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EFFECT OF HEAT TREATMENT ON CHARPY IMPACT ENERGY OF MICROALLOYED HSLA STEEL NIOMOL 490K

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ABSTRACT
High strength low alloy (HSLA) steels represents a group of low carbon steels that utilise small amaunts of alloying elements, such as Mo, Ti, V and Nb, to attain yield strengths in excess of 275 MPa in the as rolled condition. The main properties of HSLA steels that make them for wide variety of applications are: strength and toughness, corrosion resistance, weldability and cost effectiveness.
The high strength low alloyed (HSLA) structural steel Niomol 490K, produced in steelwork ACRONI, Jesenice, Slovenia with the microstructure of dispersion of cementite particles in ferrite, with linear grain size of aproximately 2.5 μm and the yield stress of 490 MPa has been investigated.
Heat treatment of the steel Niomol 490K consisted from austenitisation at 920 °C for 10 minutes and reheating up to 1250 °C for 5 seconds. After austenitization the quenching was carried out in both water (temperature of 70 °C) and lead bath up to 400 °C following cooling on air. It was found that Charpy impact energy is higher and the transition temperature is lower for transformation of austenite to bainite than to martensite microstructure. Experimantal results showed that different fracture surface observed.

1. INTRODUCTION
High strength low alloy (HSLA) steels represents a group of low carbon steels that utilise small amount of alloying elements, such as Mo, Ti, V and Nb, to attain yield strengths in excess of 275 MPa in the as rolled condition [1]. The main properties of HSLA steels that make them for wide variety of applications are: strength and toughness, corrosion resistance, weldability and cost effectiveness.

The high strength low alloyed (HSLA) structural steel Niomol 490K, produced in steelwork ACRONI d.o.o., Jesenice, Slovenia with the microstructure of dispersion of cementite particles in ferrite, with linear grain size of aproximately of 2.5 μm and the yield stress of 490 MPa is used for petrochemical vessels because of its excellent weldability and resistance to hidrogen embrittlement [2]. By field welding tests during the control of the erection of a reservoir for liquid natural gas of volume of 60.000 m^3 (Figure 1.), it was found that the toughness transition temperature of welds without preheating, though in the allowed range, was lower for 15 mm plates than for 25 mm plates.

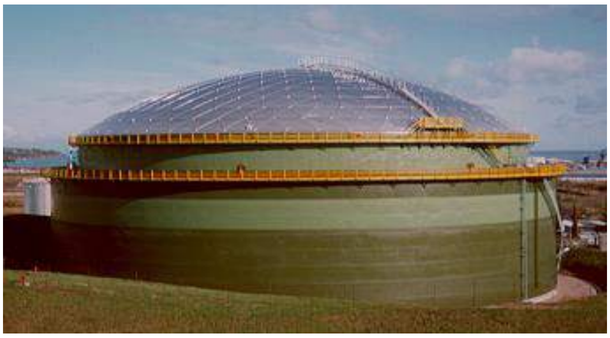

Figure 1. Reservoir for liquid natural gas manufactered from steel Niomol 490K.

For equal welds of plates of thickness 15 and 25 mm rolled from the same melt, the transition temperature was for about 20 ^{o}C higher for 15 mm plates [3]. This finding confirmed results of tests of steels after simulation with different 800 ^{o}C to 500 ^{o}C cooling rate [4].
Difference in transition temperature of HAZ of weldments of structural steels are explained with the effect of local brittle zones (LBZ) [5,6]. It was suggested that the ability of Charpy tests to detect brittle zones was questionable [6] and that for the same steel the welding procedure should be adjusted to the thickness of the welded plate. LBZ cause instable local fracture behaviour of the steel in HAZ. In highly constrained geometries, the local toughness dominates the failure process and deviates the crack into harder and more brittle weld metal, while in low constraint configurations, the size of the plastic zone promotes crack deviation into the softer and tougher parent plate [7]. Crack Tip Opening Displacement (CTOD) depends not only on the toughness of LBZ, but also on the width and position of the LBZ intersection with the crack front, it decreases rapidly with increasing LBZ width and approaches a limiting value when the LBZ exceeds a critical size. By testing of simulated welds a linear relation between the inverse square root of the fracture facets size and the impact transition temperature was found [8]. LBZ were found also in HAZ of welds of the criogenic 9 % Ni steel [9]. It is concluded from the survey of references that the harmfull effect of LBZ on toughness is well established, newetheless, no experimentally verified explanation of the the propensity of different microstructure to form LBZ in the heat affected zone (HAZ) of welds was proposed, so far. Based on field experience and investigations, it was assumed that the formation of LBZ is related to changes in particular constituents of HAZ microstructure. The aim of this investigation was to verify the effect of short reheat at a temperature of partial transformation on notch properties of fine and coarse grained martensite and lower bainite.

2. EXPERIMENTAL WORK

All experimental work was performed on the HSLA steel Niomol 490K with 0.1C, 0.5Mn, 0.7Cr, 0.27Mo, 0.032Nb and 0.025Al. Specimens cut from a 15 plate were austenitised for 10 min. at 920 or 5 s. at 1250 ^{o}C, than half quenched in lead bath at 400 ^{o}C and half in water at 70 ^{o}C. In this way, two types of microstructure and two austenite grain sizes were obtained.

Half of specimens was than reheated individually for 5 s at 750 ^oC with direct conduction heating and air cooled with the cooling time $t_{750\text{-}500^oC}$ = 17 s. On all specimens the Charpy notch was cut after heat treatment. For heat treated specimens and the as delivered steel, the Charpy tests were carried out in temperature range from − 200 ^oC to 60 ^oC. The microstructures and the fracture surfaces were investigated with scanning electron microscoppy (SEM). In the description of microstructure, the constituents formed at cooling from the austenitising temperatures of 1250 ^oC or 920 ^oC were termed as primary and as secondary the constituents formed at cooling after reheat at 750 ^oC. The microstructure of the as delivered steel consisted of fine ferrite grains with a dispersion of fine cementite particles (Figure 2).

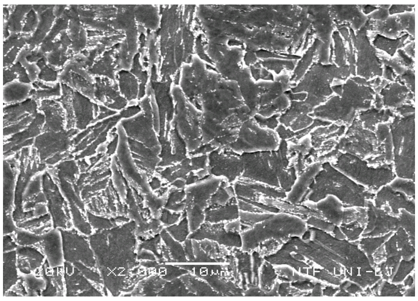

Figure 2. Microstructure of the as delivered steel.

After reheat at 750 ^oC, rare martensite platelets in the interior of ferrite grains and small inserts of martensite, mostly at triple points points, as in Figure 3 (right) were observed. With water quenching from 920 ^oC a microstructure of small ferrite and martensite grains was obtained (Figure 3 left), that changed, after reheat, to a dispersion of cementite precipitates, frequently in rows in the interior of ferrite grains and inserts of secondary martensite, mostly at triple points (Figure 3 right).

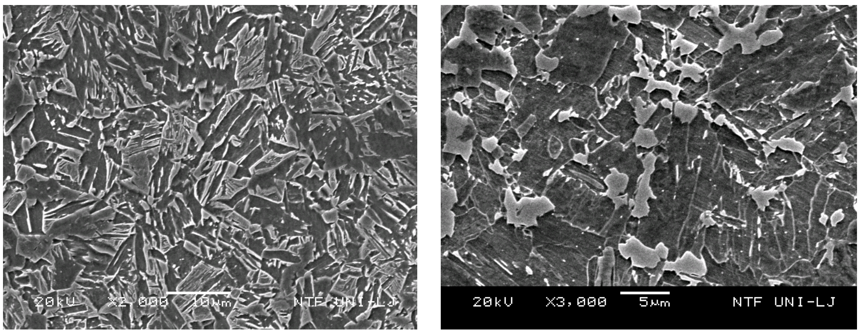

Figure 3. Microstructure after water quenching from 920 ^oC (left) and after reheating (right).

The quenching in lead bath from 920 ^OC produced a microstruture of acicular ferrite with cementite particles of different shape (Figure 4 left). After reheat, this microstructure changed to secondary martensite platelets in the interior of ferrite grains and inserts of secondary martensite at triple points (Figure 4 right).

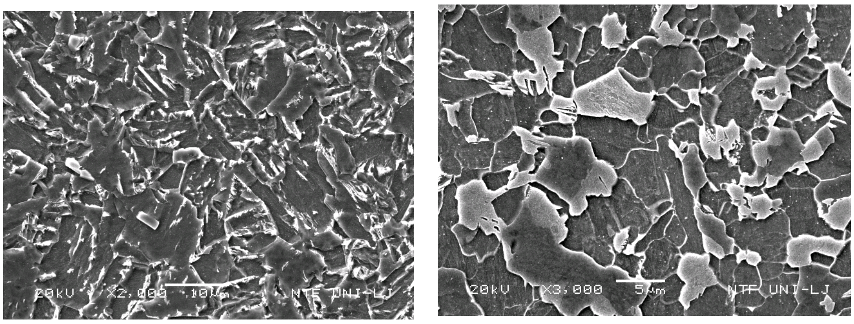

Figure 4. Microstructure after lead bath cooling from 920 ^{o}C (left) and after reheating (right).

The quenching in water from 1250 ^{o}C produced a coarse microstructure with platelets of ferrite and primary martensite (Figure 5 left). It changed to stringers of cementite particles in ferrite grains and inserts of secondary martensite at grain boundaries after reheat (Figure 5 right).

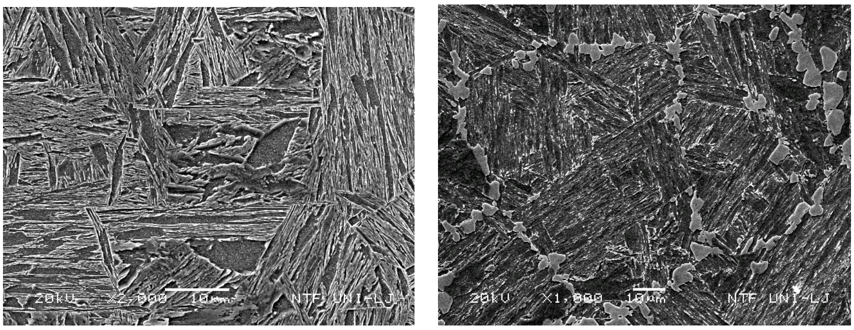

Figure 5. Microstructure after water quenching from 1250 ^{o}C (left) and after reheating (right).

The cooling in lead from 1250 ^{o}C produced a microstructure of stringers of cementite particles at borders of ferrite platelets (Figure 6 left). The formation of this microstructure was not investigated sufficiently for a reliable conclusion if it was lower bainite of displacive or reconstructive type. Also the constituent produced with transformation of austenite in water at 70 ^{o}C was not identified accurately, yet, in the following, the microstructures is termed lower bainite and martensite. After reheat lower bainite obtained with cooling in lead bath from 1250 ^{o}C, changed to a microstructure of platelets of secondary martensite and ferrite and inserts of secondary martensite at the boundaries of coarce grains (Figure 6 right).

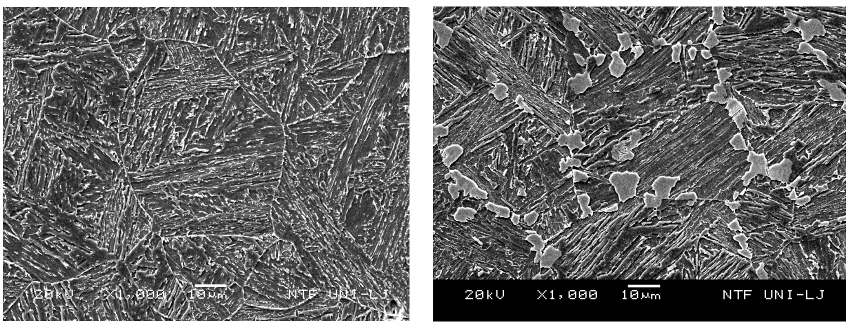

Figure 6. Microstructure after lead bath cooling from 1250 ^{o}C (left) and after reheating (right).

Table 1. Hardness of steel after different thermal treatment

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	224
1250 ˚C → water	383
1250 ˚C → water + 750 ˚C	320
1250 ˚C → lead bath	257
1250 ˚C → lead bath + 750 ˚C	298

In Table 1. the hardness is shown for the different microstructures. The low hardness of the as delivered steel increased significantly after reheat. After water quenching from 920 ^{o}C the hardness was much higher in comparison to the initial hardness (hardness of the as delivered steel) and it was lower after reheat. After quenching from 920 ^{o}C in lead bath, a relatively low hardness was obtained which did not change significantly after after reheat. After water quenching from 1250 ^{o}C, the greatest hardness was obtained that decreased significantly at reheat, still, it remained high. After quenching in lead bath from 1250 ^{o}C the hardness was increased moderately and it was higher after reheat.

The experimental findings on microstructure and hardness indicate that depending on the initial microstructure three different processes may occur at short reheat:

- the 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,
- the formation of inserts (grains) of secondary martensite at triple points and boundaries of ferrite grains, and
- the decomposition of primary martensite.

In Figures 7. to 11. the effect of test temperature on Charpy toughness is shown. The toughness of tested microstructures and it change after reheat for different microstructures show that:

- the upper shelf notch toughness is high and the Charpy transition as well as the cleavage threshold temperature are low for the as delivered steel and for fine and coarse grained bainite. For fine and coarse martensite notch toughness is much lower above the cleavage threshod temperature and the upper shelf temperature is above the highest test temperature of 40 rsp. 60 ^{o}C;
- after reheat, notch toughness is decreased little for the as delivered steel, more for martensite and the most for fine and coarse lower bainite;
- after reheat, for the as delivered steel, the transition and cleavage threshold temperature are increased little, while, the transition temperature is above the highest test temperature for all other specimens and the cleavage threshold temperature is increased, again the most, for aproximately ten times for fine and coarse lower banite;
- the comparison of microstructure and notch toughness characteristics indicates, that the effect of secondary martensite in the interior of ferrite grains prevails generally over the effect of secondary martensite inserts at boundaries of ferrite grains, and finally

- the effect of reheat on Charpy characteristics depends strongly on the initial microstructure and it is the must harmfull for fine and coarse lower bainite.

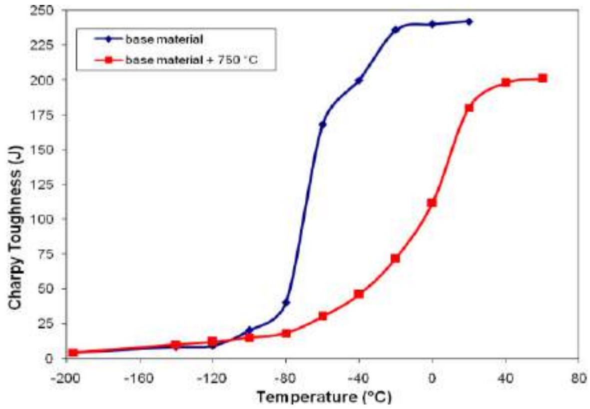

Figure 7. Charpy toughness versus testing temperature for the as delivered and reheated steel.

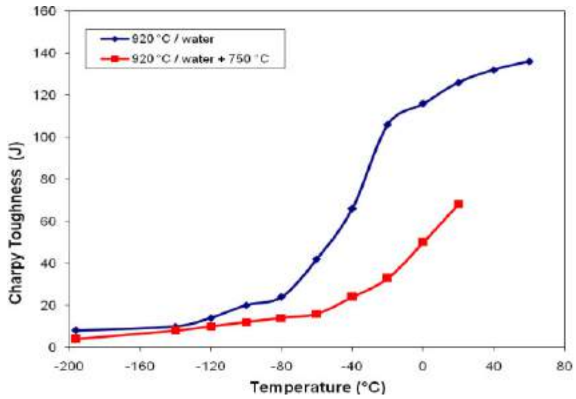

Figure 8. Charpy toughness versus testing temperature for the steel quenched in water from 920 ^{o}C and
after reheating.

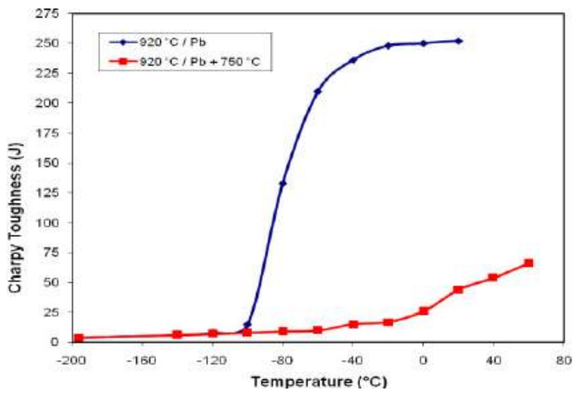

Figure 9. Charpy toughness versus testing temperature for the steel cooled from 920 ^{o}C in lead bath and
after reheating.

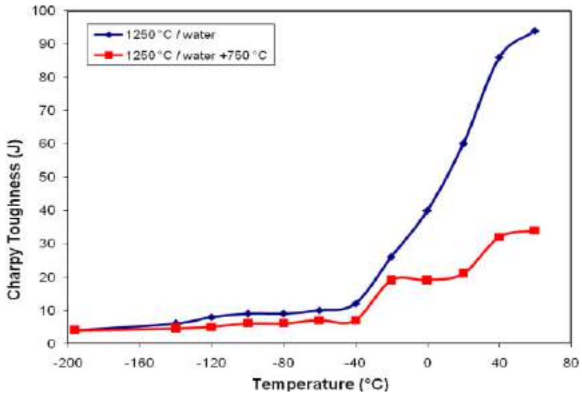

Figure 10. Charpy toughness versus testing temperature for the steel quenched in water from 1250 ^oC and after reheating.

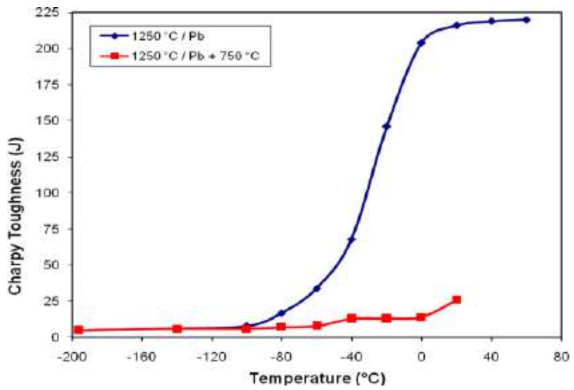

Figure 11. Charpy toughness versus testing temperature for the steel cooled from 1250 ^oC in lead bath and after reheating.

Three fracturing mechanisms were identified for the three levels of consumed energy. For high fracturing energy, the fracture surface was of irregular topography and consisted of areas of normal and of shear decohesion with dimples of different size (Figures 12 and 13). A specific fracture surface was found on specimens fractured with low energy comsumption in the range of temperature of growth of fracturing energy above 20 ^oC. It consisted of a mixture of brittle and ductile details (Figure 14) with prevalence of brittle fracturing morphology for low consumed fracturing energy. On the ductile to clevage boundary of mixed fractures details chracteristic for the change of mechanism of crack propagationfor were not identified and it is assumed that the fracturing transition occurred with plane shear.

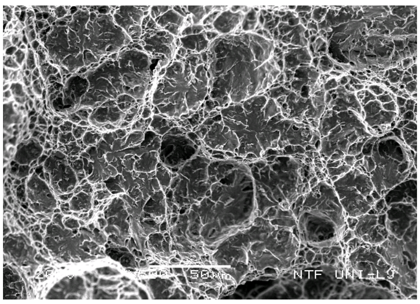

Figure 12. As delivered steel, fracture surface with normal ductile decohesion at 22 ^oC.

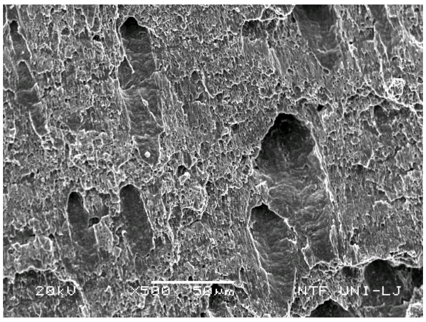

Figure 13. As delivered steel, fracture surface at 22 ^oC. Dimpled area with shear decohesion.

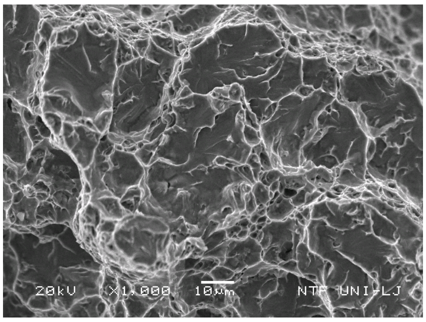

Figure 14. Fracture surface with mixed ductile and cleavage decohesion at 40 ^oC.

By fully brittle fracture, the shape and size of brittle facets was related the size of ferrite grains and it was similar for the as delivered steels and specimens cooled from 920 ^oC (Figure 15). After quenching from 1250 ^oC the clevage facets were coarse (Figure 16) and without details related to the presence of inserts of secondary martensite at grain boundaries.

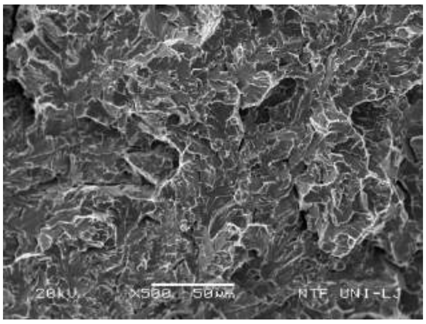

Figure 15. Steel cooled in lead bath form 920 ^oC. Cleavage fracture.

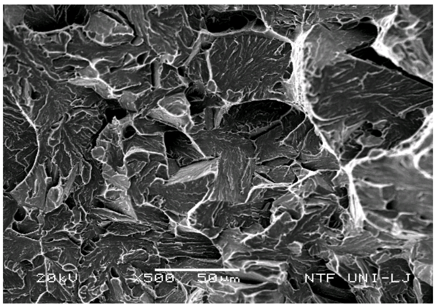

Figure 16. Steel quenched from 1250 ^oC in water and fractured at -60 ^oC. Cleavage fracture.

3. 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 and the real fracturing temperature is more than order of magnitude higher than the nominal testing temperature and the nominal temperature is equal to the fracturing temperature only in lower shelf range. It this discussion is assumed that the fracturing temperature is equal to the nominal temperature, which is given as abscissa in Figures 7. to 11. and in the caption of microfractographies.

In lower shelf range, where the fracturing occurs after elastic deflection with a consumption of 5 J to 7 J, the eventual effect of microstructure is below the level of sensitivity of the standard Charpy test. For this reason, the effect of microstructure on Charpy toughness in lower shelf range is not commented.

The results of tests on the same steel cooled to fine and coarse martensite and lower bainite show that the fracturing energy was greater and the transition temperature was lower for lower bainite than that for martensite. The effect of grain size was small for bainite and it was greater for martensite. After the applied reheat, the fracturing energy was decreased and the transition temperature increased much more for lower bainite than for martensite and virtually independently on grain size. The difference reflects the change of both initial microstructures at reheat temperature and air cooling. For bainite, in areas of cementite particles in the interior of ferrite grains secondary martensite was formed at reheat, while, at reheat virtually only a partial decomposition of primary martensite occurred in the interior of grains. In the very short reheat time of some seconds, secondary austenite rich in carbon was formed with dissolution of cementite particles and than transformed to secondary martensite at cooling. The extent and form of decomposition of primary martensite in the applied reheat are not clear, yet, it decreases notch toughness above the clevage threshold temperature. The extent of formation of secondary austenite with dissolution of cementite particles was sufficient to produce a volume of martensite that greatly diminished the notch toughness.

Also, the change of primary martensite at reheat decreased significantly the fracturing energy, however, the decrease was much lower than for bainite. An opposite effect would be expected after the completed decomposition of martensite.

The fast formation of inserts of secondary martensite at grain boundaries of ferrite for the initial microstructure of martensite and lower bainite grains suggests the grain boundary carbon segregation and the piping diffusion of segregated carbon to the points of faster formation of austenite with high solubility for carbon. The effect of these inserts is not clear, newertheless, it is possible that they are responsible for the decrease of notch toughness of martensite after reheat. It is evident that the effect of short reheating in the ferrite + austenite range is more harmfull for notch toughness of lower bainite than of martensite and independent on grain size. Therefore, it is expected that the propensity to form local brittle zones (LBZ) is greater for lower bainite that for martensite. The very different notch toughness for similar hardness suggests that the physical form of presence of carbon, in precipitates or in solid solution in martensite, affects differently notch toughness temperature than hardness.

The findings in this investigations show that for HAZ the transformation of austenite to lower bainite is more harmfull for the weld quality, than the transformation to martensite, inspite of the lower hardness of bainite. Also, for notch toughness of HAZ of structural steels of similar composition that the investigated, slower cooling could be more harmfull than faster cooling.

4. CONCLUSIONS

On the base of the experimental findings in this investigation and their analysis the following five conclusions are proposed:

- The Charpy notch toughness is higher and the transition temperature is lower for the transformation of austenite to bainite than to martensite, independently on the grain size.
- After short time reheat at 750 ^{o}C and air cooling, Charpy notch toughness is greatly diminished for lower bainite, while, it diminished much less for for martensite.
- Particularly harmfull for notch toughness and transition temperature is the transformation to secondary martensite of austenite formed at reheat in the interior of ferrite grains with dissolution of cementite particles.
- The physical form of the presence of carbon in the microstructure, as precipitates or in solution in martensite, has a different effect on notch toughness than on hardness. For this reason, at similar hardness different notch toughness properties could be obtained.
- Although beneficial in term of notch toughness and transition temperature, the transformation of austenite to lower bainite in the HAZ of welds is to be avoided becase of its higher propensity to form local brittle zones at short reheat in the austenite + ferrite range.

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