation density was high for all tested steels. Moreover, electrochemical hydrogen charging experiment on tested steels proved that all specimens were still highly susceptible to hydrogen induced cracking. Therefore, we increased the annealing temperature and its duration of the 90% cold rolled specimen (the specimen with finest grains) up to 950 °C for 5 min. Interestingly, there was no HIC crack on this steel after hydrogen charging experiment. EBSD measurements on this steel showed strong textures of {100}//ND and {111}//ND. As a result, such strong textures, low Kernel Average Misorientation data, a high proportion of recovered grains and coincidence site lattice boundaries were recognized as the most important reasons for the highest HIC resistance in the mentioned steel.

1. Introduction

The demand for pipeline steels has been recently increased due to the economic manufacturing, easy installation, low alloying elements content and more importantly an economic way for oil and gas transportation [1–3]. Basically, pipeline steels are exposed to different types of failure modes. Among these, hydrogen induced cracking (HIC) and stress corrosion cracking (SCC) phenomena have been recognized as the most important modes of failure in harsh environments. We may consider many environments, such as acidic and corrosive environments and even very cold weathers, as harsh environments. HIC and SCC cracks in pipeline steels basically nucleate and propagate from some especial regions [4–7]. For instance, nonmetallic inclusions such as aluminum oxide and manganese sulfide type inclusions are considered as HIC crack nucleation sites and center segregation zone is prone to HIC cracking [8–10]. There are some innovative techniques to reduce HIC and even SCC susceptibility in pipeline steels. Almost all HIC cracks are appeared in the mid-thickness of the pipe body where center segregation of some elements are occurred. Therefore, the most important goal is to remove the segregated elements from the center segregation zone. A homogeneous microstructure can also show better resistance against HIC cracking. Some researchers suggested that thermomechanical controlled processes (TMCP) with control of cooling rates can be considered as an effective way to reduce the amount of segregated elements from the center segregated zone.

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This method can also create a homogeneous microstructure, such as fine grain irregular ferrite, small amounts of bainite and martensite-austenite constituents [11–13]. Control of texture and grain boundary character distribution is considered as an innovative approach towards manufacturing of pipeline steel. Venegas et al. found a strong correlation between texture and mitigation of hydrogen induced cracking in pipeline steel [14–18]. There authors concluded that the local plastic deformation of ⟨111⟩//ND oriented grains resists against crack propagation. Such deflection of cracks hinders the process of failure. The results of Arafin et al. study [19] also documented that control of texture allows to improve resistance of pipeline steel to stress corrosion cracking. This work also documented that it is possible to increase the number of coincidence site lattice (CSL) grain boundaries through texture control. It is notable that such low energy boundaries can arrest the short crack after its formation. It has been also reported that some special texture components including {111}//ND, {112}//ND and {110}//ND fibers play a key role in reducing the number of intergranular and transgranular low resistance paths and consequently they increase HIC resistance in pipeline steel [14–18]. Such texture components may also reduce the probability of crack coalescence and stepwise cracking. These texture components are able to provide low-energy boundaries such as CSL boundaries and hinder the intergranular HIC crack propagation [20]. Concepts of grain boundary engineering and texture control, when adopted for innovative manufacturing of pipeline steel, may allow pipeline steel manufacturers to provide a more reliable sustainable energy supply.

In this work, due to the important role of texture and grain-boundary character on different types of failure in pipeline steels, we investigated the effect of crystallographic texture and grain boundary character provided by cold rolled followed by annealing on improvement of hydrogen induced cracking resistance in pipeline steel.

2. Experimental procedure

2.1. Cold-rolling and annealing treatments

In the current research, we investigated an API 5L X60 pipeline steel. Table 1 shows the chemical composition of the above-mentioned steel. We simply abbreviated the rolling, transverse and normal directions of X60 steel as RD, TD and ND, respectively. We prepared four specimens with the dimensions of 40 (RD) × 40 (TD) × 6 (ND) mm from the as-received (AR) X60 pipe plate. We did not perform any cold-rolling and annealing treatment for the first specimen and consequently we named it as AR specimen. We cold rolled the samples number two, three and four in their rolling direction for 20%, 50% and 90% reduction in thickness and then annealed at 850 °C for 90 s. The thickness of as-received specimens was reduced by 0.1 mm during each unidirectional rolling pass to get desirable reductions. Moreover, the rolling speed was constant with the amount of 0.2 m/s. To simplify the text, we abbreviated the names of the 20%, 50% and 90% cold-rolled and heat treated specimens as 20% CRA, 50% CRA and 90% CRA. At the end, we also annealed the 90% cold rolled specimen at 950 °C for 5 min and named it as 90% CRT.

After cold rolled followed by annealing, we accurately polished the RD-TD surfaces of all specimens up to a 1 μm diamond paste. Then, we utilized a Bruker D8 Discover diffraction system to measure the texture on RD-TD surfaces of all tested specimens. After completing the texture measurements, we used some software facilities, such as Multex3, Tools and Resmat-Textools, to post-process and calculate pole figures. It is notable that an additional polishing process was necessary to for electron backscatter diffraction (EBSD) measurements. Therefore, we vibrometry polished all RD-TD polished surfaces for 12 h by using a slurry silica solution. We utilized a scanning electron microscope (SEM) equipped with an Oxford Instruments Nordlys nano EBSD detector to carry out the EBSD measurements. Finally, we used Tango and Mambo facilities to analyze the raw EBSD data.

It is worth-mentioning that since we chose a large area on 90% CRT specimen for EBSD measurement, only EBSD measurement provided a scientific information about the texture and micro-texture data.

2.2. Electrochemical hydrogen charging

In order to create HIC cracks in steel specimens, we charged all cold rolled and heat treated specimens electrochemically with hydrogen using a mixed solution of 0.2 M sulfuric acid and 3 g/L ammonium thiocyanate. During the electrochemical hydrogen charging, the following reactions are occurred to produce hydrogen [18]:

$$\text{Oxidation at anode: } 2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^- \quad (1)$$

$$\text{Reduction at cathode: } 4H^+(aq) + 4e^- \rightarrow 4H \rightarrow 2H_2(g) \quad (2)$$

$$\text{Overall chemical reaction:} 2H_2O(l) \rightarrow 2H_2(g) + O_2(g) \quad (3)$$

It is worth-mentioning that most of the produced hydrogen in the form of hydrogen molecules goes out from the solution and does not enter the steel. Ammonium thiocyanate acting as hydrogen recombination poison increases the amount of hydrogen inside the steel specimens by preventing hydrogen molecule formation.

Table 1
Chemical composition of the X60 pipeline steel (wt%).

Pipeline steel	C	Mn	Si	Nb	Mo	Ti	Cr	Cu	Ni	V	S	P	N
X60	0.052	1.50	0.15	0.067	0.096	0.022	0.07	0.18	0.19	0.001	0.0027	0.007	0.009