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EFFECT OF 3 S REHEATING ON CHARPY NOTCH TOUGHNESS AND HARDNESS OF MARTENSITE AND LOWER BAINITE

VPLIV 3 S POGREVANJA NA CHARPYJEVO ZAREZNO ŽILAVOST IN TRDOTO MARTENZITA IN SPODNJEGA BAINITA

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The 0.1C 0.032Nb fine grained steel was heat treated to fine and coarse grained lower bainite and martensite. Half of specimens was reheated for 3 s at 750 °C with current conduction. Charpy notch tests were performed in temperatrure range from –200 °C to 60 °C, room temperature hardness determined and microstructure and fracture surface examined with SEM. Notch toughness and transition temperature are similar for lower bainite and delivered steel and much lower for martensite. After reheating, noth toughness was decreased for about ten times for lower bainite and the cleavage temperature increased for about 80 °C. Both changes were much lower for martensite and for as delivered steel. The effect of reheating on hardness was different for different microstructure and much smaller as for notch toughness.

Key words: microalloyed structural steel, lower bainite, martensite, reheating, notch toughness, cleavage temperature, hardness

V drobnozrnatem jeklu z 0.1 C in 0.32 Nb je bila s toplotno obdelavo ustvarjena mikrostruktura iz martenzita in spodnjega bainita. Polovica preizkušancev je bila nato zmova segreta 3 s pri 750 °C z električnim tokom. Charpy preizkusi so bili izvršeni v razponu temperature od –200 °C do +60 °C, trdota izmerjena pri sobni temperaturi, mikrostruktura in prelomne površine pa pregledane v SEM.. Zarezna žilavost in prehodna temperatura sta podobni za dobavljeno jeklo in spodnji bajnit in nižji za martenzit. Po ponovnem segretju je bila zarezna žilavost zmanjšana za okoli 10 krat, temperatura cepilnega preloma pa povečana za okoli 80 °C za spodnji bainit. Obe spremembi sta bili mnogo manjši pri martemnzitu. Vpliv ponovnega segravanja je bil manjši pri trdoti in različen pri različni mikrostrukturi.

Ključne besede: mikrolegirano jeklo, spodnji bainit, martenzit, ponovno segrevanje, zarezna žilavost, temperatura cepilnega preloma, trdota

1 INTRODUCTION AND AIM OF THE WORK

In the heat affected zone (HAZ) od welds of structural steels local brittle zones (LBZ) could form and decrease the local toughness [1–13]. Field experience and laboratory tests suggested that for a 490 MPa fine grained microalloyed steel with Charpy notch toughness of about 250 J, lower bainite could be more propensive to the formation of LBZ than martensite [14] and that the HAZ propensity to embrittlement was for this steel greater than for a conventional steel with the yield stress of 350 MPa [15]. Martensite and lower banite were assumed to be more sensistive to the formation of LBZ than other constituents of the HAZ microstructure an in this work this assumption was verified and the effect of grain sizeon Charpy toughness and transition temperature, rsp. cleavage temperature, and hardness was investigated.

2 EXPERIMENTAL WORK

The investigation was carried ou with the high strength low alloyed (HSLA) structural steel with 0.1C-0.5Mn-0.025Al-0.27Mo-0.032Nb-0.15Ni, the initial microstructure of fine grained ferrite and cementite particles and the yield stress of 490 MPa. Austenite grain size similar to that found in HAZ in contact with the deposed metal was obtained with 3–4 s of heating of

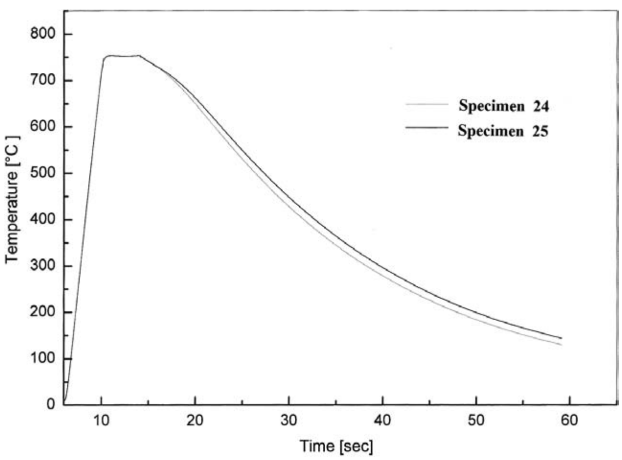

Figure 1: Reheating cycle for specimens
Slika 1: Diagram ponovnega segrevanja preizkušancev

single Charpy specimens at 1250 °C. These specimens and specimens annealed for 20 min. at 920 °C were quenched half in water at 70 °C and half in lead bath at 400 °C and martensite and lower bainite with different grain size obtained. Half of specimens was than reheated for 5 s at 750 °C with direct conduction heating and air cooled according to **Figure 1** in the heating part of a hot deformation simulator. On all specimens the Charpy notch was cut out after the heat treatment. The effect of testing temperature in the range of -200 °C to 60 °C on fracturing energy was than determined and the results for as delivered steel used for comparison. The microstructure and of the brittle fracture surface were investigated with optical and SE microscopy.

3 MICROSTRUCTURE

The constituents of microstructure formed at cooling from 1250 °C and 920 °C are termed as primary and as secondary the constituents formed at cooling from 750 °C. The fine grained microstructure of the as delivered steel consisted mostly of acicular ferrite with small stringers of fine cementite particles (**Figure 2**). After reheating at 750 °C, small martensite inserts at triple points and rare secondary martensite platelets were found in the interior of ferrite grains. After quenching from 920 °C in water a microstructure of martensite platelets in ferrite matrix was obtained (**Figure 3**) that changed after reheating to intergranular inserts and rare intragranular platelets of secondary martensite (**Figure 4**). The cooling in lead bath from 920 °C produced a microstruture with ferrite laths and stringers of cementite particles. After reheating, the microstructure was similar than for reheated martensite, however, it had more frequent intragranular platelets and grain boundary inserts of secondary martensite. After quenching from 1250 °C in water the microstructure consisted of the same constituents as after cooling from 920 °C but with a greater share of martensite, while, the grain size coarser for 3 to 4 ASTM grades. After reheating, ferrite platelets had frequently boundaries marked with stringers of fine carbide particles and grain boundary inserts of secondary martensite. After lead cooling from 1250 °C the microstructure consisted of platelets of ferrite with boundary marked with cementite particles (**Figure 5**). The lower bainite was not investigated to a sufficient detail to conclude on the mechanism of transformation, displacive or reconstructive [16,17,18]. After reheating, it changed to a microstructure of platelets of secondary martensite and ferrite inside and inserts of secondary martensite at boundaries of coarce grains (**Figure 6**).

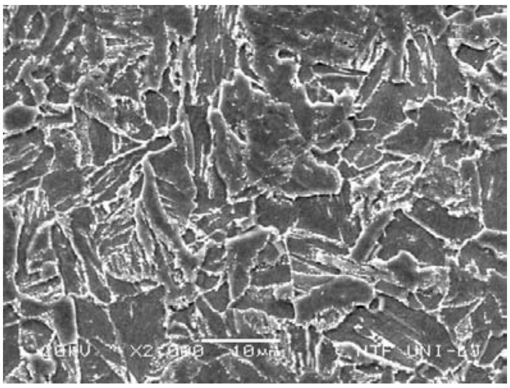

Figure 2: Microstructure of as delivered steel
Slika 2: Mikrostruktura uporabljenega jekla

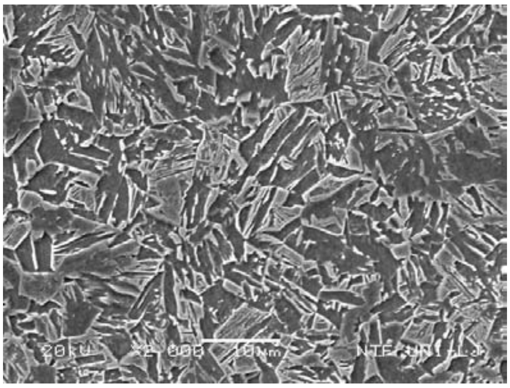

Figure 3: Microstructure after water quenching from 920 °C
Slika 3: Mikrostruktura po kaljenju v vodi z 920 °C

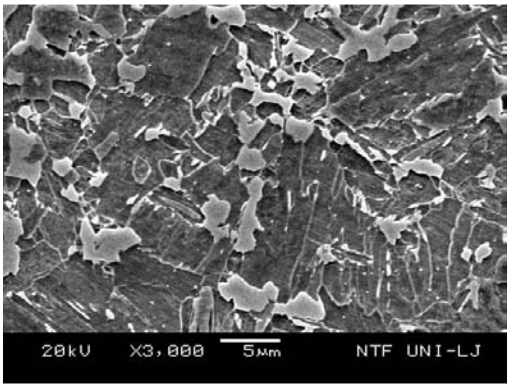

Figure 4: Microstructure after reheating
Slika 4: Mikrostruktura po ponovnem segrevanju

The short reheating at 750 °C and air cooling produced the following changes of initial microstructures of ferrite+bainite and ferrite+martensite:

- stringers of cementite particles in bainite were dissolved producing platelets of secondary austenite rich in carbon that transformed at cooling to platelets of secondary martensite in the interior of ferrite grains;
- primary martensite platelets were partially decomposed to ferrite and carbide precipitates;
- triple grain points and grain boundary inserts of secondary austenite were formed and at cooling transformed to secondary martensite. The size of these inserts suggests a fast transport of carbon towards the nucleation points of secondary austenite at triple grains points It is possible that the nucleation and growth of inserts were enhanced by

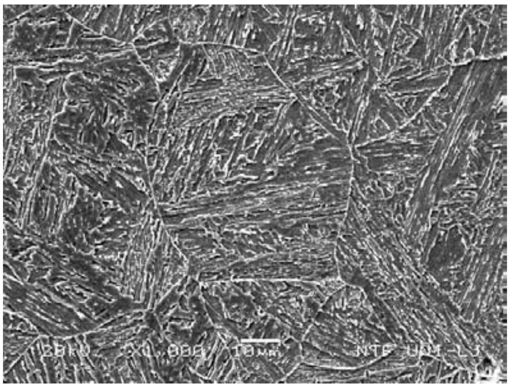

Figure 5: Microstructure after lead bath quenching from 1250 °C
Slika 5: Mikrostruktura po kaljenju v vodi s 1250 °C

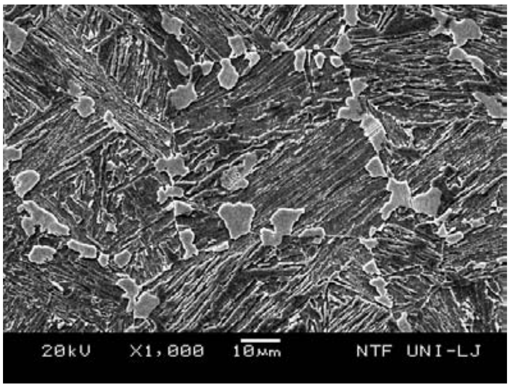

Figure 6: Microstructure after reheat
Slika 6: Mikrostruktura po ponovnem segrevanju

segregation of carbon atoms at primary austenite grains.

4 CHARPY TOUGHNESS AND TRANSITION TEMPERATURE

In **Figures 7 to 11** Charpy toughness is shown in dependence of testing temperature. The upper shelf toughness is high for the as delivered steel and for steel with the microstructure of lower bainite with small effect of grain size, as after cooling from 1250 °C the upper shelf value is of about 220 J and after cooling from 920 °C it is of about 250 J. The upper shelf toughness temperature was for martensite before and after reheating above 60 °C. The lower shelf notch toughness is very similar for all specimens, as found ealier [19] for a number of structural steels. In the frame of accuracy of tests it was not possible to determine an eventual effect of microstructure on fracturing energy in clevage range.

With ecception of the as delivered steel, upper shelf toughness, cleavage and transition temperature (half upper shelf toughness temperature for high upper shelf energy), were strongly affected by the change of microstructure after reheating and the changes were particularly great for lower bainite. In all cases, the upper shelf toughness was lower and the transition temperature was higher for the reheated steel.

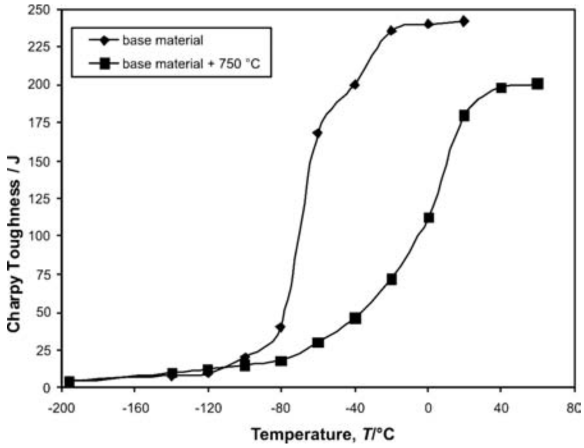

Figure 7: Dependence Charpy toughness versus testing temperature for the steel with the as delivered steel and after reheating at 750 °C
Slika 7: Odvisnost med Charpyjevo žilavostjo in temperaturo preizkušanja za dobavljeno jeklo in po ponovnem segrevanju pri 750 °C

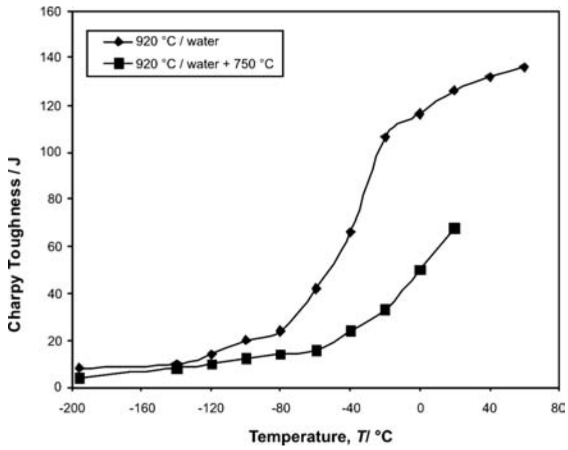

Figure 8: Dependence Charpy toughness versus testing temperature after hot water quenching from 920 °C and after reheating at 750 °C
Slika 8: Odvisnost med Charpyjevo žilavostjo in temperaturo preizkušanja za jeklo kaljeno z 920 °C v vroči vodi in po ponovnem segrevanju pri 750 °C

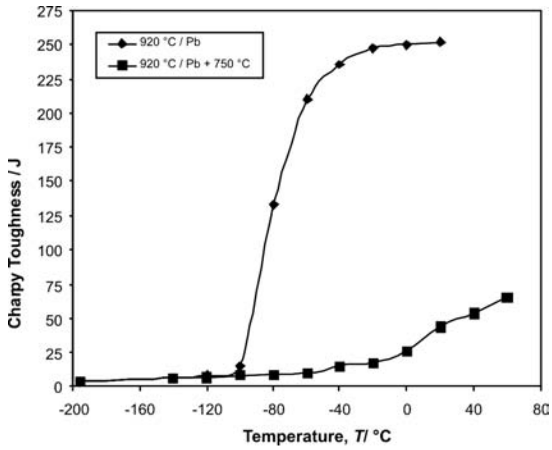

Figure 9: Dependence Charpy toughness versus testing temperature after cooling from 920 °C in lead bath at 400 °C and after reheating at 750 °C
Slika 9: Odvisnost med Charpyjevo žilavostjo in temperaturo preizkušanja za jeklo ohlajeno z 920 °C v svincu in po ponovnem segrevanju pri 750 °C

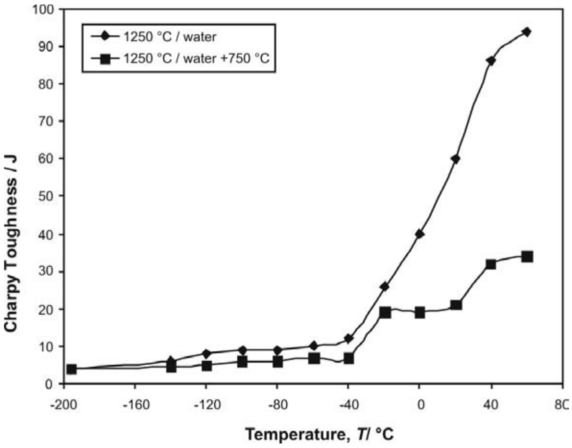

Figure 10: Dependence Charpy toughness versus testing temperature after hot water quenching from 1250 °C and after reheating at 750 °C

Slika 10: Odvisnost med Charpyjevo žilavostjo in temperaturo preizkušanja za jeklo kaljeno z 1250 °C v vroči vodi in po ponovnem segrevanju pri 750 °C

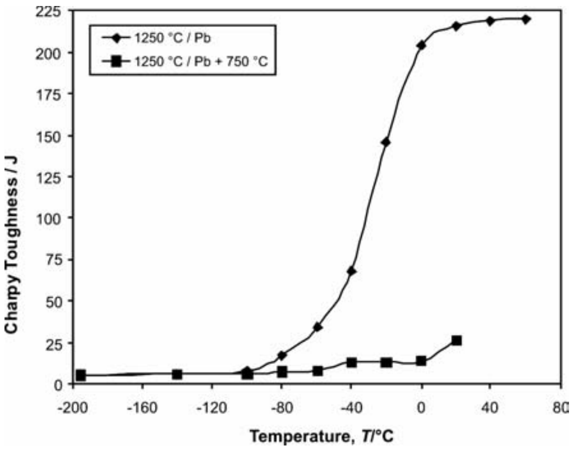

Figure 11: Dependence Charpy toughness versus testing temperature after cooling from 1250 °C in lead bath at 400 °C and after reheating at 750 °C

Slika 11: Odvisnost med Charpyjevo žilavostjo in temperaturo preizkušanja za jeklo ohlajeno z 1250 °C v svincu in po ponovnem segrevanju pri 750 °C

After reheating the as delivered steel, the transition temperature increased from –67 °C to –3 °C (**Figure 7**) and the upper shelf toughness lovered from 240 J to 200 J. After quenching in water from 920 °C, notch toughness at 0 °C was diminished to one half and after reheating to one fourth of that for the as delivered steel (**Figure 8**). The upper shelf range of the water quenched steel was not achieved at 60 °C. With comparison to water cooling from 920 °C, after higher austenitising temperature notch toughness was affected stronger, the 0 °C energy was lower for about 2.5 to 3 times after quenching and reheating, while the clevage temperature was virtually not affected (**Figure 9**).

The Charpy toughness of about 250 J and the transition temperature of –80 °C were obtained for steel cooled from 920 °C in lead bath (**Figure 10**). After reheating, the Charpy level was diminiseh the must of all tested cases, at 0 °C by aproximately ten times, from 250 J to about 25 J. The cleavage temperature was increased from about –100 °C to 0 °C and at 60 °C the Charpy energy was still about four times smaller than that for the investigated steel. The upper shelf energy was lower for about 35 J after cooling from the higher temperature and the clevage and transition temperature increased for about 40 °C (**Figure 11**). The effect of reheating was even stronger that after cooling from 920 °C and 0 °C energy lowered for about 20 times and the the cleavage temperature higher for about 80 °C (**Figure 13**).

These results indicate that independently on grain size lower bainite is much nore prone to embrittlement after short reheat at 750 °C than the steel with the microstructure of small grained ferrite and pearlite as well of fine and coarse grained martensite.

5 HARDNESS

In **Table 1** hardness is shown for specimens with different microstructure. The lowest hardness of the as delivered steel increased significantly after reheating. After water quenching from 920 °C the hardness was increased greatly and it was lower after reheating. After quenching from 920 °C in lead bath a relatively low hardness was obtained, which was even lower after reheating. After water quenching from 1250 °C the greatest hardness was obtained that diminished significantly after reheating, still, remaining high. After quenching in lead bath from 1250 °C the hardness was increased moderately in comparison to the as delivered steel and it was higher after reheating.

The hardness level corresponds to the microstructure after cooling and changes of hardness after reheating agree with changes of microstructure. The effect of reheating is for hardness in most cases lower than for notch toughness. The changes of both properties are not allways correlated, since in some cases by lower hardness notch toughness is lower, also.

Table 1: Hardness of steel after different thermal treatmen

Tabela 1: Trdota jekla po različni toplotnim obdelavi

Thermal treatment	Hardness HV 5
As delivered	205
As delivered + 750 °C	248
920 °C → water	282
920 °C → water + 750 °C	244
920 °C → lead bath	222
920 °C → lead bath + 750 °C	214
1250 °C → water	383
1250 °C → water + 750 °C	320
1250 °C → lead bath	257
1250 °C → lead bath + 750 °C	298

6 FRACTURE SURFACE

Three fracturing mechanisms were identified for the three levels of consumed energy. For high fracturing

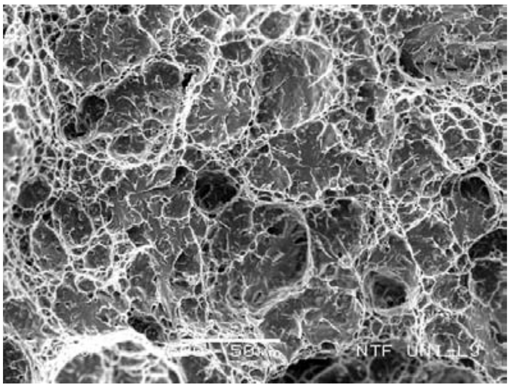

Figure 12: As delivered steel, fracture surface at 22 °C
Slika 12: Dobavljeno jeklo, prelomna površina pri 22 °C

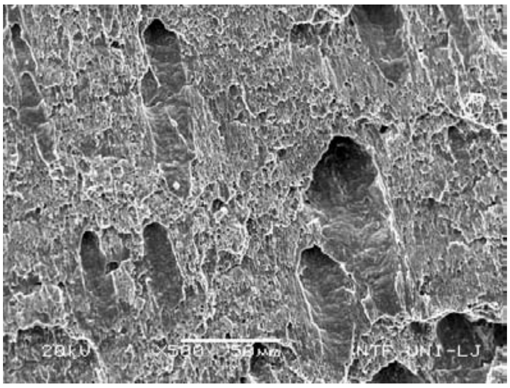

Figure 13: As delivered steel, fracture surface at 22 °C. Shear decohesion
Slika 13: Dobavljeno jeklo, prelomna površina pri 22 °C. Cepilna dekohezija

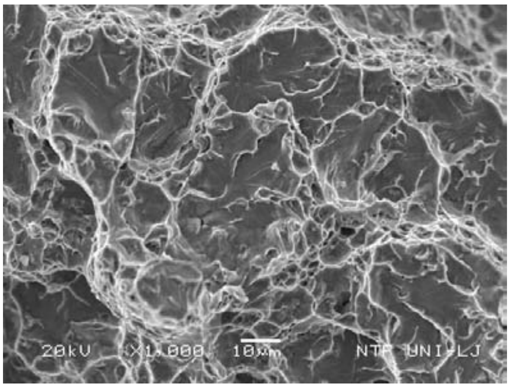

Figure 14: Steel quenched from 920 °C in water and fractured at 0 °C
Slika 14: Jeklo kaljeno z 920 °C v vodi in prelomljeno pri 0 °C

energy, the fracture surface was of uneven profile and consisted of normal and areas of shear decohesion (**Figure 12 and 13**) [19] with dimples of different shape and size. A specific fracture surface was observed on specimens fractured with low energy consumption in the range of temperature of growth of fracturing energy above the cleavage threshold. It consisted of a mixture of brittle and ductile morphology with prevalence of brittle fracturing for low consumed energy (**Figure 14**) and an

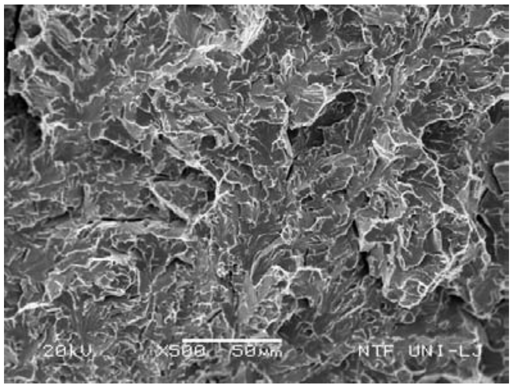

Figure 15: Steel quenched in water from 920 °C and fractured at –60 °C
Slika 15: Jeklo kaljeno v vodi z 920 °C in prelomljeno pri –60 °C

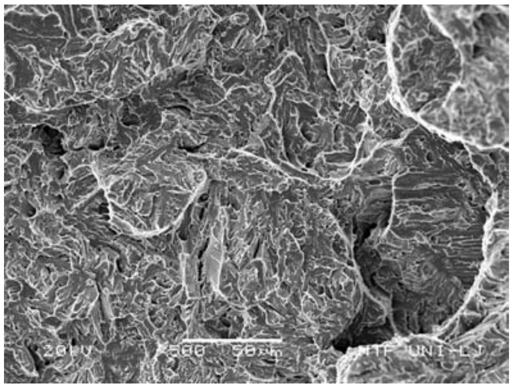

Figure 16: Steel quenched from 1250 °C in lead and fractured at –60 °C
Slika 16: Jeklo ohlajeno s 1250 °C v svincu in prelomljeno pri –60 °C

increased share of of ductile fracturing for greater consumed energy. In flat part the boundary of cleavage propagation area was not clear and it is assumed that the transition from brittle to ductile propagation occurred with plane slip [20].

In lower shelf range on the fracture of the as received steels, the shape and size of brittle facets was dependent on the size of ferrite or austenite grains (**Figure 15**). Generally, on the fracture surface of specimens cooled to lower bainite, a greater number of rivers – ligaments of microcracks propagating at different level of the same cleavage plane was observed (**Figure 16**). After quenching for 1250 °C the fracture constituents were coarser because of the greater austenite grain size and for lower bainite again more rivers and a more fragmented fracture facets were found. In presence of martensite and ferrite platelets, the crak propagates with coalescence of microcracks in grains wit different lattice orientation and microcracks in parallel lattice planes index join in rivers that did not mark the croissing of fracture from ferrite to martensite area. Also, no particular fracture details were found that could be assotiated with the presence of grain boundary inserts of secondary martensite in reheated steels. No difference in clevage morfphology was found between specimens with low and increaseed clevage

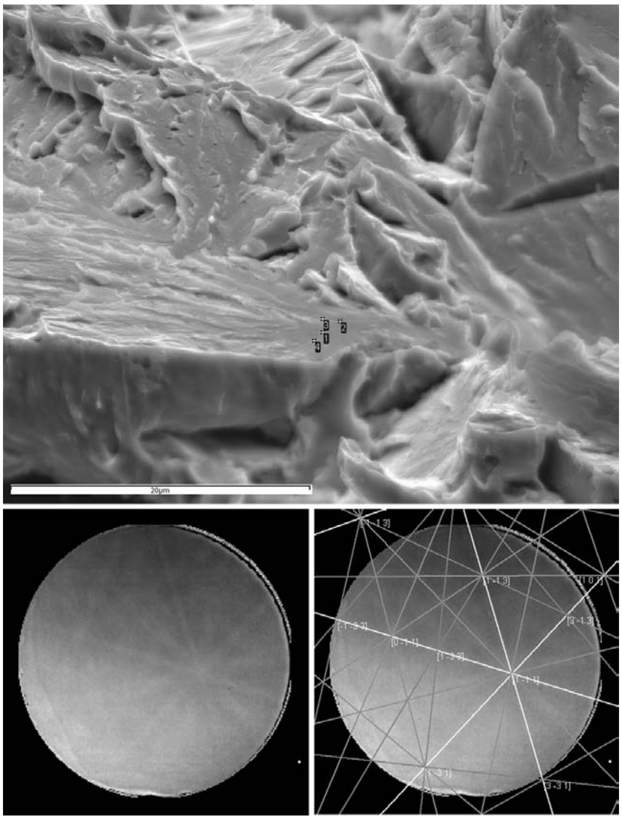

Figure 17: (a) SE micrography of the fracture surface of the steel quenched from 1250 °C in water at 70 °C and reheated at 750 °C; (b) EBSD analysis and indexing of a cleavage facet [23]
Slika 17: (a) SE posnetek prelomne površine jekla, ki je bilo kaljeno s 1250 °C v vodi pri 70 °C in ponovno segreto pri 750 °C; (b) EBSD analiza in indeksi cepilne ravnine

temperature. According to [21] the number of rivers is greater by crack propagation in (110) than in (100) ferrite lattice planes. EBSD examination of clevage facets has shown that for the investigated microstructures clevage occurred only in the (100) lattice plane (**Figure17**) [15].

7 DISCUSSION

Most of the fracturing energy in ductile range is consumed for the plastic deformation before the crack is started at the notch tip and it is dissipated as adiabatic heat [22]. For this reason, the fracturing temperature at the crack tip is higher than the nominal test temperature and both temperatures are equal only below the cleavage threshold temperature,while, in transition and ductile fracturing range the difference increases with greater plastic deformation in the limited volume of steel involved in the deformation and fracturing events [22]. In this discussion it is assumed that the fracturing temperature is equal to the nominal temperature, which is given as abscissa in **Figure 7 to 11** and in the captions of microfractographies.

In lower shelf range, where the fracturing occurs after elastic deflection with a consumption of 5 J to 7 J [19], the eventual effect of microstructure was below the level of sensitivity of performed Charpy tests. For the same steel the fracturing energy is different for different grain size and the transition temperature is much lower for lower bainite than for martensite, while after reheating, the fracturing energy is decreased and the transition temperature increased much more for lower bainite. The higher sensistivity of lower bainite to reheating reflects the effect of changes of microstructure. As for martensite and lower bainite inserts of secondary martensite are found after reheating, it is clear that the extension of cleavage range is due to intragranular changes, specifically the presence of secondary martensite platelets formed with dissolution of cementite particles in secondary austenite. The nature of changes in lower bainite because of short reheating and changes in martensite at short reheating that lower notch toughness are investigated. The so far obtained experimental findings indicate that at reheating temperature no direct transformation of martensite to austenite took place and that rate of dissolution of carbon in ferrite resp. scondary austenite is faster that the precipitation of iron carbide from the solid solution in martensite.

For some microstructures the changes of notch toughness and hardness are as expected: by increased hardness notch toughness is lower and opposite. Two cases deviate significantly for the general rule: hardness and notch toughness are lower for martensite after reheating, while by very small difference in hardness notch toughness is much lower for lower bainite. This suggests that in weld heat affected zone lower hardness is not always related to higher notch toughness.

8 CONCLUSIONS

On the base of experimental findings and their analysis the following conclusions are proposed:

- independently on grain size, Charpy notch toughness is much higher and the transition temperature is much lower in case of transformation of coarse and fine grained HAZ austenite to bainite than to martensite;
- inpendently on grain size, after short reheating at 750 °C, Charpy notch toughness is greatly diminished for lower bainite, while, it is only slightly diminished for martensite;
- particularly deleterious for notch toughness and transition temperature is the formation of secondary martensite from secondary austenite formed with dissolution of cementite particles in interior of grains at reheating;
- depending on microstructure, by similar hardness different notch toughness and transition temperature can be obtained for different microstructure;
- although beneficial in terms of notch toughness and transition temperature, lower bainite in heat affected

zone of welds increases more the sensibility to formation of LBZ than martensite.

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