www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

Arch. Metall. Mater., Vol. 61 (2016), No 1, p. 127–132

DOI: 10.1515/amm-2016-0024

M. ST. WĘGLOWSKI*,#, M. ZEMAN*, A. GROCHOLEWSKI**

EFFECT OF WELDING THERMAL CYCLES ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF SIMULATED HEAT AFFECTED ZONE FOR A WELDOX 1300 ULTRA-HIGH STRENGTH ALLOY STEEL

In the present study, the investigation of weldability of ultra-high strength steel has been presented. The thermal simulated samples were used to investigate the effect of welding cooling time $t_{8/5}$ on microstructure and mechanical properties of heat affected zone (HAZ) for a Weldox 1300 ultra-high strength steel. In the frame of these investigation the microstructure was studied by light and transmission electron microscopies. Mechanical properties of parent material were analysed by tensile, impact and hardness tests. In details the influence of cooling time in the range of 2,5 ÷ 300 sec. on hardness, impact toughness and microstructure of simulated HAZ was studied by using welding thermal simulation test. The microstructure of ultra-high strength steel is mainly composed of tempered martensite. The results show that the impact toughness and hardness decrease with increase of $t_{8/5}$ under condition of a single thermal cycle in simulated HAZ. The increase of cooling time to 300 s causes that the microstructure consists of ferrite and bainite mixture. Lower hardness, for $t_{8/5} \geq 60$ s indicated that low risk of cold cracking in HAZ for longer cooling time, exists.

Keywords: ultra-high strength steel, Weldox 1300 steel, weldability, physical simulation

1. Introduction

Structures of high dimensions like drilling-rig platforms, bridges, containers, hulls, cranes [1] and others, operating in changing load conditions and at low temperatures, require the application of new kinds of steel with a high yield strength, the lowest possible ductility transition temperature (T_t) to the brittle state, a good technological weldability as well as reasonable costs. These properties are characteristic for the more and more generally used micro-alloyed structural steels containing up to 0,25% wt. carbon, about 1,5% wt. manganese and microadditions of Nb, V, Ti and B, known as high strength low alloy (HSLA) or high strengthening steels (HSS) [1]. The kinds of steels with a high yield strength are also useful for automotive industry [2-9].

According to the definition developed by the Prof. Pilarczyk [10] "weldability is the capacity to fabricate the welded joints of required physical properties, which are able to carry the load designed for the structure made of specific steel". Base on this definition, some base metals or alloys may exhibit good weldability under some conditions, but poor weldability under other conditions.

While weldability depends on the process, operating parameters (especially net linear heat input), procedures, degree of restraint and environment (especially presence of hydrogen from any form of water or hydrocarbon), the most important factor is base metal composition. Composition can determine inherent weldability, with some alloys being essentially unweldable. For those materials that are inherently difficult to weld, special attention and care must be given to the conditions under which welds are to be made, most particularly the degree of restraint, but also the net heat input [11]. A good example is heat-treated, quenched and tempered steel, such as Weldox 1300 structural steel.

To evaluating the weldability of steel many methods can be used [12-14]. No single test can be expected to measure all of the aspects of so complex property. Direct test (e.g. underbead-cracking tests, restrain-cracking tests, external-load cracking test, sample-joint tests) for weldability can be carry out as those tests which specify welding as an essential features of the test specimen. If such tests are to be useful in connection with fabrication, they must be designed to measure the susceptibility of the weld metal and heat effected zone (HAZ) to such defects as cracks, porosity or inclusions under realistic and properly controlled conditions of welding. Ideally they should be sensitive to the effects of welding on steel, reproducible, simple to prepare and to test, and productive of information which can be related to the requirements of satisfactory fabrication [12].

Although many practical test can be used to judge the weldability of metals, the physical simulation techniques are popular and useful.

Under thermal effect of welding, evident change of microstructure and property occurs in the base metal adjacent to the weld metal. Sometimes the change of the microstructure may lead to local brittles in the heat affected zone (HAZ). In addition defects, stress concentrations and higher residual stresses are easy to coexist in the welded joint. Thus, fracture failure of weldment cannot be completely prevented till now. HAZ of welded joints is very narrow in width, and the HAZ

* INSTITUTE OF WELDING, TESTING OF MATERIALS WELDABILITY AND WELDED CONSTRUCTIONS DEPARTMENT, 16-18 BŁ.CZESŁAWA STR., 44-100 GLIWICE, POLAND
** SSAB POLAND SP. Z O.O., KOLEJOWA STR. 15, 55-020 ŻÓRAWINA, POLAND
# Corresponding author: Marek.Weglowski@is.gliwice.pl

consists of many fine regions having different structures. When the fracture toughness is measured using true weldment, the results may represent a global property of HAZ. The measured results cannot be used to describe the property of the fine region of HAZ. Thus it is very difficult to analyse the effect of a characteristic microstructure on fracture toughness using the true weldment. Since the thermal simulation technique has generated the research on the relation between microstructure and property for the welded joints the analysis become easy [15].

The width of mean temperature zone in thermo simulation sample often is larger than that of the real zone in practical HAZ. The austenitic grain in the mean temperature zone of the simulated sample grew up easily and was not affected by the temperature gradient. Therefore, the impact toughness of simulated HAZ can be lower than that of the corresponding regions in practical HAZ. Beside of this, the thermo-simulation technique still has an important significance in indicating the tendency in microstructure, toughness and fracture morphology in real zone of the practical welding HAZ [16].

The new kind of steel of the 1300 MPa type is the highest strength grade steel used in welding structures in recent years. However there is no information about the welding research on 1300 steel in the open literatures. The latest investigations were focused on determine the proper preheating temperature [17] as well as cooling transformation diagram [18]. Therefore in the presented work the effect of weld thermal cycles on mechanical properties and microstructure by using the thermal stress welding simulator was examined. An effort was made to study the influence of cooling time $t_{8/5}$ on the microstructure of simulated HAZ of Weldox 1300 steel using light microscopy and mechanical properties (hardness and impact energy).

2. Experimental procedure

Investigations were carried out on ultra-high strength microalloy structural Weldox steel, type 1300, smelted at the commercial scale in the Swedish firm SSAB. The chemical composition of the investigated steels is presented in Table 1.

TABLE 1

Chemical composition of Weldox 1300 steel [%]

Chemical composition in mass [%]								
C	Mn	Si	P	S	Cr	Ni	Mo	Cu
0,21	0,85	0,21	0,008	0,002	0,47	1,26	0,39	0,02
Cu	Al	V	Ti	B	Nb	Zr	N	
0,02	0,006	0,021	0,003	0,001	0,015	0,002	0,0038	

The thermomechanical simulation was conducted in a thermal stress cycle simulator designed and build at the Instytut Spawalnictwa (Fig. 1a). The main concept of the thermal-mechanical simulator is simple, the electric current flows through the specimen and the Joule heat generates the heat flow from the centre of specimen towards cold copper jaws, producing real temperature gradients [19].

The single thermal cycles at the peak temperature of 1250°C, and at the cooling time in the range of 2,5 ÷ 300 s were carry out. During the welding thermal cycles, a part of the HAZ material at first expands on heating and during this is compressed being restrained crosswise by the cold portions of the parent material, while in the second portion of this cycle the faster cooling down portions of thermal gradient zones once again compress it. In this second part of the thermal cycle also tensile strains appear, in particular in the main direction of the heat flow, and these may assist embrittlement due to generation of dislocations and interaction of these with interstitials, or even initiate intergranular cracking. The magnitude of crosswise deformation due to thermal gradient, which in the case of a stiff real component may result in substantial residual stresses. The simulator is composed of: an AC electric resistance heating system, servo-hydraulic mechanical deformation system, the computer control plus data acquisition and processing.

Square specimens (10 mm × 10 mm × 55 mm) with V notched were prepared and subjected to thermal cycles. The maximum temperature, holding time and cooling rate of the thermal cycle (Fig. 1b) parameters were selected according to possible conditions during arc welding.

Transverse sections of the base metal were prepared by a standard metallographic procedure and etching in 3% alcoholic nitric acid solution (acc. to EN 1321:2000 [20]). The microstructural examinations were carried out by a light microscope LEICA MEF4M. The microstructure of base metal was also examined by transmission electron microscope TEM - JEM200CX.

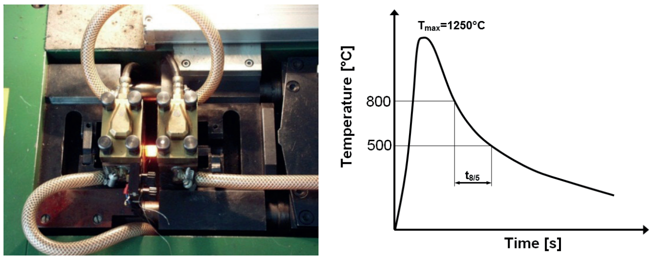


Fig. 1. a) thermal stress cycle simulator – view of copper jaws, b) time - temperature curve during simulation process in the HAZ zone

The Vickers hardness measurement across the simulated HAZ and the base metal was carried out on metallographic specimens at a load of 10 kg. During hardness testing the indentations were randomly made on the matrix without marking the specific phases. Hardness measurement of the steel was performed using the Brickers 220 hardness tester (acc. to EN ISO 9015 [21] and EN ISO 6507 [22]).

The tensile tests of the base metal (acc. to EN ISO 6892-1 [23]) was performed on a mechanical universal testing machine (INSTRON 4120) by using two specimens. The tensile tests were performed at room temperature.

The influence temperature on toughness was determined basing on impact tests with Charpy's method, applying standard samples (10 mm × 10 mm × 55 mm) and notched samples type V (acc. to EN ISO 148-1[24]). The impact test was carried out on of Charpy pendulum machine type Amsler RPK 300, using a container for freezing the samples in denaturant. Lower freezing temperatures were achieved in a mixture of liquid nitrogen with denatured alcohol. The same procedure was used for determine the influence of cooling time $t_{8/5}$ on toughness (after welding thermal cycles).

3. Results and discussion

The microstructure of the investigated Weldox 1300 steel in its delivery state after thermo-mechanical treatment (quenching and tempering) are presented on photographs of microstructures (Figs. 2 and 3). Observations of the structure of Weldox 1300 proved that a martensitic structure occurred in the cross-section of the steel sheet with a hardness of about 501 HV10.

Figure 2b shows the TEM microstructure of base metal which is composed of lath tempered martensite. Inside the laths the minor precipitations were observed (Fig. 3). Based on solve the diffraction the carbidenitrides of vanadium – V(CN) and molybdenum carbide Mo_2C were detected. Taking into account that the chemical composition of Weldox 1300 steel comprised also niobium (0,015 %) and titanium (0,003 %), generally it should be mentioned about MX phases where M means V, Nb or Ti and X means C and N.

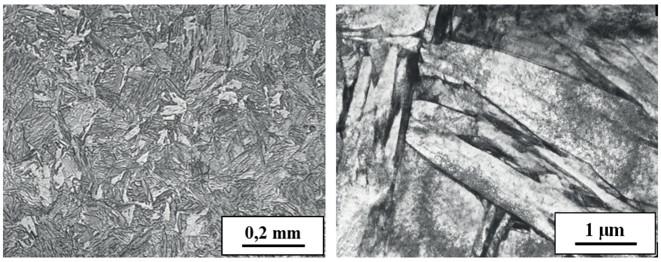


Fig. 2. Martensitic structure of Weldox 1300 steel in the delivered state, a) light microscope, b) TEM

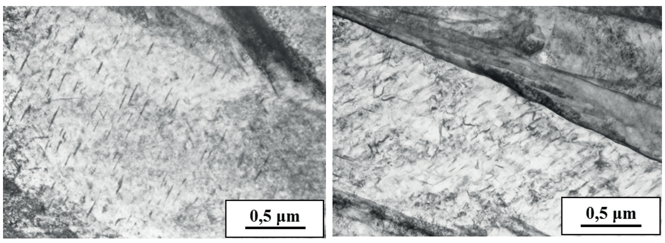


Fig. 3. Microstructure of Weldox 1300 steel, tempered martensite with precipitations

The results of mechanical investigations of Weldox 1300 steel are gathered in Table 2. It has been found that Weldox 1300 displays a high strength R_m in the range of 1539,6 ÷ 1573,5 MPa with a satisfactory plasticity (A about 10%) and hardness (about 501 HV10). The results of the investigations on the impact strength of Weldox steel at temperatures in the range of -120°C ÷ 20°C are shown in Figure 4. It has been found that the investigated kind of Weldox steel is characterized by high values of impact strength both at room and lower temperatures.

TABLE 2

Mechanical properties of Weldox 1300 steel

Mechanical properties	Orientation to rolling direction			
	longitudinal		transverse	
	Value [MPa]	Mean value [MPa]	Value [MPa]	Mean value [MPa]
Rm [MPa]	1570,1	1554,9	1573,5	1572,9
	1539,6		1572,2	
Re [MPa]	1333,4	1294,2	1498,6	1356,6
	1255,0		1214,5	
A5 [%]	11,9	11,8	10,8	10,8
	11,7		10,8	
Hardness on the cross section: 498÷507: HVmean=501 HV10				

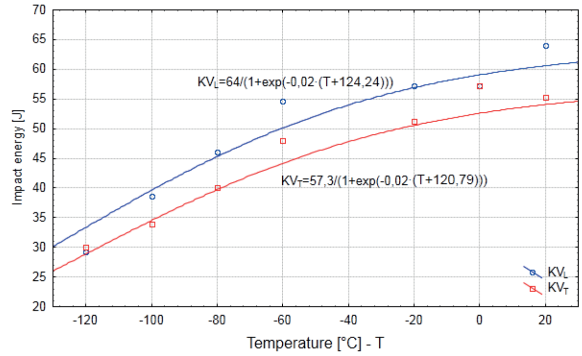


Fig. 4. Impact energy KV of Weldox 1300 steel. KVL – impact energy longitudinal of orientation to rolling direction of KVT – impact energy transverse of orientation to rolling direction

Under the simulation test conditions, $t_{8/5}$ has obvious effect on the impact toughness in the simulated HAZ of Weldox 1300 steel (the results are presented in Figure 5). Effected by the single thermal cycle, the impact toughness and hardness tended to decrease with the increase of $t_{8/5}$ from 2,5 s to 300 s. The change of impact toughness and hardness has close relationship with microstructure in the simulated HAZ. Cooling time $t_{8/5}$ directly affects the austenitic homogeneity, solution of carbide and transfer of microstructure during cooling. The microstructure of the simulated HAZ at the cooling time of 2,5 s to 300 s are given in Table 3.The test results indicated that $t_{8/5}$ should be controlled shorter than 20 s. Because the larger the weld heat input easier the deterioration of impact toughness in the HAZ.

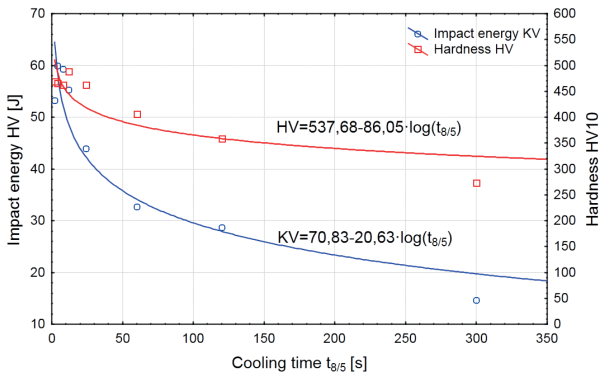


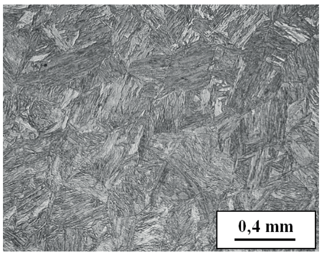
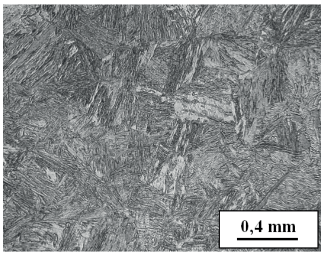
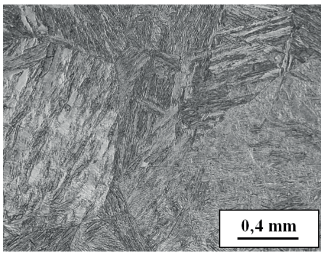
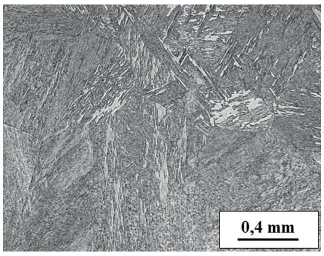
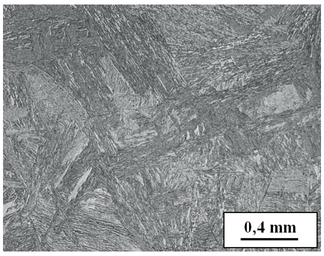
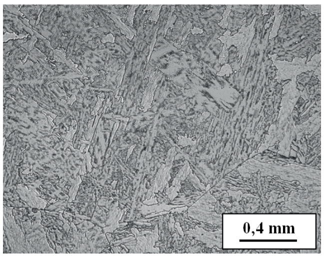
Fig. 5. Impact energy KV and hardness HV of simulated HAZ of Weldox 1300 steel, temperature of the impact test 20°C

It is clear that with increasing cooling time $t_{8/5}$, caused by the increase of holding time at higher temperature, the size of the austenite grain increases. At the same time the volume fraction of martensite decreases and the volume fraction of bainitic-ferrite increases, with the increasing cooling time $t_{8/5}$. If the cooling time is longer than 100 s, the allotriomorphic ferrite starts to appear [11].

It should be mentioned that the austenite grain size of the coarsened grain HAZ for the real welded joints will be slightly larger than that for the simulated HAZ. The main reason may be related to the peak temperature of 1250 ◦C selected in the thermal weld simulation experiments. The peak temperature used in the simulation was slightly lower than that in real HAZ.

From the results above, it is indicated that at the cooling time in the range of 2,5 to 120 s the microstructure mainly is composed of martensite and bainite characterised by the hardness in the range of 488 HV10 to 358 HV10. The increase of cooling time to 300 s causes that the microstructure consists of ferrite and bainite mixture (274 HV10). Lower hardness (lower than 380 HV10), for $t_{8/5} \geq 120$ s, indicated that there is low risk of cold cracking in HAZ for longer cooling time.

TABLE 3
Influence of cooling time $t_{8/5}$ on microstructure of simulated heat affected zone

 Cooling time $t_{8/5}$ 2,5 s Martensitic-bainitic structure 488,6 HV10	 Cooling time $t_{8/5}$ 8 s Martensitic-bainitic structure 463,1 HV10
 Cooling time $t_{8/5}$ 24 s Martensitic-bainitic structure 462,2 HV10	 Cooling time $t_{8/5}$ 60 s Martensitic-bainitic structure 406,9 HV10
 Cooling time $t_{8/5}$ 120 s Martensitic-bainitic plus small amount of ferrite structure 358,8 HV10	 Cooling time $t_{8/5}$ 300 s Martensitic-bainitic structure plus ferrite 274,0 HV10

4. Conclusions

The characteristics of Weldox 1300 steel and simulated HAZ were investigated in respects of microstructure, hardness, mechanical properties and the following results were obtained:

- the microstructure of the Weldox 1300 steel is composed of the tempered martensite with a hardness of about 501 HV10,
- Weldox 1300 steel is characterized by high values of impact strength both at room temperature and lower temperatures,
- under the condition of single thermal cycle, when the cooling time increases from 2,5 s to 300 s, the impact toughness and hardness decrease correspondingly,
- the weldability of Weldox 1300 steel is good but to avoid cold cracking the preheating procedure or medium net linear heat input should be use.

Acknowledgements

The authors would like to thank The Polish Ministry of Science and Higher Education for financing the research. The research was performed within the framework of the statutory activity of the Instytut Spawalnictwa.

REFERENCES

[1] W. Ozgowicz, E. Kalinowska-Ozgowicz, Investigations on the impact strength of constructional high-strength Weldox steel at lowered temperaturę, Archives of Materials Science and Engineering **32**, 89-94 (2008).
[2] M.St. Węglowski, K. Krasnowski, K. Kwieciński, R. Jachym, The characteristics of Nd:YAG laser welded joints of dual phase steel, Archives of Civil and Mechanical Engineering **9**, 85-97 (2009).
[3] A. Grajcar, M. Rozanski, M. Kaminska, et al., Study on non-metallic inclusions in laser-welded TRIP-aided Nb-microalloyed steel, Archives of Metallurgy and Materials **59**, 1163-1169 (2014).
[4] A. Grajcar, M. Rozanski, S. Stano, et al., Microstructure characterization of laser-welded Nb-microalloyed silicon-aluminum TRIP steel, Journal of Materials Engineering and Performance **23**, 3400-3406 (2014).
[5] A. Grajcar, M. Rozanski, S. Stano, et al., Effect of heat input on microstructure and hardness distribution of laser welded Si-Al TRIP-type steel, Advances in Materials Science and Engineering, Article Number: 658947 (2014).
[6] T. Wegrzyn, S.Wieszala, Significant alloy elements in welded steel structures of car body, Archives of Metallurgy and Materials **57**, 45-52 (2012).
[7] A. Grajcar, P. Skrzypczyk, D. Wozniak, Thermomechanically rolled medium-Mn steels containing retained austenite, Archives of Metallurgy and Materials **59**, 1691-1697 (2014)
[8] A. Grajcar, A. Kilarski, K. Radwanski, et al., Microstructural features of strain-induced martensitic transformation in medium-Mn steels with metastable retained austenite, Archives of Metallurgy and Materials **59**, 1673-1678 (2014).
[9] M. St. Węglowski, S. Stano, G. Michta, W. Osuch, Structural characterization of Nd:YAG laser welded joint of dual phase steel, Archives of Metallurgy and Materials **55**, 211-220 (2010).
[10] J. Pilarczyk, Welding metal science. Warsaw University of

Technology, Warsaw 1977. (in Polish).
[11] R.W. Messler, Principles of welding. John Wiley and Sons, New York, 1999.
[12] R.D. Stout, W.D. Doty, Weldability of steels. Welding Research Council, New York 1971.
[13] M. Lomozik, New methodology of testing phase transformations in structural steels in welding thermal cycle conditions, Kovove Materialy-Metallic Materials **50**, 97-105 (2012)
[14] J. Slania, Influence of phase transformations in the temperature rangers of 1250-1000 C and 650-350 C on the ferrite content in austenitic welds made with T 23 12 LRM3 tubular electrode, Archives of Metallurgy and Materials **50**, 757-767 (2005)
[15] Y. Shi, Z. Han, Effect of weld thermal cycle on microstructure and fracture toughness of simulated heat-affected zone for a 800 MPa grade high strength low alloy steel, Journal of Materials Processing Technology 207, 30-39 (2008).
[16] B. Liu, J.X. Qu, W.J. Sun, Effects of Thermal Cycle on Mechanical Properties and Fractography in HAZ of HQ130 Steel, Acta Metallurgica Sinica (English Letters) **17**, 274-278 (2004).
[17] M.St. Weglowski, M. Zeman, Prevention of cold cracking in ultra-high strength steel Weldox 1300, Archives of Civil and Mechanical Engineering **14**, 417-424 (2014).
[18] M.St. Weglowski, M. Zeman, M. Lomozik, Physical Simulation of Weldability of Weldox 1300 Steel, Materials Science Forum **762**, 551-555 (2013).
[19] S. Mandziej, Physical simulation of metallurgical processes, Materials and technology **44**, 105–119 (2010).
[20] EN 1321:1996 Destructive tests on welds in metallic materials - Macroscopic and microscopic examination of welds.
[21] EN ISO 9015-1:2011 Destructive tests on welds in metallic materials - Hardness testing - Part 1: Hardness test on arc welded joints.
[22] EN ISO 6507-1:2005 Metallic materials - Vickers hardness test - Part 1: Test method.
[23] EN ISO 6892-1: 2010 Metallic materials - Tensile testing - Part 1: Method of test at room temperature.
[24] EN ISO 148-1:2010 Metallic materials - Charpy pendulum impact test - Part 1: Test method.

Received: 20 January 2015.