Effect of molybdenum on the intercritical heat-affected zone of the low carbon Cr-Mo steels

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Abstract- In the present study, the effect of molybdenum with a content of 0.8 wt % chromium on the microstructure and hardness of intercritical heat-affected zone (HAZ) of a low carbon Cr-Mo steel were investigated. Low carbon steel specimens containing 0.4, 0.8, 1.4, 1.8 and 2.3 wt % Mo were welded using a submerged arc welding process with the heat inputs of 0.5, 1 and 2 kJ mm^{-1}. After welding, microstructure and hardness of the intercritical HAZs were investigated. From the microstructural observations, for a heat input of 0.5 kJ mm^{-1} it was seen that 0.4 wt % molybdenum was effective on the formation of bainite with martensite and greater values of that encouraged the formation of martensite producing higher content hardness values. As the heat input increased to 1 kJ mm^{-1}, it was seen that 0.8 wt % molybdenum and higher values of that were effective on the formation of bainite and martensite. However, bainite and martensite did not appear for the low molybdenum contents with the heat input of 2 kJ mm^{-1}.

Index Terms :Microstructure, Welding, Steel-molybdenum; Hardness

I. INTRODUCTION

In the welding of transformable steels, the heat affected zone (HAZ) are composed of a number of regions characterized by specific changes in microstructure such as a spheroidised zone, a partially transformed zone (intercritical heat-affected zone), a grain refined zone, and a grain coarsened zone [1-4]. The grain-coarsened zone [3-7] and the intercritical heat-affected zone (HAZ) [8-11] are critical zones since Charpy V-notch and fracture toughness tests have shown that embrittlement is located within these zones in the welding of low-carbon and low-alloyed steels. For the grain-coarsened zone in the HAZ the embrittlement depends on the chemical composition of the steel welded and on cooling rate. In the intercritical HAZ, which experiences a peak temperature between the Ac_1 and Ac_3 temperatures, partial transformation of austenite takes place. In a carbon steel having a ferrite/pearlite structure prior to welding, the pearlite islands, which are of eutectoidic carbon content, first transform to austenite on heating and then to ferrite-pearlite, upper bainite, auto-tempered martensite or high-carbon martensite on cooling [1,2,10,11-13]. Brittle fracture behavior in the intercritical HAZ is associated with the formation of martensite [2-10,11].

There have been some investigations on the microstructure and mechanical properties of the intercritical HAZ [8-11,13,14], to the knowledge of the present authors there is nothing in the literature that focuses on the effects molybdenum on the microstructure of the intercritical HAZ in the welding of low carbon Cr-Mo steels. Therefore, the present study was undertaken to clarify the effects of molybdenum content ranging from 0.4 wt % to 2.3 wt % along with a constant chromium content of 0.8 wt % and the effect of different heat inputs on the microstructure and hardness of the intercritical HAZ.

II. EXPERIMENTAL DETAILS

The specimens used in the experimental study were obtained by casting. The cast specimens measuring 150 x 200 x 30 mm were forged at 1100 ^{o}C to the thickness of 15 mm, then normalized at 900 ^{o}C for 30 min and cooled in air. Before welding, the final dimensions of the welding specimens were machined to the dimensions of 150 x 200 x 12.5 mm. The chemical composition of the specimens are given in Table 1.

Table 1. Chemical compositions of welding specimens, wt %

Spec. num.	Elements							
	C	Si	Mn	P	S	Cr	Mo	Fe
1	0.13	0.25	0.49	0.03	0.02	0.75	0.42	Bal.
2	0.13	0.25	0.48	0.02	0.02	0.85	0.82	Bal.
3	0.14	0.24	0.49	0.02	0.02	0.88	1.41	Bal.
4	0.13	0.26	0.49	0.02	0.02	0.82	1.83	Bal.
5	0.13	0.24	0.47	0.02	0.03	0.79	2.31	Bal.

Bead-on-plate welds were made by a submerged arc welding machine with the heat inputs of 0.5, 1 and 2 kJ mm^{-1}. The welding parameters are given in Table 2. An electrode of AWS EL 12K specification and a diameter of 4 mm was used with granular basic type flux.

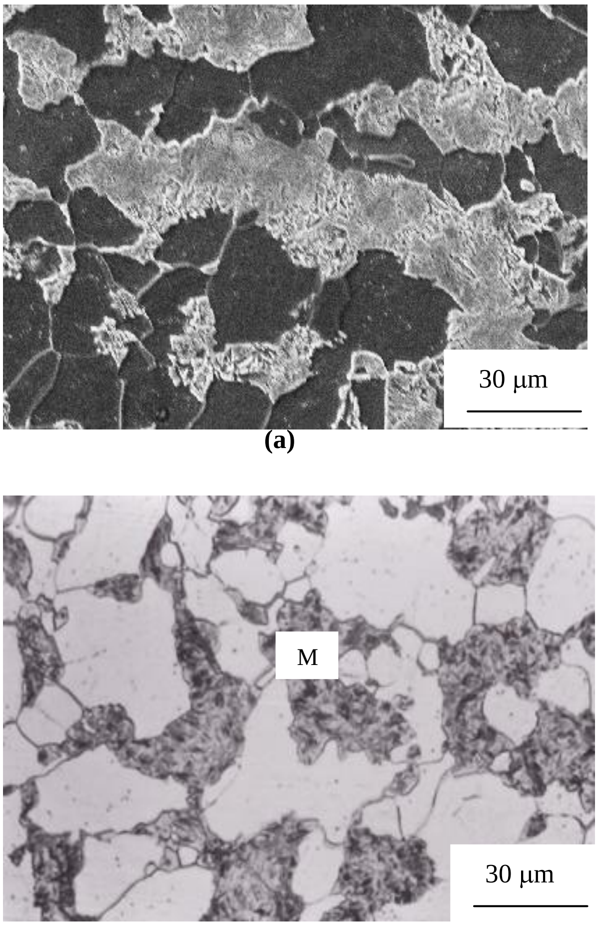
Table 2. Welding parameters

Current (A)	Voltage (V)	Travel speed (mm min^{-1})	Nominal heat input (kJ mm^{-1})
510	20	1225	0.5
450	20	541	1
430	20	259	2

After welding, samples characterized the welding zones were obtained from the welded specimens for microstructural examination and hardness measurement. The samples were ground, polished and etched with 2 % nital. Microstructural analyses were performed by optical and scanning electron microscopy (SEM). Microhardness indentations in the intercritical HAZ were made with a 15 g load.).

III. RESULTS AND DISCUSSION

The microstructure examinations of the tested specimens for different heat input values are given in Fig.1-3. From the results of the microstructural examination, it was seen that molybdenum strongly influenced the phases formed from carbon rich austenite in the intercritical HAZ. The microstructure of the specimen 1 with a heat input of 0.5 kJ mm^{-1} is given in Fig.1a. it was shown that the microstructure formed from carbon rich austenite in the intercritical HAZ of specimen 1 consisted mainly of bainite (B) and martensite (M). Figure 1b shows the microstructure of the specimen 5 with a heat input of 0.5 kJ mm^{-1}. The microstructures of that were mainly composed of martensite. The same microstructures were observed for the specimens from 2 to 5. In addition, in those specimens, some bainite were observed along with the martensite. The molybdenum content of 0.8 wt % and greater values of that encouraged the formation of martensite. Considering that the high molybdenum content lowers the critical cooling rate [15], the above results seem reliable.

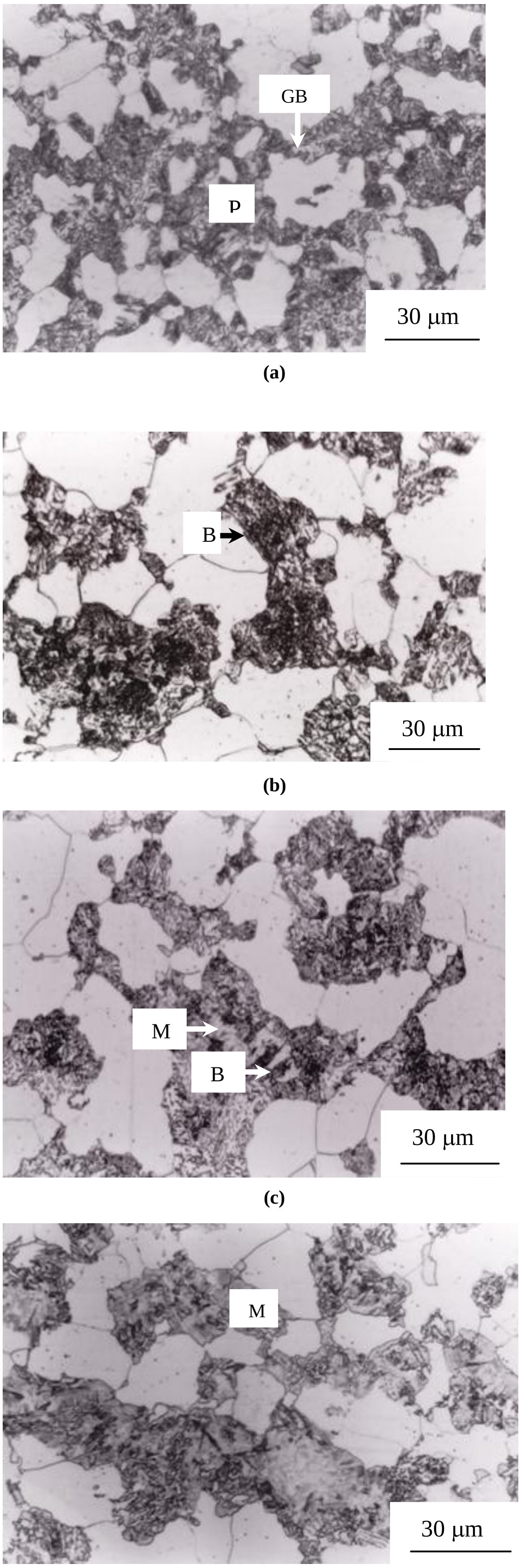


(a)

(b)

Figure 1. Microstructure of intercritical HAZ in specimens containing *a*) 0.4 wt %Mo (SEM) and *b*) 2.3 wt %Mo (optical) with a heat input of 0.5 kJ mm^{-1} (M: Martensite).

With a heat input of 1 kJ mm^{-1}, the microstructure formed from the carbon-rich austenite in the intercritical HAZ of specimen 1 consisted of grain boundary ferrite (GBF) and fine grain pearlite (P), as shown in Figure 2-a. The microstructure was mainly composed of bainite in the specimens 2 and 3, as shown in Figure 2-b, taken from specimen 3; bainite and martensite in the specimen 4, as shown in Figure 2-c; and martensite in the specimen 5, as illustrated in Figure 2-d. Relatively higher heat input caused the formation of ductile phases, such as ferrite and pearlite in the specimen 1. However, bainite and martensite are deduced in the specimen 2 and 5, respectively. Although the presence of bainite and martensite was increased with increasing the heat input in the those specimens, it was show that molybdenum contents of 0.8 wt % - 2.3 wt % are still effective on the formation of the lower temperature transformation products at the medium heat input. In addition, it was also seen that the molybdenum content of 0.8 wt % was a critical molybdenum content with a heat input of 1 kJ mm^{-1} for the formation of bainite.



(a)

(b)

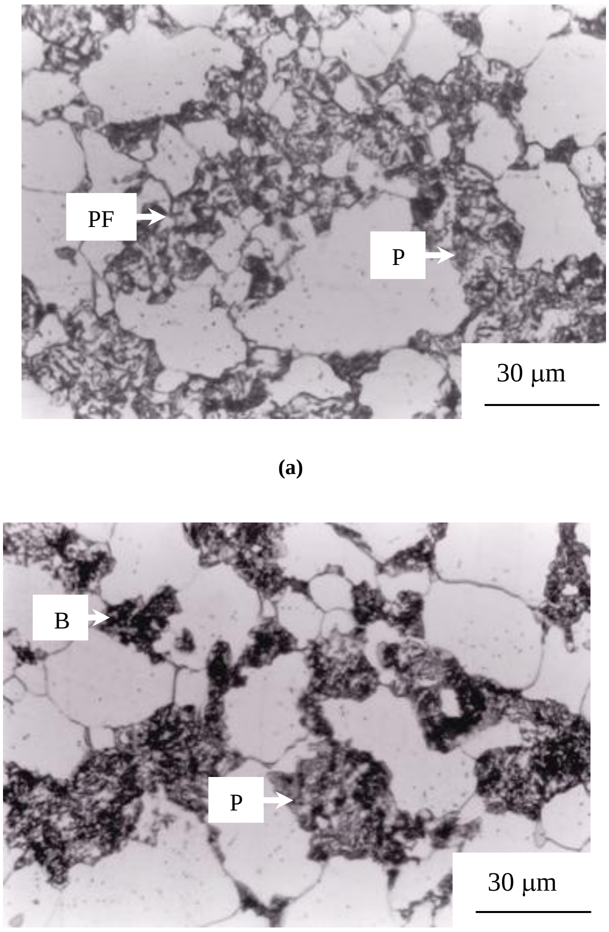
(c)

(d)

Figure 2. Microstructure(optical) of intercritical HAZ in specimens containing *a*) 0.4 wt %Mo, *b*) 1.4 wt %Mo, *c*) 1.8 wt %Mo and *d*) 2.3 wt %Mo with a heat input of 1 kJ mm^{-1}.M: Martensite, B: Bainite, P: Pearlite, GBF: Grain Boundary Ferrite.

With a heat input of 2 kJ mm^{-1}, the microstructure formed from carbon-rich austenite in specimens 1 and 2 were mainly composed of polygonal ferrite (PF) and fine grain pearlite, as shown in Figure 3a, taken from specimen 1. With this heat input, the microstructure consisted of pearlite with bainite in specimen 3, as shown in Figure 3b, and bainite in specimens 4 and 5, as illustrated in Figure 3c, taken from specimen 5.

The higher heat input gives sufficient time for carbon diffusion from the carbon-rich austenite to neighbouring ferrite grains. As a result, carbon content of the austenite formed from pearlite decreases and this austenite produces ferrite and pearlite [10,11] in specimens 1 and 2. However, the formation of bainite in specimens 3-5 is related to the effect of higher molybdenum content, which is known to lower the critical cooling rate [15].



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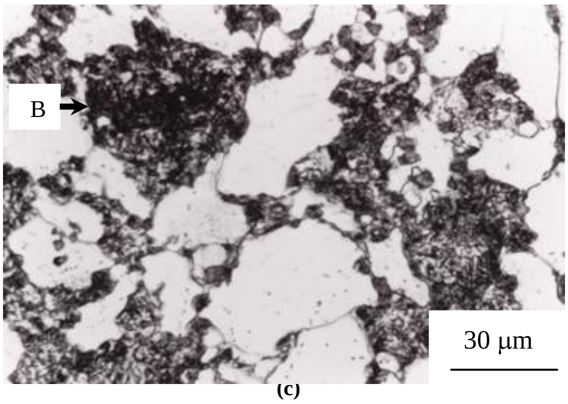

(c)

Figure 3. Microstructure (optical) of intercritical HAZ in specimens containing *a*) 0.4 wt %Mo, *b*) 1.4 wt %Mo and *c*) 2.3 wt %Mo with a heat input of 0.5 kJ mm^{-1}. P: Pearlite, B: Bainite, PF: Polygonal Ferrite.

In general, the results of microstructural developments observed in the specimens are in good agreement with the study investigating the effect of chromium on the properties of intercritical HAZ [11]. However, in the present study it was shown for the first time that the lower temperature transformation products, such as bainite and martensite, were formed for the medium and higher heat inputs as the molybdenum content increased in the presence of chromium of 0.8 wt%. From the results of the microstructural observation, the phases formed from carbon-rich austenite in the intercritical HAZ are summarised in Table 3.

The hardness values taken on the phases formed from carbon rich austenite in the intercritical HAZs of the specimens are given in Figure 4. It can be seen from the hardness profiles that maximum hardness values of the specimens were obtained with the lowest heat input. However, among the specimens, maximum hardness was obtained in specimen 5, which can be directly related to the molybdenum-rich martensite. As the heat input increased to 1 kJ mm^{-1}, the hardness values of specimens from1 to 3 started to decrease sharply because of the formation of ferrite and pearlite in specimen 1 and bainite in specimens 2 and 3. At the same condition, hardness in the specimen 4 and 5 was still higher due to the formation of martensite compared with the heat input of 0.5 kJ mm^{-1}.

Table 3. Phases formed from carbon rich austenite in the intercritical HAZ. . P: Pearlite, B: Bainite, PF: Polygonal Ferrite, M:Martensite, GBF: Grain Boundary Ferrite, FGP:Fine Grain Pearlite.

Nominal Heat Input (kJ mm^{-1})	Specimen number				
	1	2	3	4	5
	Phases				
0.5	M-B	M	M	M	M
1	GBF – FGP	B	B	M-B	M
2	PF – FGP	PF – FGP	P-B	B	B

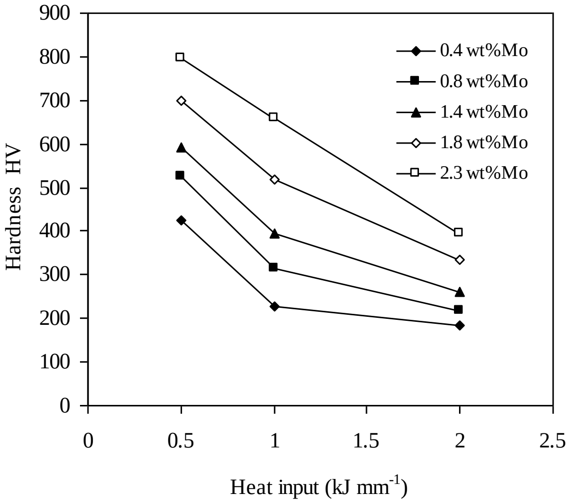

Figure 4. Relationship between microhardness of the phases formed from carbon-rich austenite in the intercritical HAZ and heat input.

Maximum decrease in hardness in the intercritical HAZs was seen with the heat input of 2 kJ mm^{-1}. The decrease in the hardness is associated with the formation of polygonal ferrite in specimens 1 and 2, pearlite in specimen 3 and bainite in specimens 4 and 5. However, the loss of hardness of specimens 1-3 is higher than those of the specimen 4 and 5. This is mainly because of the great amount of ductile phases in those specimens [11].

IV. CONCLUSION

The effect of molybdenum with varying heat input on the microstructure and hardness of the intercritical HAZ of a low carbon Cr-Mo steel was investigated. The following results were obtained with increasing the heat input;

- The microstructure formed from carbon rich austenite in the specimen containing 0.4 wt % Mo changed from bainite and martensite to polygonal ferrite and fine grain pearlite.
- The microstructure formed from carbon rich austenite in the specimen containing 0.8 wt % Mo changed from martensite to polygonal ferrite and fine grain pearlite.
- The microstructure formed carbon rich austenite in the specimen containing 1.8 wt % Mo changed from martensite to pearlite and bainite.

- The microstructure formed carbon rich austenite in the specimens containing 1.8 wt %Mo and 2.3 wt % Mo changed from martensite to bainite.
- The molybdenum content of 1.8 wt % was a critical value with a heat input of 1 kJ mm^{-1} for the formation of martensite.
- The molybdenum content of 1.4 wt % was a critical value with a heat input of 2 kJ mm^{-1} for the formation of bainite.
- The highest hardness value was obtained for the molybdenum content of 2.3 wt % with the 0.5 kJ mm^{-1} heat input.

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