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Structure and hardness changes in welded joints of Hardox steels

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In the article, the structure and change in hardness of the welded Hardox 400 and Hardox 500 steels have been presented. It has been shown that structures of lower wear resistance are being created as a result of welding those materials in the "as delivered" state (i.e. with the tempered martensite structure) within the heat-affected zones. They are as much as up to 90 mm wide, and that causes their non-uniform and fast wear in the anticipated applications. Based on microscopic tests and hardness measurements a method of thermal joints treatment has been proposed, consisting in their hardening and low-temperature tempering (self-tempering) at the heat-affected zones. It leads to reproduction of that area structure, similar to the native material structure. In the laboratory conditions, a heat treatment differing from the usual practice (stress-relief annealing or normalizing) has not led to welding incompatibilities (cracks).

Keywords: *wear-resistant alloys, martensitic steels, welded joints, hardness changes, structures*

1. Introduction

Based at test results concerning Hardox 400 and Hardox 500 steels collected among others in [1], a proposal has been formulated of using those materials in the surface mining machinery construction. The own test results [2–4] confirm good weldability of the materials and very high strength properties of the joints obtained. As a result of heat processes during welding, damage is being introduced into the as delivered structures in the heat-affected zones (tempered martensite). It introduces significant change in such area hardness, as well as local drop in wear resistance. Similar phenomena are being observed in structural components cut out of metal sheets using welding methods.

Significance of such phenomena is high when intending to use Hardox steel plates for brown coal excavator parts, which are exposed to wear in the dynamic load conditions (chutes, hoppers, dumpers and scoop structure elements). The significance is even higher, because they are usually being fixed to the main structure by welding. Unfavourable structure and joint hardness appearing in low-carbon and low-alloyed steels may be reversed by heat treatment of such joints (Figure 1). In case of toughened steel, martensitic steel, as well as hyperquenched and aged aluminum alloys, the issues look different from the usual practice.

In the works [7, 8] they have been presented in relation to toughened steels in the following statements:

• in the heat-affected zone a problem of soft layer appears, which determines the strength of the whole structure,

• in the heat-affected zone of steel joints, hardened and tempered before welding, changes appear which lead to creation of tempering zones of lowered hardness and tensile strength.

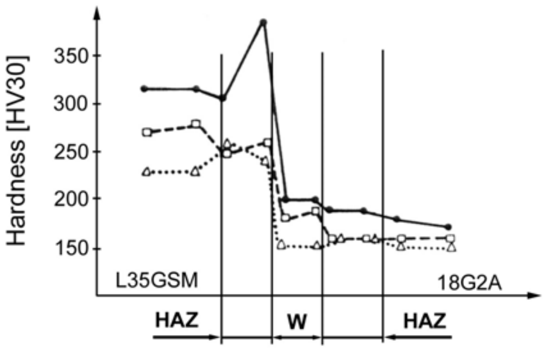

Fig. 1. Hardness distribution in welded joints of the L35GSM cast steel with 18G2A steel:
● – as delivered, □ – after stress relief annealing, Δ – after normalizing, W – joint area,
HAZ – heat-affected zone [5, 6]

Authors of the works [7, 8] and [9–11] state, however, that due to the proper chemical composition of materials and proper selection of welding conditions and parameters, it is possible to obtain structures of similar material properties to the base one in the heat-affected zone, without additional efforts. In case of welding with limited line energy the "soft layer" is very narrow and the joint exhibits no clear reduction of mechanical properties. This is interpreted as "reinforcing" activity of neighbour structural areas, as a result of three-axial stress creation in that zone.

Table 1. Chemical composition of Hardox 400, Hardox 500, HTK 700H and HTK 900H steels

Material	C	Si	Mn	P	S	Cr	Ni	Mo	B
	Maximum values [%]								
Hardox 400	0.320	0.700	1.600	0.025	0.010	0.300	0.250	0.250	0.004
Hardox 500	0.300	0.700	1.600	0.025	0.010	1.000	0.250	0.250	0.004
HTK 700H	0.180	0.450	1.400	0.025	0.010	0.500	0.300	0.030	0.002
HTK 900H	0.180	0.450	1.500	0.025	0.010	1.000	0.300	0.040	0.003
AR 400	0.240	0.700	1.700	0.025	0.010	1.000	0.700	0.500	0.004

Table 2. Structural properties of investigated steels

Material	Structure
Hardox 400	martensitic
Hardox 500	martensitic
HTK 700H	martensitic – bainitic
HTK 900H	martensitic
AR 400	martensitic

Hardox Steels, as well as HTK steels (Table 1 and 2) are well weldable materials with low, or depending on conditions, crack sensitivity (susceptibility) (Figure 2). In the as delivered state they have the structure of tempered martensite. According to the producer data for those materials the hardness changes are as presented in Figure 3. As it comes out of the graph, hardness reduction in the heat-affected zone could go as high as 65% in relation to materials in the as delivered state. The extension of such area of hardness reduction is not being determined by the steel producer. However, the problem itself is being recognized in the form of recommendation for the zones to be padded for hardening.

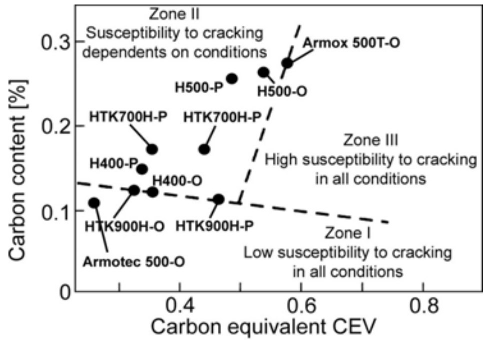

Fig. 2. Crack sensitivity of welded joints in Hardox 400 and Hardox 500, as well as HTK 700H and HTK 900H steels, for sheets of 8 mm thickness as a function of carbon contents and carbon equivalent: P – according to a producer data, W – according to own chemical analysis [3, 12]

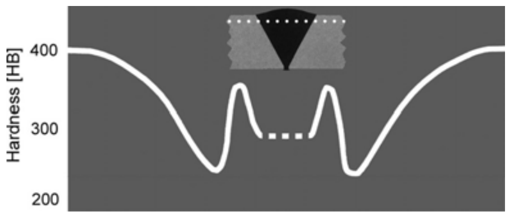

Fig. 3. Hardness change diagram in the welded joint of Hardox 400 steel [13]

However, the method does not solve the problem, as the hardening process of padding must cause new zones of unfavourable structural changes shifted toward edges of padding weld. The following aims of the current studies emerge in the context of the presented information:

- identification of microscopic structure in welded joints of Hardox 400 and Hardox 500 steels in the as delivered state and determination of structure and hardness change extension caused by welding,
- introduction of such structural transformations in joints by heat treatment as to eliminate the changes to the maximum degree.

2. Study results

2.1. Welding conditions

Joints in Hardox steels have been performed using technology of submerged arc welding (SAW), considering welding materials and parameters recommended by producer. As welding material the Multimet IMT9 ϕ 3 mm (carbon contents 0.09 %) filler wire and Lincoln Electric FX 780-25 flux have been used. The samples were made of Hardox steel sheets of 500×300 dimensions (8 mm thickness) joined with double-sided weld with the following parameters providing for correct material penetration:

- minimum current for the first joint layer I_1 = 300 A,
- minimum current for the second joint layer I_2 = 500 A,
- electric arc voltage for both joint layers U = 30 V,
- constant welding speed v = 0.35 m/min,
- maximum linear energy: 2.57 kJ/mm.

Table 3 presents real chemical compositions of the welded steels. Their comparison with producer data indicates for lower contents of alloy additions. This justifies for more favourable location of points determining crack sensitivity of welded steels (Figure 2).

Table 3. Real chemical compositions of the welded Hardox steels and filler wire

Material	C	Si	Mn	P	S	Cr	Ni	Mo	B
Hardox 400	0.120	1.050	0.34	0.006	0.001	0.240	0.040	0.017	0.002
Hardox 500	0.260	0.750	0.200	0.005	0.005	0.700	0.05	–	0.001
IMT9 Wire	0.090	0.140	1.000	–	–	–	–	–	–

Table 4. Heat treatment pattern and parameters for Hardox 400 and Hardox 500 steels

Pos.	Sample marking		Heat treatment pattern	Heat treatment parameters
	Hardox 400	Hardox 500		
1	I – 1	II – 1	As delivered state	–
2	I – 4	II – 4	Hardening	930°C/20min/cooling in H_2O
3	I – 6	II – 6	Hard./H_2O/Temp.	Temp. 200°C/2h/air cooling
4	I – 7	II – 7	Hard./H_2O/Temp.	Temp. 300°C/2h/air cooling

Table 4 presents methods and parameters of heat treatments applied to the joints tested. They were performed in the as delivered state (pos. 1), hardened after welding (pos. 2) or after hardening and tempering (pos. 2 and 3). Tempering temperature limitation to 300 °C results from hardness and structure tests performed for the Hardox 400 and Hardox 500 steels within the tempering temperature range from 200 °C to 700 °C. Up to the tempering temperature of 300 °C the steels preserve average hardness: 363 HV10 – Hardox 400 and 428 HV10 Hardox 500. From the tempering temperature of 400 °C their hardness drops fast, which excludes them from use in the wear conditions.

2.2. Joint structure and hardness changes in the as delivered state

Figure 4 presents exemplary structure of Hardox 500 steel as delivered. Joint welding has introduced apparent changes and diversification in structure (Figure 5). Graphs of hardness measurement (Figure 6 and 7) prove the extension of lowered hardness zones. In case of Hardox 400 steel the zone is 70 mm wide, and for Hardox 500 it goes up to as much as 90 mm.

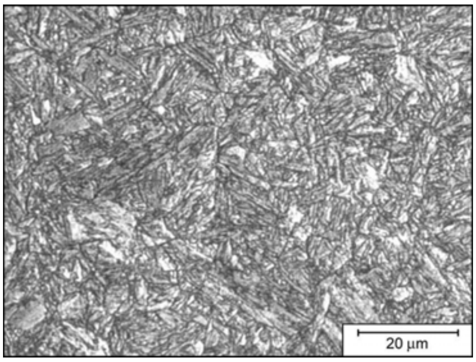

Fig. 4. Microstructure of Hardox 500 steel "as delivered". Tempered martensite without clear grain orders of the previous austenite. Mi1Fe etched, LM [2]

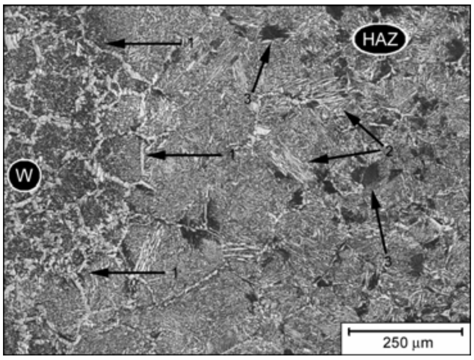

Fig. 5. Structure of welded joint of Hardox 500 steel in the fusion zone: W – weld material, HAZ – heat-affecting zone. Arrows (1) indicate weak outline of the fusion area. In the heat affecting zone a structure of post-martensitic orientation with areas of bainite (2) and troostite (3) is clearly visible. Widmanstätten's structures typical for significant over-cooling have been observed locally. Mi1Fe etched, LM [2]

Also, the content of carbon in the joint material is clearly higher than it could result from Table 3. It demonstrates itself with high quantity of fine-dispersive pearlite in the joint material (Figure 5, zone W). A lack of welding incompatibilities is also a result of macro- and microscopic observations of the tested joints.

Welded joint strength test results in the as delivered state have shown an average joint strength of Hardox 400 steel equal to 615 MPa, and for Hardox 500 the strength was 634 MPa. These are very high values and they constitute about 60% of the yield point for Hardox 400 and about 50% for Hardox 500 steel.

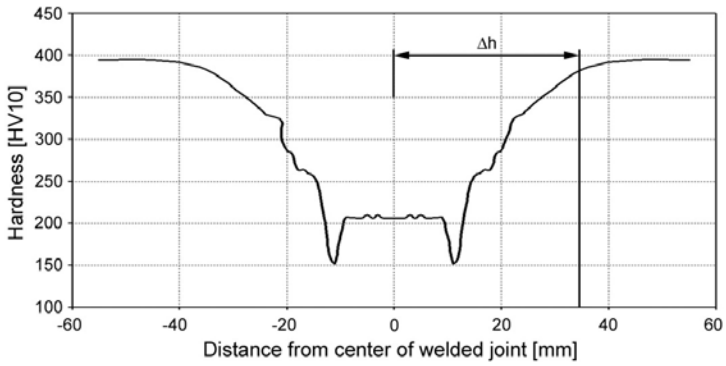

Fig. 6. Hardness changes in welded joint of Hardox 400 steel in the as delivered state: Δh ≈ 35 mm, weld hardness ≈ 210 HV10

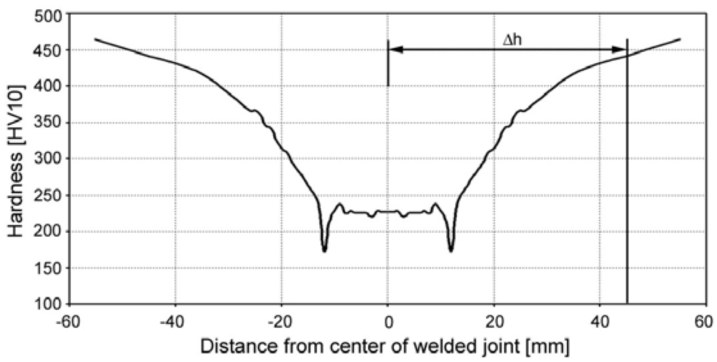

Fig. 7. Hardness changes in welded joint of Hardox 500 steel in the as delivered state: Δh ≈ 45 mm, weld hardness ≈ 230 HV10

2.3. Structures and hardness changes in joints after heat treatment

Overview of hardness changes and joint structures after heat treatment is presented in Figures 8–16. Macro- and microscopic studies have not shown that joint failures in the form of cracks appeared as a result of the heat treatment. All joint zones (marked in Figure 5) have transformed structurally by changing towards the native material structure in the as delivered state. Data concerning extension of the lowered hardness zones have been collected in Table 5. Minimum values of hardness measurements in the as delivered state have been assumed as border of that zone.

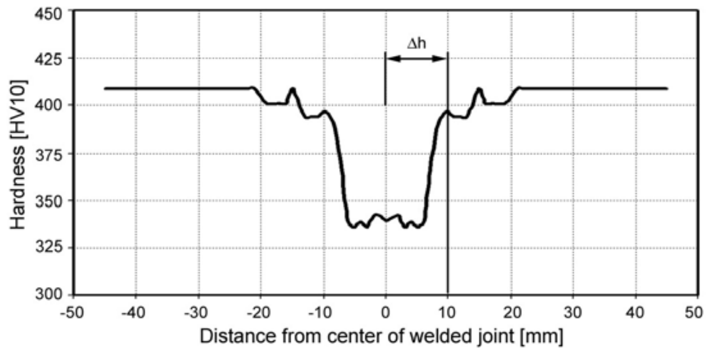

Fig. 8. Hardness changes in welded joint of Hardox 400 steel after hardening. Maximum hardness in the HAZ ≈ 410 HV10. Minimum hardness of the weld material ≈ 340 HV10

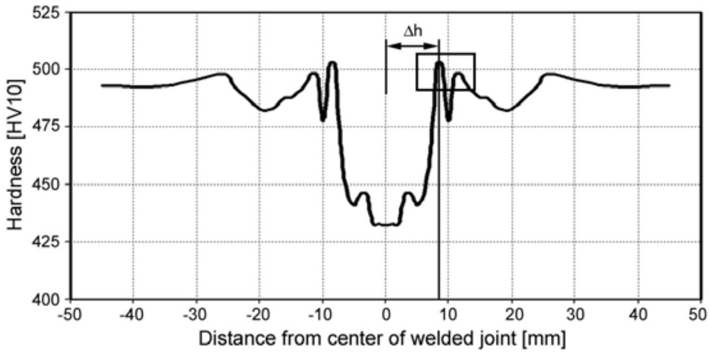

Fig. 9. Hardness changes in welded joint of Hardox 500 steel after hardening. Maximum hardness in the HAZ ≈ 503 HV10. Minimum hardness of the weld material ≈ 430 HV10

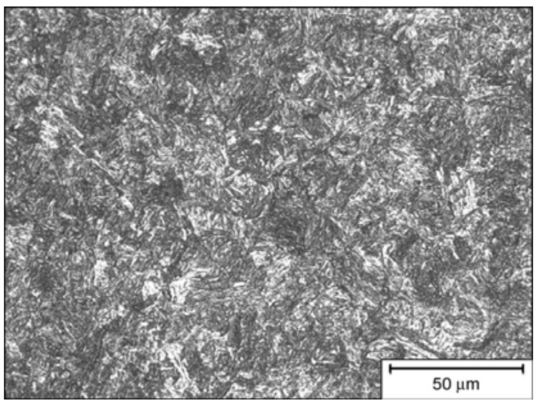

Fig. 10. Structure of welded joint of Hardox 500 steel after hardening from the area marked with frame at Figure 9. Martensitic structure of maximum hardness ≈ 503 HV10. Mi1Fe etched, LM

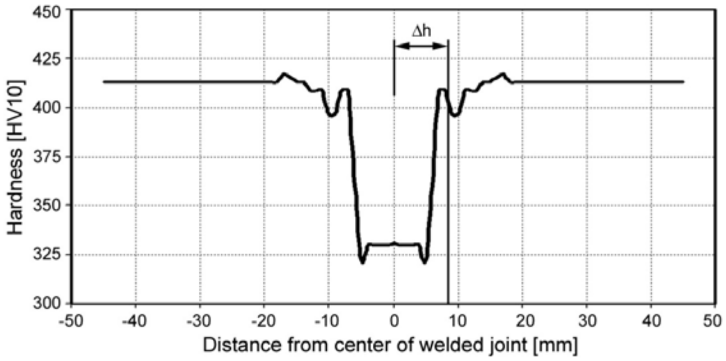

Fig. 11. Hardness changes in welded joint of Hardox 400 steel after hardening and tempering at 200 °C temperature. Maximum hardness in the HAZ ≈ 416 HV10

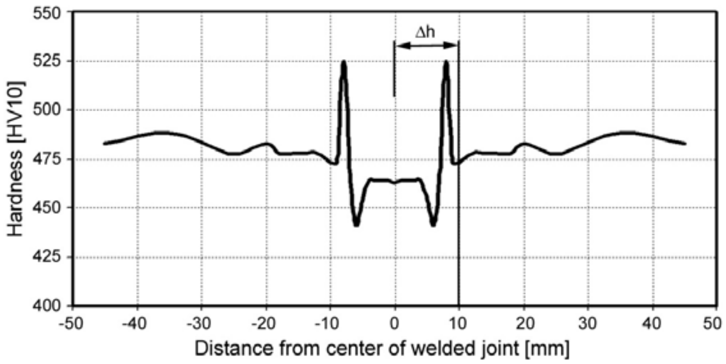

Fig. 12. Hardness changes in welded joint of Hardox 500 steel after hardening and tempering at 200 °C temperature. Maximum hardness in the HAZ ≈ 523 HV10

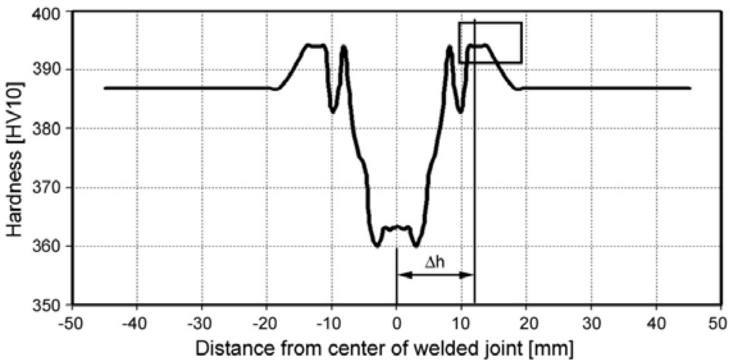

Fig. 13. Hardness changes in welded joint of Hardox 400 steel after hardening and tempering at 300 °C temperature. Maximum hardness in the HAZ ≈ 393 HV10

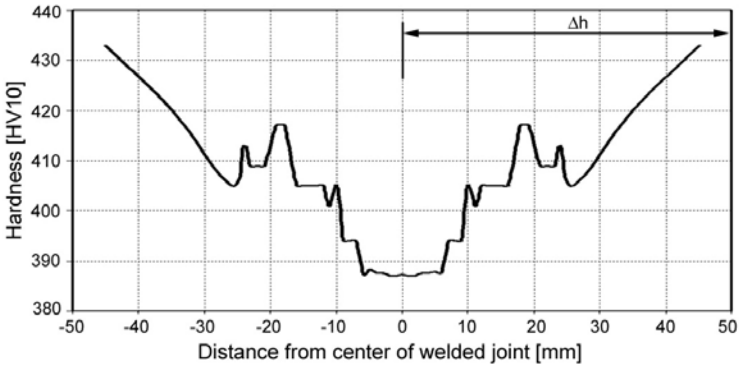

Fig. 14. Hardness changes in welded joint of Hardox 500 steel after hardening and tempering at 300 °C temperature. Maximum hardness in the HAZ ≈ 417 HV10

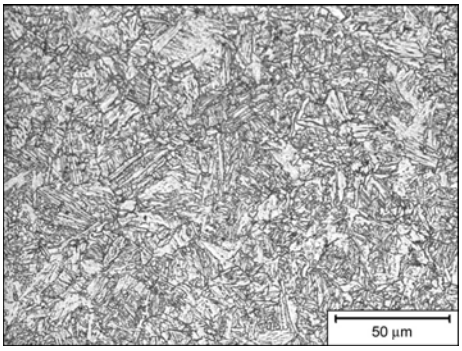

Fig. 15. Material microstructure in welded joint of Hardox 400 steel after hardening and tempering at 300 °C temperature. Sorbitic type structure. Mi1Fe etched, LM

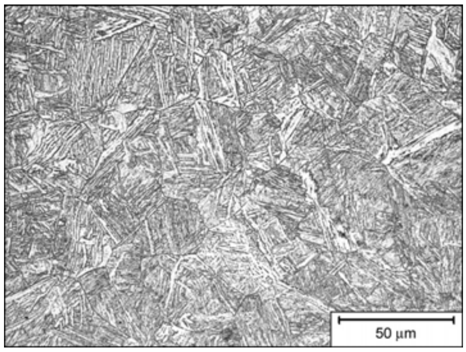

Fig. 16. Microstructure of heat-affecting zone in welded joint of Hardox 400 steel after hardening and tempering at 300 °C temperature. Microstructure from area marked with frame at Figure 13. Mi1Fe etched, LM

3. Summary

Measurement results in hardness change have been collected in Table 5. The following observations result from the data:

a) Width of the lower hardness zone in HAZ in relation to that zone width in the as delivered state has been significantly limited as the result of all patterns of heat processing. Besides the case of hardening and tempering of the Hardox 500 steel at the 300 °C temperature, the areas of lowered hardness have been narrowed by 3 to 6 times.

b) As a result of heat treatment the hardness of weld material has increased significantly. In extreme cases they changed by 70% for Hardox 400, and by 90% for Hardox 500 steel. This indicates that also those areas should present higher wear resistance in relation to the as delivered state.

c) In case of welding the Hardox 500 steel hardened and tempered at 300 °C temperature the width of lower hardness zone is similar to that as delivered. Essential difference, however, constitutes a flattening of hardness change between native material and HAZ and weld material hardness. After heat treatment the $\Delta HV10 \approx 290$. That indicates also for probable increase in wear resistance in the welded joint structure change zone.

Table 5. Comparison of hardness measurement results

Pos.	Welded joint state	Material	Δh	HV_W	HV_{MAX}	HV_{FZ}
			[mm]	HV10	HV10	HV10
1	As delivered	Hardox 400	35	210	375	250
		Hardox 500	45	230	440	280
2	Hardened	Hardox 400	10	340	410	395
		Hardox 500	8	430	503	503
3	Hardened and tempered at 200 °C	Hardox 400	8	330	416	410
		Hardox 500	10	440	523	523
4	Hardened and tempered at 300 °C	Hardox 400	12	363	393	393
		Hardox 500	60	385	□500	417

Δh – width of lowered hardness zone, HV_W – weld material hardness,
HV_{MAX} – maximum hardness in HAZ, HV_{FZ} – maximum hardness in fusion zone

Microscopic tests have confirmed changes in structure of particular zones of welded joints in relation to their structures at the as delivered state. The material shows structural transformations consisting in:

a) Change in weld material structure from quasieutectoid with ferrite halo at grain borders (Figure 5, area W) into a structure of low-carbon tempered martensite (Figure 15).

b) Obtaining the structure of tempered martensite in the whole heat-affected zone (Figure 16). The structure is very similar to that of Hardox 500 steel in the as delivered state (Figure 4). Moreover, as a result of heat treatment the structure variation in the fusion zone has been eliminated.

In the welded Hardox 400 steel the structural changes in various conditions of heat treatment show departures from joint structures of Hardox 500 steel. They consist in:

a) Sorbitic, and not martensitic structure of weld material.

b) Narrow zone of fine ferrite grains (from the Hardox 400 steel side) in the fusion zone.

c) Martensite structure with more advanced tempering process at the heat-affected zone than in case of Hardox 500 steel (Figure 16).

From the data contained in Table 3, it results that difference in carbon density between Hardox 400 steel and filler wire amounts to 0.03%, and between Hardox 500 steel and the wire to 0.17%. During welding, the carbon diffusion fluxes from Hardox steel to the created weld are being initiated. That way, the weld material is being enriched in that hardness improving element. In case of welding sheets of Hardox 500 steel this leads to martensitic type structures also in the weld material. Lowering the carbon contents in the fusion zone (from the Hardox 500 steel side) is not, however, that intensive as not to allow reproduction during the heat treatment of the structure similar to the native material as delivered.In Hardox 400 steel the saturation of weld material with carbon could be lower as a result of its smaller contents in that steel. Thus, hardenability of the weld material is insufficient for obtaining the martensitic structure. A thesis could also be formulated concerning presence of a narrow strip of equilibrium ferrite (from the Hardox 400 side) in the fusion zone. From that zone, plenty of carbon passed to the weld material and, as a result, its hardenability was lowered. The effect of that phenomenon is lack of low-carbon martensite in that zone. The above assumptions could be confirmed by the results of spectral analysis of chemical composition of the weld materials. They have shown:

- average carbon contents higher by several hundredths of percent from 0.09,
- higher carbon contents in joint connecting sheets of Hardox 500 steel than that of Hardox 400.

The laboratory results indicate that in case of steel with martensitic structure a correction of joint hardness and structure is possible by means of hardening and tempering. This concerns the Hardox 400, Hardox 500 steels and, undoubtedly, the HTK 900H steel. That last one in the as delivered state has structure and hardness similar to Hardox 400. Proposals of applying such heat treatment to welded joint have to arouse some controversies and causes some technological problems. Usually (see Figure 1), the relief or normalizing annealing processes are being applied to welded joints. It has been proposed that during applying the last layer of weld a water jet followed an electrode causing hardening of the heat-affected zone (similar solution to the surface hardening). The cooling process would terminate at such point as to allow for self-tempering by heat cumulated in the material. Trials of welding and heat treatment of excavator scoop knives will be conducted in the second half of 2008. The proposal verification would follow during the operating experiment. Before such tests, metallographic studies of welded joints made at structure components of shapes and sizes corresponding to the scoop knives will be conducted.

Hardox steels, and their Polish equivalents – HTK steels, may find far wider application then before in the construction of basic machines for brown coal mining. It simply comes out from their very high mechanical properties and uniform structure at the sheet thickness (even exceeding 100 mm). The second of the features is very special one because, as opposed to the non-homogeneous padded layers, it allows for precise prediction of durability (the higher one from padding weld) of various type lining plates. As shown in the paper [1], using the Hardox steel in real conditions consists in uniform wear, without cracks and local thickness change. That is why they could be used until complete wear. The only areas of intensive wear of such steel lining are joints (stack welding) with the main structure. Should the failure be eliminated in scoop lining and knives, a new, economically justified application area of those materials emerge [1].

Justification and inspiration for works at improving the structure and properties of welded joints in Hardox and HTK steels may also be found among the modern materials for power industry. Martensitic steels, type 9–12% Cr (containing boron), are also in consideration. Since developing the first of them (TAF steel from Japan, middle of seventies in the 20th century), attempts of applying it to superheater pipes were restrained by its low elastic properties and inadequate weldability. It happened so even despite its excellent resistance to creep. It required subsequent years to develop P91 and P92 steels and apply them to steam superheater header (e.g. at the Opole Power Plant BOT). As an effect, the weight of piping dropped by some 30% and significant investments and start-up savings were achieved [14]. It is not unlikely that similar way the technology of welded joint heat processing for Hardox and HTK steels should pass for the anticipated applications.

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Zagadnienia zmian struktur i twardości połączeń spawanych stali Hardox i HTK

W artykule przedstawiono budowę strukturalną i zmiany twardości połączeń spawanych stali Hardox 400 i Hardox 500. Wykazano, że w wyniku spawania tych materiałów w stanie dostarczenia (o strukturze martenzytu odpuszczonego) w strefach wpływu ciepła powstają struktury obniżające odporność na zużywanie ścierne. Mają one szerokość do 90 mm, co w przewidywanych zastosowaniach powoduje ich nierównomierne i szybkie zużywanie. Na podstawie badań mikroskopowych i pomiarów twardości, zaproponowano obróbkę cieplną połączeń polegającą na hartowaniu i niskim odpuszczaniu (samoodpuszczaniu) stref wpływu ciepła. Prowadzi to do odtworzenia struktur tego obszaru zbliżonych do struktury materiału rodzimego. Różniąca się od zazwyczaj stosowanych (wyżarzanie odprężające lub normalizujące) obróbka cieplna nie wywołała w warunkach laboratoryjnych powstawania w połączeniach niezgodności spawalniczych (pęknięć).