Study of Heat Affected Zone after Cutting and Welding of Armoured Ultra-high Strength Steels

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The paper deals with heat affection of selected armoured ultra-high strength steels after their cutting by plasma and laser and their welding with using MAG welding method where critical degradation of mechanical properties could occur in heat affected zone after application of these technologies. Armox steels are armoured ultra-high strength martensitic steels with the usage in special technology. The steels are produced in the form of forged semiproducts as sheets and plates. These sheets are cut and most commonly welded in a way to made the final product. Experimental samples made of Armox 500 steel with using of aforesaid thermal based technologies are studied in the paper to evaluate selected heat affected zone parameters.

Keywords: high strength steel, martensite, tempering, armoured steel, hardness, microstructure

1 Introduction

The Armox steels are group of armoured middle alloyed steels with martensitic structure, heat treated on very high strength and hardness as well as good toughness. These properties result from specific production process of the steel where most important steps are minimizing of H, N and O content by the vacuum furnace and heat treatment consist of quenching with very rapid cooling and low tempering at temperatures about 150÷200 °C. If the final steel is exposed to the temperature above the 200°C some phase transformations take place in the microstructure and the degradation of mechanical properties needed for the steel usage occurs. These conditions are typical for secondary processing of the steel as are cutting or welding.

There are published several studies about microstructure changes of carbon or low alloyed steels after welding or plasma or laser cutting in scientific literature [1, 2].

Heat affected zone (HAZ) after the cutting by these processes could be classified to three different areas according that knowledge [3, 4]:

1. Surface area with full recrystallization to the austenite and back to pearlite, bainite or martensite (temperature range from A_3 to the solidus). The depth of this area is relatively low (about 50 µm) and depends on chemical composition of steel and parameters of used cutting process as are cutting speed or heat input. If martensitic transformation occurs in the area it may cause the internal stresses and consequently the crack creation.
2. Area with partial recrystallization (temperature range from A1 to A3) where the heating up period is very short and therefore the autenitization is just partial. There is new phase created because of partial austenitization beside origin microstructure phases. The amount of new phase decreases in relation to distance from surface. In contrast to full recrystallization area in surface layer, the heatig up temperature of this area is not so high and followed cooling is not so rapid. Therefore, the new created phases are more in steady state (bainitic or pearlitic type). The depth of this area is about 500 µm.
3. Transition area between HAZ and core material (heating up below A1) where any essential phase transformation is not present. Processes known from basics of tempering process take place in steels with martensitic structure. Morphology of martensite is changed from tetragonal to cubic tempered martensite, transformation of the residual austenite occurs and cementite and other carbides are created. This area could reach the depth of several millimetres from surface.

The first step of structure changes in area 1 and 2 is full or partial austenitizing of origin structure. The simplified model with equilibrium state of the strucure is mostly used to describe austenitizing but equilibrium pealitic structure is very rare in real steels because most of them are used in quenched state with martensitic structure as Armox steel are. Therefore, the austenitizing of these steels starts with more complex reverse martensitic transformation.

The reverse transformation mechanism of martensite to austenite and the volume fraction of created austenite have been studied in some steels by means of dilatometry, transmission electron microscopy and X-ray diffraction. It can be diffusion as well as difusionless process. The determining factors are temperature and heating rate. Below a heating rate of 10 $°C \cdot s^{-1}$ the reverse transformation of martensite to austenite occurs by diffusion, whereas it occurs by a diffusionless shear mechanism above 10 $°C \cdot s^{-1}$ s. After reversion treatment at low temperatures, filmlike austenite is observed along martensite lath boundaries, while reversion treatment at high temperatures produces granular austenite inside the martensite laths in addition to filmlike retained austenite. The volume fraction of austenite increases with increasing of reversion treatment temperature [5].

After partial or full austenizing in the form of reversrse martensitic transformation repeard standard transformation of austenite to martensite one of other transformation phases as bainite or pearlite according to cooling condition, when the temepraature in HAZ area starts to decrease. Therefore, the final structure of areas of HAZ sffected by this means can be very complex and consist of many phases.

2 Material and Methods

Armox 500 ultra high strengh martensitic steel is used for experiment. Armox steels are mainly used as a armor material and protection for vehicles, mobile containers and other components in armament as well as civil applications. Ballistic resistance of these steels is given by combination of high hardness and strength with optimal value of toughness in a view of materials characteristics. Armox steel were used in Slovakia for construction of Aligator army vehicle body, demining system Bozena, mobile army containers for modular communication system Mokys or some other special armament application [6]. Scientific research and development in production of those steels allows to reduce active thickness of armor on 50 % with the same ballistic resistance.

Basic mechanical characteristics and chemical composition of the Armox 500 steel are described in the table 1. Showed mechanical properties were evaluated on base unaffected material by standard tensile strength test (EN ISO 6892-1), Charpy impact test (EN ISO 148-1) and Brinell hardness test (EN ISO 6506-1). Chcemical composition was measured by spectral analyzer Spectrolab Jr CCD.

***Tab. 1** Chemical composition and mechanical properties of examined steel Armox 500 [7, 8]*

<table>
<tr><td rowspan="2">Chemical composition [wt. %]</td><td>C</td><td>Si</td><td>Mn</td><td>P</td><td>S</td><td>Cr</td><td>Ni</td><td>Mo</td><td>B</td></tr>
<tr><td>0.27</td><td>0.23</td><td>1.10</td><td>0.014</td><td>0.009</td><td>0.81</td><td>1.58</td><td>0.7</td><td>0.004</td></tr>
<tr><td rowspan="2">Mechanical properties</td><td colspan="2">Tensile strength R_m [MPa]</td><td colspan="2">Yield strength $R_{p0.2}$ [MPa]</td><td colspan="2">Toughness KCU [J]</td><td colspan="2">Hardness [HBW]</td><td>Elongation A_5 [%]</td></tr>
<tr><td colspan="2">1638</td><td colspan="2">1422</td><td colspan="2">25</td><td colspan="2">516</td><td>9</td></tr>
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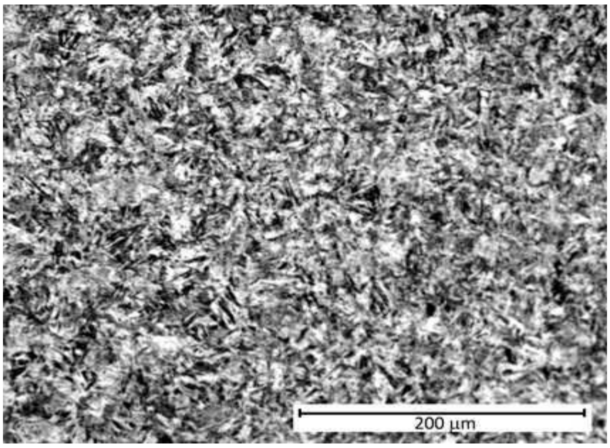

***Fig. 1** Basic microstructure of Armox 500 steel*

Basic microstructure of this steel is shown in fig. 1. The microstructure consists of tempered martensite with assumed small amount of retained austenite. There are observed some carbides as a product of tetragonal martensite transformation to cubic tempered martensite during tempering.

The objects of experiment are samples of Armox steel with heat affected zone (HAZ) after cutting by laser and plasma thermal processes and welded by using of MAG (Metal inert gas) arc welding. The basic parameters of all three used processes are shown in table 1, table 2 and table 3. Heat affected zones after application of these thermal processes were evaluated by microhardness Vicker's test on samples with three thickness – 4, 5 and 8 mm.

***Tab. 2** Basic parameters of used laser cutting process*

Thickness [mm]	Laser Output [W]	Frequency [Hz]	Cutting speed [m.min^{-1}]
4	1900	10000	3.1
5	3200	10000	2.9
8	3200	10000	2.9

***Tab. 3** Basic parameters of used plasma cutting process*

Thickness [mm]	Voltage [V]	Current [A]	Cutting speed [m.min^{-1}]	Plasma gas: O_2
4	120	30	0.9	
5	125	45	0.85	Supplementary gas: O_2 / N_2
8	130	50	0.55	

***Tab. 4** Basic welding parameters of used MAG method*

Current [A]	Voltage [V]	Polarity	Wire feed rate [m·min^{-1}]	Filler material
145÷155	27-29	= (+)	15-16	Thermanit X

3 Heat affected zone after cutting processes

There were measured the microhardness profile in cross setion to the cut face on three group of experimental samples with three difrent thickness. Course of microhardnes of Armox steel with thickness 5 mm cut by plasma and laser is shown in fig. 2 as an example whereby corresponding microstructures of HAZ are in fig. 3 and fig. 4. All measured microhardness courses have the chracteristic shape with three basic areas of heat affected zone:

- increase of hardness in narrow area close under the cut face (heating up to the temperature in austenite area and rapid cooling)
- decrease of hardness with minimum in depth about 0,5÷1 mm under the cut face (uncontrolled tempering of origin martensitic structure)
- slow increase of microhardness to the value of basse material hardness

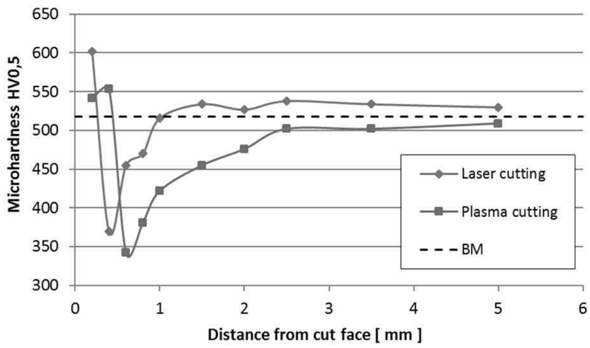

***Fig. 2** Course of microhardness in cross section to the cut face for Armox 500 steel with thickness 5 mm cut by plasma and laser*

The width of uncontolled tempering area is bigger in case of plasma cutting. This process uses lower cutting speeds and plasma arc is greater heat input source than laser beam. The width of uncontrolled tempering area also depends to cut thickness because lower cutting speed and more power output is required for cutting of bigger thicknesses.

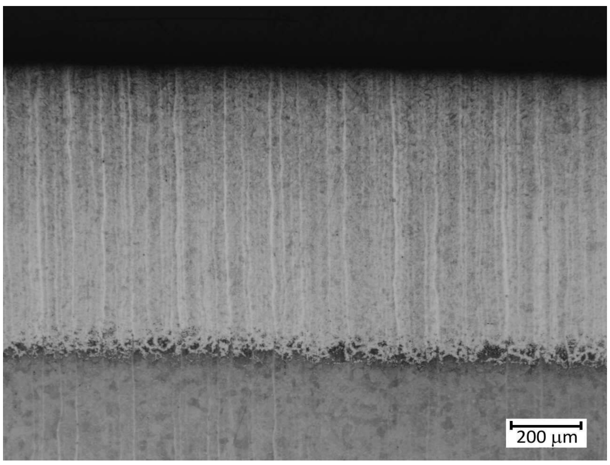

***Fig. 3** HAZ of Armox 500 steel with 5 mm thickness cut by laser*

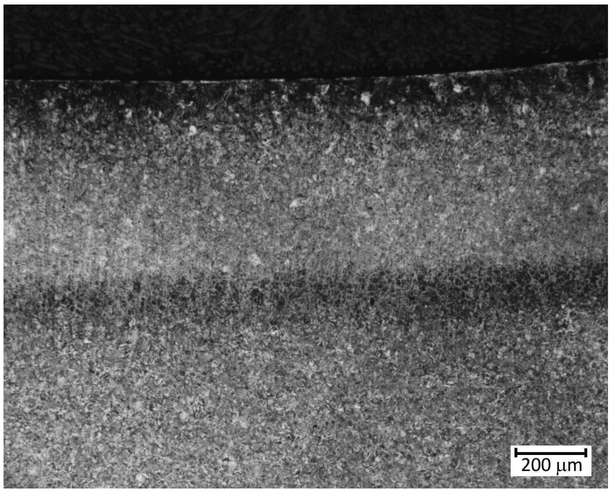

***Fig. 4** HAZ of Armox 500 steel with 5 mm thickness cut by plasma*

Also, depth of heat affected zones were measured from microhardnes courses and avereaged values for all three material thicknesess are shown in table 5. The values of the depth are determined by modified method used for hardened surfaces based on limit hardness as a criterion for reading the depth value from hardness course [9]. Morover, the part of hardness courses where the hardness slowly increases is used only for depth of HAZ evaluating. The hardness of base material is considered as the limit hardness.

The percentage decrease of hardness in minimal point of microhardness course in relation to the base material hardness is also calculated and shown in table 6. The values proved the decrease about 20÷40 % of base material hardness in critical area of heat affected zone. The decrease is more noticeable in plasma cutting than laser cutting.

***Tab. 5** Depths of HAZ for laser and plasma cutting*

Thickness [mm]	Depth of heat affected zone [mm]	
	Laser cutting	Plasma cutting
4	0.77	2.40
5	1.06	2.63
8	3.30	4.80

***Tab. 6** Percentage decrease of hardness in minimal point of microhardness course in relation to the base material*

Thickness [mm]	Percentage decrease of hardness in minimal point of microhardness course in relation to the base material [%]	
	Laser cutting	Plasma cutting
4	18.1	26.2
5	28.6	34.0
8	37.1	40.4

4 Heat affected zone after MAG welding

There is shown course of microhardness across the weld joing of Armox 500 steel made by MAG welding in fig. 5. Some characteristic areas of welding joint are noticeable in the course. Zone with highest decrease of microhardness (a) in the center of the weld joint which is about 5÷6 mm wide and almost completely consists of filler material only. Mechanical properties of this part correspond to used consumable properties and is not consodered as a parrt of heat affected zone. The choice of welding consumable material for Armox steel is a separate problem. High strength ferritic cosumable material or less strength but more tough autenitic material with higher resitance agains hydrogen craks and with lower density of internal stresses could be chosen. Even the high strength consublable is used, it's strength is still less than base material. Therefore, the weld metal area is the weakest part of weld joint [10].

Next characteristic zone of the course is the area with increased hardness with comparison to the base material hardness. This is the area with full recrystallization and consequent repeard martensitic transformation what results to the high hard martensitic needle structure with residual austenite (fig. 6). The wide of this area is relatively narrow (1÷1,5 mm).

Last characteristic area (c) is typical for rapid decreasing of hardness and the slow increase to the value of base material hardness. It is the area with uncontrolled tempering and relative decrease of hardness in the area is about 30 % for Armox 500 steel in comparison to the base material hardness. Microstructure of the area (fig. 7) is consisted of ferritic – carbidic mixture with lighter boundaries borders.

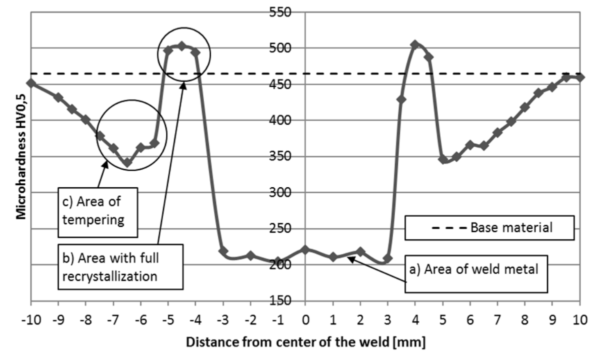

Fig. 5 *Course of microhardness across the weld joint of Armox 500 steel made by MAG welding*

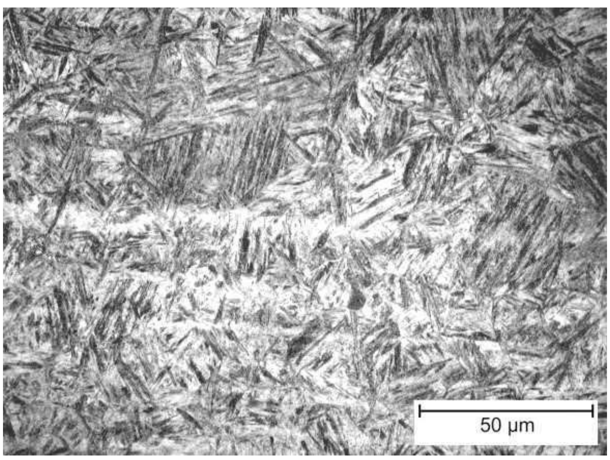

Fig. 6 *Microstructure of HAZ area with full recrysrtallization*

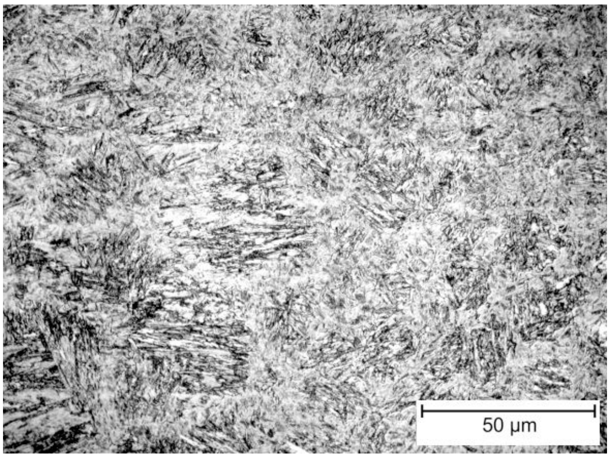

Fig. 7 *Microstructure of HAZ area with uncontrolled tempering*

Showed course of microhardness and the corresponding width of HAZ according to total thickness of samples proved that Armox 500 steel has high sensitivity of heat affection by welding.

5 Conclusions

The processing of ultra high strength martensitic steels Armox with using the processes based on thermal transfer causes the formation of significant heat affected zone. The width of the HAZ depends on heat input brought to the processed material which is a function of specific welding or cutting parameters.

Described influence may affect final quality of processed product with smaller intersections mainly. Due to these reasons is advisable to cut Armox materials by using of the water jet cutting process which is without the heat affection in principle. Welding of Armox is more problematic because the heat transfer is essential to made the weld joint. Optimizing of welding parameters considering heat input could help to minimize heat affection. Also, some progressive welding method could be used besides conventional arc welding methods as is friction stir welding that using lower welding temperatures. However, FSW of Armox steel could be difficult due to its very high hardness.

Acceptance of these recommendations supports the increasing of reliability and safety of products made of Armox steels as are civil and army car protection, building protection or mobile army containers construction.

Acknowledgement

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