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Elimination of Hydrogen Induced Cracks by Slow Cooling After Hot Rolling of Medium Carbon Molybdenum Steel Blooms

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Abstract - At JSW Steel Limited, Salem Works (JSWSL), hydrogen induced cracks contribute more to ultrasonic defects in medium carbon molybdenum steel such as JDM 1046. As hydrogen tend to escape during cooling due to its smaller atomic radius and high diffusivity in the solid phase, experiments were conducted to reduce hydrogen induced cracks by slow cooling of blooms/bars. A study was conducted wherein few blooms/bars of the same heat were slow cooled and others were normal cooled (air cooled). After cooling, hardness, microscopic and ultrasonic examinations were carried out on these blooms/bars. Results revealed that, the slow cooled blooms/bars were found to be free from ultrasonic defects and showed reduced as rolled hardness when compared with air cooled blooms/bars. Slow cooling resulted in defect free steel against 15-35% defect levels observed in air cooled bars. The paper discusses various metallurgical changes, which facilitated the elimination of hydrogen in JDM 1046 grade steel.

Keywords: JDM 1046, ultrasonic defect, hydrogen induced cracks, air cooling, slow cooling, microstructure, hardness, blooms, bars.

I. INTRODUCTION

When liquid steels cool from a temperature above austenitization temperature, it transforms into other phase configurations according to the austenite composition and cooling rate. As a result of phase transformation, the steel crystal structure and consequently, both the shape and the lattice parameter of the unit cell, change. These changes may introduce dilatational strains into the microstructure, which result in the creation of residual stress concentration zones within the microstructure. These stress concentration zones are vulnerable regions to the formation of micro cracks or growth of the flaws in these regions [1]. Three processes are involved pertaining to hydrogen: (a) hydrogen evolution from the molten steel and segregation of hydrogen in blooms during solidification, (b) homogenization and redistribution of hydrogen in steel during solidification and (c) hydrogen diffusion from blooms during cooling. Hydrogen diffusion is considered paramount to obtain high quality blooms with low hydrogen content [2]. Diffusible hydrogen is considered to be mobile at or near room temperature, whereas the remaining residual hydrogen is trapped in the metal. Total hydrogen is the combination of the two fractions. Residual hydrogen can be retained through interaction with micro structural discontinuities or by the formation of hydrides with alloying elements [3]. The presence of hydrogen and other factors lead to the delayed formation of internal defects that appear as hairline cracks, shatter cracks or flakes. Flake cracks develop only after an incubation period at temperatures below 200^{o}C and are usually found at approximately mid radius towards the center. Flaking is more difficult to avoid in ultra clean steels and with the advent of ultra clean steels, hydrogen flaking is observed even in steels with less than 2 ppm hydrogen and even steels with 1.5 ppm hydrogen cannot be considered to be immune to hydrogen flaking [4].

Hydrogen accumulates on the surface of manganese sulphide inclusions and forms molecular hydrogen (H_2) and develop sufficient pressure to create internal cracks. However, if the product is slow cooled from the rolling temperature, the atomic hydrogen has sufficient time to diffuse from the product, thus avoiding hydrogen damage [5]. At JSWSL, hydrogen induced cracks and center unsoundness contributed more to ultrasonic rejections in chrome-moly and high manganese steels, which was subsequently minimized by increasing argon flow rate during vacuum degassing and optimizing superheats [6]. The present paper discusses the study conducted to eliminate the hydrogen induced cracks by slow cooling in JDM 1046, a medium carbon molybdenum grade steel

II. EXPERIMENTATIONS

The chemical composition of steel was determined by ARL-4460 optical emission spectrometer and hydrogen content was determined by Leco RH-402 hydrogen analyser. Steel microstructure was studied by Leica optical microscope, model DMI5000M. Ultrasonic testing is being carried out as per ASTM A388. Hardness was measured by using Brinell Hardness testing machine, model TKB 3000. Temperature of bars was recorded by using optical pyrometer, model Raynger 3I-Raytek. The chemical composition of JDM 1046 is presented in Table 1.

TABLE I CHEMICAL COMPOSITION OF JDM 1046

Grade	C (%)	Si (%)	Mn (%)	P(%)	S (%)	Al (%)	Cr (%)	Mo (%)	H (ppm)
JDM1046	0.49	0.22	1.03	0.016	0.004	0.026	0.19	0.10	1.89

A. Method for slow cooling

The method involves subjecting few hot rolled bars to slow cooling and remaining bars of the same heat to air cooling to determine the effect of slow cooling on the quality of rolled bars. Slow cooling of bars was carried out in mild steel box.

A mild steel box having a capacity of 20 tons, capable of housing 6 meter length hot rolled bars, is lined inside with 40 mm thick glass wool to thermally insulate it from atmosphere during cooling, is used for the study. The bars after rolling are placed inside the box and the box is immediately closed with a top door lined inside with 40 mm thick glass wool. The bars are allowed to remain inside the box until it cools down to room temperature. The box is provided with a sliding door for measuring temperature of bars.

III. RESULTS AND DISCUSSION

Blast furnace – Energy Optimising Furnace – Ladle Refining Furnace – Vacuum Degassing – Continuous Casting is the route followed for steel making at JSWSL. 340 x 400 mm blooms of JDM 1046 cast by continuous caster were further rolled into 125 mm dia bars. The initial temperature at the exit pass was found to between 920-900^{o}C. Few hot rolled bars were slow cooled in the box and other bars were air cooled as per normal practice. The temperatures of both air cooled and slow cooled bars were recorded at various intervals right from the exit pass until the temperature of bars came down to around 200^{o}C. Cooling data were plotted as temperature versus time and Fig.1 presents temperature profile of air cooled and slow cooled bars.

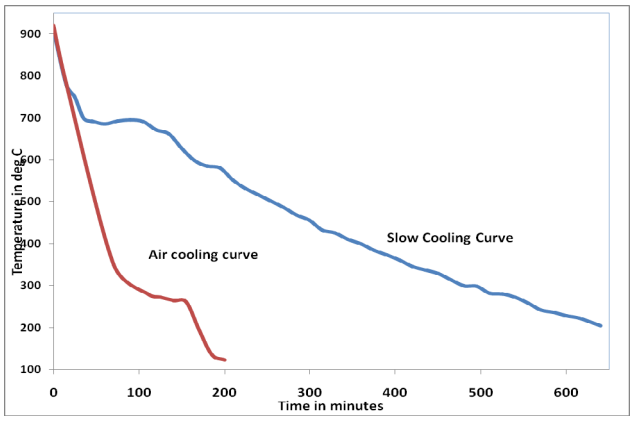


Fig.1 Temperature profile of slow cooled and air cooled bars

Data revealed that, 640 minutes were required by slow cooled bars against only 168 minutes required for air cooled bars to cool to 200^{o}C, indicating approximately a fourfold increase in time for slow cooling.

After cooling, the slow cooled and air cooled bars were subjected to hardness, microscopic and ultrasonic examinations and the results were compiled to determine the effect of slow cooling on these properties. Table 2 presents the comparison of hardness of three air cooled and three slow cooled bars for illustration.

TABLE II COMPARISON OF HARDNESS OF AIR COOLED AND SLOW COOLED BARS

Type of cooling	Grade	Bars *	Hardness (BHN)		
			At center	At mid radius	At sub surface
Air cooled	JDM 1046	A1	223	223	229
		A2	212	217	207
		A3	212	212	197
Slow cooled		S1	197	197	187
		S2	207	207	195
		S3	202	204	194

**A & S signifies air cooling and slow cooling*

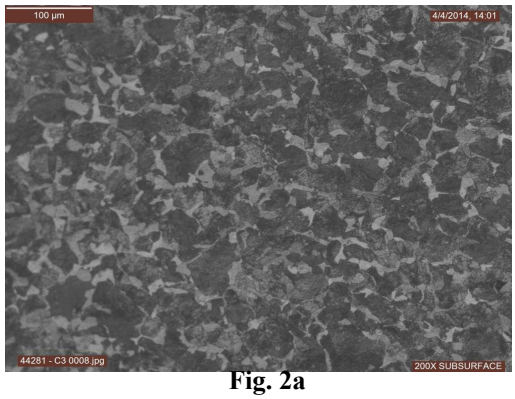


Fig. 2a

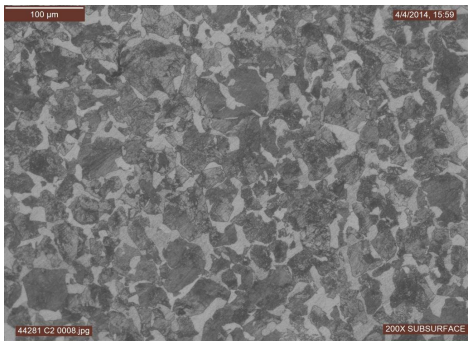
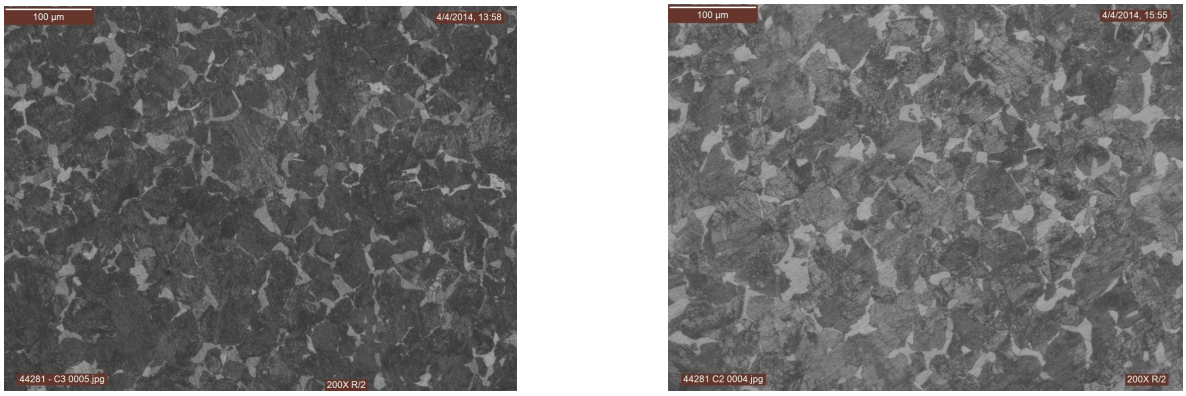


Fig.(b)

Fig.2 Micrographs of JDM1046 - sub surface (a) air cooled (b) slow cooled



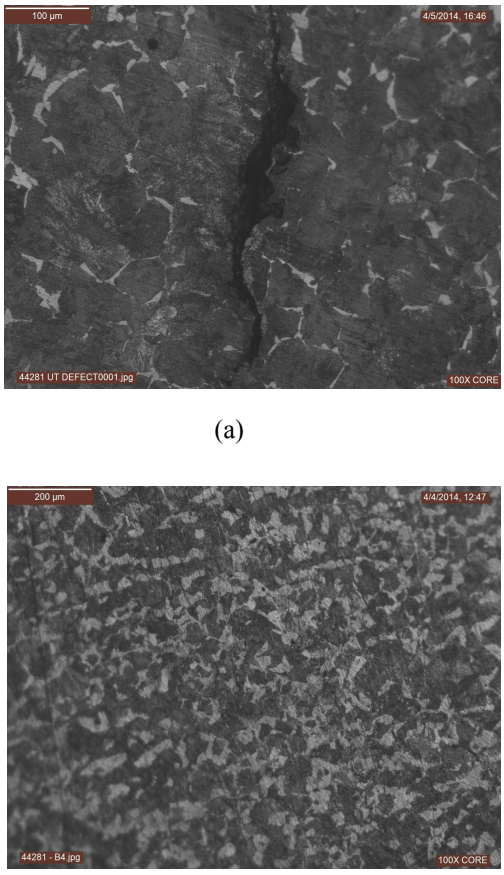
(a) (b)

Fig. 3 Micrographs of JDM1046 – mid radius (a) air cooled (b) slow cooled

All the micrographs shown were captured at 200 X magnification for ease of comparison. It is seen that, the micrographs of slow cooled bars are richer in ferrite phase and the grains are coarser and uniformly distributed than the corresponding micrographs of air cooled bars.

During the process of air cooling, due to rapid cooling of bars, there will be little diffusion of hydrogen out of steel bars and the surface of steel cools faster than the center. The larger the difference in temperature between the surface and the center, higher will be the concentration of hydrogen in its interior. The increase in hydrogen concentration in the interior zones is likely to occur because during cooling, hydrogen diffuses toward the inside, that is, from surface to center, in the direction of hotter zones in the body of the product [7]. It is known from literature that, hydrogen causes pinholes and porosity in steel [8]. The excess hydrogen gets collected in micro-pores, voids and shrinkage cavities. Furthermore, as the hydrogen solubility decreases with a decrease in temperature, local hydrogen pressure builds up in the steel matrix, this on subsequent rolling operation might have led to cracks. The results of the experiment are in agreement with this phenomenon as it is evidenced by the fact that, few air cooled bars of JDM 1046 were found to have an ultrasonic defect at the core. Fig. 4 presents the micrograph of the UT defect observed at core in the air cooled bar and a micrograph of defect free slow cooled bar.

Another reason for the defect observed in air cooled bar could be attributed to its chemical composition [9]. It is common knowledge that, sulphur forms manganese sulphide during cooling, which act as weak hydrogen traps in that they trap hydrogen at low temperatures (<200^{o}C). As the sulphur content is very low in JDM 1046 (0.004%), the number of sulphide inclusions will be small and hence the amount of hydrogen accumulating at each inclusion will be more. In other words, there are an insufficient number of sulphide hydrogen traps to adequately distribute the hydrogen. This increases local hydrogen pressure and facilitate cracking. Therefore for low sulphur steels, hydrogen flaking may occur at lower hydrogen contents than for high sulphur steels. Hence, possibly less than 1ppm hydrogen would be necessary to completely avoid flaking in ultra low sulphur steels [4]. Thus, porosity and low sulphur content in JDM 1046 contributed to hydrogen induced cracking observed as UT defect in air cooled bars. From the experiments, it is learned, not to desulphurise the steel to levels below what is required to meet its properties.



(a)

(b)

Fig. 4 Micrographs of (a) UT defect in air cooled bar at core (b) slow cooled bar

But, the scenario in the case of slow cooling is different in that, during slow cooling of steel, as most of diffusible hydrogen escapes to the atmosphere and does not concentrate in the inner zones to such a degree as is observed in air cooling, thermal stresses are reduced and flakes do not form [7] in slow cooled bars. Hence, no such defects were found in any of the slow cooled bars. Fig. 4 (b) shows the presence of ferrite and pearlite in the micrograph captured at the core of slow cooled bar.
Ultrasonic testing was performed on air cooled and slow cooled bars and Table 3 presents the defect levels observed in few air cooled bars.

TABLE III RESULTS OF ULTRASONIC TESTING

Type of cooling	Bars	Defect level (%)	Defect at depth from surface (mm)
Air cooled bars	A1	15-35%	60-68
	A2	15-30%	60-70
	A3	20-35%	60-65
Slow cooled bars	All bars	Nil	Nil

A defective bar was hardness tested and was found to have a hardness of 229 BHN, 241 BHN and 235 BHN at sub surface, mid radius and at center respectively, which are much higher than the corresponding hardness of any of the slow cooled bars. Ultrasonic testing reveals a defect level of 15-35% at a depth of 60-70 mm in air cooled bars whereas slow cooled bars were found to be free from such defects.

IV. CONCLUSION

Slow cooling is proved beneficial as it ensures the maximum removal of diffusible hydrogen due to increased time available for diffusion and increased ferrite phase in microstructure. Porosity and too low sulphur content were found to initiate hydrogen cracking in air cooled bars. Slow cooled bars showed less hardness up to 40 BHN when compared to air cooled bars, which is advantageous considering subsequent forging operation. Slow cooling resulted in defect free steel against a defect level of 15-35% observed in air cooled bars. Results of experiment also reveal not to desulphurise steel to levels below what is needed to meet its application.

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