EFFECT OF WELDING REGIME AND FILLER CONTENT ON STRUCTURE OF MICROALLOYED Nb/Ti STEEL WELDMENTS

N. BAJIC [1], *V. SIJACKI-ZERAVCIC* [2], *M. RAKIN* [3], *K. KOVACEVIC* [4]

[1] *IHIS Research and Development Center, Belgrade, Serbia;*
[2] *Faculty of Mechanical Engineering, Belgrade, Serbia;*
[3] *Faculty of Technology and Metallurgy, Belgrade, Serbia;*
[4] *Institute of Ferrous Metallurgy, Niksic, Montenegro*

In this paper changes in the proportions of certain microconstituents in the structure of weld metal and the heat affected zone are described and the mechanical and technological properties of welded joints of high-strength microalloyed Nb/Ti steel performed by E-process and MAG-process of welding with modification of the filler composition and welding parameters were analysed. The influence of different structures of filler material and welding parameters on the microstructure of HAZ and weld metal is studied with the aim to explain changes of mechanical and technological properties of welded microalloyed Nb/Ti steel joints.

Key words: *microalloyed steels, weld metal, heat affected zone, thermomechanical processing, microstructure.*

Depending on quality, microalloyed steels for X-grade wires can be alloyed with Nb, V or Ti, or a combination of the three. Main property of microalloyed steels is a fine-grain ferrite structure with grain size up to No13 according to the ASTM standard. As it is well known, mechanical and technological properties of welded joints are directly related to both chemical composition of the filler and structure of the weld metal (WM) and heat-affected zone (HAZ). The microstructure of welded joints of fine-grain microalloyed steels consists of three basic ferrite modifications: acicular ferrite, primary ferrite and Windmanstatten ferrite, originating as a result of different mechanisms of transformation and differently affecting strength and ductility of a welded joint. Besides, small size of acicular ferrite grains and presence of high-carbon boundaries also ensure maximum resistance to crack initiation [1, 2]. By applying different welding technologies and post-weld heat treatment methods, it is possible to obtain a whole spectrum of different structures in HAZ and WM, which means a series of properties in the same fine-grain microalloyed steel and also changes of mechanical and technological properties of the welded joints. Therefore the aim of this work was to determine an optimum combination of composition of the filler and welding parameters to achieve the highest possible values of tensile strength and toughness of the welded microalloyed Nb/Ti steel joints using the welding E- and MAG-processes.

Materials and welding processes. Experimental welding of prepared specimens – plates made of microalloyed Nb/Ti steels was carried out using two welding processes: MAG-process and E-process, where welding parameters were modified on two levels.

MAG (Metal Active Gas) is a welding process which uses consumable electrode wire in an active shielding gas, CO_2 or its mixtures with inert gases (argon,

Corresponding author: M. RAKIN, e-mail: marko@tmf.bg.ac.rs

helium) are most commonly used. The electrode wire can be a classical solid wire or a powder filled wire. The latest type of this wire is produced under the name "activated" filled wire which differs from the classical wires by the type of components that are included in the composition of the core and the chemical composition of the metal casing. Welding with filled electrode wire is characterized by a series of techno-economic advantages compared to classical solid wire welding.

E-process welding is carried out with the coated electrode consisting of a metallic core and a casing composed of various powdered ingredients (carbonates, oxides, fluorides, alloying elements, etc.). By electrode melting during welding a part of casing turn into a liquid slag, which as a protective layer covers the droplets of melted metal and weld metal, while the other part of the electrodes casing transforms into gases that surround and protect the area of the electric arc and molten metal in the welding area from the surrounding air.

For E-process the quantity of the input heat was E_1 = 7.5 kJ/cm and E_2 = = 21 kJ/cm, while the quantity of input heat in MAG-process was somewhat lower: E_1 = 7.3 kJ/cm, E_2 = 18.5 kJ/cm.

Base metal. For the realization of experimental work the specimens of hot-rolled thermo-mechanically processed steel bands made of Nb/Ti microalloyed steel were chosen (according to API-5L designations they were as follows: A (X52), B (X60) and C (X60), 7 and 12.5 mm thick, in which titanium content was constant (0.011...0.013%); manganese content ranged from 1.182 to 1.375%, while niobium content varied between 0.014 and 0.035% [3]. Batch designations, band thickness and chemical composition of chosen grades of microalloyed steel are given in Table 1. The results of testing (average values) of mechanical and technological properties of the base metal bands in the direction perpendicular to the direction of rolling, as well as a calculated value of carbon equivalent C_{eqv} (according to the International Institute of Welding) are given in Table 2.

Table 1. Chemical composition of microalloyed Nb/Ti steels

Steel grade	Designation	Thick., mm	Chemical elements (mass.%)								
			C	Si	Mn	P	S	Al	Cu	Nb	Ti
Nb/Ti	A	12.5	0.071	0.160	1.375	0.009	0.005	0.036	0.037	0.014	0.012
Nb/Ti	B	7.0	0.053	0.264	1.182	0.020	0.006	0.031	0.018	0.027	0.011
Nb/Ti	C	7.0	0.065	0.261	1.360	0.020	0.007	0.028	0.049	0.035	0.013

Table 2. Mechanical and technological properties and calculated value of C_{eqv}

Steel grade	R_e, MPa	R_m, MPa	A, %	Toughness (Charpy energy) KV, J			C_{eqv}
				+20°C	–40°C	–60°C	
Nb/Ti–A	427	496	42	166	158	126	0.302
Nb/Ti–B	499	560	32	146	142	127	0.251
Nb/Ti–C	489	550	25	127	123	101	0.295

R_e – yield stress; R_m – ultimate tensile strength; C_{eqv} = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15.

Filler metal. For welding of experimental specimens in E-process, four metallurgical grades of coated electrodes were chosen: 1 – EVB Ni Mo (of NM1 designation), alloyed with Ni and Mo, with alkaline coating of 4 mm dia; 2 – ELE 53 B Ni (of N1 designation), alloyed with Ni, with alkaline coating of 3.25 mm dia; 3 – PIVA 255 B Mo Ni (of NM2 designation), alloyed with Ni and Mo of 4 mm dia; 4 – PIVA 255 B (of N2 designation), alloyed with Ni of 3.25 mm dia.

For welding of the specimens in MAG-process three grades of electrode wires were chosen: 1 – PIVA 60 Ni (of W2 designation), alloyed with Ni of 1.2 mm dia; 2 – PIVA 60 (of W1 designation), alloyed with Ni of 1.2 mm dia; 3 – filled activated wire SW-10 (of FW designation), alloyed with Ti of 1.2 mm dia. The designations of coated electrodes and electrode wires as well as chemical composition and mechanical properties of the weld metal for each grade of the filler material separately are given in Table 3.

Table 3. Designation of used filler materials and WM properties

Desig-nat.	Chemical composition of WM, %					Mechanical properties of WM		
	C	Si	Mn	Ni	Mo	R_e, MPa	R_m, MPa	KV, J (–40°C)
NM1	0.06	0.40	0.90	1.10	0.35	> 520	640–710	> 125
NM2	0.08	0.5	0.95	2.50	0.35	550–640	650–750	60–90
N1	0.06	0.5	0.90	1.10	–	> 460	570–650	> 47
N2	0.06	0.35	0.95	2.70	–	510–590	590–610	8 (–20)
W1	0.06–0.13	0.8–1.0	1.4–1.6	–	–	410–490	510–590	80–125
W2	0.08–0.10	0.7–1.0	1.4–1.6	1.0–1.2	–	450–510	550–650	80–120
FW	0.08	0.50	1.50	–	< 0.35Ti	600	700	120–160

Experimental welding. The preparation of the specimens for experimental welding was carried out by cutting the hot-rolled steel bands with the longer side in the direction of rolling, so that the outer dimensions of all specimens were the same (400 by 125 mm). The notch was prepared by finishing the specimen edges at an angles of 30° (for MAG-process) and 45° (for E-process), respectively [4].

The experimental welding of prepared specimens was performed using the MAG-device and the device for welding in E-process. The welding process temperature was controlled by means of a contact thermometer in order to maintain it for all welding passes at 100°C. Experimental welding was carried out without the base metal preheating, as the calculated values of C_{eqv} were below the allowable limit for all grades of microalloyed steels. The number of passes during the process of welding depended on anticipated heat input that was varied on two levels. Experimental welding was carried out on 12 pairs of steel plates by applying: MAG-process with three grades of filler (W1, W2, FW) and in 3 (W1, FW) and 4 (W2) passes and E-process with four electrode grades (N1, N2, NM1, NM2) in 3 and 4 passes.

The analysis of the test results. ***Microstructural analysis of the weld metal.*** Using the light microscope, the microstructure of the weld metal was observed in the last pass of welded joints of Nb/Ti steels of A and B quality, obtained using E-process of welding with filler metals of N1, NM1 and N2, NM2 quality with two levels of heat input. Microphotographs of characteristic structural spots are given in Fig. 1. In the WM of all presented welded joints the presence of various morphological forms of ferrite was observed according to [5]. Most frequently present is acicular ferrite (AF), followed by the secondary-phase containing ferrite (FS) and Widmanstatten ferrite (WF).

The results of microstructure analysis of the weld metal are shown in Table 4.

The WM microstructure obtained with the N1 electrode in Nb/Ti steel (A designation) and low-heat input consists of acicular ferrite (75…77%), while the rest of it consisted of primary (PF) and secondary (FS) ferrite distributed along the former austenite grain boundaries (Fig. 1*a*). For the same steel (Nb/Ti-A) in the WM microstructure obtained using NM1 electrode, 78…82% of AF was found, while the rest of it consisted of FS + PF (Fig. 1*b*). By comparison of the microstructural properties of the WM obtained using the electrodes of different quality (N1 and NM1) with the same base metal, band thickness and almost the same quantity of input heat (E_1 = 8.6 kJ/cm and E_2 = 9.1 kJ/cm), one can conclude that with the electrode of N1 quality a higher quantity of acicular ferrite (78…82%) was obtained than in case of welding with NM1-electrode (75…77%). Supposing that the welded joints were cooled at approximate cooling rates, a certain decrease of the AF portion can be correlated to the molybdenum present in the NM1-electrode. The microstructure of the WM obtained with the N2-electrode in Nb/Ti-grade steel B (low heat input) consisted of 56…58% of AF, while the rest consisted of FS + PF + WF (Fig. 1*c*). Primary ferrite was isolated as fine-grain and coarse-grain, while WF was rather coarse. At higher heat input, the structure consisted of ~50% of AF (Fig. 1*d*), while the rest mostly consisted of fine-grain primary ferrite with small portion of FS.

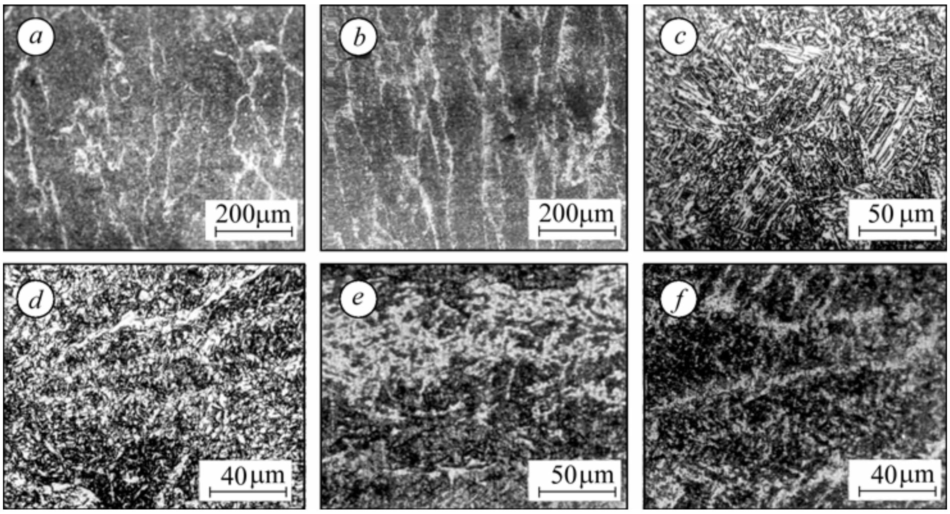


Fig. 1. WM microstructure in last pass of welded steels Nb/Ti (A, B) obtained with E-process using fillers N1, NM1, N2 and NM2: *a* – steel-A, FM-N1, *E* = 8.6 kJ/cm; *b* – steel-A, FM-NM1, *E* = 9.1 kJ/cm; *c* – steel-B, FM-N2, *E* = 11.5 kJ/cm; *d* – steel-B, FM-NM2, *E* = 7.5 kJ/cm; *e* – steel-B, FM-N2, *E* = 18.5 kJ/cm; *f* – steel-B, FM-NM2, *E* = 21 kJ/cm.

Table 4. Results of microstructure analysis of weld metal specimens

Steel	Nb/Ti-A		Nb/Ti-B			
WM	N1	NM1	N2	N2	NM2	NM2
Arc Energy	E_1 = 8.6 kJ/cm	E_1 = 9.0 kJ/cm	E_1 = 11.5 kJ/cm	E_2 = 18.5 kJ/cm	E_1 = 7.5 kJ/cm	E_2 = 21 kJ/cm
Micro-structure	78…82% AF Rest PF + FS	75…77% AF Rest PF + FS	56…58% AF Rest PF + FS + WS	~50% AF Rest PF + FS	72% AF Rest PF + FS	70% AF Rest PF + FS
Fig.	1*a*	1*b*	1*c*	1*d*	1*e*	1*f*

With welded joints made of the same base metal (Nb/Ti-B), with the same N2 electrode and the same band thickness but different heat input, somewhat different morphological characteristics of the WM were obtained – related both to quantity and grain size of different ferrite modifications. Higher heat input favoured formation of a smaller quantity of AF, but of higher grain fineness. The microstructure in the last pass, made using the NM2 electrode in Nb/Ti-B steel with low heat input, consisted of AF (~72%) and PF + FS isolated on grain boundaries (Fig. 1*e*). The structure of the WM obtained with a higher heat input, and other welding parameters unmodified, consisted of a reduced AF portion (~70%) and increased PF and also of lower FS portion, which is illustrated in Fig. 1*f*. Varied heat input in case of welding of Nb/Ti-B steel with NM2 electrode and with the same band thickness also resulted in somewhat varied quantities of AF.

The weld metal microstructure of Nb/Ti-A steel specimen made of electrode W2 wire consists of AF (~55%), while the rest consists of coarse-grain, locally even block-type, PF with small quantity of FS (Fig. 2*a*). The same steel grade welded with filled wire in the WM contains ~68% of AF, while the rest consists of coarse-grain PF with FS in traces (Fig. 2*b*).

The weld metal of Nb/Ti-B steel specimen made with filled wire and two different heat inputs showed different fraction and grain fineness of morphological ferrite forms. In the WM obtained with a lower heat input (Fig. 2*c*) AF was present in the quantity of ~65%, while the rest consisted of fine-grain uniformly distributed PF. The microstructure of the WM obtained with higher heat input consisted of 45…50% of AF, very coarse and here and there block-type PF, WF and FS in traces (Fig. 2*d*).

By welding with filled wire FW the largest quantity of AF was obtained (~78…80%), while the rest consisted of very fine PF and FS. The reason for a larger share of AF in the weld metal structure is explained by the influence of the composition of the activator and microalloying elements in the core composition of the filled wire.

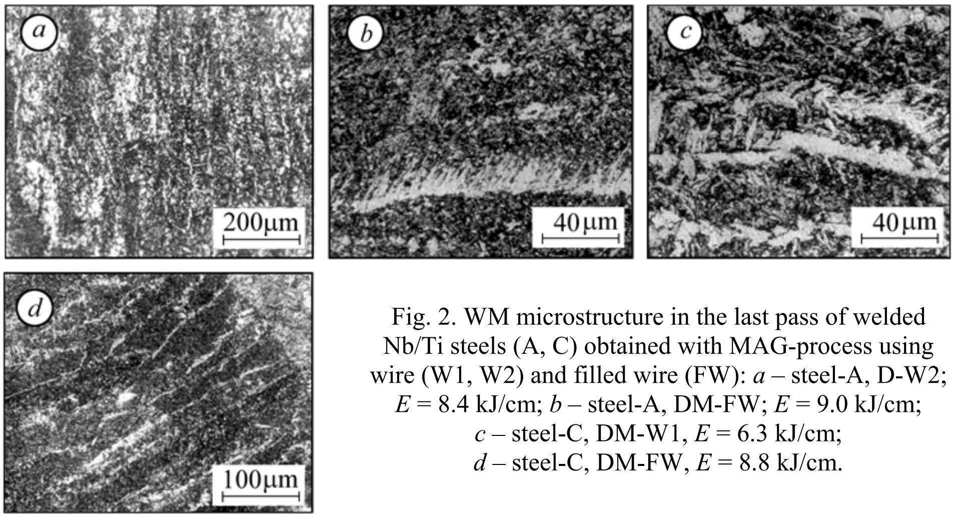


Fig. 2. WM microstructure in the last pass of welded Nb/Ti steels (A, C) obtained with MAG-process using wire (W1, W2) and filled wire (FW): *a* – steel-A, D-W2; E = 8.4 kJ/cm; *b* – steel-A, DM-FW; E = 9.0 kJ/cm; *c* – steel-C, DM-W1, E = 6.3 kJ/cm; *d* – steel-C, DM-FW, E = 8.8 kJ/cm.

Microstructural analysis of HAZ. The microstructure of Nb/Ti steel (A, B, C) consists of fine-grain ferrite and pearlite. Scanning electronic microscope (SEM) analysis of HAZ structure was carried out on Nb/Ti steel, A (Fig. 3) and B (Fig. 4) quality from BM to WM, which means that all zones in HAZ were included. On microphotographs of Nb/Ti steel (A) one can observe a fine-grain ferrite/pearlite structure of the BM (Fig. 3*a*, *b*) and the appearance of the structure in the zone of normalization (Fig. 3*c*, *d*); the microphotographs in Fig. 3*e*, *f* show a part of the structure in the overheated zone of HAZ (a part of the WM structure can be seen up to the fusion line). SEM microphotographs (Fig. 4*a*–*d*) show the HAZ structure up to the fusion line for the joints made with two levels of heat input (E_1 = 7.5 kJ/cm and E_2 = 21 kJ/cm) for Nb/Ti steel (B quality). One can see that with the specimens of welded joints made with higher heat input the HAZ structure in the zones of normalization and overheating is coarser than the HAZ structure of welded joints made with lower heat input (Fig. 4*a*–*c*).

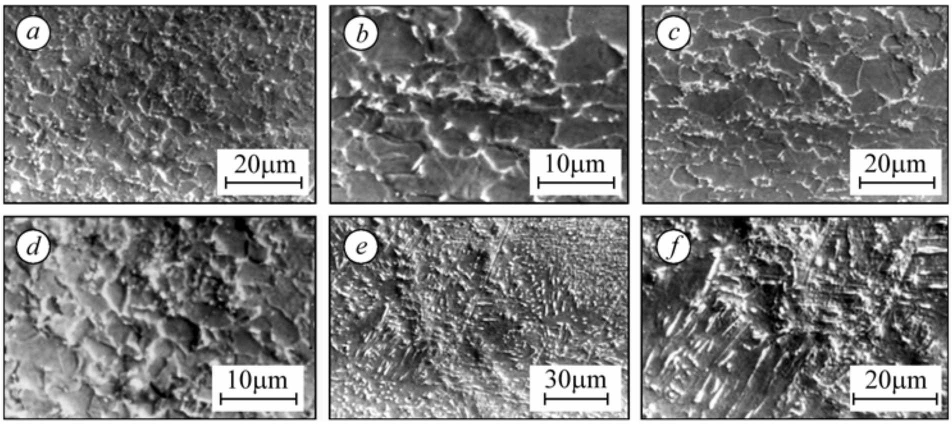


Fig. 3. SEM microphotographs of different zones of microstructure of welded steel Nb/Ti-A: *a* – base metal (ferrite + pearlite); *b* – magnification of photograph *a*; *c* – zone of normalization; *d* – magnification of photograph *c*; *e* – WM zone; *f* – magnification of photograph *e*.

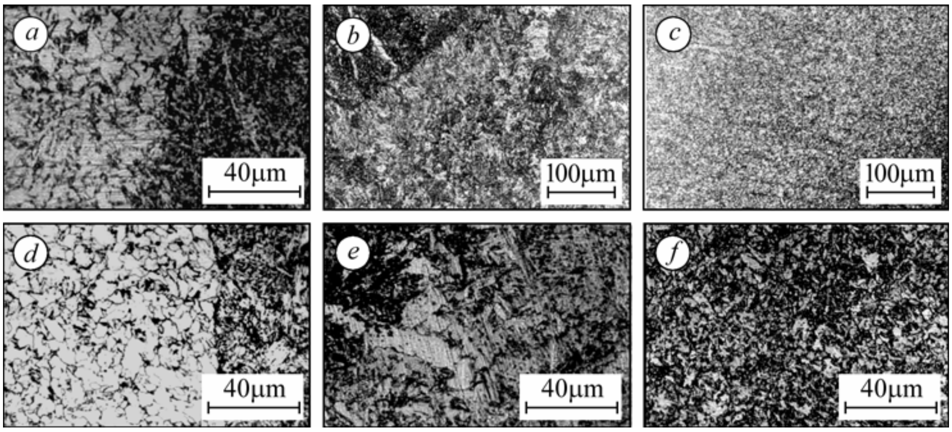


Fig. 4. HAZ microstructure of welded steel Nb/Ti-B: *a–c* – E_1 = 7.5 kJ/cm; *d–f* – E_2 = 21 kJ/cm.

SEM microphotographs (Fig. 4*a–d*) show the HAZ structure up to the fusion line for the joints made with two levels of heat input (E_1 = 7.5 kJ/cm and E_2 = 21 kJ/cm) for Nb/Ti steel (B). One can see that for the specimens of welded joints made with higher heat input the HAZ structure in the zones of normalization and overheating is coarser than the that of welded joints made with lower heat input (Fig. 4*a–c*). The SEM analysis of the HAZ structure of Nb/Ti-B steel made with low heat input (7.5 kJ/cm) demonstrated that the fine-grain structure was obtained in the overheated zone.

Analysis of mechanical properties of welded joints. Testing results of tensile strength of welded microalloyed steel specimens (quality Nb/Ti) are shown in comparison with tensile strength values of the base metal in the chart, Fig. 5. Comparison of testing results of tensile strength of the welded joints and the base metal Nb/Ti steel indicates that for steel marked (A) the highest values were achieved in specimens welded with an electrode (1.1% Ni, 0.35% Mo) EVB Ni Mo while specimens welded with N1 and W2 have lower values but still higher than tensile strength values of the base metal, and steel (B) has tensile strength of welded joints much higher than that of the base metal for both electrode qualities; NM2 alloyed with nickel and molybdenum (2.5% Ni, 0.35% Mo), PIVA 253B Mo and N2 alloyed with 2.7% Ni (PIVA 255 B). Steel (C) has tensile strength of welded joints much higher than that of the base metal. On the basis of tensile strength analysis in welded joints the conclusion is done that the best results have been achieved with electrodes NM2, N2 and electrode wires W1, FW.

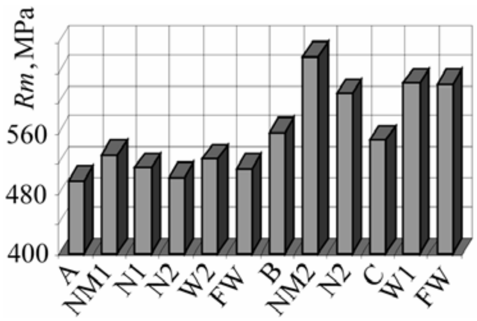
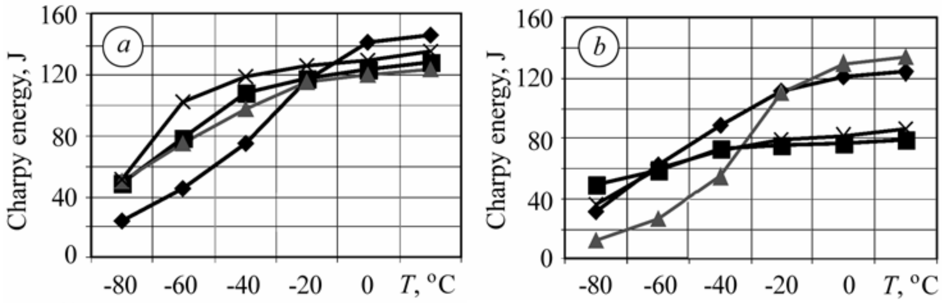


Fig. 5. Compared values of tensile strength of base metal and welded joints made by: E-process with electrode quality NM1, NM2, N1, N2; MAG-process with electrode wire W1, W2, FW. Designations: *A*, *B*, *C* – steel type Nb/Ti (X65); NM1, NM2, N1, N2 – coated electrode; W1, W2 – classical electrode wire; FW – filled wire.

Toughness analysis on the Charpy pendulum. Change in toughness depending on testing temperature for weld metal and HAZ (base metal B), carried out with E-process and electrode NM2 (2.5% Ni + 0.35% Mo) with two levels of heat input (E_1 = 7.5 kJ/cm, E_2 = 21 kJ/cm) is shown in Fig. 6*a*, where toughness increase has been detected in HAZ with lower heat input during welding, while the toughness values of weld metal at lower temperatures are much higher than of those in HAZ because of the content of Ni and Mo in the weld metal.

Toughness vs. temperature dependence of welded joints (base metal C), carried out with MAG process with electrode wire W1 (1.5% Mn) and two levels of heat input (E_1 = 6.3 kJ/cm, E_2 = 15.5 kJ/cm) is shown in Fig. 6*b*, where there is a large difference between toughness of the weld metal and the HAZ but no difference in toughness for the two mentioned levels of heat input.



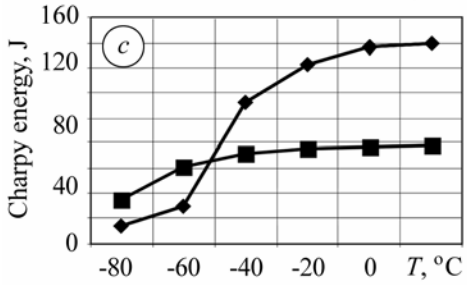


Fig. 6. Dependences of Charpy energy on testing temperature for weld metal and HAZ: *a* – steel Nb/Ti (B); *b*, *c* – steel Nb/Ti (C): ♦ – B-WM (E_2); ■ – B-HAZ (E_2); ▲ – B-WM (E_1); × – B-HAZ (E_1).

Toughness change subject to testing temperature in HAZ and weld metal carried out in MAG process with filled wire FW-10 (0.35% Ti) on the base metal Nb/Ti (C) and one level of heat input (E = 8.8 kJ/cm) is shown in Fig. 6*c*, and there is a large difference between toughness values in the HAZ and the weld metal.

CONCLUSIONS

Based on the results obtained by experimental testing of the effects of filler material and welding parameters on modification of the WM and HAZ structure of fine-grain microalloyed steels, the following conclusions can be drawn.

– In the WM made in E-process with NM1 electrode in the last pass, AF portion was approx. 75…77% and the rest consisted of PF and FS, while in the WM made with NM2 electrode AF portion in the structure was 72% and the rest consisted of PF and FS. The portion of AF in the WM made with N2 electrode was 56…58% and it was significantly higher with N1 electrode (78…82%) that particularly affected impact toughness.

– Formation of various quantities of acicular ferrite in the weld metal of welded joints, obtained using N1 and NM1 electrodes, can be attributed to very low cooling rates rather than to molybdenum with which the NM1 electrode was alloyed (Table 3), considering that all other variables such as base metal quality, steel-band thickness and quantity of input heat were the same.

– The structure of the WM obtained in MAG-process with electrode wire W2 in the last pass contained 55…65% of AF and the rest consisted of PF and FS, while in the WM made with FW the portion of AF in the structure was 78…80% and the rest consisted of PF and FS. The quantity of AF is directly correlated to the increase of WM toughness.

– Microstructural analysis of HAZ of tested welded joints made with two levels of heat input (E_1 = 7.5 kJ/cm and E_2 = 21 kJ/cm) has shown that the structure was finer with the lower level of heat input in the zone of normalization and overheating which is another significant factor in the technology planning and selection of optimum welding regime of the above mentioned steel grades.

– In Nb/Ti steel, the best mechanical and technological properties of welded joints were obtained after welding with NM2 electrode (2.5% Ni + 0.35% Mo) with low heat input (7.5 kJ/cm).

РЕЗЮМЕ. Описано зміни в пропорціях між певними складниками мікроструктури металу зварного шва і зони термічного впливу; проаналізовано механічні та технологічні параметри зварних з’єднань високоміцної мікролегованої Nb/Ti сталі, виконаних за різних технологій зварювання з модифікацією складу наповнювача і параметрів зварювання. Вивчено вплив структури матеріалу наповнювача і параметрів зварювання на мікроструктуру зварних з’єднань для пояснення їх механічних і технологічних властивостей.

РЕЗЮМЕ. Описаны изменения в пропорциях между некоторыми составляющими микроструктуры металла сварного шва и зоны термического влияния; проанализированы механические и технологические параметры сварных соединений высокопрочной микролегированной Nb/Ti стали, выполненных в условиях разных технологий сварки с модификацией состава наполнителя и параметров сварки. Изучено влияние структуры материала наполнителя и параметров сварки на микроструктуру сварных соединений для объяснения их механических и технологических свойств.

Acknowledgements. This work is supported by the Serbian Ministry of Science and Technological Development (project number 19061).

1. *Precipitation* Behavior and its Effect on Strengthening of an HSLA-Nb/Ti Steel / M. Charleux, W. J. Poole, M. Militzer and A. Deschamps // Metall. and Mater. Trans. A. – 2001. – **32**. – P. 1635–1647.
2. *Effect* of vanadium and niobium on the properties and microstructure of the intercritically reheated coarse grained heat affected zone in low carbon microalloyed steels / Y. Li, D. N. Crowther, M. J. W. Green and P. S. Mitchell // ISIJ International. – 2001. – **41**. – P. 46–55.
3. *Bajić N. and Šijački-Žeravčić V.* The analysis of change of structural and mechanical properties of welded joints of microalloyed NB/V steel grade by changing the composition of filler material // Int. Conf. Weld. 2003. – Belgrade, 2003.
4. *Bajić N.* Analysis of the filler material and welding parameters influence on properties of weld joints of new generation of high strength microalloyed steels (in Serbian), Ph D Dissertation, Faculty of Mechanical Engineering, Belgrade. – 2004.
5. *Zhang Z. and Farrar R. A.* An atlas of continuous cooling transformation (CCT) diagrams applicable to low carbon low alloy weld metals. – London: The Institute of Materials, 1995.

Received 01.04.2009