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Effect of simulated double cycle welding on HAZ microstructure for HSLA steels

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Abstract. High Strength low alloy steels containing various levels of C, Nb and Mn were used and for each of which, a simulated double thermal cycle was applied with the same first peak temperature and different second peak temperatures to produce HAZ microstructure corresponding to multi-pass weld. Effect of double cycle second temperature on the microstructure was observed and compared with single cycle results obtained from previous works, it was found that the percentage of martensite austenite constituent (MA) increases by Nb addition for all steels with the same Mn content and the increase in Mn content at the same Nb content shows an increase in MA area fraction as well. MA area fraction obtained for the double cycle is larger than that obtained for the single cycle for all steels used which imply that MA will have great role in the brittle fracture initiation for double cycle and the inter-pass temperature should be controlled for medium and high-carbon Mn steel to avoid large area fraction of MA. The beneficial effects of Niobium obtained in single pass weld were not observed for the double cycle or multi pass welds.

Keywords: HAZ; double cycle; multi pass weld; microstructure; carbon; manganese; niobium; MA

1. Introduction

The microstructure of HSLA steels depends on the composition and thermo-mechanical processing. There are disagreements about the cause of HAZ embrittlement in steels containing Nb. There is division in the literature concerning the influence of Nb on HAZ properties under certain conditions. There is conflicting interest among researchers about how Nb affects MA formation in HAZ single pass and there is no data available about the multi-pass weld. Ohya et al. reported that the brittle fracture initiates at the intersections of bainitic ferrite areas with different orientations and they added that MA has no main role in the brittle fracture initiation. However, they didn't investigate the effect of steel composition and double cycle on MA content as they used only one steel composition. On the contrary, Baker et al. insist that MA content is the dominant factor in determining the HAZ toughness. Furthermore, they got correlations between the toughness and MA area fraction. El-Kashif and Koseki reported the existance of MA phase in single pass welding in many works using Lapera etching technique and other techniques and they confirmed the role of

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MA in determining the HAZ toughness. As there is few works done on the multi pass welded HSLA steels and most of them used only one steel composition, the present study was carried out in order to reveal the MA formation in the HAZ of multi-pass welding for HSLA steels compared with the single pass one.

2. Experimental work

The study involved eleven different chemical compositions of HSLA steels. HSLA steels were chosen as the base metal and to find out the effect of Nb addition to different C equivalent, three groups of steels have the same Mn content with three levels of C (0.05, 0.1 and 0.15 mass%) were prepared. Each group has three steels, with Nb content 0.0, 0.015 and 0.03 mass% respectively. There are three different C equivalents which is 0.3, 0.35 and 0.4 for the three groups respectively. El-Kashif and Koseki used the following equation for calculating the carbon equivalent: Ceq. = C+Si/24+Mn/6+Ni/40+Cr/4+V/14 (wt%) and it was used in this work as well. Two more steels were added for comparison, they have the same Nb content (0.015) and different Mn content; KT 10 to be compared with KT8 (same Nb content and same carbon equivalent but different contents of Mn and C) and KT11 to be compared with KT2 (same Nb content and same carbon equivalent but different contents of Mn and C). The chemical compositions of the steels used are given in Table 1. The steels were designated as KT1~ KT11.

The simulated double HAZ cycles were carried out for all Steels. The simulation route was chosen to obtain the multi-pass HAZ properties. This is obtained by a thermal cycle with a peak temperature of 1300°C representing the highest heat input which causes the most coarse-grained HAZ. The cooling rate is 20 K/s followed by heating up to second peak of 700°C or 800°C or 900°C then cooling again to RT via 20 K/s to simulate the multi pass welding. After the thermal double cycle, the optical microstructure specimens were prepared and then etched with 2% nital and LePera solution used by Lepera. Quantitative analysis of MA was conducted using image analyzer for all steels and compared with single cycle results obtained from previous works made by El-Kashif and Koseki.

Table 1 The chemical compositions (mass %) of the steels used

Steels	C	Si	Mn	P	S	Al	Nb	N	Cequ
KT1	**0.05**	0.2	**1.5**	0.01	0.005	0.03	**0**	0.003	**0.30**
KT2	**0.05**	0.2	**1.5**	0.01	0.005	0.03	**0.015**	0.003	**0.30**
KT3	**0.05**	0.2	**1.5**	0.01	0.005	0.02	**0.030**	0.003	**0.30**
KT4	**0.10**	0.2	**1.5**	0.01	0.005	0.02	**0.000**	0.003	**0.35**
KT5	**0.10**	0.2	**1.5**	0.01	0.005	0.02	**0.015**	0.003	**0.35**
KT6	**0.10**	0.2	**1.5**	0.01	0.005	0.02	**0.030**	0.003	**0.35**
KT7	**0.15**	0.2	**1.5**	0.01	0.005	0.03	**0.000**	0.003	**0.40**
KT8	**0.15**	0.2	**1.5**	0.01	0.005	0.02	**0.015**	0.003	**0.40**
KT9	**0.15**	0.2	**1.5**	0.01	0.005	0.02	**0.030**	0.003	**0.40**
KT10	**0.05**	0.2	**2.1**	0.01	0.005	0.02	**0.015**	0.003	**0.40**
KT11	**0.15**	0.2	**0.9**	0.01	0.005	0.02	**0.015**	0.003	**0.30**

3. Results and discussion

The microstructure obtained for all steels used after different second peak temperatures are polygonal ferrite, regenerated pearlite and by increasing the carbon and Mn content, areas of widmanstatten ferrite occurs; the grain size decreases with the increase in Carbon and Mn as expected, the increase in second peak temperature from 700 to 900°C results in finer grain size as shown in Figs. 1 and 2.

It was observed that the increase in Nb content results in larger area fraction of MA in all steels but the rate of increase is small for high carbon compared with low and medium carbon steels as shown in Figs. 3 and 4. This may be attributed to the precipitation of Niobium carbides which consume most of the Nb and there is no enough Niobium for MA formation as reported by El-Kashif in his study on the formation mechanism of MA.

According to the overall microstructure obtained for the two groups of steels, (group A with second peak temperature of 700°C and group B second peak temperature of 900°C), the two groups can be categorized to two categories according to microstructural features, very thin grain boundary ferrite plus intragranular acicular ferrite for high C or high Mn content and polygonal ferrite structure with thick and continuous grain boundary ferrite for low C or low Mn content. El-Kashif studied the formation mechanism of MA using Electron probe micro-analyzer (EPMA) and the results can be summarized in that the grain boundary ferrite causes an enrichment of alloying elements and C at the interface between the grain boundary ferrite and the bainite and also near the interface region. This enrichment is mainly due to the low solubility of alloying elements in ferrite compared to that in austenite. This micro-segregation enhances the formation of MA or M*. This mechanism was confirmed using EPMA technique for all steels.

Wang *et al*. (2017) studied the reheated zone of multi pass weld of 550 MPa grade offshore steel using Gleeble-3500 simulator. Their results showed that reheating changed the prior austenite morphology from columnar to equi-axed structure and they found necklace type MA decorating

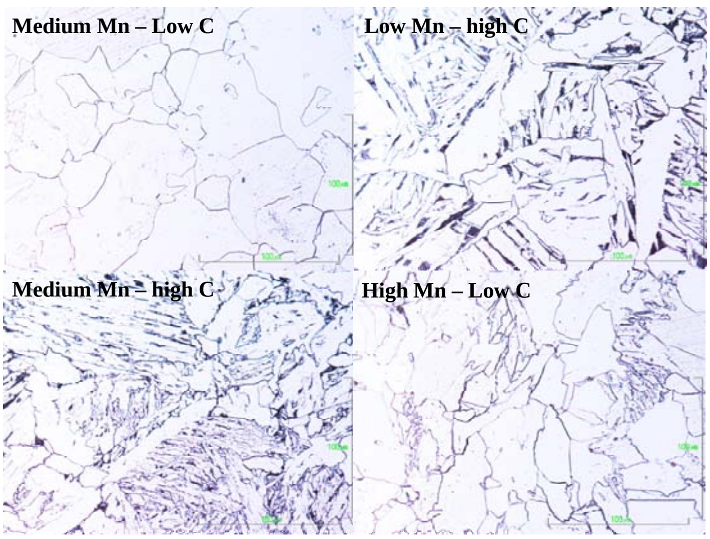

Fig. 1 The effect of variation in Mn and C within the same C equivalent on the microstructure at constant Nb (0.015%) after double cycle of 1300°C followed by 700°C

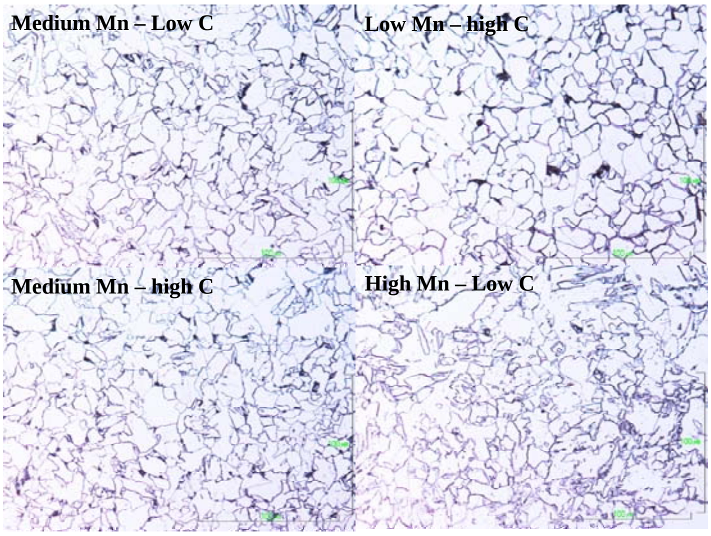

Fig. 2 The effect of variation in Mn and C within the same C equivalent on the microstructure at constant Nb (0.015%) after double cycle of 1300°C followed by 900°C

prior austenite grain boundaries and deteriorated toughness and they recommended avoid later welding passes. They used only one chemical composition and their results doesn't agree with the obtained results in this work as the MA is formed at both prior austenite grain boundaries and polygonal ferrite grain boundaries which is clear in Figs. 3 and 4.

Wang *et al*. (2016) in another work investigated the correlation of microstructure and toughness from multi-pass weld using SAW with steel of 0.1% C and 2% Mn. They found MA with necklace-type in the HAZ which lead to low toughness; they tried to improve the toughness by tempering and by combination of quenching plus inter-critical annealing and tempering. The

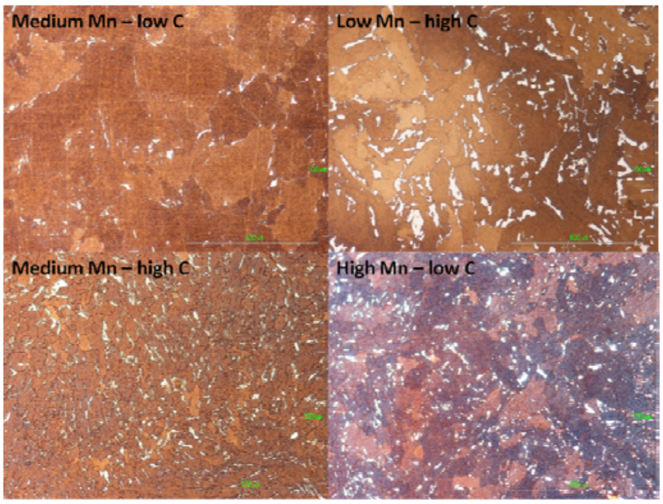

Fig. 3 The effect of variation in Mn and C within the same C equivalent on the microstructure at constant Nb content of 0.015% after double cycle of 1300°C followed by 700°C

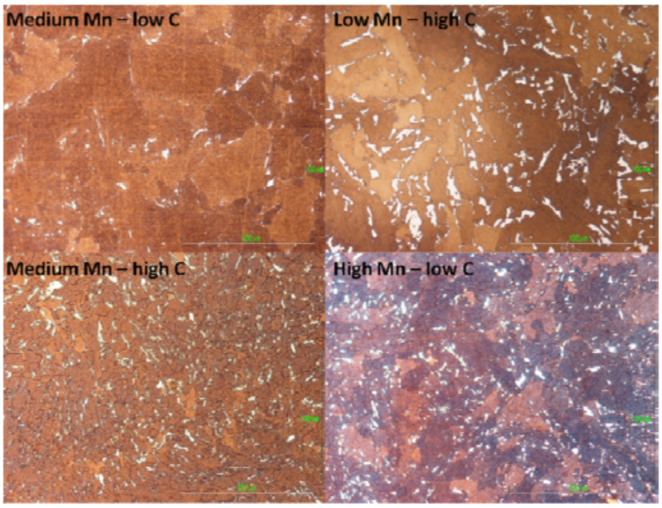

Fig. 4 The effect of variation in Mn and C within the same C equivalent on the microstructure at constant Nb (0.015%) after double cycle of 1300°C followed by 900°C

tempering shows no obvious improvement in toughness but the quenching plus inter-critical annealing and tempering shows great improvement in toughness; almost double the toughness obtained before heat treatment.

The LaPera etching revealed the MA as white area while the other microstructure features appeared tan which gives good contrast for image analysis to calculate the MA area fraction using image analyzer. It can be observed that from Figs. 3 and 4 that most of the formed MA are slender type high aspect ratio and not massive ones. Luo *et al.* (2018) studied the effect of morphology of MA on impact toughness of HAZ steels using the Gleeble-3500 simulator and they concluded that slender MA are more harmful to toughness compared with massive ones. Li *et al*. (2017) studied the distribution of carbon and alloying elements in MA using atom probe tomography (APT). They noticed enrichment of C and Mn within MA constituents. They attributed the nucleation of cleavage cracks due to the de-bonding mechanism resulting from the segregation at the interface between MA constituents and matrix. Li *et al*. (2018) in another work studied the structure and crystallography of MA constituents in HAZ of X100 steel welded joint. They found that the majority of MA was primarily consisted of lath martensite (87%) and retained austenite (9%) which was found between the martensite laths. They added that the martensite laths in MA constituents didn't have the same crystallographic orientation of the parent matrix during reheating and subsequent cooling of second pass welding.

The quantitative analysis results of MA area fraction are shown in Figs. 5 and 6; Fig. 5 shows the effect of Nb on the area fraction of MA for two second cycle temperatures 700 and 900°C.

The increase of Nb content at the same Mn content of 1.5% results in larger area fraction of MA for all steels, however higher carbon steels shows the largest area fraction of MA but the rate of increase in MA area fraction is the lowest for high carbon group which may be due to the carbides precipitation which consume most of the carbon and this trend was observed for the two second cycle temperatures but the increase in the second peak temperature from 700 to 900°C results in larger MA area fraction as the higher second peak temperature enhances the micro-segregation.

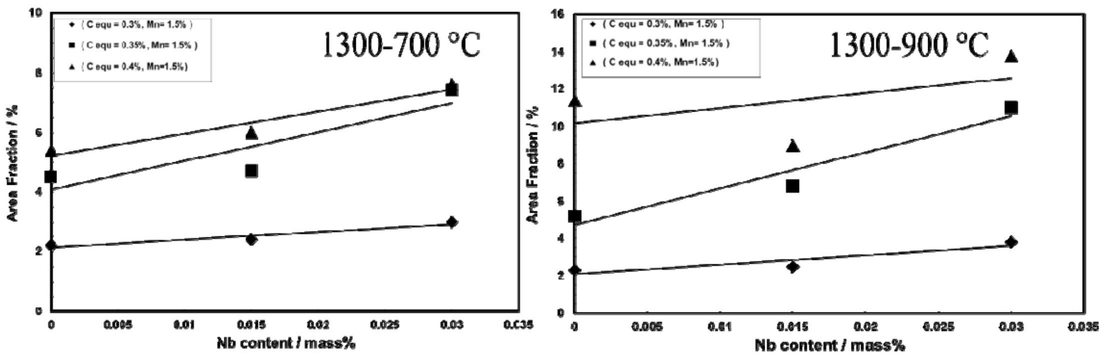

Fig. 5 The effect of Nb on the area fraction of MA at constant Mn (1.5%) after different heat cycles

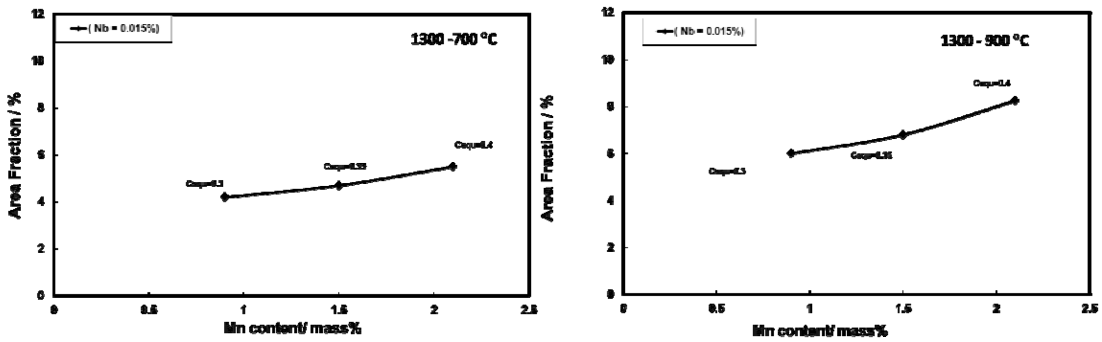

Fig. 6 The effect of Mn on the area fraction of MA at constant Nb (0.015%) after different heat cycles

Fig. 6 shows the effect of Mn content on the area fraction of MA at constant Nb content of 0.015% after different heat cycles; The increase in Mn shows larger area fraction of MA for the two cycles used however the increase in the second peak temperature from 700 to 900°C results in larger MA area fraction. The results obtained recommend lowering the inter-pass temperature as much as possible to lower the area fraction of MA.

Comparing the results obtained from the double cycle with those obtained from the single cycle, the comparison reveal that the double cycle resulted in larger MA area fraction for the same steel and this trend was observed for all steels. This imply that double cycle which is corresponding to multi-pass weld has an adverse effect on the toughness compared with single-pass weld and further investigation using thermodynamic analysis is needed.

4. Conclusions

Effect of simulated double cycle welding on HAZ microstructure for HSLA steels was investigated experimentally and the following conclusions were drawn:

- The overall microstructure obtained for the eleven steels used after different cycles are polygonal ferrite and regenerated pearlite; by increasing the carbon and Nb content, areas of widmanstatten ferrite occurs; the grain size decreases with the increase in Carbon content, the increase in second peak temperature from 700 to 900°C results in finer grain size and larger MA area fraction.

- The increase in Mn content results in larger area fraction of MA in all steels but the rate of increase is small for high carbon compared with low and medium carbon steels, which may be due to the precipitation of carbides which consume most of the C and lowers the segregation levels. The double cycle welding should be avoided for medium and high-carbon Mn steel containing Nb due to the large area fraction of MA which may cause brittle fracture initiation or to solve this problem; the inter-pass temperature must be lowered as much as possible to avoid the formation of large MA area fraction.
- Multi-pass weld showed larger MA area fraction than single-pass weld for the same steel and this trend is observed for all steels used, which will affect adversely on the toughness.
- Most of the MA constituents obtained for all steels used are slender type MA and not massive type MA.

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