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CHARPY NOTCH TOUGHNESS AND CLEAVAGE STRENGTH OF REHEATED MARTENSITE AND LOWER BAINITE

ZAREZNA ŽILAVOST PO ŠARPIJU I ČVRSTOĆA CEPANJA PONOVO ZAGREJANOG MARTENZITA I DONJEG BEINITA

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Keywords
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- martensite
- lower bainite
- reheating
- Charpy notch toughness
- transition temperature
- cleavage strength

Ključne reči
- HSLA čelik
- martenzit
- donji beinit
- ponovno zagrevanje
- zarezna žilavost po Šarpiju
- prelazna temperatura
- čvrstoća cepanja

Abstract

A V-Nb HSLA steel was heat treated to martensite and lower bainite with different grain size, reheated for 3 s at 750°C with conduction heating and air cooled. Charpy notch tests were performed from –100°C to 60°C and notched tensile tests at –115°C.

For as delivered steel and lower bainite, the upper shelf toughness was above 200 J and the transition temperature low, for martensite the upper shelf toughness threshold above 60°C. After reheating, notch toughness has slightly decreased for martensite, while for lower bainite it decreased about ten times at 0°C and the upper shelf temperature increased above 40°C. In conclusion, independently on grain size, lower bainite was more prone than martensite to form in heat affected zone local brittle zones.

Charpy notch toughness, cleavage fracture and transition temperature were found to be related to the cleavage strength at –115°C. EBSD examinations of tensile fracture surface have shown that for bainite and martensite the cleavage occurred in the plane (001).

Izvod

HSLA čelik legiran V-Nb je termički obrađen na martenzit i donji beinit različitih veličina zrna ponovnim zagrevanjem tokom 3 s na 750°C dovođenjem toplote i hlađenjem vazduhom. Šarpi ispitivanja su izvedena na –100°C do 60°C i zatezno ispitivanje zarezane epruvete na –115°C.

Za čelik u stanju isporuke i za donji beinit, gornji nivo žilavosti je bio iznad 200 J sa niskom prelaznom temperaturom, dok je za martenzit prag gornje žilavosti iznad 60°C. Posle ponovnog zagrevanja zarezna žilavost je neznatno niža za martenzit, dok je za donji beinit smanjena oko deset puta, na 0°C, a temperatura gornjeg nivoa je povećana iznad 40°C. Zaključak je da, nezavisno od veličine zrna, sklonost ka stvaranju lokalno krtih zona u zoni uticaja toplote mnogo je veća kod donjeg beinita nego kod martenzita.

Utvrđeno je da se žilavost po Šarpiju, čvrstoća cepanja i prelazna temperatura mogu dovesti u vezu sa čvrstoćom cepanja na –115°C. EBSD ispitivanje površine preloma pri zatezanju pokazuje da se i kod beinita i kod martenzita cepanje javlja u ravni (001).

INTRODUCTION

The resistance to hydrogen embrittlement is essential for steels in vessels for hydrocarbons storage and depends on the effect of absorbed hydrogen on steel ductility. API tests have shown for 490 MPa yield stress HSLA steels with a microstructure of ferrite and cementite particles a much greater reduction of area than for the 350 MPa steel with a microstructure of polygonal ferrite and pearlite, /1, 2/. Routine tests, during the construction of a 60.000 m^3 vessel, have found that by equal welding procedure, the Charpy toughness was lower for 15 mm plates than for 25 mm plates of the same HSLA steel. This was confirmed by tests of 15 and 25 mm plates of same microstructure rolled from the same HSLA melt, /3/. Also, it was found that Charpy toughness was lower after reheating for slower primary cooling of the same steels from 1200°C, /1, 2/. It was assumed that the differences were related to the propensity of HAZ microstructural constituents to form local brittle zones (LBZ) that affect the Charpy toughness and transition temperature of structural steel welds, /4-15/.

Martensite and lower bainite were evaluated as most sensible for change of notch toughness at short reheating. Hence, the effect of reheating was investigated for the mother steel with as delivered microstructure as well as coarse and fine grained martensite and lower bainite.

EXPERIMENTAL WORK

Tests and examinations were carried out with the 0.1C-0,5Mn-0.7Cr-0.27Mo-0.032Nb-0.025Al HSLA steel with the initial microstructure of a dispersion of cementite precipitates in mostly acicular ferrite grains with intercept size of about 2.5 μm. Specimens were annealed at 920°C or at 1250°C, then half quenched in lead bath at 400°C and half in water at 70°C. In this way, two types of microstructures and two austenite grain sizes (ASTM grades 1-3 and 8) were obtained. Half of specimens were then reheated individually for 3 s at 750°C with direct conduction heating and air cooled with $t_{800-500°C}$ = 17 s. Charpy notch was cut on all specimens after heat treatment.

Heat treated and mother steel Charpy specimens were tested in temperature range −200°C to 60°C. The microstructures and fracture surfaces were investigated by scanning microscopy and electron back-scatter diffraction (EBSD).

Tensile tests were performed on round specimens with a circumferential notch of Charpy size. The test temperature –115°C was below the cleavage threshold for all investigated microstructures. The cleavage strength was deduced from the brittle tensile strength by applying the equation /16, 17/:

$$\sigma_{c1} = \sigma_n \left[1 + \ln\left(1 + r_s / r_n\right) \right]$$

with σ_{cl} – cleavage strength, σ_n – normal (tensile) strength, r_s – radius of tensile specimen and r_n – radius of notch tip.

MICROSTRUCTURE 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 at 750°C, it 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 (Fig. 1). 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 (Fig. 2). The lead bath cooling from 1250°C produced a microstructure of stringers of cementite particles and ferrite platelets (Fig. 3), 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 coarse grains (Fig. 4). After cooling from 920°C and reheating, the microstructure was similar than after cooling from the higher temperature, however, the grain size was smaller for about 6 grades ASTM.

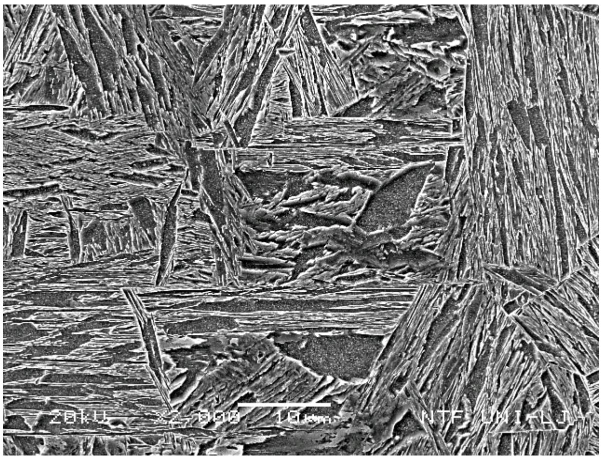

Figure 1. Microstructure after water quenching from 1250°C.
Slika 1. Mikrostruktura posle kaljenja u vodi sa 1250°C

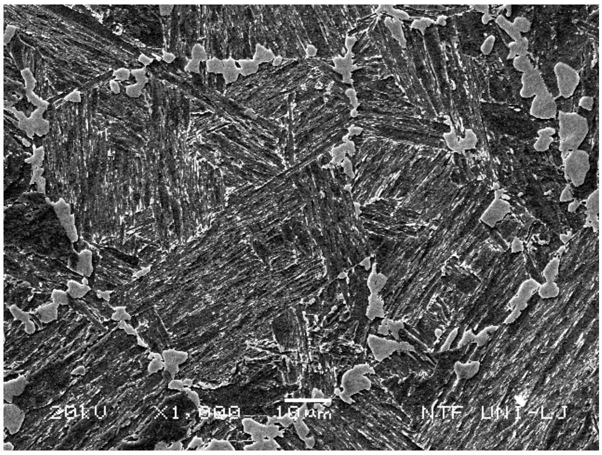

Figure 2. Microstructure from Figure 1 after reheating.
Slika 2. Mikrostruktura sa slike 1, posle ponovnog zagrevanja

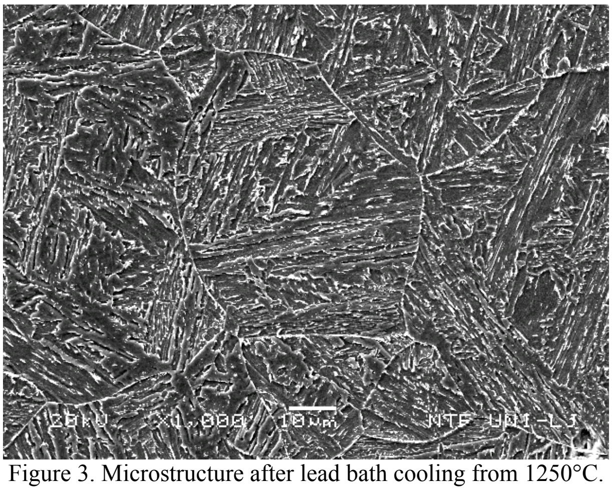

Figure 3. Microstructure after lead bath cooling from 1250°C.
Slika 3. Mikrostruktura posle hlađenja u kupatilu olova sa 1250°C

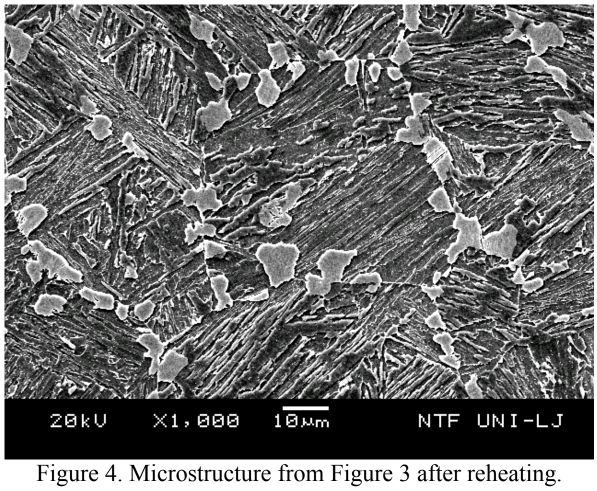

Figure 4. Microstructure from Figure 3 after reheating.
Slika 4. Mikrostruktura sa slike 3, posle ponovnog zagrevanja

These findings suggest that at short reheating at 750°C, three different processes may occur in the investigated microstructures:

– decomposition of primary martensite;
– dissolution of cementite and formation of secondary austenite around cementite particles in ferrite grain interior, which transformed to secondary martensite at cooling;
– formation of secondary martensite grains at triple points and boundaries of ferrite grains.

In Table 1 hardness is shown for different microstructures of the same steel. The low hardness of the as-delivered steel increased significantly after reheating. After water quenching from 920°C, the hardness was much higher in comparison with that of the mother steel and it was lower after reheating. After quenching from 920°C in lead bath, a relatively low hardness was obtained that did not change significantly after reheating. After water quenching from 1250°C, the highest hardness was obtained that decreased significantly at reheat, still remaining high. After cooling in lead bath from 1250°C, hardness increased moderately and was higher after reheating. After cooling from 920°C the hardness was lower and changed after reheating as for the steel cooled from 1250°C.

CHARPY TOUGHNESS, TRANSITION TEMPERATURE AND CLEVAGE STRENGTH

In Figures 5 and 6 the dependences Charpy toughness–test temperature are shown for steel cooled from 1250°C in water and in lead bath and reheated. The dependences are similar for specimens cooled from 920°C and reheated. The reheating affected much less notch toughness and transition temperature of the mother steel, /18/.

In Table 1 cleavage strength, Charpy toughness at 0°C and tensile plastic extension are shown for all tested specimens. The analysis of experimental findings shows that:

– the upper shelf notch toughness is high and the Charpy transition is low for fine and coarse grained bainite and the increase of notch toughness above cleavage threshold is very fast;
– for fine and coarse martensite, notch toughness at 0°C is low, it increases slowly above the cleavage threshold temperature and the upper shelf temperature is above the highest test temperature;
– after reheating, notch toughness is lowered little for martensite and very much (for about ten times at 0°C) for coarse and fine lower bainite;
– for reheated lower bainite, the harmful effect of secondary martensite platelets in ferrite grain interior is strong;

Table 1. Hardness, some tensile and Charpy test data after different heat treatment.
Tabela 1. Tvrdoća, podaci nekih ispitivanja zatezanjem i Šarpi udarom posle različitih termičkih obrada

Specimen	Hardness HV 5	BFS (MPa)	CS (MPa)	PE (mm)	WDS (mm)	CT0 (J)	CTT (°C)
Mother steel	205	1063	1934	1.33	0.41	240	–100
" + 750 °C	249	1231	2240	2.41	0.37	95	–80
920°C water	282	1449	2637	1.35	0.13	120	–100
" + 750°C	244	1329	2402	0.65	0.07	50	–50
1250°C water	383	1257	2287	0.23	0.07	45	–40
" + 750°C	320	1230	2238	0.11	0.06	20	–40
920 lead	222	1208	2198	0.97	0.09	250	–100
" + 750°C	241	1106	2012	0.59	0.07	27	–20
1250 lead	204	1255	2284	0.82	0.11	205	–80
" + 750°C	248	1052	1914	0.35	0.08	14	0

BFS – brittle fracture strength; CS – cleavage strength; PE – plastic tensile extension; WDS – width of the ring of ductile shearing; CTO – Charpy notch toughness at 0°C; CTT – cleavage threshold temperature

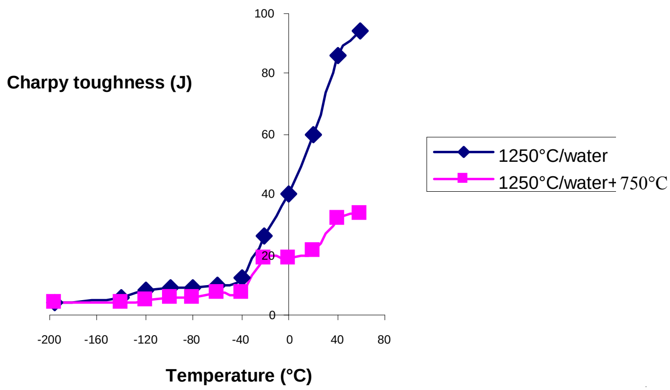

Figure 5. Charpy toughness versus testing temperature for the steel quenched in water from 1250°C and reheated.
Slika 5. Zavisnost žilavosti po Šarpiju od temperature ispitivanja za čelik kaljen u vodi sa 1250°C i ponovo zagrejan

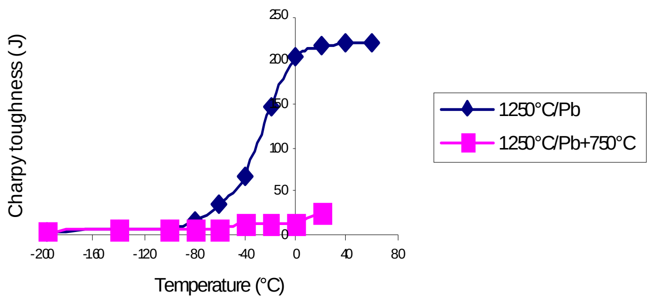

Figure 6. Charpy toughness versus testing temperature for the steel cooled from 1250°C in lead bath and reheated.
Slika 6. Zavisnost žilavosti po Šarpiju od temperature ispitivanja za čelik hlađen u kupatilu olova sa 1250°C i ponovo zagrejan

- grain boundary inserts of secondary martensite decrease only moderately the Charpy toughness of reheated primary martensite;
- for primary microstructure, notch toughness at 0°C is higher by lower hardness. However after reheating, by lower hardness notch toughness is also lower. The difference shows, that for HAZ, lower hardness is not always an indication of higher notch toughness;
- for martensite and lower bainite, cleavage strength is lower after reheating, when also 0°C Charpy notch is lower. Cleavage strength and cleavage temperature are higher for primary martensite than for lower bainite. These findings suggest that Charpy cleavage temperature is higher by higher cleavage strength;
- reheating processes affect differently notch toughness and hardness of different microstructures. The effect is strong for lower bainite, as hardness increases from 222 and 204 to 241 and 248 HV at 0°C, notch toughness at 0°C decreased about ten times and the transition temperature increased 80 and 120°C. For martensite, after reheating, the decrease of 0°C notch toughness was 20 J in respect to 40 J and lower for hardness 40 and 60 HV;
- all experimental findings support the conclusion that lower bainite is more prone than martensite to embrittlement after short reheat in the ferrite + austenite range and more prone to formation of LBZ than martensite.

FRACTURE SURFACE

For the three levels of notch toughness three fracturing mechanisms were identified. For high toughness, the fracture surface was of irregular topography and consisted of areas of dimples with different size formed with normal (Fig. 7) and shear decohesion (Fig. 8), /19/.

At low notch toughness in the temperature range of toughness growth above cleavage threshold, the fracture surface consisted of cleavage and ductile areas (Fig. 9), with increasing ductile decohesion for higher toughness. Dimples are found mostly in areas inclined toward cleavage facets. On the ductile to cleavage boundary of mixed fractures, characteristics of change in the crack propagation mechanism is not identified and it is assumed that the fracturing transition occurred with plane slip, /20/.

By brittle fracture, the shape and size of cleavage facets (Fig. 10) are coarser by coarser grains and it is similar for as-delivered steels and specimens cooled from 920°C and 1250°C. Details related to the presence of inserts of secondary martensite at grain boundaries are not found on cleavage facets.

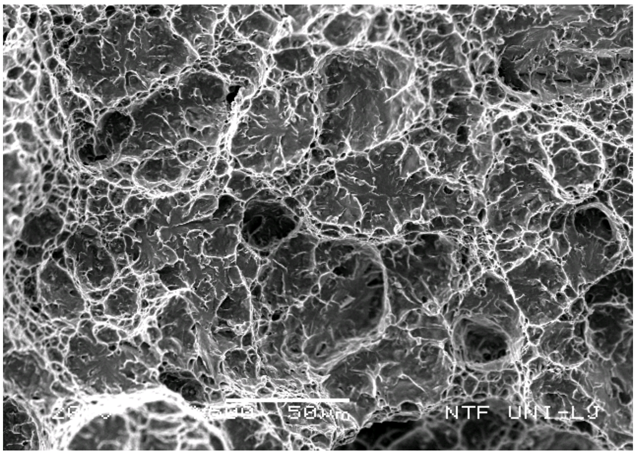

Figure 7. Normal ductile decohesion at 22°C.
Slika 7. Duktilna dekohezija u normalnom pravu na 22°C

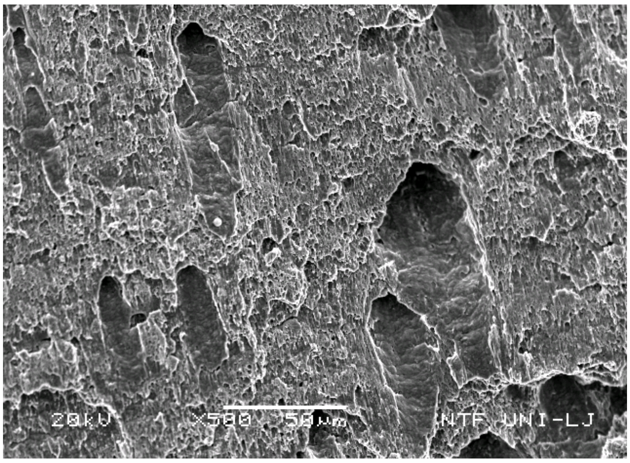

Figure 8. Shearing ductile decohesion at 22°C.
Slika 8. Duktilna dekohezija klizanjem na 22°C

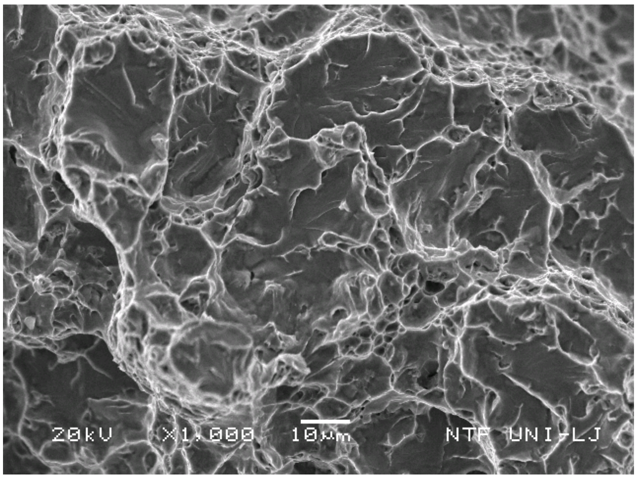

Figure 9. Fracture at 0°C of steel quenched in water from 920°C.
Slika 9. Prelom na 0°C čelika kaljenog u vodi sa 920°C

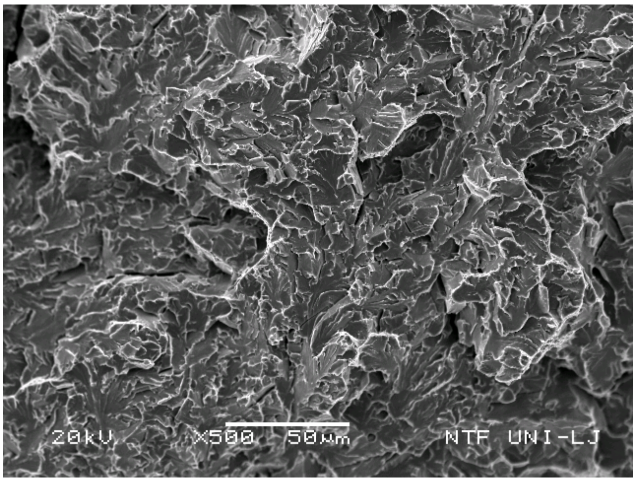

Figure 10. Fracture at –60°C of steel quenched in water from 920°C.
Slika 10. Prelom na –60°C čelika kaljenog u vodi sa 920°C

The fracture surface at –115°C of notched tensile specimens consisted of a ring of plastic shear at the notch tip and central cleavage area (Fig. 11). At the notch tip, several crack initials are found on all specimens and the fracture changed after a layer of shearing of different width to cleavage (Fig. 12).

According to /21/, cleavage occurs in (110) and (100) lattice planes with a greater density of rivers for the (110) planes. The EBSD examinations of fracture showed that the cleavage plane was (001) for all investigated microstructures and the density of rivers was greater on the cleavage facets of lower bainite, /21/.

Figure 11. Fracture surface at –115°C of notched tensile specimen quenched in water from 1250°C.
Slika 11. Površina preloma na –115°C zarezane zatezne epruvete kaljene u vodi sa 1250°C

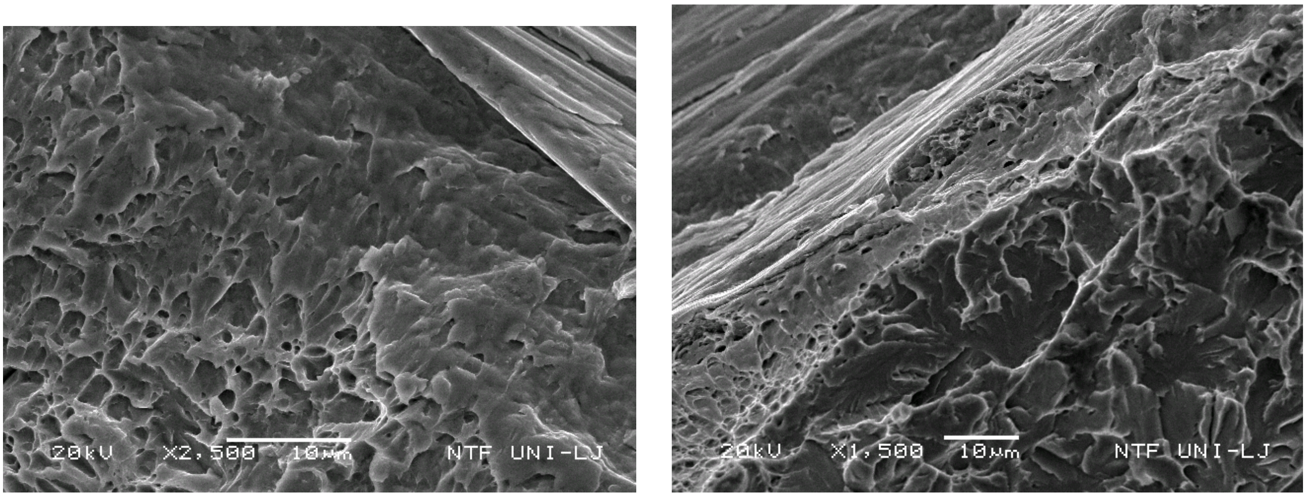

Figure 12. Details of the shearing ring at notch tip of notched tensile specimens fractured at –115°C.
Slika 12. Detalji klizanja na prstenu vrha zareza epruvete za zatezanje slomljene na –115°C

CONCLUSIONS

Performed experiments allowed to conclude that:

– Charpy notch toughness is higher and the transition temperature is lower for lower bainite than for martensite, independently on grain size;
– after 3 s of reheating at 750°C and air cooling, Charpy notch toughness is greatly diminished and transition temperature increased for lower bainite and much less for martensite;
– particularly harmful 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, significant changes of notch toughness were obtained and lower notch toughness was found for lower hardness, also;
– cleavage strength is higher for martensite with higher cleavage Charpy notch temperature. After reheating, by lower cleavage strength the 0°C notch toughness is lower for martensite and for lower bainite;
– lower bainite was found to be more propensive to form LBZ in HAZ of structural steels than martensite, independently of grain size.

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