The 2015 World Congress on
Advances in Structural Engineering and Mechanics (ASEM15)
Incheon, Korea, August 25-29, 2015

The Effects of Post Weld Heat Treatment on the Mechanical Properties of Tempered Martensite and High Strength Steel Welded Joints

Umut Yasar Uzunali[1)] and Hamdullah Cuvalci[2)]

[1)] Karadeniz Technical University, Abdullah Kanca Vocational School of Higher Education, 61530, Turkey
[2)] Karadeniz Technical University, Department of Metallurgical and Material Engineering, 69000, Turkey
[1)] uuzunali@ktu.edu.tr

ABSTRACT

In this study, it was aimed to investigate post weld heat effects on the mechanical properties of tempered martensite steel and high strength steel welded joints. These welded joints were performed in accordance with related standards which were EN 15609, EN 15614 etc. In terms of welding process, Hardox450 and Optim700MC were chosen due to their partially high carbon equivalent. Chemical analysis, hardness tests and microscopic examination were implemented to validate the mechanical properties of experiment parts before the welding process. Test pieces were joined with MAG welding method applied in PB position. Specimens were welded with different welding parameters to observe the welding penetration. Filler metal and shielding gas were chosen according to the technical procedures recommended by the manufacturers. In compliance with standards, EN ISO 14341-A G46 4 C 1 G 4 Si 1 filler metal and EN ISO 14175 M 24 mixed shielding gas were chosen for this study. In pursuit of the welding operation, post weld heat treatments were applied on same duration and different temperatures for each specimen. 150^{o}C, 300^{o}C and 450^{o}C were determined as post weld heat treatment temperatures. After the post weld heat treatment, cross sections were taken from the area exposed to post weld heat. Specimens were subjected to microscopic examination, hardness test and non-destructive testing. As a consequence, it was determined that hardness values in heat affected zones of tempered martensite steel were decreased with increasing post weld temperatures.

Keywords: Hardox450 material, Optim700MC material, welding, post weld heat treatment,

---

[1)] Graduate Student
[2)] Associate Professor, Dr.

1. INTRODUCTION

Tempered martensite steel and high strength steel are widely used in many industries due to their excellent mechanical properties, such as tensile and hardness. Actually, martensite structure is very hard however it is very brittle. For this reason, after the quenching operation martensite structure is subjected to the tempering operation to obtain ductility. Tempering is used to improve the ductility and toughness of martensite. In this case some strength and hardness is lost. Ultimately, the final structure has very good strength and hardness, along with good toughness and ductility (Althouse). For instance; elastic limits of Hardox 450 is 3 times higher than S420 and the hardness of Hardox 450 is approximately 3-4 times higher than the regular steel (SSAB).

The steel Hardox made by SSAB is high strength and abrasion resistant steel produced for constructing machinery applications. Hardox steels are categorized according to their alloy components and the hardness. The basic range of the steel has the five-number code for determination of the Brinell hardness; 400, 450, 500, 550, 600. The increasing code number means higher hardness, abrasion resistance, tensile strength and on the other hand it means also decreasing ductility, toughness and weldabilitiy (Hub, 2009). Chemical composition and mechanical properties of Hardox steels are listed in Table 1, Table 2;

Table 1. Chemical Composition of Hardox Steels (SSAB)

Material	**Chemical Composition**								
	%C max	**%Si max**	**%Mn max**	**%P max**	**%S max**	**%Cr max**	**%Ni max**	**%Mo max**	**%B max**
Hardox400	0,32	0,7	1,6	0,025	0,01	1,4	1,5	0,6	0,004
Hardox450	0,26	0,7	1,6	0,025	0,01	1,4	1,5	0,6	0,005
Hardox500	0,3	0,7	1,6	0,02	0,01	1,5	1,5	0,6	0,005
Hardox550	0,37	0,5	1,3	x	x	1,14	1,4	0,6	0,004
Hardox600	0,47	0,7	1	0,015	0,01	1,2	2,5	0,7	0,005

Table 2. Mechanical Properties of Hardox Steels (SSAB)

Material	Mechanical Properties					
	Hardness HBW (min-max)	Toughness -40^{o}C [J]	Yield Strength $RP_{0,2}$ (MPa)	Tensile Strength Rm (MPa)	Carbon Equivalent	
					CEV [%]	CET [%]
Hardox400	370-430	45	1000	1250	0,37	0,35
Hardox450	425-475	40	1200	1400	0,48	0,35
Hardox500	470-530	30	1300	1550	0,62	0,41
Hardox550	525-575	30	1400	1700	0,72	0,48
Hardox600	570-640	20	1650	2000	0,73	0,55

In comparison with Hardox450, Optim700MC which is a thermomechanically rolled and cold formable steel has low carbon and has an extremely high impact strength which exceeds standard requirements (Ruukki). Thermomechanically processing, also known as thermo-mechanical treatment, is a metallurgical process that integrates work hardening and heat treatment into a single process (Degamo, 2003). These steels are called light steels which mean increased payloads for machines and equipment, reduced fuel consumption and sustainable development. These steels are used in frame structures for mobile vehicles, superstructures of commercial vehicles, frames and booms for forestry vehicles, crane arms and other lifting equipment. Optim (thermomechanically rolled) steels are categorized into 5 groups according to their yield strength differently from Hardox steels. Chemical composition and mechanical properties of Optim steels are listed in Tab3 and Tab4;

Table 3. Chemical Composition of Optim Steel (Ruukki)

Material	Chemical Composition					
	%C max	%Si max	%Mn max	%P max	%S max	%Al min
Optim500MC	0,1	0,2	1,5	0,02	0,01	0,015
Optim550MC	0,1	0,2	1,7	0,02	0,01	0,015
Optim600MC	0,1	0,2	1,9	0,02	0,01	0,015
Optim650MC	0,1	0,2	2	0,02	0,01	0,015
Optim700MC	0,1	0,2	2,1	0,02	0,01	0,015

Tab 4. Mechanical Properties of Optim Steel (Ruukki)

Material	**Mechanical Properties**				
	Toughness -40°C [J]	**Yield Strength $RP_{0,2}$ (MPa)**	**Tensile Strength Rm (MPa)**	**Carbon Equivalent**	
				CE [%] ave.	**CET [%] max.**
Optim500MC	min 27	500	550-700	0,32	0,36
Optim550MC	min 27	550	600-760	0,33	0,38
Optim600MC	min 27	600	650-820	0,34	0,41
Optim650MC	min 27	650	700-880	0,35	0,41
Optim700MC	min 27	700	750-950	0,37	0,41

Generally, weldability is considered very good for low carbon steel (carbon level ≤ %0,15), good for mild steel (carbon level %0,15 to %0,30), fair for medium carbon steel (carbon level %0,30 to %0,50) and questionable for high carbon steel (carbon level %0,50 to %1,00). Since weldability normally decreases with increasing carbon content, special precautions such as preheating, controlling heat input and post weld heat treating are normally required for steel with a carbon content reaching %0,30. In addition to carbon content, the presence of other alloying elements will have an effect on weldability. Preheating or post weld heat treatment can be necessary with increasing carbon and alloying elements. Due to this reason carbon equivalent formula is used to determine whether materials can be welded without preheating or post weld heat treatment. In 1967, the International Institute for Welding adopted a somewhat simplified form of Dearden and O'neill's formula for hardenability which became a generally accepted measure of steel weldability (Dearden, 1940). Carbon equivalent formula is stated below;

$$CE_{IIW} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

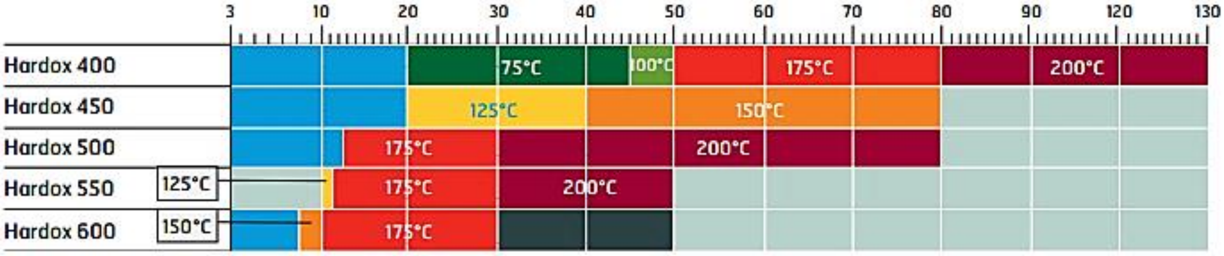
A higher carbon equivalent usually requires a higher preheat and interpass temperature (SSAB). In terms of welding process, Hardox450 and Optim700MC were chosen due to their partially high carbon equivalent. According to $CE_{IIW\ formula}$, carbon equivalent of Hardox450 and Optim700MC are given below;

Table 5. Carbon Equivalent of Hardox450 and Optim700MC

Material	**Carbon Equivalent (CE_{IIW})**
Hardox450	0,48
Optim700MC	0,37

In these steel types, preheating or post weld heat treatment may be required and should range 75-200^{o}C depending on materials thickness. Producer recommends for heat treatment are given below;

Tab 6. Minimum Recommend Preheat Temperatures for Single Plate Thickness in Hardox Steel (SSAB)



Briefly, weldability describes the relative ease or difficulty with which a metal or alloy can be welded. High carbon equivalent cause hardness increasing in heat affected zones of welded parts. According to the Hardox producer data for these materials the hardness changes are presented in Fig2;

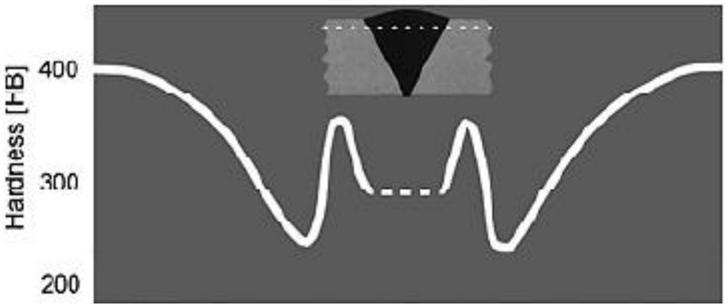


Fig. 1 Hardness change diagram in welded joint of Hardox400 steel (SSAB)

After the welding operation hardness tests were applied to butt welded specimen in this test. Hardness values increased in heat affected zones due to partially high carbon equivalent as shown in the diagram. Owing to the fact that Hardox450 has high carbon equivalent than Hardox400, hardness increasing in heat affected zone of Hardox450 is expected more than Hardox400.

Although there are not so many studies which contain the effects of post weld heat treatment on the mechanical properties of tempered martensite and high strength steel welded joints, there are a lot of researches related to post weld heat treatment and tempered martensite steels separately. In these studies, it was aimed to investigate post weld heat effects on the tensile strength, creeping properties, residual stress, corrosion resistance etc. Park, Min-Ji (2014) et al. carried out a study on 690 MPa Grade quenched and tempered steel weld metals to investigate the effect of preheating on weldability and corrosion resistance. In terms of hydrogen embrittlement, Moon (2003) et al. investigated the post weld heat treatment effect to mechanical properties and hydrogen embrittlement for heat affected zone of a RE steel. Huo LX (2003) et al. investigated post weld heat treatment on microstructure and fracture toughness of 30CrMnSiNi2A steel welded joints. Rajasekhar et al. (2008) investigated influence of post weld heat treatments on microstructure and mechanical properties of AISI 431 martensitic stainless steel friction welds. In this study, they observed that retained austenite content decreases with an increase in the post weld heat treatment tempering temperature. Olabi et al. (1995) investigated the effect of post weld heat treatment on mechanical properties and residual stresses mapping in welded structural steel. However in this study, low-carbon structural steel was used, the chemical composition of this steel being (wt%): 0.141 C, 0.246 Si, 0.820 Mn, 0.008 P, 0.025 S, 0.075 Cr, 0.083 Ni, 0.019 Mo, 0.269 Cu, 0.003 Al and 0.001Ti. Kavousi et al. (2014) investigated effect of post weld heat treatment on microstructure and mechanical properties of X52 Linepipe HFIW Joints. In this study, ıt was determined that 950^{o}C was the optimum normalization temperature from the standpoint of fracture toughness for the X52 steel joints.

As a result, it was determined to investigate post weld heat effects on the mechanical properties of Hardox450 and Optim700MC steel welded joints

2. EXPERIMENTAL STUDY and RESULTS

2.1. Parent metals and welding consumables

For these investigations, Hardox450 (produced by SSAB) and Optim700MC (produced by Ruukki) steels 8mm in thickness were selected. Before the welding operation, specimens were subjected to chemical analysis, micro examination and hardness test to validate the chemical composition and mechanical properties of experimental parts. Chemical analysis, micro examination and hardness test results are stated below for each specimen.

Carbon equivalent values of Hardox450 and Optim700MC are close to each other according to CE_{IIW} formula. Even though carbon content of Hardox450 is more than Optim700MC steel, Optim700MC has a high carbon equivalent value than Hardox450 owing to its other alloy elements which are Mn, Cr and Ni. Chemical analysis test results are given in Tab7;

Table 7. Chemical Analysis Test Results of Hardox450 and Optim700MC

Material	**Chemical Composition**								**Carbon Equivalent (CE_{IIW})**
	%C	**%Si**	**%Mn**	**%P**	**%S**	**%Cr**	**%Ni**	**%Mo**	
HARDOX450	0,11	0,46	1,39	0,01	0,002	0,25	0,07	0,017	0,39
Optim700MC	0,064	0,25	1,84	0,015	0,018	0,22	0,25	0,0001	0,41

Hardness tests were applied to each specimen according to EN ISO 6507-1. Three hardness values were taken from the specimens. Hardness test results are given in Tab8. According to producer datasheet values, it was determined that hardness test results of Hardox450 and Optim700MC were in range.

Table 8. Hardness Test Results of Hardox450 and Optim700MC

Material	**Hardness Test Results (HV1)**			
	No1	**No2**	**No3**	**Average**
Hardox450	499	487	510	498
Optim700MC	326	309	338	324

Micro examinations of experimental parts made in accordance with the related standards were carried out by the light microscope. Micro examination specimens were mechanically ground and polished. %3 nital etching reagent was used to show up the microstructure of the experimental parts. Microstructures of Hardox450 and Optim700MC are shown below;

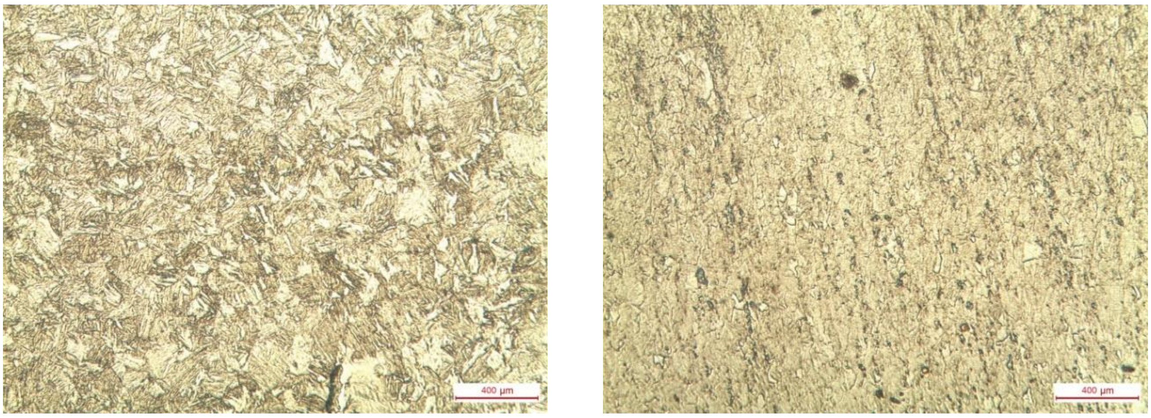


Fig. 2 Microstructures of Hardox450 and Optim700MC steel

In accordance with the technical procedures recommended by the manufacturers G46 4 C 1 G 4 Si 1 filler metal was chosen as a weld metal. Chemical composition and mechanical properties of this filler metal is given Tab9 and Tab10;

Table 9. Chemical Composition of Filler Metal

Filler Metal	**Chemical Composition**		
	%C	**%Si**	**%Mn**
G46 4 C 1 G 4 Si 1	0,08	0,9	1,65

Table 10. Mechanical Properties of Filler Metal

Filler Metal	**Mechanical Composition**		
	Toughness -40^{o}C [J]	**Yield Strength (N/mm^2)**	**Tensile Strength (N/mm^2)**
G46 4 C 1 G 4 Si 1	55	470	540

Even though filler metal has a low carbon content, carbon equivalent value of this filler metal is 0,36.

2.2. Welding Process

In this study, tempered martensite steel and thermomechanically rolled steel used as a base material for welding were joined with MAG welding method applied in PB position and a single pass. Dimensions of the test parts were determined as 150x350mm according to EN 15614-1. Specimens were welded with two different welding parameters to observe the welding penetration for each specimen. In compliance with standards, EN ISO 14175 M 24 mixed shielding gas was chosen for this study. Welding parameters for each specimen and shielding gas are stated below, respectively;

Table 11. Welding parameters of test specimens

Specimen	**Run**	**Welding Process**	**Size of filler metal (mm)**	**Current (A)**	**Voltage (V)**	**Type of current and polarity**	**Wire feed speed (m/dk)**	**Travel Speed (mm/sn)**	**Heat Input (kjmm/sn)**	**Preheat Temperatures**
Specimen A	1	135	1	170-190	22-24	DC (+)	12	4,48	0,83-1,01	x
Specimen B	1	135	1	190-210	24-26	DC (+)	13,5	5,8	0,78-0,94	x

Table 12. Composition of shielding gas

Shielding gas	**Components**		
	CO_2	**O_2**	**Ar**
M24 mixed gas	$5 < CO_2 \leq 25$	$10 < O_2 \leq 15$	Balance

After the welding operation, visual, penatrant and magnetic tests were applied to the specimens according to the related standarts which are EN ISO 17637, EN ISO 3452 and EN ISO 17638. These standards define methods of related testing used to detect discontinuities, e.g. craks, laps, folds, porosity and lack of fusion, which are open to the surface of the material to be tested. It was determined that there were no imperfections such as crack, surface pore on welded specimens. Test results are given below;

Table 13. Results of non-destructive methods

Specimen	**Non-Destructive Methods**		
	Visual Testing	**Penetrant Testing**	**Magnetic Testing**
Specimen A	ok	ok	ok
Specimen B	ok	ok	ok

Fig. 3 Results of visual testing

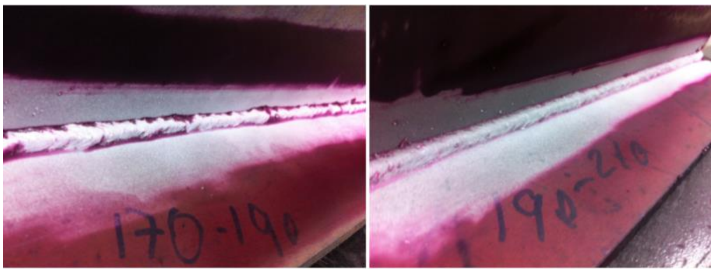


Fig. 4 Results of penetrant testing

Fig. 5 Results of magnetic testing

After the non-destructive tests, specimens were cut into five parts to carry out the destructive tests which are hardness tests, microscopic-macroscopic examination. Welded cross sections were prepared for hardness tests and microscopic-macroscopic examinations, as shown below, according to EN ISO 9015-1 and EN ISO 17639 respectively.

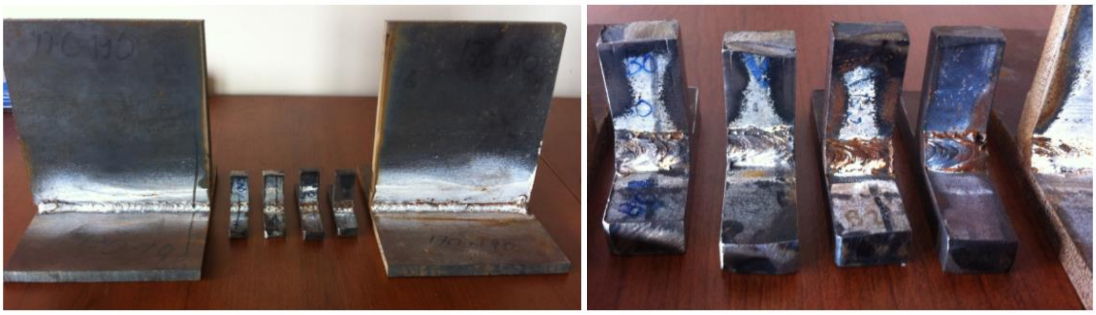


Fig. 6 Image of welded cutting parts

After the cutting operation, specimens were subjected to heat treatment to investigate the hardness change in heat affected zone for each specimen. Post weld heat treatments applied to specimens are stated in Table 14;

Table 14. Heat Treatment Parameters of Each Specimen

Specimen	**Heat Treatment Specimen**	**Parameters of Post Weld Heat Treatment**	
		Temperature (^oC)	**Duration (h)**
Specimen A	Specimen A0	20	x
	Specimen A1	150	2 hours
	Specimen A2	300	
	Specimen A3	450	
Specimen B	Specimen B0	20	x
	Specimen B1	150	2 hours
	Specimen B2	300	
	Specimen B3	450	

As mentioned above, it was aimed to investigate post weld heat effects on the mechanical properties of tempered martensite steel and high strength steel welded joints. For this reason, 150^{o}C, 300^{o}C and 450^{o}C were determined as post weld heat treatment temperatures applied on same duration. Hardness measured using Micro Vickers-Hardness tester is applied for each specimen to observe the hardness change from weld metal to base metal as described below;

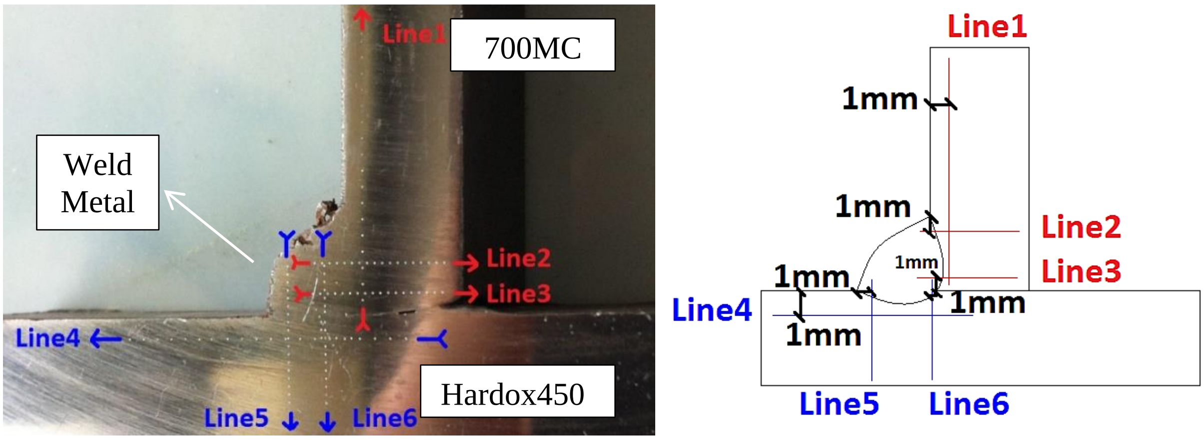


Fig. 7 Hardness line for hardness specimens

The distance between two hardness points were determined as 1mm in line1 and line4, and 0,5mm in line2, line3, line5 and line6. 120 hardness values were taken from each specimen to observe the hardness changes from weld metal to base metal. Hardness values are given by taking into consideration hardness lines for each specimen in Fig. 9-14.

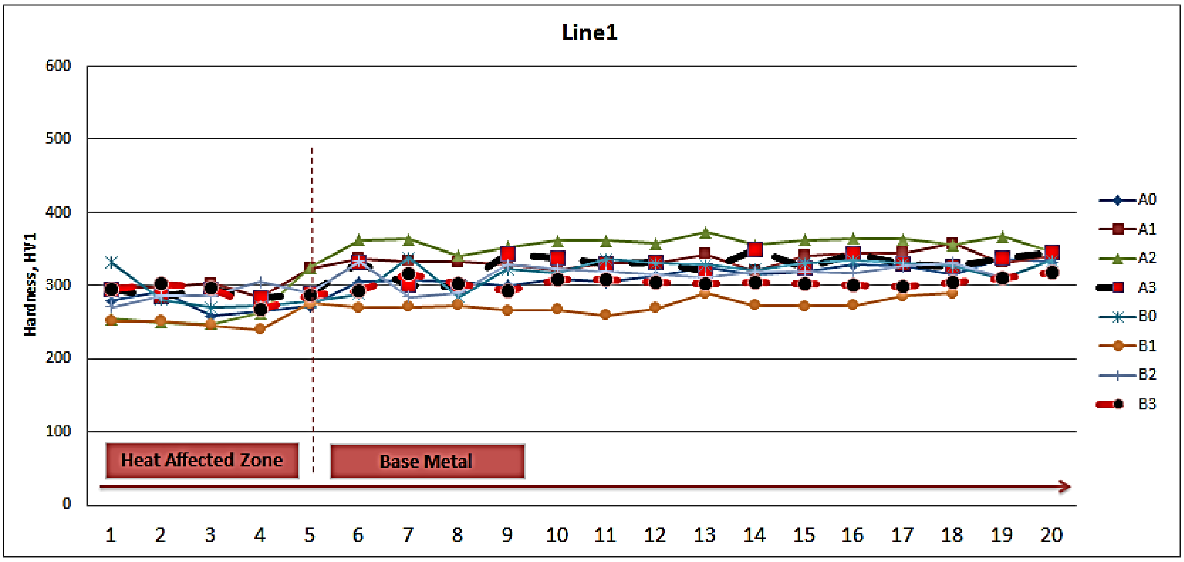


Fig. 8 Hardness results for each specimen on line1

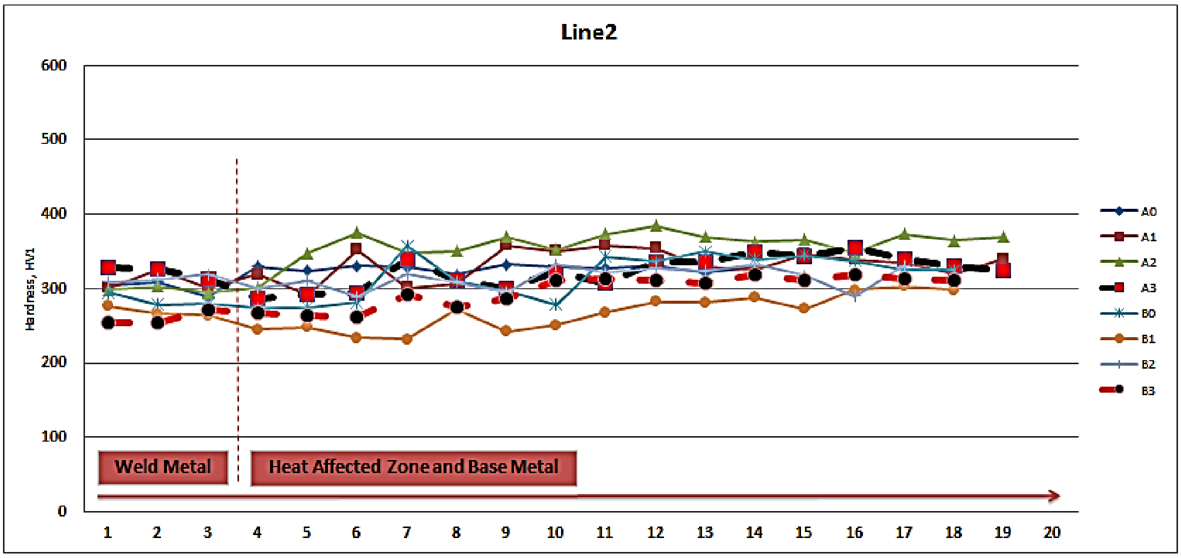


Fig. 9 Hardness results for each specimen on line2

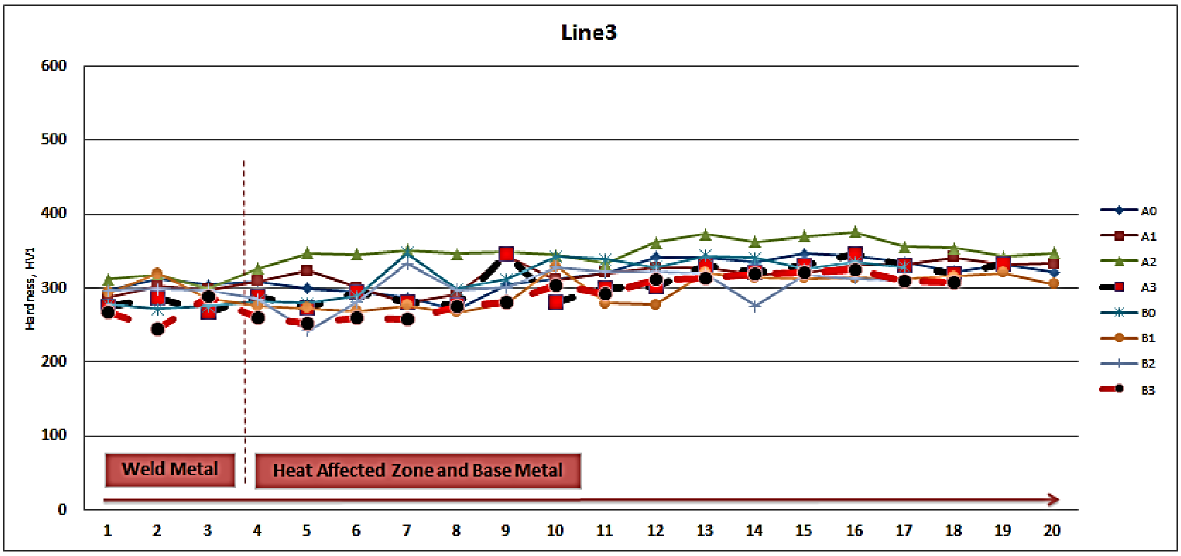


Fig. 10 Hardness results for each specimen on line3

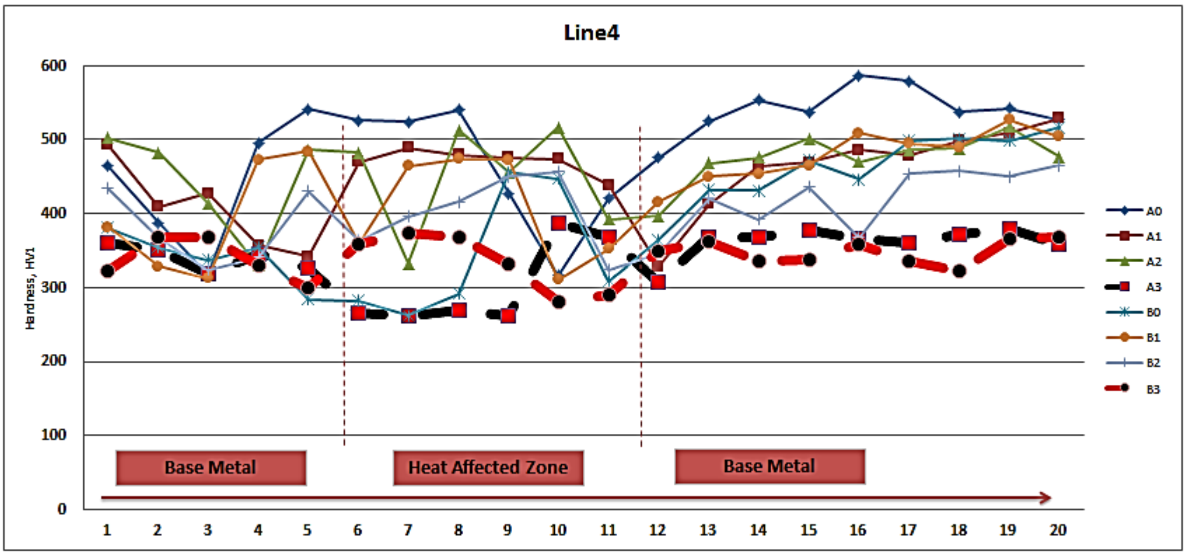


Fig. 11 Hardness results for each specimen on line4

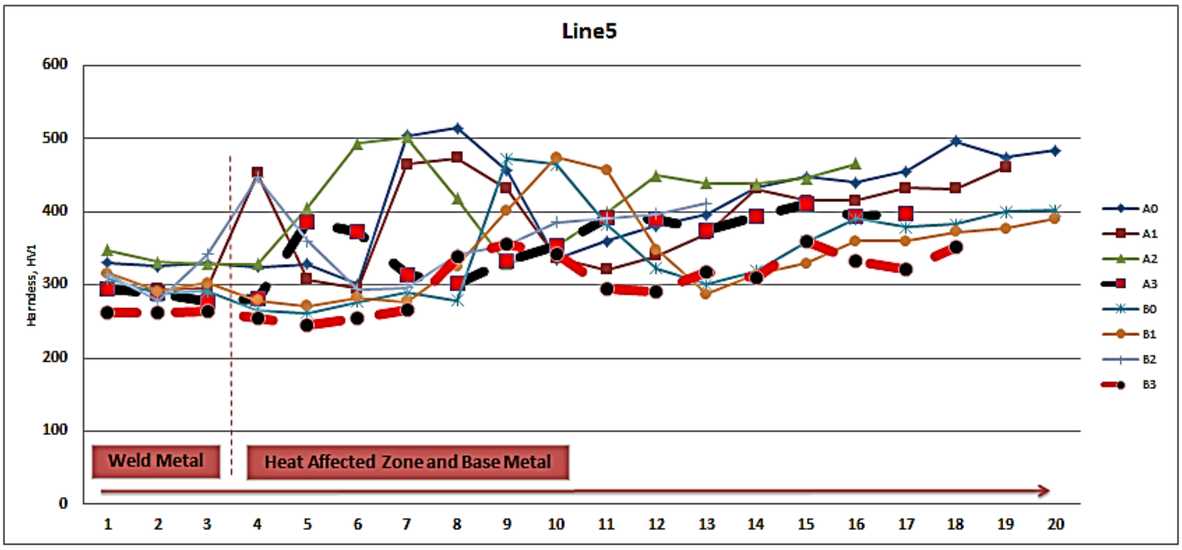


Fig.12 Hardness results for each specimen on line5

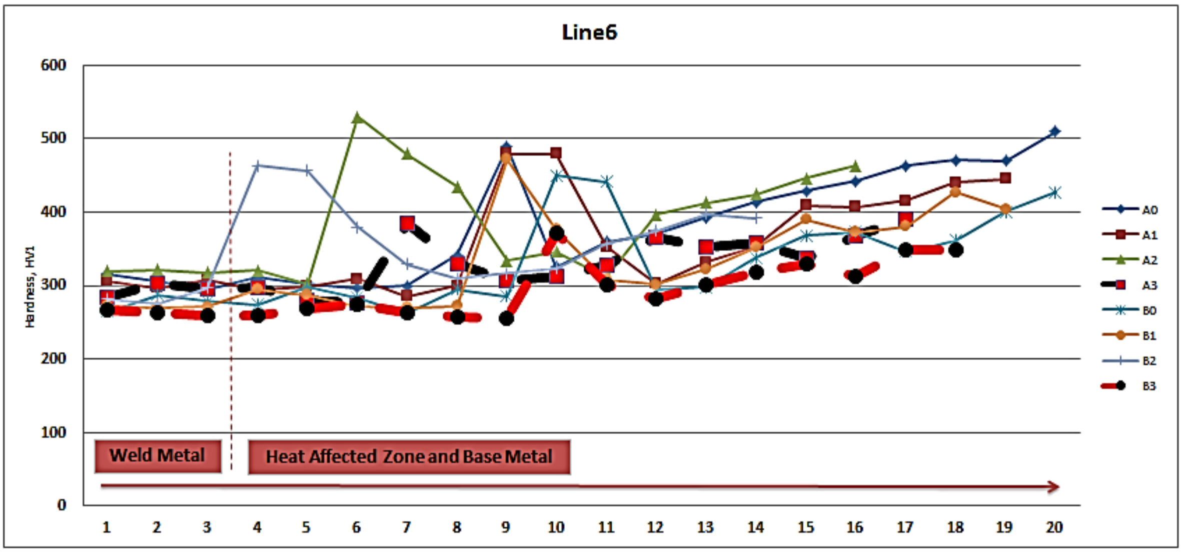


Fig.13 Hardness results for each specimen on line6

Hardness test results were evaluated depending on the post weld heat treatment. Line1, line2 and line3 are on the S700MC material's side and line4, line5, lin6 are on hardox450 material's side.

Even though carbon equivalent of Optim700MC material is 0,41, it has a low carbon content (Table 7). Owing to low carbon content, it was not determined any hardness increasing (like a peak) in heat affected zone on line1, line2 and line3. However, on line4, line5 and line6 hardness increasing was determined in heat affected zone. Especially, when line5 and line6 were observed in detail (Hardox450 material side), hardness values in heat affected zone were determined to be approximately 480-500HV.

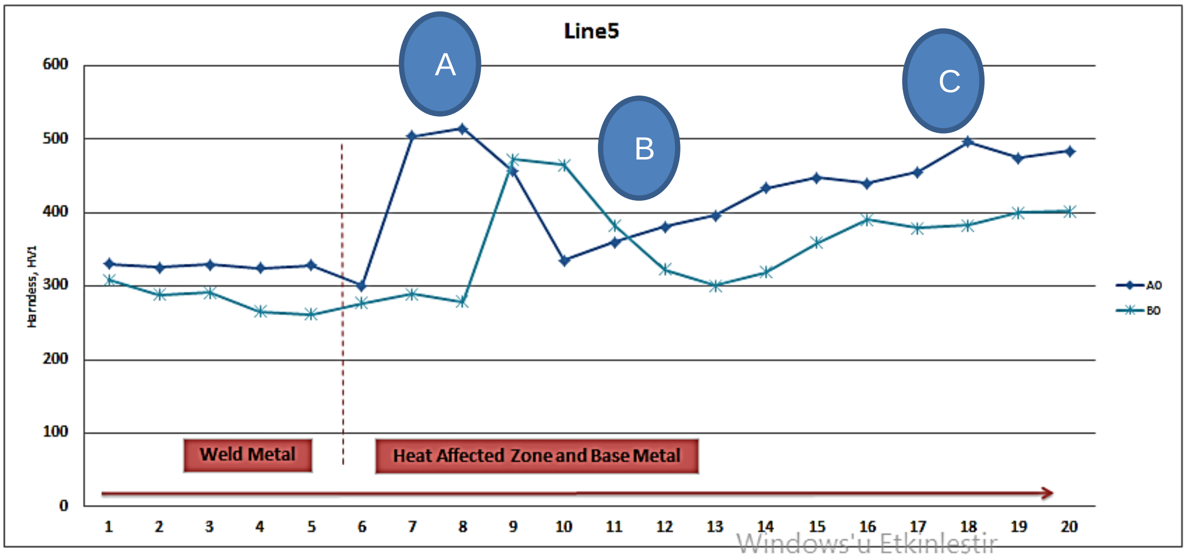


Fig. 14 Hardness results of A0 and B0 specimens on line5

As mentioned above, carbon elements can cause hardness increasing in heat affected zone depending on the cooling rate of specimen. When hardness values of A0 and B0 (non-heat treatment specimen) specimens were evaluated, firstly hardness increasing in heat affected zone due to the cooling rate was determined (A), at a distance from the weld zone hardness values decreased due to the annealing temperatures (B) as shown fig16, finally moving away from weld zone adequately hardness increasing was determined in A0 and B0 specimen (C), like A1, A2, B1 and B2 specimens (Fig15).

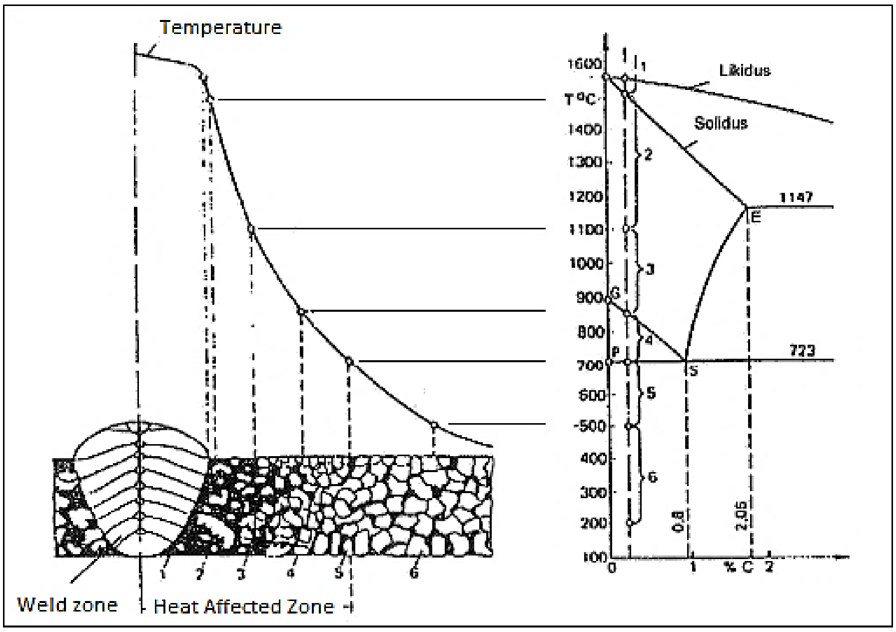


Fig. 15 Temperature distribution during the welding

A1-B1 and A2-B2 specimens were subjected to the post weld heat treatments performed 150^{o}C-2 hours and 300^{o}C-2hours respectively. These temperature values neither affected nor minimised the hardness increasing due to the cooling rate in heat affected zone of A1-B1 and A2-B2 specimens.

On the other hand, A3-B3 specimens were subjected to the post weld heat treatments which were 450^{o}C and 2 hours and decrease of hardness in heat affected zone was determined in A3-B3 specimens. When non-heat treatment specimen (A0 and B0) and (450^{o}C - 2 hours) post weld heat treatment specimen (A3 and B3) are compared, hardness softening in heat affected zone is obviously determined as shown detail fig17;

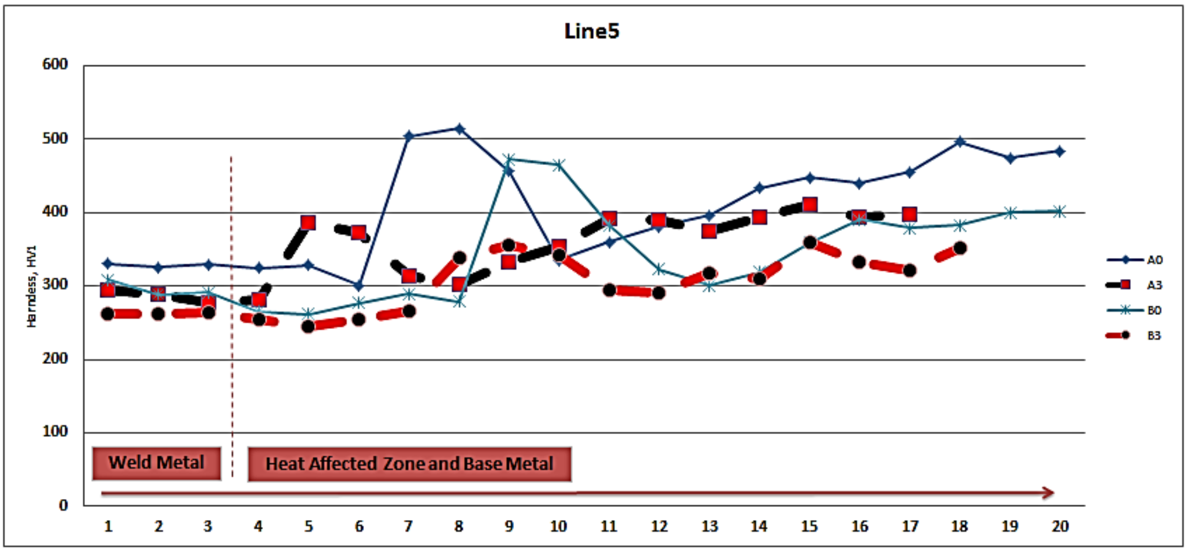


Fig. 16 Hardness results of A0, A3, B0 and B3 on line5

In this microscopic study, it was aimed to observe whether the microstructure change in heat affected zone of each specimen occured with selected post weld heat treatment temperatures. For this reason, A0, A1, A2 and A3 specimens were prepared for microscopic examination. Microscopic examination specimens were mechanically grinded and polished according to the related standards. %3 nital etching reagent was used to show up the microstructure of the experimental parts. Microstructure images of the specimens are given below;

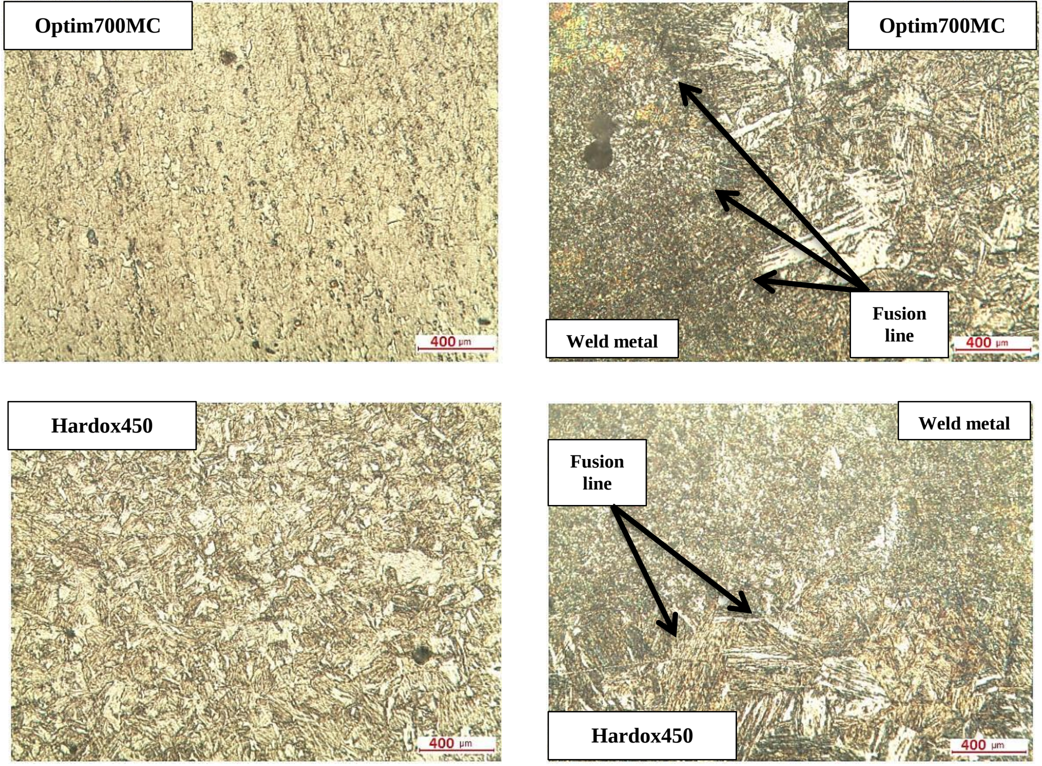


Fig. 17 Microstructure images of A0 specimen (non-heat treatment)

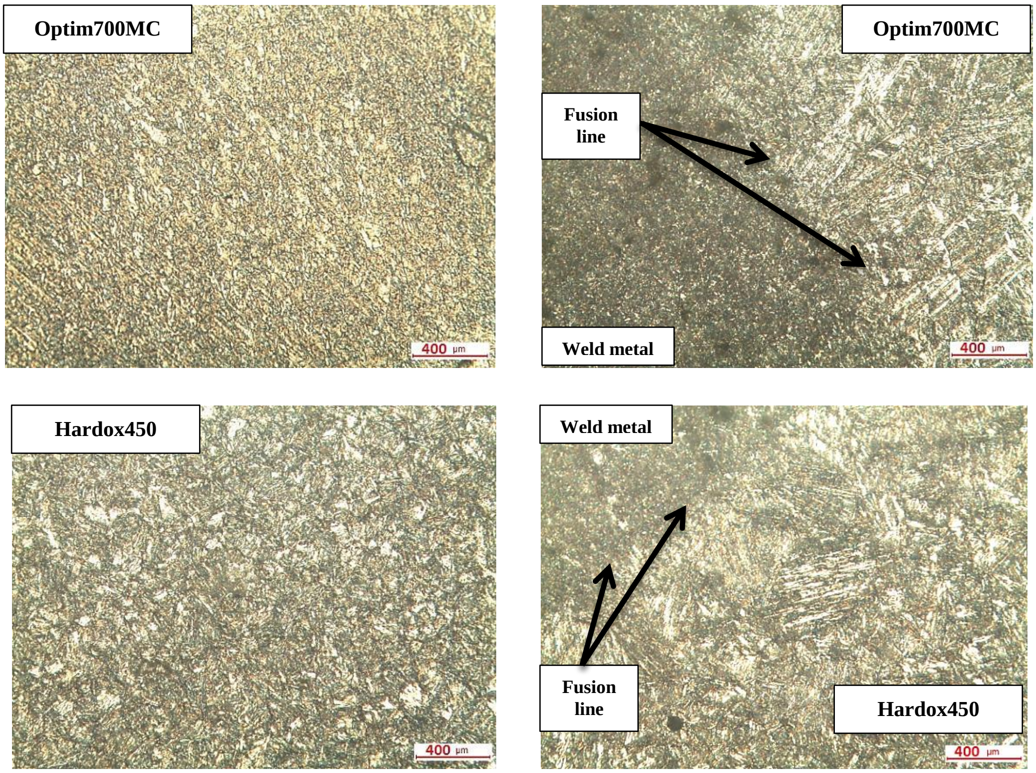


Fig. 18 Microstructure images of A1 specimen (150^{o}C - 2 hours heat treatment)

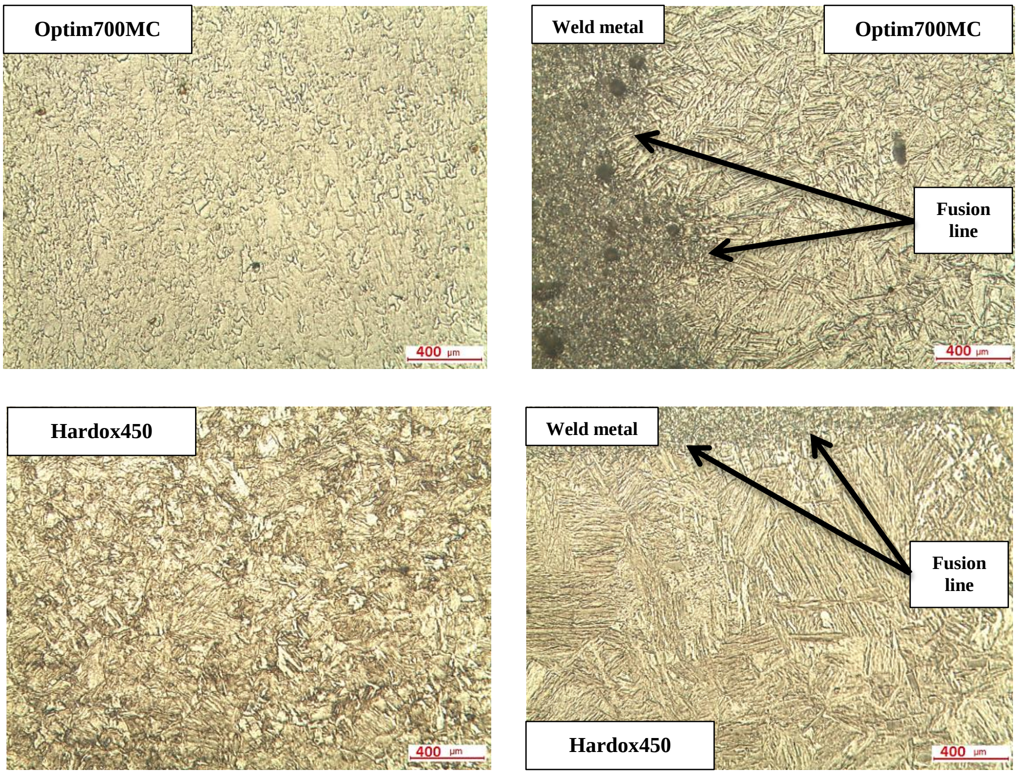


Fig. 19 Microstructure images of A2 specimen (300^{o}C - 2 hours heat treatment)

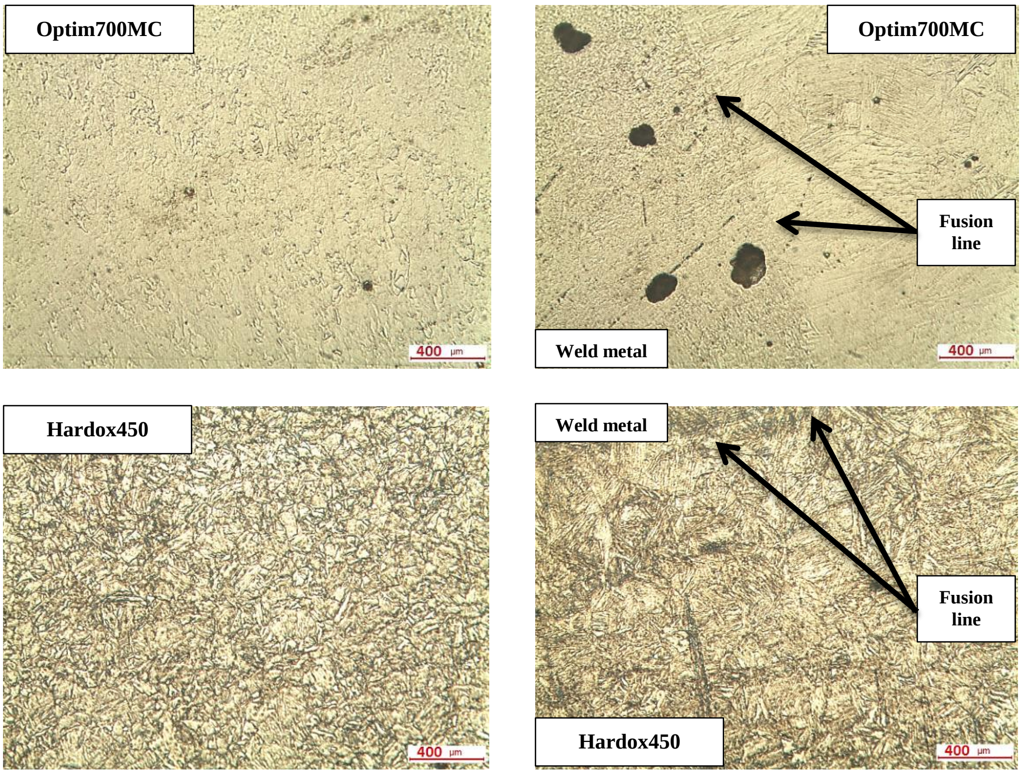


Fig. 20 Microstructure images of A3 specimen (450^{o}C - 2 hours heat treatment)

During the welding operation, temperature distribution in heat affected zone cause the microstructure changing in this zone as shown in fig16. Grain growth (shown in microstructure images) causes decreasing of hardness. Besides, nearby the fusion line, temperatures exceed the austenite temperatures and martensite structure is formed in by the rapid cooling of austenite at such a high rate that carbon atoms do not have time to diffuse out of the crystal structure. As a result, the face-centered cubic austenite transforms to a highly strained body-centered tetragonal form of ferrite that is supersaturated with carbon.

5. Conclusion

Tempered martensite and thermomechanically rolled steels were chosen the base material. Specimens were welded to each other different welding parameters. After the welding operation, specimens were subjected to post weld heat treatment applied on the same duration and different temperatures. 150^{0}C, 300^{0}C and 450^{0}C were determined as post weld heat treatment temperatures. In this study, it was aimed to investigate post weld heat effects on the mechanical properties of tempered martensite steel and high strength steel welded joints.

The findings from this study are summarized below;

- Hardness incerasing due to the temperature distribution and cooling rate was determined only in heat affected zone of Hardox450 materials approximately between 470-520 vickers.

- Hardness increasing due to temperature distribution and cooling rate was not determined in heat affected zone of Optim700MC

- Hardness of the weld metal has not been affected by post weld heat treatment.

- In the heat affected zone of Hardox450, hardness decreasing was only observed with post weld heat treatments which were carried out 450^{o}C - 2 hours.

- Nearby the fusion line (base materials side), grain growth was determined for each specimen. In terms of the different post weld heat treatment temperatures, it was not obviously determined the difference between the grain structures in heat affected zone of hardox450 and optim700MC in itself.

The results show that Hardox450 due to its carbon equivalent can be subjected to the post weld heat treatment after the welding operation to decrease the hardness increasing in heat affected zone.

REFERENCES

Andrew D. Althouse, Carl H. Turnquist, William A. Bowditch, Kevin E. Bowditch, Mark A. Bowditch (2004), *Modern Welding Book*, 658-660

Dearden J and O'Neill H, 1940, “A guide to the selection and welding of low alloy structural steel”,*Transactions of the Institute of Welding*, 3, 203-214

Degarmo E. Paul, J Black, T.Kohser, Ronald A. (2003), *Materials and Processes in Manufacturing* (9th ed.), 388

J.Hub,J. Komenda (2009), “Ballistic resistance of steel plate hardox upon impact of non-penetrating projectiles”, *Advances in Military Technology*, 4, 2

Kavoisi Sisi A., Mirsalehi S. E. (2014), “Effect of post weld heat treatment on microstructure and mechanical properties of X52 Linepipe HFIW Joints”, *Journal of Materails Engineering and Performance*, 24, 4, 1626-1633

Moon Kyung Man, Lee Myung Hoon, Kim Ki Joon, Kim Jin Gyeong, Kim Seong Jong (2003), “A study on the post weld heat treatment effect to mechanical properties and hydrogen embrittlement for heating affected zone of a RE 36 steel”, *Materials Science*, 43, 38, 283-288

Olabi A.G., Hashmi M.S.J (1995), “The effect of post weld heat treatment on mechanical properties and residual stresses mapping in welded structural steel”, *Journal of Materials Processing Technology*, 55, 2, 117-122

Park Min-Ji and Lee Hae-Woo (2014), “Effect of Preheating on Weldability and Corrosion Resistance in 690 MPa Grade Quenched and Tempered Steel weld metals”, *Korean Journal of Metals and Materials*, 52, 12, 983-993

Rajasekhar A, Reddy GM, Mohandas T, Murti VSR (2008), “Influence of post weld heat treatments on microstructure and mechanical properties of AISI 431 martensitic stainless steel friction welds”, *Materials science and technology*, 24, 2, 201-212

SSAB,http://www.joskin.com/pdf/prospec/bennes/en/21%20HARDOX.pdf

SSAB,http://www.hardox.com/en/About-Hardox/Properties

SSAB,http://www.winfa.sk/pdf/harpropproc.pdf

SSAB,http://realsteel.co.nz/site/realsteel2/images/PDFS/Swedish%20steel/103-EN-Welding%20of%20Hardox%20-%20V1-2014.pdf

SSAB,http://www.brunswicksteel.com/pdf/hardox/welding-hardox-and-weldox.pdf

Ruukki,http://www.ruukki.com/~/media/Files/Steel-products/Hot rolled%20steels%20brochures/Ruukki-Optim-MC-Plus.pdf

Ruuki,http://www.ruukki.co.uk/Steel/Hot-rolled-steels/Structural-steels/Optim-MC