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Weldability of conventional high manganese steel and ladle treatment one

In the present work, the effect of welding procedure on weldability of conventional high manganese steel compared with the recent developed ladle treated one. This research aims at disclosing the microstructure, hardness, impact toughness and tensile strength of the welded joints. The optical micrograph of the conventional high manganese steel welded joint without cooling between passes shows that the heat affected zone (HAZ) has a high density of carbides formed at the grain boundaries. However, cooling between passes using compressed air resulted in a decrease in the density of carbides formed at the grain boundaries of the HAZ. In the ladle treatment samples, the microstructure shows an increase the density of the eutectic phase of the HAZ as a result of welding without cooling. On the other hand, application of cooling using compressed air between passes results in a low density of the eutectic phase in the HAZ.

Application of cooling between deposited passes resulted in a significant improvement of the impact toughness of weldment in both conventional and ladle treated samples of high manganese steel. The result obtained by SEM observation shows the reduction of both carbides at the grain boundaries in HAZ of conventional high manganese steel and the eutectic phase in HAZ of ladle treated one.

1 - Introduction

High manganese steel considers as the most applicable steel in the heavy duty equipment's from its invention date at 1882 by Sir Robert Hadfield. High manganese steel has high wear resistance, and high toughness, and high strain hardening rate. The High manganese steel is used in the heavy industrial components manufacturing such as mill hammers, oil derrick, crusher jaws, and rail road [1-2].

The typical chemical composition of Hadfield steel is 1.0% to 1.2% wt. C, 11% to 14% wt. Mn, and 0.3% to 0.5% wt. Si. [3]. The microstructure contains austenite and cementite in the as-cast state. In as-cast state the cementite phase as a secondary phase, with precipitation at a grain boundaries like a carbide net-work improves the hardness and also the decreases toughness to which extent doesn't allow use of this steel in the as-cast state [4].

High manganese steel is produced by two methods, the first method is conventional process in it Hadfield steel normally has a structure of metastable austenite which is obtained by water quenching the steel from an annealing temperature of 1050°C to dissolve the carbides and desired to form one γ phase, this austenitic alloy work hardens rapidly under repeated impact and displays remarkable toughness [5-6]. The second method called ladle treatment process. This process works to compensate for conventional heat treatment process by addition of Mg, Ca-Si, Ce, Y, Li. [7-8]. These elements have the ability to form oxide and sulfide. The oxide and sulfide phases act as heterogeneous nuclei for the nucleation of cementite and austenite into a new eutectic granular phase between the austenite dendrites at the beginning of solidification. It was found that the new granular phase is well dispersed throughout the austenite matrix [9,11].

When welding of high manganese steel must keep the temperature of the steel below 300°C to avoid carbide precipitation. where this carbides reasons to embrittlement of high manganese steel during welding. Therefore, the temperature of the zone 12 mm from the weld should not exceed 250°C [12-13].

The strength of the weld metal of high manganese steel and plasticity are increasing due to used welding electrodes with a different alloying system. In this state, the fracture of the welded joint occurs at the heat affected zone due to the appearance of cracks resulting from segregation of carbides at the grain boundaries [14-15]. Thus, improvement of the HAZ future in welding of these types of steels became an important topic.

Ladle treatment high manganese steel is not welded yet. So, this study investigated the welding of ladle treated high manganese steel by using SMAW process. The samples were welded under two conditions with and without cooling by compressed air. After that, welding of ladle treatment samples were compared with welding conventional heat treatment high manganese steel samples. The mechanical properties of the welding joint are measured, such as the tensile strength, the impact toughness and hardness test. And the microstructures of the welding joint are studied through the optical microscope and scanning electron microscope.

2 - Methods

Four samples (180 mm in length, 20 mm in width and 12 mm in thickness) of conventional high manganese steel were heated at 1100°C for 2hrs and rapidly quenched in water (S1). Another four samples were produced by the ladle treatment process (S2) [7]. The chemical compositions are shown in Table 1.

SMAW process was applied in welding of the samples. A high manganese steel electrode AWS A5.13 EFeMn-A was used in this study. Chemical composition of the weld metal deposited using this electrode is shown in Table 2. The samples were welded by two conditions. First, continuous welding without cooling and the other using short beads and allow cooling by compressed air. The amperage and voltage applied were 110 A and 24 V, respectively for 3.2 mm electrode. The width of the sample for welding is 20 mm. It takes the time to welding a single pass in average 40 sec when used cooling. On the other hand, the continuous welding without cooling takes 1.10 min. the calculate of Heat input by using Eq.1:

$$\text{Heat input} = (I \times V \times 60) / \text{Travel Speed}$$

Steel type	Chemical composition, wt.%							Producing process	
	C	Si	Mn	S	P	Cr	Al	Heat treatment Process	Ladle treatment Process
S1	1.10	0.6	11.0	0.01	0.04	0.05	0.005	Solution treatment at 1100°C, followed by quenching in water.	------------
S2	1.07	1.2	10.0	0.01	0.07	1.0	0.013	--------------	0.25kgFeSiMg 0.2KgCa-Si/1 kg

Table 1: The chemical compositions of the two types of high manganese steel

C	Si	Mn	P	S	Cr	Ni	Cu	Fe
0.661	0.0504	14.65	0.0168	0.0225	0.0667	3.49	0.167	80.83

Table 2: The chemical composition of the deposited weld metal, mass %

The welded samples were cut out using cooling disk machine. The cross sections were ground through grit silicon papers (from 180 to 1000). Final polishing was performed using 0.5 µm-alumina past, then clean and dried. The polished specimens were etched by 2% Nital solution. Microstructures of welded specimens were observed using Nickon-

Epiphot optical microscope. Hardness test was conducted using micro-hardness tester with 200 gm load.

The tensile test was carried out to determine the ultimate tensile strength of the welded joint, the dimensions of the tensile tested samples are shown Figure 1

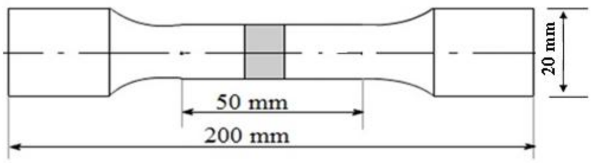


Figure 1: Dimension of the sample for tensile test

according to ASTM E8 standard. The impact test was conducted for detecting the toughness of the welded joint and introduced to the impact test apparatus as non-notch samples in order to avoid crack sensitivity of this type of steel. The samples were prepared according to ASTM E23 standard. The dimensions of the impact tested samples are shown in Figure 2.

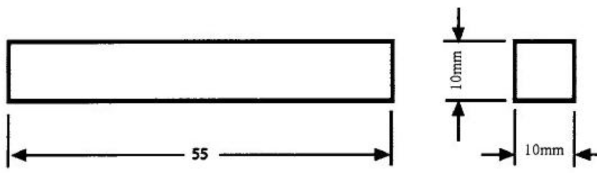


Figure 2: Dimensions of impact test sample

SEM observation was conducted to observe the configuration of carbides in the Heat affected zone (HAZ) in the conventional high manganese steel and the eutectic phase in HAZ of the ladle treated one.

3 - Results and Discussions

3.1 - Microstructure of the conventional high manganese steel weldments

Figure 3a shows the microstructure of base metal of conventional high manganese steel after heat treatment as shown in Table 1. Solution of carbides was observed and the microstructure is free from carbides.

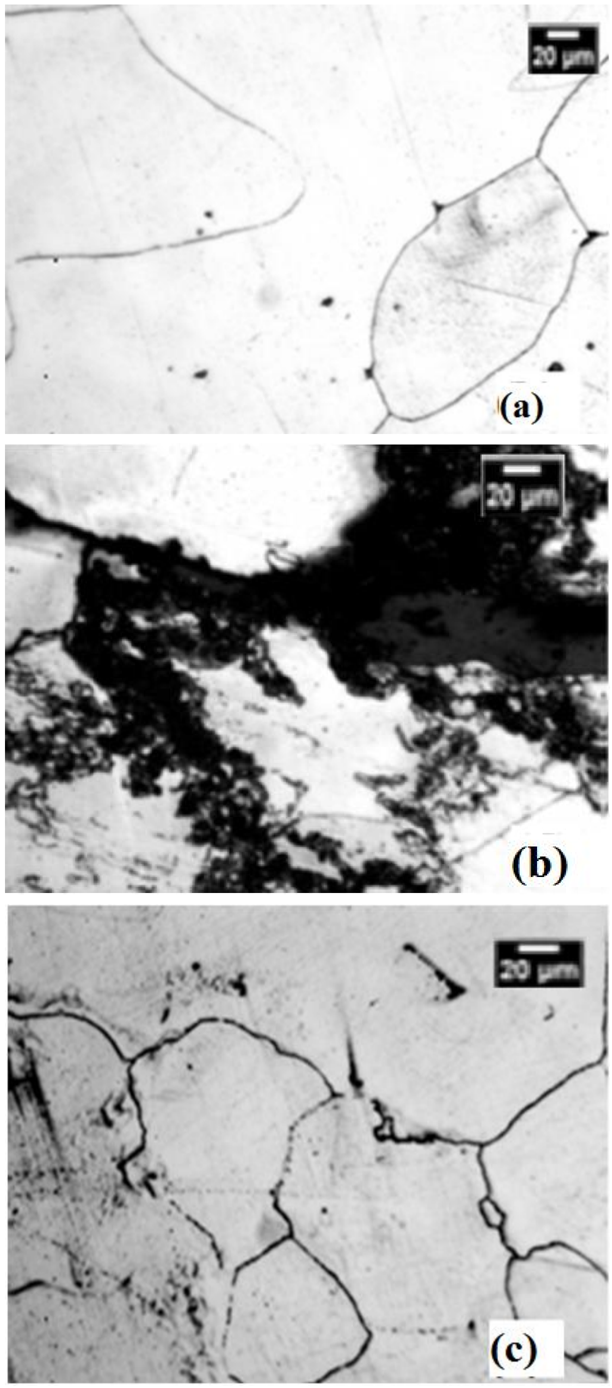
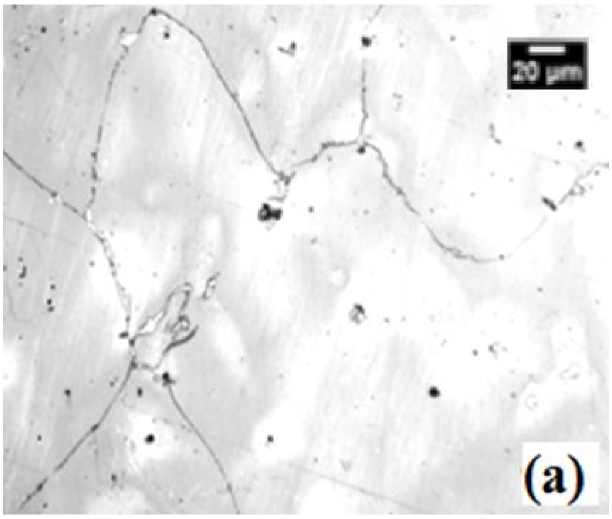
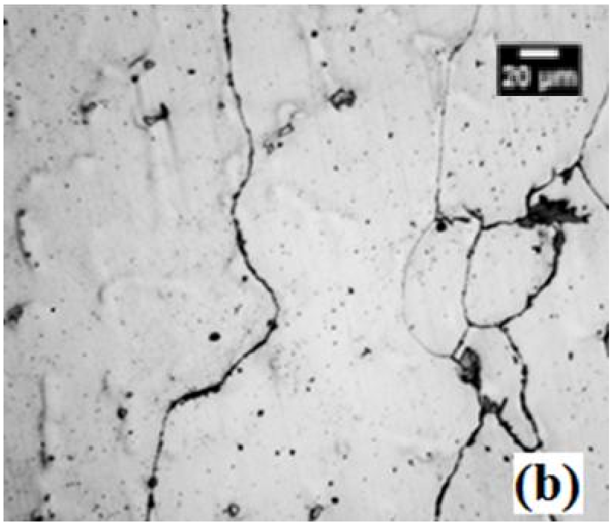


Figure 3: Microstructure of high manganese steel base metal (a) HAZ without cooling (b) HAZ with cooling (c)

Figure 3b shows the microstructure at the HAZ of joint welded without cooling between passes. The microstructure shows a high density of carbides formed at the grain boundary.

Using short beads and application of cooling between passes results in a reduction of the density of carbides as shown in Figure 3c.





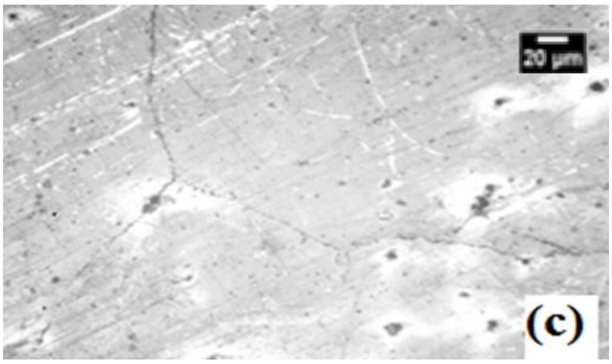


Figure 4: Microstructure of ladle treated high manganese steel base metal (a), HAZ without cooling (b), and HAZ with cooling (c)

3.2 - Microstructure of the ladle treated high manganese steel weldments

Figure 4a shows the microstructure of the base metal of ladle treated high manganese steel. The base metal has the configuration of eutectic phase at the austenite grain.

Figure 4b shows the microstructure of the HAZ of welded joint of ladle treatment high manganese steel without cooling between passes. The microstructure shows a high density of the eutectic phase between dendrite of austenite grain. Figure 4c shows the microstructure of the HAZ of welded joint of ladle treatment high manganese steel with cooling between passes. The microstructure shows the low density of the eutectic phase between dendrite of the austenite grain in HAZ. This reflects the role of high temperature in re-configuration of the eutectic phases and reduces the configuration by cooling application.

3.3 - Micro-Hardness

Micro-hardness at the HAZ of the conventional high manganese steel joint welded without cooling between passes is shown in Table 3. An increase in the grain boundary hardness from its value at the base metal was observed (from 185 HV at the base metal to 252 HV at the HAZ). On the other hand, the hardness of the austenite grain is identical to that of the base metal (185 HV) as shown in Table 3.

Application of cooling between passes resulted in an increase in the hardness at the grain boundary of the HAZ to 252 HV which is identical to that obtained at the HAZ of the welded joint without cooling. Thus, cooling affects the density of carbide as described in the microstructure observation in Figure 3 (see section 3.1).

Micro-hardness at the HAZ of the ladle

Samples	Micro hardness at the HAZ		Tensile strength, Mpa
	Grain boundary	Austenite grain	
S1 cooling	252	185	423
S1 without cooling	252	185	414
S2 cooling	245	230	390
S2 without cooling	252	260	413

Table 3: Mechanical property of welded joint

treated high manganese steel joint welded without cooling between passes is shown in Table 3. An increase in the grain boundary hardness from its value at the base metal was observed (from 185 HV at the base metal to 252 HV at the HAZ). On the other hand, the hardness of the austenite grain is close to that of the base metal (260 HV) as shown in Table 3.

Application of cooling between passes resulted in an increase in the hardness at the grain boundary of the HAZ to 245 HV which is close to that obtained at the HAZ of the welded joint without cooling. Thus, cooling affects the density of eutectic phase as described in the microstructure observation in Figure 4 (see section 3.2).

3.4 - Tensile strength of welded joint

From the microstructures of the welded joint, it is expected that good mechanical properties will be obtained of high manganese steel by ladle treated.

For the sample (S1 cooling) of conventional high manganese steel, the strength slightly increased because of the decrease in the precipitation of carbides at the grain boundary.

For the sample (S2 cooling) of ladle treatment high manganese steel joint, the strength differs from the strength of the samples (S2 without cooling) of ladle treatment joint. The cooling helps on rapid configuration of the eutectic phase, but the configuration is not extensively in the austenite matrix. The samples (S2 without cooling), the strength slightly increased because of the configuration of the eutectic phase. This configuration leads to increase of yield strength and decrease of the ductility. Values of the strength are shown in Table 3. The strength of ladle treatment high manganese steel similar for the strength of conventional high manganese, this is reinforcement and improves the weldability of ladle treatment high manganese steel.

The toughness is considered as the characteristic feature of Hadfield steel in severe load conditions, it's proved that the most significant deterioration of toughness has occurred as result of cementite phase that is precipitated at the grain boundary of the austenite. In the samples of (S1 cooling) appeared high-impact toughness due to used cooling while a procedure welding process, also, it leads to decrease precipitation of carbides at grain boundaries. On the other hand, the impact toughness decreased in the samples (S1 without cooling) due to widely precipitation carbides at grain boundaries.

On the other hand, it was found that the ladle treated high manganese steel (S2 cooling) has a toughness close to that of the heat treated steel (S1 cooling) as shown in Figure 5. However, the toughness of samples (S2 without cooling) decreased due to a configuration of the eutectic phase extensively in HAZ.

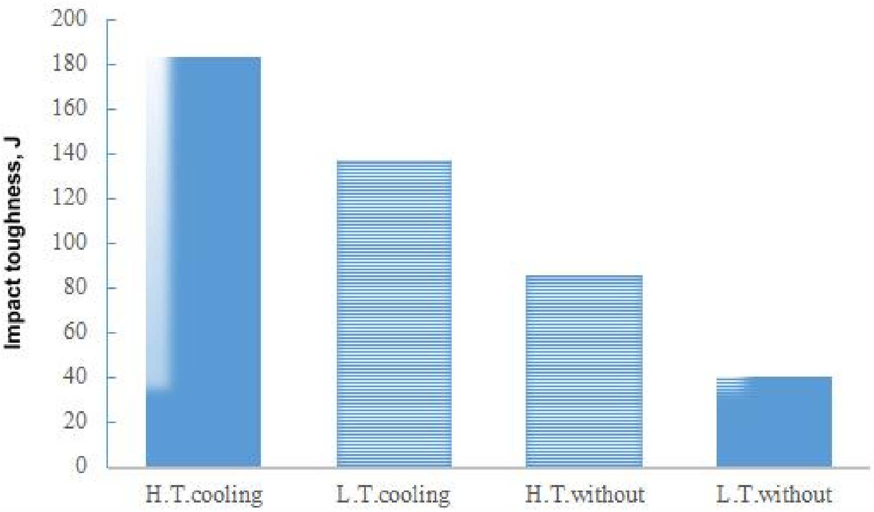


Figure 5: impact toughness of welded joint

3.5 - SEM

Figure 6a shows SEM observation at the HAZ of conventional high manganese steel welded with cooling between passes. There are small carbides at the grain boundaries of the samples (S1 cooling). Figure 6b shows the EDX analysis at the area of the sample. Analysis of carbides was observed with a small percentage.

Figure 7a shows SEM observation at the HAZ of the conventional high manganese steel welded without cooling between passes. The carbides intensity increased more than that welded with cooling. This observation was strongly explained by EDX analysis where the amount of carbides increased as shown in Figure 7b. There are micro-voids that coalescence to form voids. Formation of a micro cracks was clearly observed that damages the joint. The same results were obtained with

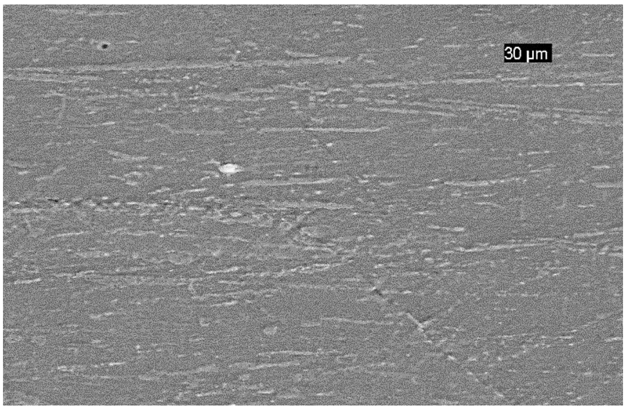


Figure 6a: SEM observed at the HAZ of the conventional high manganese steel with cooling (S1 cooling)

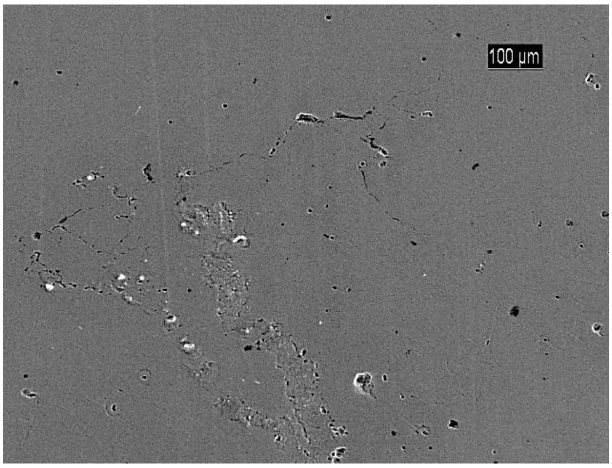
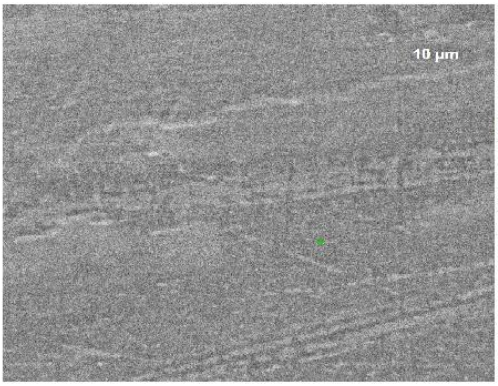


Figure 7a: SEM observed at the HAZ of the conventional high manganese steel without cooling (S1 without cooling)



Element	Weight %	Atom%
Fe k	85.13	72.31
Mn k	9.65	8.3
C k	4.93	19.39
Total	100	

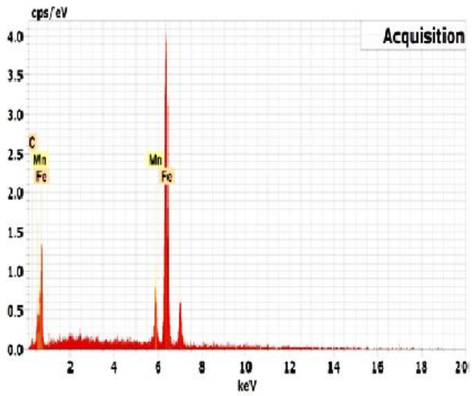


Figure 6b: EDX analysis at the area of the conventional high manganese steel with cooling (S1 cooling)

Element	Weight %	Atom%
Fe k	80.13	59.93
Mn k	9.97	7.58
C k	8.93	31.05
Si k	0.96	1.43
Total	100	

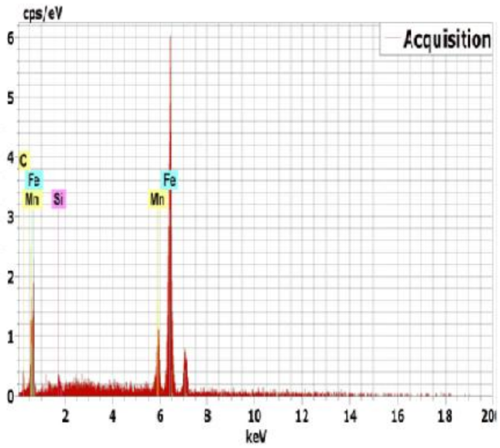


Figure 7b: EDX analysis at the area of the conventional high manganese steel without cooling (S1 without cooling)

Yoshida et al [16] and Herrera et al. [17]. This reflects the higher toughness value of the high manganese steel welded with cooling compared with the welded without cooling as shown in Figure 5.

Figure 8 shows the HAZ of the ladle treatment specimen after welding with cooling between passes. The eutectic phase was observed with a low density similar to that of the base metal as shown in Figure 9.

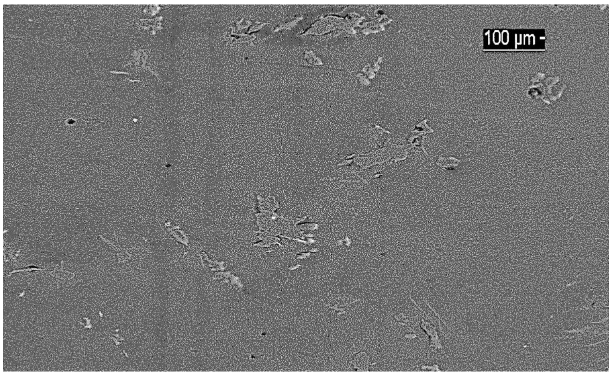


Figure 8: SEM observed at the HAZ of the ladle treated with cooling (S2 cooling)

Figure 10 shows the HAZ of the ladle treatment specimen after welding without

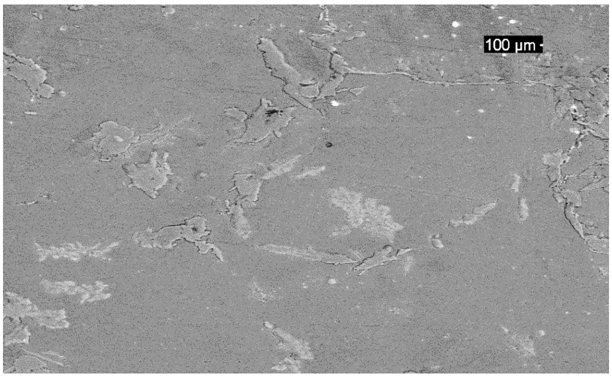


Figure 9: SEM observed at the base metal of the ladle treated with cooling (S2 cooling)

cooling between passes. The density of the eutectic phase was highly increased to give a chance to a heterogeneous nucleation, which occurred in its natural state. These results reflected the higher toughness level of the joint welded with cooling as shown in Figure 5 compared with the joint welded without cooling.

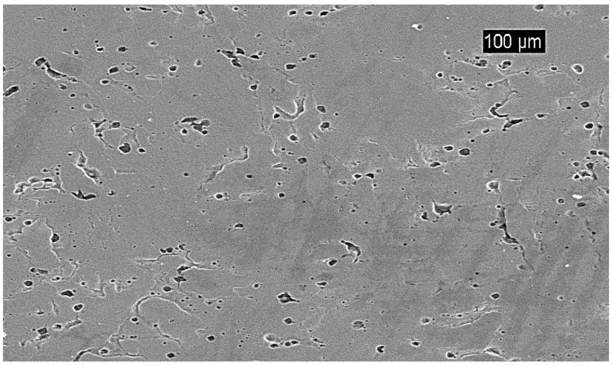


Figure 10: SEM observed at the HAZ of the ladle treated with cooling (S2 cooling)

4 - Conclusions

1. Welding of conventional high manganese steel without cooling results in formation of micro-voids, which it is the beginning of configuration, the cracks.
2. When using the cooling in welding of conventional high manganese steel, reduces precipitation of carbides in HAZ and increases the toughness of the welded joint.
3. The eutectic phase formed in HAZ of ladle treatment high manganese steel regardless of the cooling process, on the other hand, when used cooling increase the toughness and without cooling decrease the toughness.
4. The strength of ladle treatment high manganese steel similar for the strength of conventional high manganese steel, this works on improve the weldability of ladle treatment high manganese steel.
5. SEM analysis shows existence of precipitation carbides at the grain boundary in HAZ of conventional high manganese steel, and existence eutectic phase in HAZ of high manganese steel by ladle treatment.

5 - References

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