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ISSN 0543-5846
METABK 49(3) 149-154 (2010)
UDC – UDK 669.14/15:620.171.70/178:620.18 = 111

CHARPY NOTCH TOUGHNESS AND HARDNESS OF REHEATED MARTENSITE AND LOWER BAINITE

Received – Prispjelo: 2009-09-18
Accepted – Prihvaćeno: 2010-02-08
Original scientific paper- Izvorni znanstveni rad

A high strength low alloyed (HSLA) V-Nb steel was heat treated to martensite and lower bainite with different grain size, reheated for 3 seconds at 750 °C and air cooled. Charpy notch tests were performed from -100 °C to 60 °C and the hardness assessed at room temperature. For as delivered steel and lower bainite, the upper shelf toughness was above 200 J and the transition temperature low, while, for martensite the upper shelf toughness threshold was aproximateky at 0 °C. After reheating, notch toughness was decreased moderatly for martensite and strongly for lower bainite. Independently on grain size, lower bainite was more propensive than martensite to embritlement after short reheating in the (α+γ) range. For martensite, the change of notch toughness was not related to change of hardness, as by lower hardness lower, also toughness was lower.

Key words: HSLA steel, martensite, lower bainite, reheating, Charpy notch toughness, hardness

Charpy udarna žilavost i tvrdoća odžarenog materijala i donjeg bainita. Nisko legirani V-Nb čelik visoke čvrstoće (HSLA) je toplinsko obrađen na martenzit i bainit sa različitom veličinom zrna, odžaren 3 sekunde na 750 °C i ohlađen na zraku. Chapy žilavost je određena u intervalu od -100 °C do 60 °C, a tvrdoća kod sobne temperature. Kod čelika sa početnom mikrostrukturom čelika i donjeg bainita, je bila veoma visoka žilavost iznad 200 J i tranzicijska temperatura niska, dok je bio kod martenzita prag približno kod 0 °C. Poslije odžarivanja se je žilavost smanjila malo kod martenzita i jako kod bainita. Nezavisno od veličine zrna, donji bainit je bio mnogo osetljiviji na pojavu krtosti poslije kratkog odžarivanja u području (α + γ). Kod martenzita, promjena žilavosti nije u vezi za tvrdoćom, jer kod niže žilavosti je niža i tvrdoća.

Ključne riječi: HSLA čelik, martenzit, donji bainit, odžarivanje, Charpy udarna žilavost, tvrdoća

INTRODUCTION

The resistance to hydrogen embrittlement is of essential importance for steels for vessels for storage of hydrocarbons and depends on the effect of absorbed hydrogen on steel ductility.

API tests have shown for the 490 MPa yield stress HSLA steels with the microstructure of ferrite and cementite particles a much greater reduction of area than for the 350 MPa steel with the microstructure of polygonal ferrite and pearlite [1,2]. By routine tests during the construction of a 60.000 m^3 vessel, it was found that by the equal welding procedure, Charpy toughness was lower for 15 mm plates than for 25 mm plates of the same HSLA steel. It was assumed that the differences were related to the propensity of constituents of heat affected zone (HAZ) to embrittlemenst by short reheating in the two phase (ferrite+austenite) range for the steel that produces local brittle zones in the HAZ of welds [3–15].

Earlier simulation tests have shown [3] that the sensibility to embrittlement after reheating was different for a microalloyed than a conventional steel. As shown in Figures 1 and 2, after cooling from 1300 ^{0}C Charpy notch toughness was slightly lower for the steel Č.0562 with yield stress of 350 MPa than for the microalloyed steel Niomol 490 K with yield stress of 490 MPa, while, after reheating toughness was for this steel sligthly lover. The different behaviour of both steels was confirmed with Charpy tests on HAZ of welds of 20 mm plates [3]. The aim of this work was to check these findinds with more systematical tests and to verify if the embrittlement propensity was related to the difference of steels in chemical composition or to the constituents of microstructure obtained with cooling from high temperature. Martensite and lower bainite in the microalloyed steel Niomol 490 K were investigated because assumed to be most sensible to reheat embrittlement than other constituents of HAZ of welds. For comparison, the steel with the as delivered microstructure was used.

EXPERIMENTAL WORK

The tests and examinations were performed with specimens cut out from a plate of microalloyed structural steel Niomol 490K (0,1%C-0,5%Mn-0,7%Cr-0,27%Mo- 0,032%Nb-0,025%Al) with the initial

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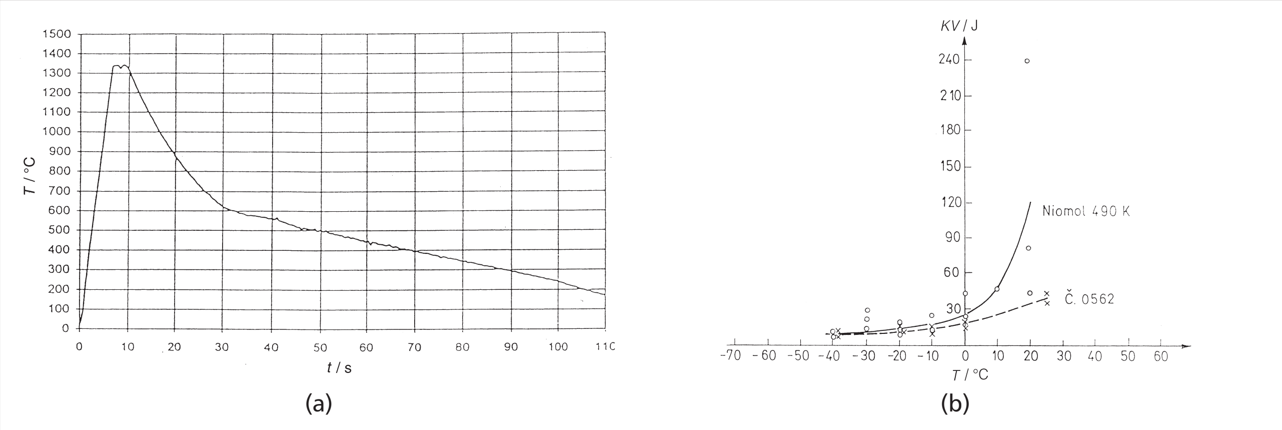


Figure 1 Thermal cycle (a) and dependence Charpy toughness dependes of test temperature (**b**) for the classical structural steel Č.0562 with yield stress of 350 MPa and the microalloyed structural steel Niomol 490 K

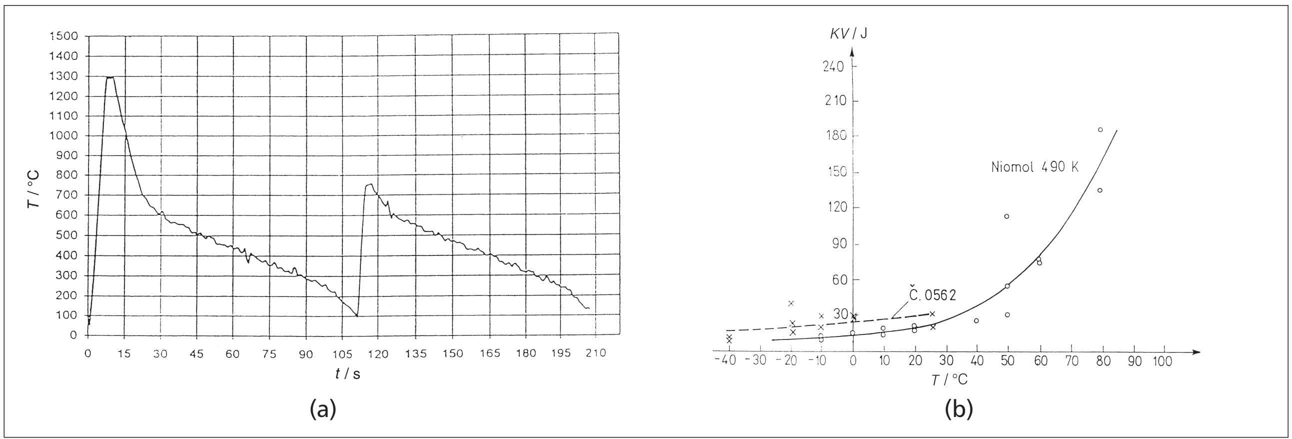


Figure 2 Thermal cycle (a) and dependence Charpy toughness (b) vs. test temperature for the classical structural steel Č.0562 with yield stress of 350 MPa and the microalloyed structural steel Niomol 490 K

microstructure of a dispersion of cementite precipitates in mostly acicular ferrite grains with linear intercept size of about 2,5 μm. The specimens were annealed at 920 °C or at 1250 °C, than half quenched in lead bath at 400 ^{0}C and half in water at 70 ^{0}C. In this way, two types of microstructure and two austenite grain sizes (ASTM grades 1-3 and 8-9) were obtained. Half of specimens was than reheated individually for 3 seconds at 750 °C with direct conduction heating and air cooled with $t_{800\text{-}500°C}$ = 17 seconds. On all specimens the Charpy notch was cut after heat treatment.

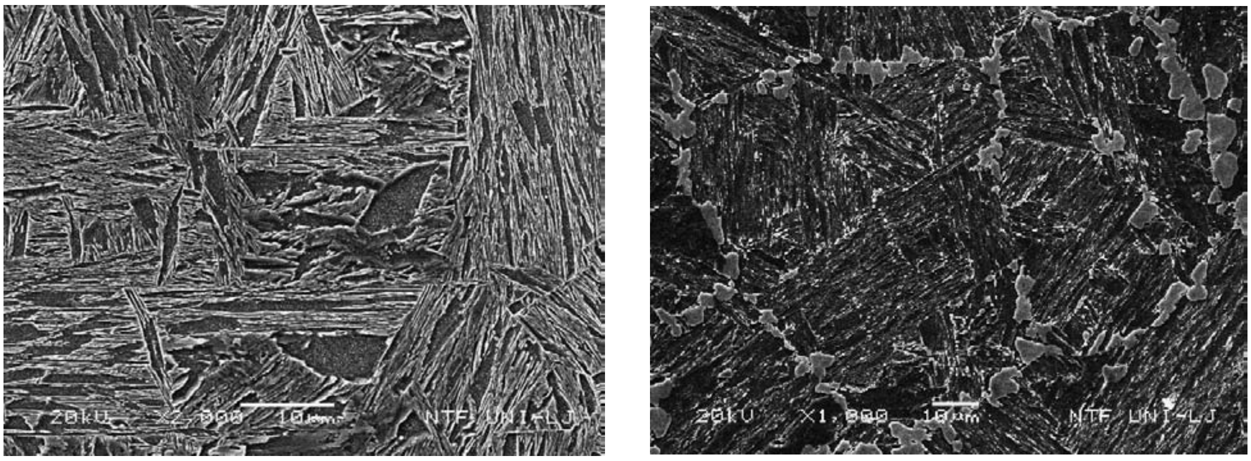
For heat treated specimens and the mother steel, the Charpy tests were carried out in temperature range -200 °C to 60 °C. The microstructure and the fracture surface was investigated with scanning microscopy.

MICROSTRUCTURE, NOTCH TOUGHNESS AND HARDNESS

The constituents formed at cooling from austenitising temperatures are termed as primary and as secondary those formed at cooling after reheating. The microstructure of the as delivered steel consisted of fine ferrite grains with a dispersion of cementite precipitates. After reheating, it was changed to platelets of martensite and ferrite in the interior of grains and inserts of secondary martensite, mostly at triple points. After water quenching from 1250 °C, platelets of primary martensite and ferrite were found in coarse grains (Figure 3a). After reheating, this microstructure changed to partially decomposed martensite and stringers of cementite particles in ferrite grains and inserts of secondary martensite at ferrite grain boundaries (Figure 3b). The lead bath cooling from 1250 °C produced a coarse grained microstructure of stringers of cementite particles and ferrite platelets (Figure 4a) termed lower bainite. After reheat, it changed to a microstructure of platelets of secondary martensite in interior of ferrite grains and inserts of secondary martensite at boundaries of coarce grains (Figure 4b). After cooling from 920 °C and reheating, the microstructure was similar than after cooling from the higher temperature, while, the grain size was smaller for about 6 ASTM grades.

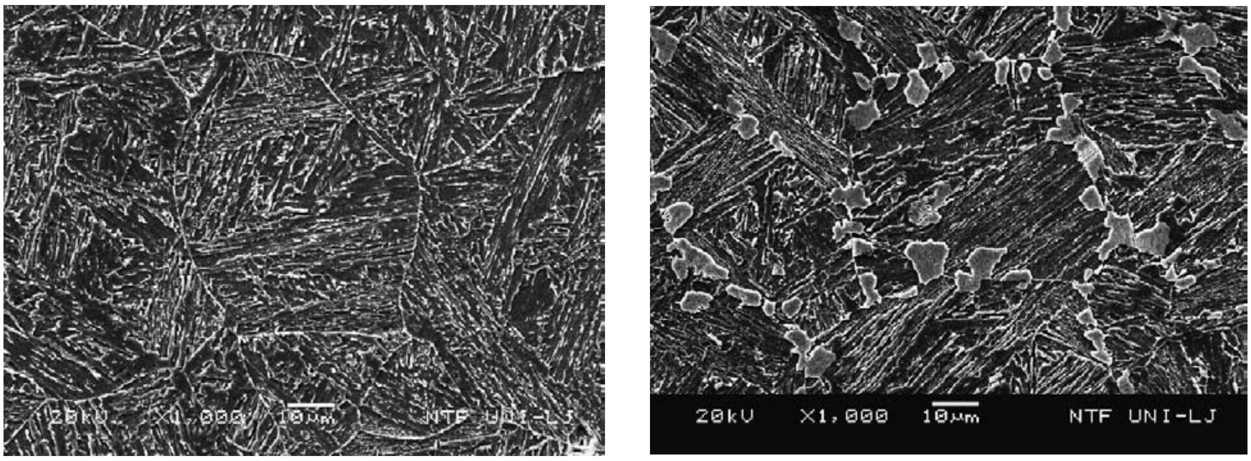
These observations indicate that at short reheating at 750 °C, three different processes occur in the investigated microstructures:

a) dissolution of cementite with formation of secondary austenite around cementite particles in the interior of ferrite grains and its transformation to secondary martensite at cooling;



(a) (b)

Figure 3 Microstructure after water quenching from 1250 °C (a) and after reheating (b).



(a) (b)

Figure 4 Microstructure after lead bath cooling from 1250 °C (a) and after reheating (b).

b) decomposition of primary martensite and eventual formation of some secondary austenite and martensite;
c) formation od secondary martensite inserts (small grains) at triple points and boundaries of ferrite grains.

In **Figures** 5a and 5b the dependence Charpy notch toughness vs. test temperature is shown for coarse martensite and lower bainite after cooling from 1250 °C and after reheating. For other heat treated specimens the dependences had a similar shape, while for the as delivered microstructure the effect of reheating was much lower. The upper shelf notch toughness is high and the cleavage threshold and Charpy transition temperatures are low for the as delivered steel and fine and coarse grained bainite. After reheating, the cleavage threshold temperature is for aprox. 80 °C higher for bainite, while the transition temperature was above the highest test temperatrure of 60 °C. The effect of reheating on Charpy toughness was much lower for the as delivered steel as, the cleavage threhshold was higher for aprox. 20 °C and the transition temperature for about 60 °C. Above the cleavage temperature, the increase of toughness for the as delivered steels and as cooled lower bainite is fast and the upper shelf is achieved by a temperature higher for about 40 °C. For fine and coarse martensite, as cooled and after reheating, the cleavage threshold temperature is similar and it is for 40-50 °C higher than for the as delivered steel and bainite, the increase of toughness is slower and the upper shelf temperature is above the highest test temperature of 60 °C. At this temperature notch toughness is lower for about 50 J after reheating.

Three fracturing mechanisms were identified. For high toughness, the fracture surface had an irregular topography of areas of dimples with different size formed with normal (Figure 6b) and shear decohesion. By low notch toughness in the range of temperature of growth of toughness above the cleavage threshold, the fracture surface consisted of cleavage and ductile areas with increasing ductile decohesion for higher toughness mostly in areas inclined toward the clevage facets (Figure 7). On the ductile to clevage boundary of mixed fractures clear chacteristics of change of mechanism of crack propagation were not identified and it is assumed that

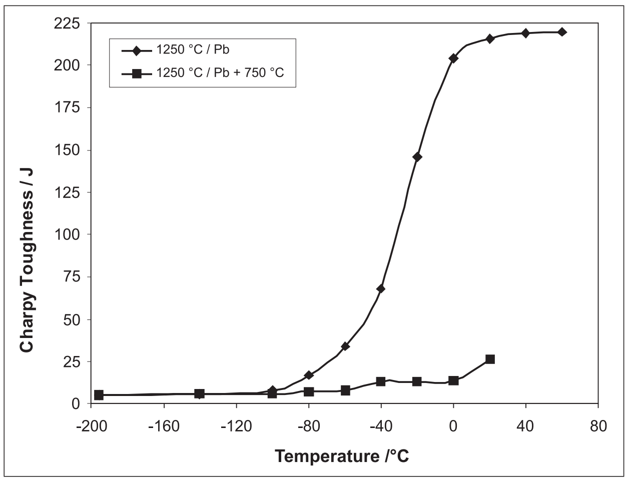


Figure 5a Charpy toughness vs testing temperature for the steel quenched in water from 1250 °C and reheated.

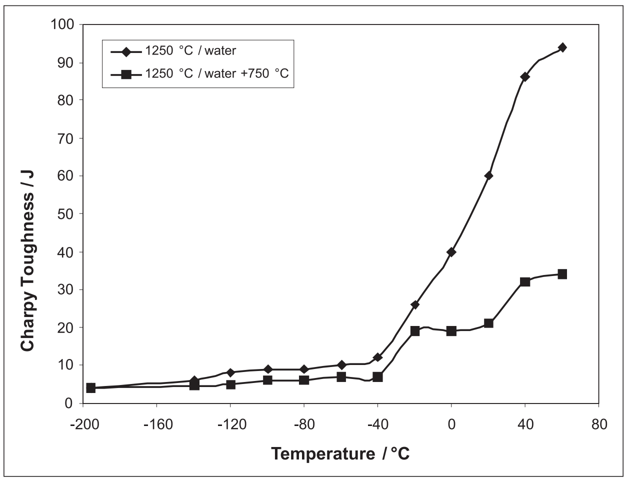
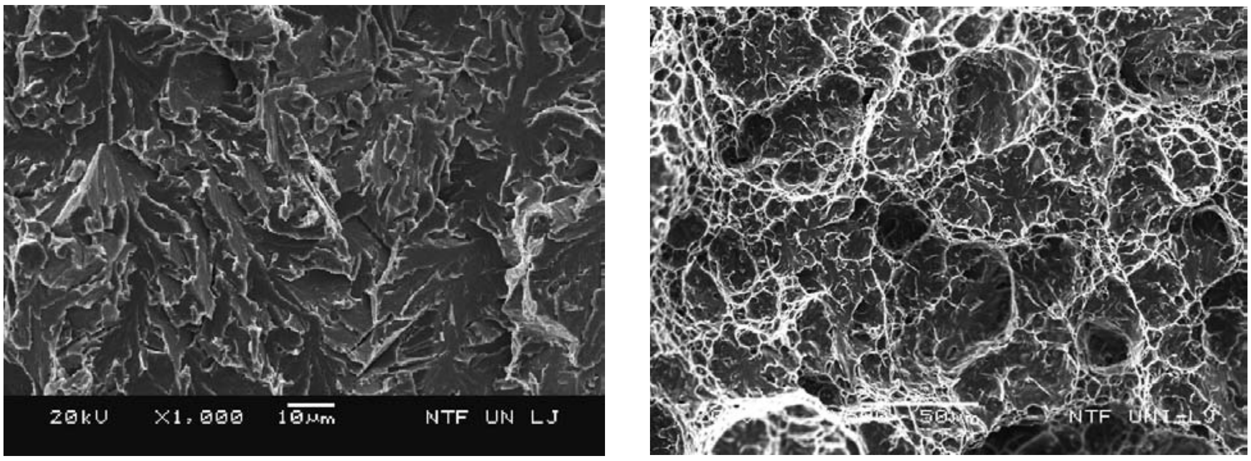


Figure 5b Charpy toughness vs testing temperature for the steel cooled from 1250 °C in lead bath and reheated.



(a) (b)

Figures 6 a) Clevage fracture; specimene cooled in lead bath from 920 °C and reheated at 750 °C. b) Ductile fracture; specimen cooled in lead bath from 920 °C; both cases test temperature -20 °C

the fracturing transition occurred with plane slip [15-19]. In cleavage range the fracture consists of clevage facets (Figure 6a) by coarser grain size and no difference in micromorphology was found for facets micromorphology for tested specimens. In transition range the share of facets decreased with increasing tougness and the share of ductile dimples increased.

Details related to the presence of inserts of secondary martensite at grain boundaries were not found on cleavage and ductile areas.

In Table 1 hardness and room temperature Charpy notch toughness are shown for the different microstructures. After reheating, hardness is little or moderately increased for the as delivered steel and lower bainite and it is decreased stronger for martensite. For the as delivered steel and martensite, after reheating hardness is lower and notch toughness at room temperature is lower, while, for bainite hardness and noth toughness are both lower after reheating. It is evident that the effect of processes occurring at short reheating in (α+γ) region is different for hardness and notch toughness

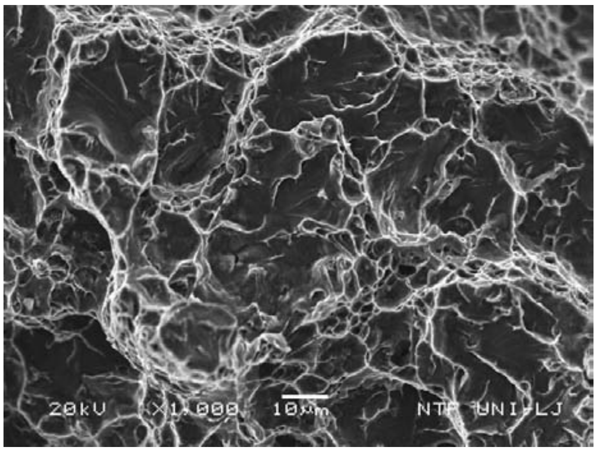


Figure 7 Fracture surface with mixed ductile and cleavage decohesion at 40 °C

The results of this investigation demonstrate that after identical short reheating in the two phases range hardness is changed less than notch toughness and that independently of grain size, toughness is diminished much more for lower bainite than for austenite. Considering the findings in Figures 1 and 2 and earlier investigations, it is also concluded that the propensity for embrittlement is a property of constituent of microstructure and is not related to the steel chemical composition. Not only the type of earlier stated reheating processes in microstructure is different for martensite and for lower bainite, also the extent of the process is different for both constituents. At this step of the investigation, it is clear that the dissolution of cementite particles in lower bainite is faster than the tempering of martensite and that, in their initial phase, both processes decrease the notch toughness and have a different effect on hardness and notch toughness for lower bainite and for martensite. No details related to the intergranular inserts of martensite was found on fracture surfacesand it seems justified to conclude that the changes in properties are related to the change of microstructure in the interior of grains. These changes are being investigated and will be reported later.

Table 1 **Room temperature hardness and Charpy notch toughness after different thermal treatment**

Thermal treatment	Hardness HV_5	Charpy notch toughness, J
As delivered	205	243
As delivered + 750 ^{0}C	248	196
920 °C → water	282	122
920 °C → water + 750 ^{0}C	244	68
920 °C → lead bath	214	60
920 °C → lead bath + 750 ^{0}C	222	21
1250 °C → water	383	253
1250 °C → water + 750 ^{0}C	320	26,5
1250 °C → lead bath	257	217
1250 °C → lead bath + 750 ^{0}C	298	14

CONCLUSIONS

- Charpy notch toughness is higher and the transition temperature is lower for lower bainite than for martensite, independently on grain size;
- after reheating, the microstructure of steel in changed differently for different initial constituents in the interior of grains, while independently on initial microstructure and grain size after reheating inserts of secondary martensite are formed at triple points of initial grains;
- after reheating at 750 °C and air cooling, Charpy notch toughness is greatly diminished for lower bainite independently on grain size. The cleavage temperature is increased after reheating for about 80 °C for lower bainite and it is virtually unchanged for martensite;
- particularly harmfull after reheating for notch toughness and transition temperature is the presence of secondary martensite platelets in the interior of ferrite grains;
- the change of the initial microstructure at reheating affects very differently notch toughness and hardness. By smaller changes of hardness, very significant changes of notch toughness were obtained and lower notch toughness was found for lower hardness, also;
- the results of this investigation and in quoted references suggest that the reheating embrittlement is a propety of the constituent of the microstructure and not of the chamical composition of the structural steel.

The authors aknowledge the support of the Ministry of High Education, Science and Technology of Slovenia, Ljubljana and of the company SIJ, Acroni d.o.o., Jesenice, Slovenia and are indebted to Mr. Boris Arzenšek for the experimental tests.

REFERENCES

[1] S. Ažman, L. Vehovar, J. Vojvodič-Tuma: Development of a Steel microalloyed with niobium molybdenum; Intern. Symposium Welding, 1996, Belgrade, Proceed. 58-60.

[2] Vojvodič-Tuma J., Jenko M.: Strain ageing of a 490 MPa Microalloyed Structural Steel; Welding in South-East Asia: A Challenge for the Future – Proceedings, 2006, 758-766.

[3] F. Vodopivec, G. Kosec, S. Grbić, D. Kmetič: Materiali in Tehnologije 38 (2004), 149-153.

[4] H.G. Pisarski: HAZ Toughness Evaluation in: Proceed. Intern. Conf. "The Metallurgy, Welding and Qualification of Microalloyed (HSLA) Steels Weldments", American Welding Society, 1990, 351-382.

[5] T.M. Sconover: Evaluation of Local Brittle Zones in HSLA-80 Weldments: Proceed. Intern. Conf. "The Metallurgy, Welding and Qualification of Microalloyed (HSLA) Steels Weldments", American Welding Society, 1990, 276-305.

[6] S. Aihara, K. Okamoto: Influence of Local Brittle Zones on HAZ Toughness of TMCP Steels: Proceed. Intern. Conf. "The Metallurgy, Welding and Qualification of Microalloyed (HSLA) Steels Weldments", American Welding Society, 1990, 401-425.

[7] Q. Liu, X Diao, Y.W Mai: Engineering Fracture Mechanics 49 (1994), 741-750.

[8] Q. Liu, T. Varga: Engineering Fracture Mechanics 49 (1994), 435-444.

[9] T. Moltubakk, C. Thaulow, Z.L. Zhang: Engineering Fracture Mechanics 62 (1999), 445-462.

[10] J. Vojvodič-Tuma, A. Sedmak: Engineering Fracture Mechanics 71 (2004), 1435-1451.

[11] B. Bezensek, J.W. Hancok: Engineering Fracture Mechanics 74 (2007), 2395-2419.

[12] Q. Liu, T. Varga: Engineering Fracture Mechanics 49 (1994, 435-444.

[13] T. Lee, Y.T. Pan: Materials Science and Engineering A 136 (1991), 109-119.

[14] J. Il Jang, Y.-S. Lee, J.-B. Ju, B.W.Lee, D. Kwon, W.S. Kim: Materials Science and Engineering 351 (2003),183-189.

[15] J.Il Jang, B.W. Lee, J.B.Ju, D. Kwon, W.S. Kim: Engineerimng Fracture Mechanics 70 (2003), 1245-1257.
[16] G. Kosec, B. Arzenšek, J. Vojvodič-Tuma, F. Vodopivec: Materiali in Tehnologije 43 (2009), 31-37.
[17] F. Vodopivec, B. Arzenšek, J. Vojvodič-Tuma, R. Celin: Metalurgija 47 (2008), 173-179.
[18] F. Vodopivec, B. Breskvar, B. Arzenšek, D. Kmetič, J. Vojvodič-Tuma: J Mater. Sci. Techn. 17 (2001), 1-7
[19] F. Vodopivec, J. Vojvodič-Tuma: The Charpy behaviour of structural steels with different microstructure; Proceedings of the Intern. Conf. Mechanical Properties of Advanced Engineering Materials, ed. M. Tokuda nd B. Xu, Mie Un. Japan and Tsingua Un. China, 2001, 187-200.

Note: The responsible translator for English language is Andrej Paulin, Ljubljana, Slovenia