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Changes in Mechanical Properties of Armoured UHSLA Steel ARMOX 500 After Over Tempering*

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Abstract. ARMOX steel is an armoured steel with excellent mechanical properties as well as dense hardness, tensile strength and a high level of toughness. These properties result from specific production processes finished with rolling quenching and tempering. The producer of ARMOX steel recommends their secondary processing (cutting, welding, shaping) at temperatures lower than 200°C due to over tempering and the degradation of mechanical properties in heat affected areas. This paper describes the mechanisms and reasons for this degradation including the simulation of the cooling processes concerning ARMOX 500 steel.
Keywords: mechanics, mechanical properties, armoured steel

1. INTRODUCTION

The over tempering of ARMOX 500 steel or any other steel with similar production processes occurs with using any of the secondary production processes based on heat transfer (cutting, welding, shaping etc.)

ARMOX steel production processes consist of a few important steps in order to reach their required mechanical properties. The first of these steps is the continuous casting of slabs ore with a high chemical purity.

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The next step is the rolling of the slabs at a temperature of around 1250°C so as to refine its microstructure and reach the desired thickness and width. The next step is the cutting of the steel into sheets of manageable lengths. Then the sheets are quenched from a temperature of about 1000°C by rapidly and evenly distributing cooling with water to obtain its high strength properties. Next step is the tempering of sheets at temperatures between 200-500°C to make the hardened more ductile. The final step is cutting to delivering length and application of corrosive paint [1]. The microstructure resulting from described heat treatment is fine tempered martensite (Fig. 1).

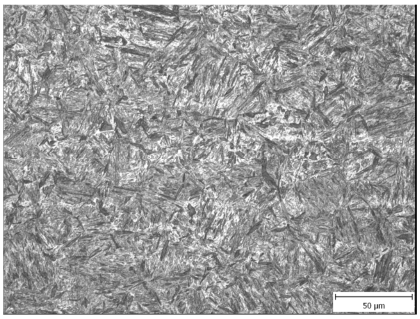

Fig. 1. Microstructure of ARMOX 500 – delivered state (mg. 500x)

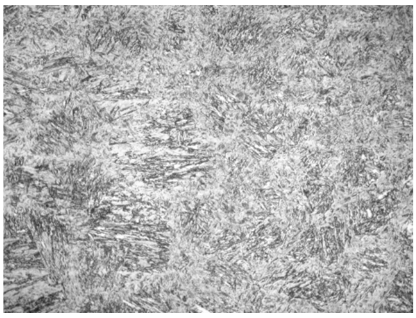

Fig. 2. Microstructure of ARMOX 500 affected by over tempering with temperature below A_1 (mg. 500x)

The producer of ARMOX steel recommends their secondary processing (cutting, welding, bending and others) at temperatures lower than the temperature of tempering (200°C) due to accidental over tempering and the degradation of mechanical properties in heat affected areas.

1.1. Over tempering of ARMOX steels

Not following the specific guidelines set by the producer described above leads to over tempering and therefore the creation of heat affected zones (HAZ) with degraded mechanical properties, mainly being its hardness.

The reason for degradation lies in the microstructural change and could be explained with the help of the tempering steel theory.

The tempering process has four stages in accordance with the occurred temperature [2].

For low tempering the first two stages are the most important. The first stage of a temperature of about 200°C is characterized with coherent carbon precipitation from martensite in a form of ε phase (Fe_2C, $Fe_{2,4}C$). The decrease in the over saturation of martensite with carbon leads to a decrease in its hardness. This change is noticeable in steel with a relatively higher carbon content.

Also the diffusion processes of some alloying elements begin at that temperature and these may start precipitating from martensite and then make the steel softer.

Figure 2 shows the microstructure of ARMOX 550 affected by over tempering with a temperature below A_1 (app. 500°C). The microstructure is prepared from samples of welding joints and are shown in the area in the middle of HAZ (heat affected zone).

Scientific sources indicate a decrease of hardness from 47.6 HRC to 28.6 HRC (40%) by the exposure of the ARMOX 440 armoured steel with a temperature of about 650°C for 5 minutes. The tensile strength decreases from 1476 to 451 MPa (70%) within the same conditions [3].

1.2. Characteristics of ARMOX 500T armoured steel

The chemical composition and mechanical properties of ARMOX 500T steel guaranteed by the producer is shown in Table 1.

Table 1. The chemical composition and mechanical properties of ARMOX 500 [5]

	Chemical composition [wt. %]								
ARMOX 500T	C	Si	Mn	P	S	Cr	Ni	Mo	B
	0.32	0.1-0.4	1.2	0.015	0.010	1.0	1.8	0.7	0.005

	Mechanical properties				
ARMOX 500T	Tensile strength R_m [MPa]	Yield strength $R_{p0.2}$ [MPa]	Toughness KV [J]	Hardness HBW	Elongation A_5 [%]
	1750	1250	25	540	8

ARMOX 500 is an armoured steel used to protect vehicles, buildings or constructions in armament as well as civil application. ARMOX steel is used as armour plating in some armoured personnel carriers (APC's) also vehicles such as the ALIGATOR produced in the Slovak Republic. Another important application of ARMOX steel is within the production of armoured containers used to build mobile army installations, mobile hospitals, service, communication and information centres. (MOKYS system – Mobile Communication System of the Armed Forces of the Slovak Republic) in Slovakia that uses ARMOX steel as armour.

2. SIMULATION OF ARMOX 500 FREE COOLING

The simulation was carried out using TTSteel 2.1 software for the simulation of quenching and tempering of low alloyed steels. Input chemical composition of ARMOX 500 steel for the simulation was obtained from the producer's datasheets as seen in the Table 1.

The purpose of this simulation is to study phase transformations during cooling after over tempering and describe the differences between the delivered microstructure state after controlled heat treatment and its state after over tempering.

The simulation was carried out twice with two different starting conditions. The first one with a starting temperature of 1000°C and second one with a starting temperature of 500°C. Both cases were conducted using free cooling in the air with a temperature of 20°C.

The first step of the steel heat treatment simulation using TTSteel software were the calculations seen in Figure 3, this shows a CCT diagram of the steel based on its chemical composition including critical temperatures (A_{c1}, A_{c3}).

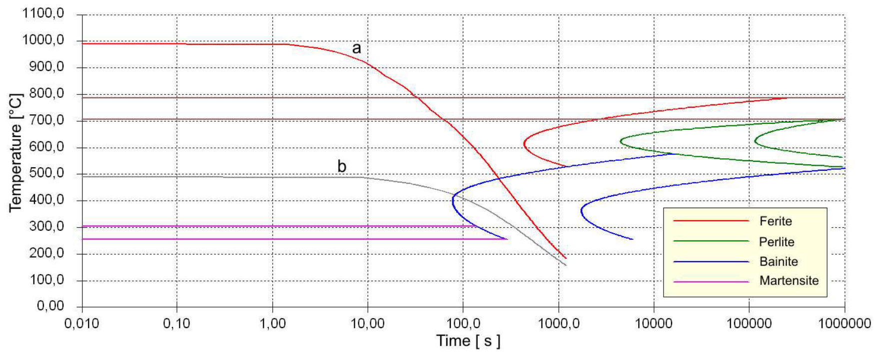

Fig. 3. CCT diagram of ARMOX 500T cooling,
a – starting temperature 1000°C, b – starting temperature 500°C

Table 2. ARMOX 500T properties calculated by cooling simulation

ARMOX 500T properties calculated by simulaton		Starting Temperature		Delivered conditions
		500°C	1000°C	
Critical temperatures [°C]	A_{c3}	786		-
	A_{c1}	707		-
Structural components [%]	Bainite	81	84.5	-
	Martensite	19	15.5	-
Mechanical properties	R_m [MPa]	1335	1312	1750
	$R_{p0.2}$ [MPa]	1070	1049	1250
	HV/HB	441/418	435/413	610/540

The second step of the simulation was the calculation of the cooling curve from which results show the ratio of structural components in percentages (bainite, martensite) present in the microstructure after cooling.

The last steep was the calculation of the final mechanical properties after heat treatment based on the ratio of structural components. The results of the simulation compared with values of the mechanical properties in a delivered state are shown in Table 2. The simulation confirms that the over tempering with temperatures of about A_{c1} and uncontrolled cooling leads to micro structural change. The original tempered martensite microstructure is changed to a bainitic one.

3. EXPERIMENT REALIZATION

Experimental measurements were implemented to describe the cause of the affect on ARMOX 550 with the over tempering temperature that was specified by the producer. The Vicker's Hardness Test was used for the experiment according to EN ISO 6507-1. The parameters of the tests were chosen as follows: load F = 4.903 N, time of indentation t = 4 s. All three samples for the test were taken from one welding joint where the welding point was situated in the middle of the samples.

The micro hardness HV0.5 was measured on the cross section of the welded joint through HAZ (heat affect area), weld metal and back to HAZ on the opposite side of the sample. The hardness of the base material was measured outside the HAZ in the area unaffected by temperature. The measured values are shown in Table 3 and graphically presented in Figure 4.

Table 3. Values of HV0.5 in cross section of ARMOX 500 weld joint and base material

Measurement no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Sample 1	430	410	386	377	367	346	301	486	520
Sample 2	429	427	400	386	351	342	329	415	482
Sample 3	389	366	351	321	306	400	476	588	506
Measurement no.	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Sample 1	501	206	187	506	438	387	324	345	367
Sample 2	594	249	239	484	518	316	397	400	331
Sample 3	387	201	489	524	303	336	327	353	398
Measurement no.	**19**	**20**	**21**	**22**	**23**	**24**	**25**	Base material	
Sample 1	397	400	425	446	451	457	454	458	
Sample 2	358	381	404	426	436	460	457	465	
Sample 3	394	413	425	441	453	462	468	472	

Imprints from 1 to 7 (and 15 to 25) were made in the area of HAZ affected by temperatures below A_1 (without recrystallization). Hardness decreases slowly in proportion to the affecting temperature.

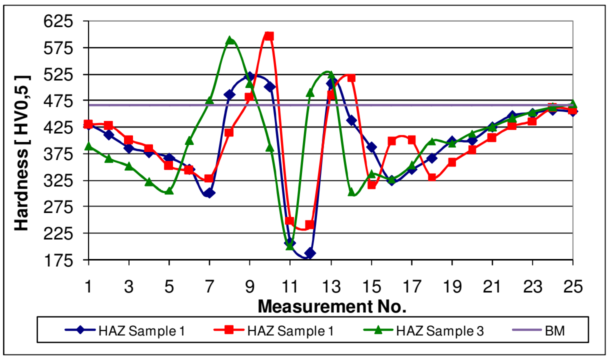

Fig. 4. Graph of micro hardness HV0.5 through HAZ in comparison with the hardness of BM

Imprints from 8 to 10 (and 13 to 14) were made in areas of HAZ by temperatures over A_1. The recrystallization occurs in this area, therefore the microstructure became a very coarse martensitic structure. Noticeably hardness increased, but the area of the material became brittle by this change in microstructure.

Imprints 11 and 12 were made in the area of welded metal; therefore the hardness was very low and its values were about the same levels of hardness of used consumable materials.

Values in the brackets show the number of imprints in corresponding areas on the other side of welded joint.

4. CONCLUSIONS

The cooling simulation, study of microstructure and also the Vicker's micro hardness test provided results confirming a noticeable degradation of the mechanical properties (hardness, tensile strength) in areas of material affected by over tempering. The parameters of tempering (temperature and time) were chosen very carefully by the producer of ARMOX 550 to achieve specifically required high mechanical properties. Additional exposure of the material to over tempering temperatures caused the accidental continuation of the tempering process and therefore degradation of the mechanical properties of the material. The intensity of degradation rises proportionally with the increase in temperature and the time of exposure.

This effect certainly occurs in other armoured steel of ARMOX similar steels produced in a similar way to ARMOX steels are (e.g. SECURE steels). These steels are used in military and civil areas to provide more security to protect human life and valuable vehicles, devices or buildings.

Therefore there is an important need for further research in this area to find a way how to minimize described negative effect.

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