Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 23
ISSUE 2
August
2007

Hardenability of steels for oil industry

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Received 01.03.2007; published in revised form 01.08.2007

Materials

ABSTRACT

Purpose: Alloying elements in steels are used for a various reasons. One of the most important is the achievement of higher strength in required shapes and sizes. Often in very large sections of steels are used for production of the oil country tubular goods (OCTG). Therefore the hardenability of steels is an important property aim for the appropriate concentration of alloying elements needed to harden the section of steel for oil industry. In this study the hardenability, the cooling rates and microstructures of low alloy Cr-Mo and Mn-Mo steels were investigated.

Design/methodology/approach: The cooling rate determines the amount of martensite structure. Hardenability test was carried out by Jominy method. During Jominy testing the temperature changes were monitored by means of CrNi-Ni thermocouples which are connected to eight-channel digital/analogues converter. Microstructure was determined using a scanning electron microscopy (SEM).

Findings: The cooling rates in the temperature range between 1133 and 973 K at different distances from the quenched end of low alloy Cr-Mo and Mn-Mo steels were found. Also the hardness and microstructures against the distances from quenched end are determined.

Research limitations/implications: It is known that carbon has a marked the effect on hardenability of steel, but its use at higher levels is limited because lower toughness and increased probability of distortion and cracking during heat treatment and welding. Addition of manganese at low alloy steels is very useful for improvement of their hardenability.

Practical implications: Chemical composition of low alloy steels for oil industry is usually complex and defined in most cases by standard which give range of concentration of the important alloying elements (Cr, Mo, Mn, etc.) as well as the upper limits of impurity elements (S and P). Alloying elements increase the cost of the steel and from these reason it is important to select only steels which required to ensure compliance with specifications. The economical way of increasing the hardenability of steels (at constant carbon content) is to increase the manganese content.

Originality/value: Originality and high value of our research work based on development and application of a new grade of low alloy Mn-Mo steel for oil country tubular goods.

Keywords: Steel; Hardenability; Hardness; Jominy test; Cooling rates

1. Introduction

Low alloy steels have large range of application in oil country tubular goods (OCTG). The main reasons for those applications are excellent hardenability, high strength, a good toughness and high resistance to sulfide stress corrosion cracking (SSCC) as the form of hydrogen embrittlement (HE).

The hardenability of steel can be defined in several ways [1-4]. It is the ability steel to acquire hardness being austenitized and quenched. This definition emhasize hardness. The source of hardening is the formation and presence martensite structure. Thus high hardness is related to martensite formation [5].

If the hardenability is low, fast cooling is needed to achieve a large amount of martensite. However, fast cooling causes the development residual stress, distortion and even cracking. Excess hardenability usually represents excess cost. Thus, it is expedient to optimise the least expensive and most efficient alloy system [6,7].

A numerous of articles are described on a numerical simulation of the Jominy end-quench test on simulate phase transformation in the steel [8,9]. Also today the neural networks are using as a tool for hardenability modeling [10,11].

To the evaluation of hardenability is the use the end-quench test whish is referred to as the Jominy test [12]. The test is widely used to determine hardenabilities in the range round from 10 to 60 mm. The objective of this work was compare the hardenability of low alloy CrMo and Mn-Mo steels at the same conditions testing.

2. Experimental work

Low-alloyed chromium-molybdenum and manganese-molybdenum steels were produced (Table 1).

Table 1.
Chemical composition of low-alloyed Mn–Mo and Cr-Mo steel, wt. %

C	Mn	P	S	Si	Mo	Cr
0.42	1.63	0.025	0.02	0.27	0.25	0.12
0.42	0.75	0.005	0.003	0.20	0.22	1.05

Fig. 1. Equipment and quenching system for the hardenability testing by Jominy method

The Jominy end-quench hardenability test was carried out in accordance with the ASTM Standard A255-99 [13] and SAE Standard J406 standard [14].

Figure 1 shows the equipment and quenching system. During the heating and cooling of the Jominy specimen the temperature was monitored by means of three evenly coated CrNi–Ni thermocouples located at different distances from the Jominy end specimen and connected to an eight-channel digital/analogous converter ADAM 4018 [15]. The temperature values measured were then saved by a PC. The thermocouples were set up at the specimen centre into holes 2.5 mm in diameter, at the distances of 4, 20 and 40 mm from the end face of the Jominy specimen [16]. After quenching parallel flates are grouded on opposite sides of the specimen and hardness form the quenched end.

Microstructural examination of Jominy specimens at the different distances from quenched end was carried out using a scanning electron microscope (SEM) [17]. To reveal of the microstructure the nital solution was used. Hardness was measured by Vickers method.

3. Results and discussion

By heating the Jominy specimens to the austenitizing temperature of 1133 K, a homogenous austenitic microstructure was ensured for the whole sample volume. At our experimental work four Jominy specimens were tested.

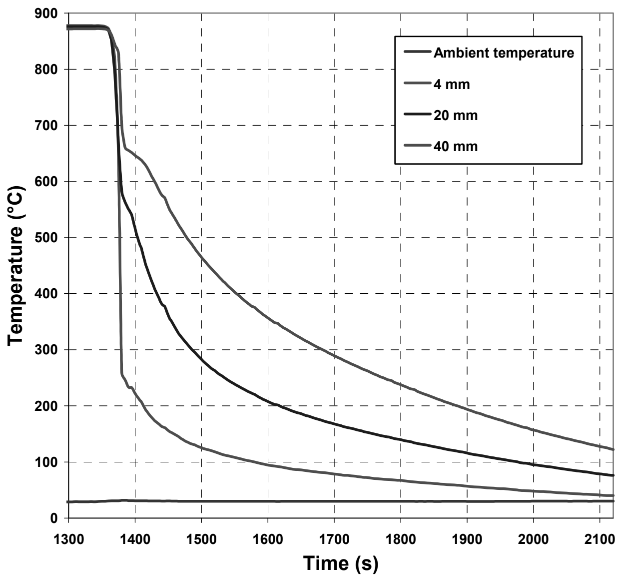


Fig. 2. Change of temperature during cooling of the Jominy specimen for Cr-Mo steel at different distances from the specimen end-face

The temperature values measured along the Jominy specimens were processed as a function of the cooling time of the sample core. The curves presented in Figures 2 and 3 indicate that the cooling process was much faster at the distance of 4 mm from the quenched end face than at other distances (20 and 40 mm). Cooling rates in the temperature range from 1133 to 973 K are calculated at several distances from the quenched end (Table 2).

The cooling rate decreased progressively from the quenched end face along the length of the Jominy specimen. The cooling rate is the highest (about 30 K s^{-1}) near the the end where the water jet impinges on the specimen and decreases from the quenched end, producing a variety of microstructural as a function of distance from the quenched end. The cooling rate at distance of 40 mm from quenched end is approximately 3.4 K s^{-1}.

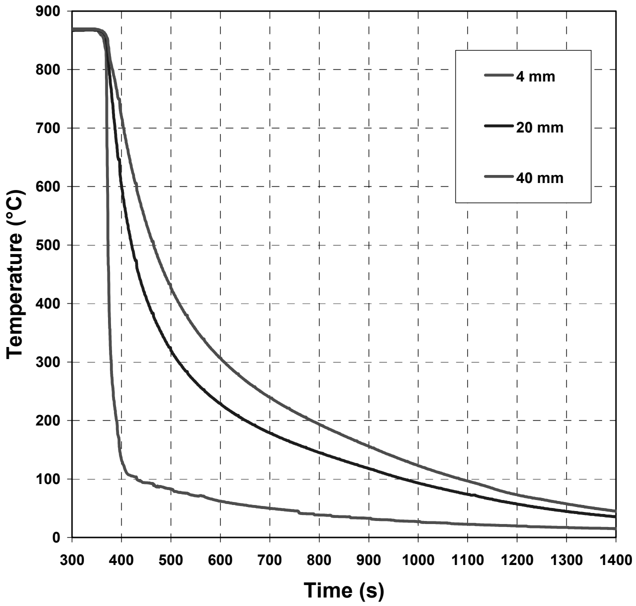


Fig. 3. Change of temperature during cooling of the Jominy specimen for Mn-Mo steel at different distances from the specimen end-face

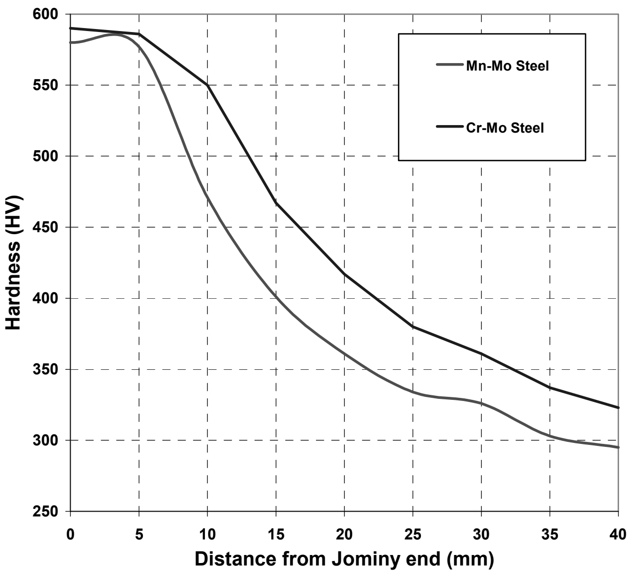
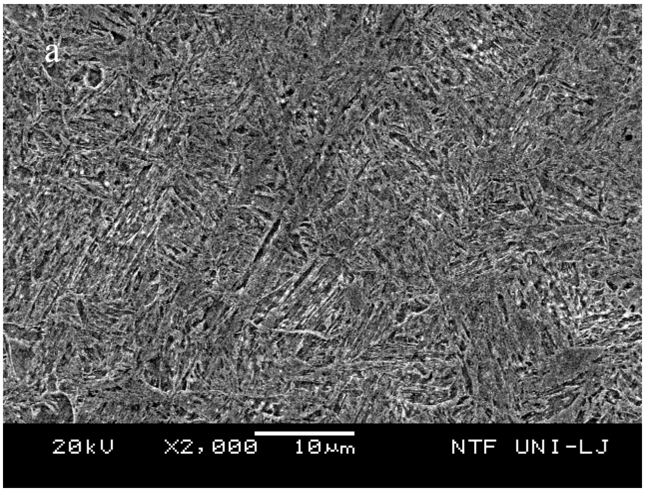


Fig. 4. Jominy curves for Cr-Mo and Mn-Mo steels

When a specimen was cooled, two diametrically opposite flats, 0.4 mm deep and parallel to the longitudinal specimen axis, were ground. Hardness was measured along the flats by the Vickers method. A good reproducibility was achieved.

Table 2.
Calculated cooling rates between 1133 and 973 K at different distances from the quenched end

Distance from quenched end, mm		4	20	40
Cooling rate, K s^{-1}	Cr-Mo Steel	31.5	8.8	3.4
	Mn-Mo Steel	30.2	14.0	3.4



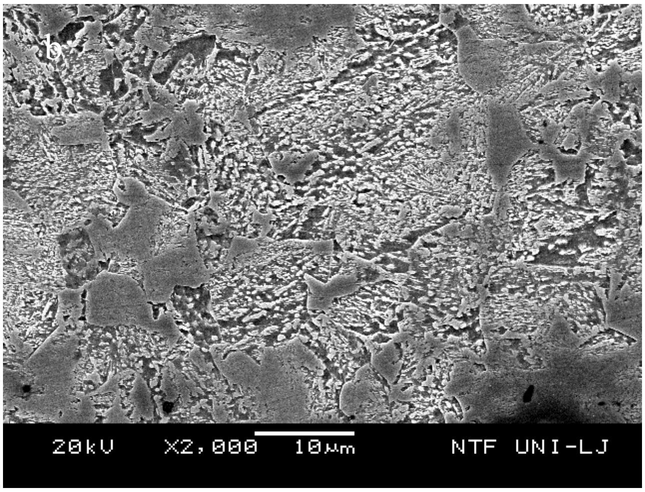


Fig. 5. SEM micrographs of Jominy specimens of Cr-Mo steel at near the quenched end (a), and 40 mm from the quenched end of the sample (b)

The hardness values were plotted against the distances from the quenched end. The Jominy curves for both investigated steels are shown in Figure 4. Increase in the distance from the quenched end face from 0 to 40 mm was accompanied by decrease in hardness. Essentially the hardness level is measure of the depth and distribution of martensite and/or bainite microstructure.

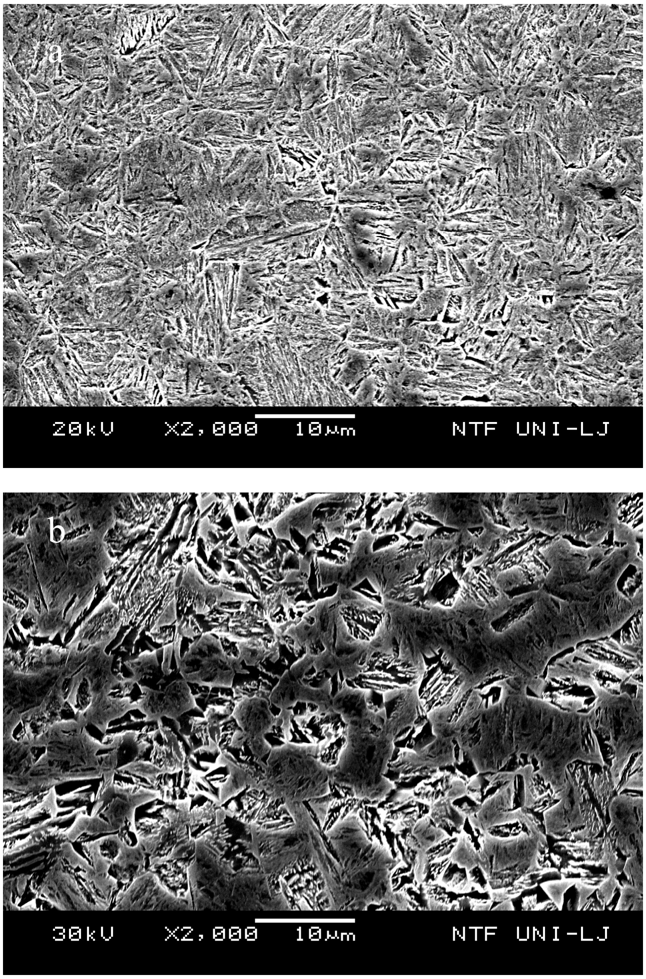


Fig. 6. SEM micrographs of Jominy specimens of Mn-Mo steel at near the quenched end (a), and 40 mm from the quenched end of the sample (b)

At distance of 4 and 10 mm from the quenched end face the martensite microstructure is observed. Figures 5a and 6a show laths martensite microstructures near to the quenched end for both steels. Figures 5b and 6b show the bainite microstructure at distance of 40 mm from quenched end.

4. Conclusions

The high hardenability of the steel is indicated by the retention of higher hardness level to the higher distances from the quenched steel.

The cooling rates in the temperature range between 1133 K and 973 K decreases from the quenched end producing the different microstructures as a function of distance from the quenched end.

This microstructural changes are confirmed by the change hardness across the cross section of the specimen.

On the basis of the hardenability we can conclude that the low alloy Mn-Mo steel can be successfull used for production of oil country tubular goods.

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