F. VODOPIVEC

ISSN 0543-5846
METABK 43 (3) 143-148 (2004)
UDC - UDK 669.14.018.2/.8:020.17=111

STRAIN AGEING OF STRUCTURAL STEELS

Received - Primljeno: 2003-11-07
Accepted - Prihvaćeno: 2004-04-10
Original Scientific Paper - Izvorni znanstveni rad

The mechanism of ferrite strain ageing is explained in terms of interaction of carbon atoms in solution in ferrite and elastic stresses due to the presence of dislocations. After strain ageing tensile properties are changed to a different extent: yield stress and tensile strength are increased, reduction of area is decreased little and uniform elongation is decreased strongly. The increase of yield stress and the decrease of uniform elongation are smaller for steels with greater as delivered yield stress. Upper and lower shelf notch toughness are affected little, while the notch toughness transition temperature is increased significantly. The change of tensile properties is related mostly to the effect of steel plastic deformation, while the increase of notch toughness transition temperature is explained in terms of synergy of dislocation structure of the plastically deformed steel and interplane segregation of carbon atoms in solid solution in ferrite.

Key words: *structural steels, microstructure, strain ageing, tensile properties, Charpy notch toughness transition temperature*

Deformacijsko starenje konstrukcijskih čelika. Mehanizam deformacijskog starenja ferita je rastumačen interakcijom atoma ugljika u otopini u feritu i elastičnih naprezanja zbog dislokacija. Po deformacijskom starenju su mehanička svojstva čelika promjenjena na različit način i u različitom obimu: granica razvlačenja i vlačna čvrstoća su jako povećane, kontrakcija je nešto, a ravnomjerno istezanje je jako smanjeno. Povećanje granice razvlačenja i smanjenje ravnomjernog istezanja su manji kod čelika sa većom početnom granicom razvlačenja. Žilavost u području duktilong loma i u području krtog loma su malo promjenjene dok je prelazna temperatura krti-duktilni lom jako povišena. Promjena mehaničkih osobina je posljedica plastične deformacije, dok je promjena prelazne temperature obrazložena sinergijom dislokacikske strukture hladno deformiranog čelika i među ravninske segregacije atoma ugljika u krutoj otopini.

Ključne riječi: *konstrukcijski čelici, mikrostruktura, deformacijsko starenje, vlačna svojstva, prelazna temperatura Charpy žilavosti*

MECHANISM

Strain ageing is a process involving atoms in interstitial solid solution in á iron (ferrite) and the elastic stresses related to the presence of dislocations [1 - 4]. For an atom situated in the centre of an edge dislocation the binding energy is greater than if the atom was bound to a carbide or nitride of iron [5, 6]. This induces the moving of initially randomly distributed interstitials atoms in deformed lattice to particular places if the elastic energy of the lattice rsp. the tetragonality of the lattice is diminished. At a certain distance of the dislocation the binding energy is small and it is overriden by the thermal agitation of atoms [7]. By a strain of 0,005 the ordering of atoms is to be found theoretically up to a distance of appr. 20 atoms spacing from the dislocation [8]. After the ageing is completed 10 to 50 atoms are segregated in the atomic plane with the dislocation in a 0,01 %C steel deformed for 10 % [9]. From measurements of internal friction is was estimated that in α iron 10 to 50 carbon atoms are segregated to each atomic plane after the completion of the ageing of a steel with above 0,01 % carbon deformed plastically for less than 10 % [10]. The segregation of about 0,001 % of carbon or nitrogen is sufficient to complete the locking of dislocations in a moderately deformed carbon steel [11].

EXPERIMENTAL WORK

Strain ageing affects all tensile properties of structural steels to a different degree and in different way. In this

---

F. Vodopivec, Institute of Metals and Technology, Ljubljana, Slovenia

article the effect of strain ageing on the properties is presented for thre types of structural steels:

- a normalised steel with the microstructure of polygonal ferrite and parlite, linear intercept grain size of 16,6 μm and the yield stress of 377 MPa;
- a steel with a microstructure of quenched and tempered ferrite and pearlite, linear intercept grain size of 4,7 μm and the yield stress of 522 MPa; and
- a steel with a microstructure of tempered martensite, linear intercept grain size of 2,5 ěm and the yield stress of 737 MPa.

Table 1. **Composition of the investigated steels**
Tablica 1. **Kemijski sastav istraženih čelika**

Steel	Content of elements / wt. %					
	C	Si	Mn	S	P	Al
1	0,17	0,32	1,28	0,010	0,02	0,045
2	0,08	0,34	0,36	0,004	0,01	0,052
3	0,11	0,28	0,27	0,007	0,01	0,043
	N	V	Nb	Mo	Ni	Cr
1	0,007	-	-	-	-	-
2	0,007	-	0,058	0,27	-	-
3	0,007	0,06	-	0,26	2,80	1,07

In Table 1. the chemical composition of the steels and in Table 2. their yield stress are given. All steels are alluminium killed and the ratio aluminium versus nitrogen is sufficient to decrease the strain ageing effect due to the residual content of nitrogen in solid solution below that of carbon. The steels have been selected for this presentation because of their different microstructure and the different share of strengthening mechanisms in the yield stress given also in table 2[12] with the aim to show that strain ageing is a general property of all types of structural steels and independent on their microstructure.

Table 2. **Share of different stregthening mechanisms in the yield stress *YS* / MPa**
Tablica 2. **Udio različitih mehanizma očvršćivanja čelika u granici razvlačenja *YS* u MPa**

Steel	1	2	3
Strengthening mechanism			
A iron *YS*	30	30	30
Content of pearlite	61	15	-
Interst. solution	17	17	17
Subst. solution	104	136	245
Grain size	135	254	348
Dispersion	-	9	42
Prec.in γ phase	25	43	25
Prec. in α phase	-	-	52
Theoretical *YS*	372	504	759
Empirical *YS*	377	522	737

The propensity of structural steels to strain ageing is generally checked with tests on steel treated according to the standard procedure consisting of 10 % of cold deformation and 30 min. of ageing at 250 °C. For this reason, the strain ageing effect could results of the effects of two different operations, cold deformation and ageing annealing and for the proper understanding of of strain ageing mechanism, it is necessary to distinguish the effect of both operations. In this paper, the effect of strain ageing is first shown on the base of disponible experimental data and than it is explained, which property is affected mostly by one of the operation and which depends on strain ageing, as combinations of both operations.

TENSILE PROPERTIES

After strain ageing yield stress and tensile strength are increased, uniform elongation is decreased greatly and reduction of area is decreased only slightly. It is decreased for approximately 10 % of the as delivered value, f.i. from 69,7 % to 64 % for a steel with a microstructure of polygonal ferrite-pearlite and from 79,5 % to 70,8 % for a steel with a microstructure of tempered martensite. In Figure 1. the effect of temperature down to NDT (Nil ductility temperature) – 20 °C on yield stress and tensile strength is given for the three as delivered and strain aged steeels in Table 1. with the as delivered yield stress from 377 to 737 MPa and three types of microstructure: polygonal ferrite-pearlite, quenched and tempered ferrite-pearlite and tempered martensite [13]. In Figure 2. the yield stress, tensile strength and uniform elongation are shown in dependence of the prop-

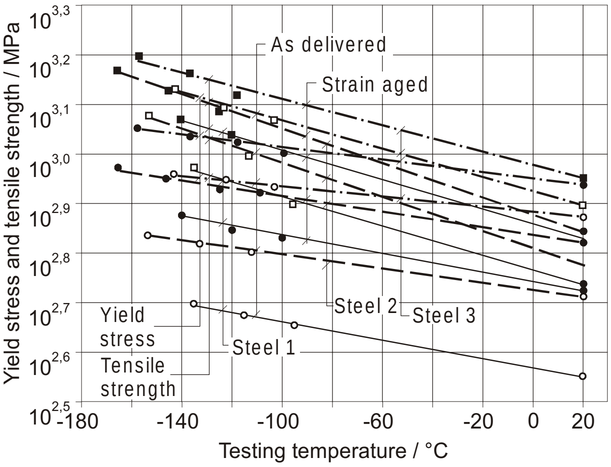

Figure 1. **Yield stress and tensile strength in log. unities versus the testing temperature [15]**
Slika 1. **Granica razvlačenja i vlačna čvrstoća u log. jedinicama u ovisnosti od temperature ispitivanja [15]**

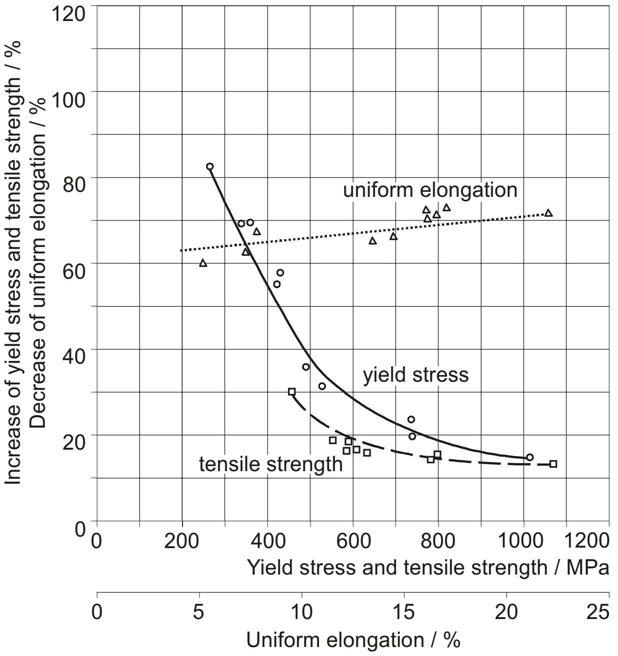

Figure 2. **Relative change of yield stress, tensile strangth and unfirm elongation after strain ageing versus these properties for as delivered steels [14]**

Slika 2. **Relativna promjena granice razvlačenja, vlačne čvrstoće i ravnomjernog istezanja po deformacijskom starenju u odnosu na početna svojstva čelika [14]**

erties of as delivered steels. For the relative increase of yield stress (ΔYS) after strain ageing the following relation was derived from tests on 10 steels with the yield stress in the range from 265 MPa to 1003 MPa [14]:

$$\Delta YS_{sa} = 1647.5\,(YS_{ad} - 200)^{-0.674}$$
$$\Delta YS_{sa} = (YS_{sa} - YS_{ad})\cdot YS_{ad} \qquad (1)$$

The notations “ad” and “sa” are related to the “as delivered” and “strain aged” steel. For the change of uniform elongation (UE) after strain ageing the following relation was derived [15]:

$$UE_{sa} = 0{,}18\cdot UE_{ad} + 1{,}70 \qquad (2)$$

In the range of experimental error for two parallel tests the ratio of properties before and after strain ageing is similar at room and at nil ductility temperature and it is smaller for steels with higher properties in as delivered state [13].

With decreasing temperature yield stress and tensile strength increase for all steels, as delivered and strain aged. The properties are related to the temperature by the simple relation [13]:

$$\text{Log}\,(YS, TS)_T = \log\,(YS, TS)_{22} + \text{n}\,(T + 22) \qquad (3)$$

YS and TS-yield stress and tensile strength,
T - testing temperature in °C below the ambient temperature 22 °C,
n - constant.

The value of the constant “n” is similar for all tested steels.

Tests for the effect of 10 % plastic deformation and strain ageing on the yield stress of a polygonal ferrite and pearlite steel with the yield stress of 280 MPa after normalisation were performed at 20 °C and and –40 °C [16]. After plastic deformation yield stress was increased form 280 MPa to 550 MPa and to 615 MPa after strain ageing (Figure 3.). For a steel with a microstructure of polygonal ferrite and pearlite the yield stress was of 347 MPa after normalisation, of 359 MPa after 30 min. of age-

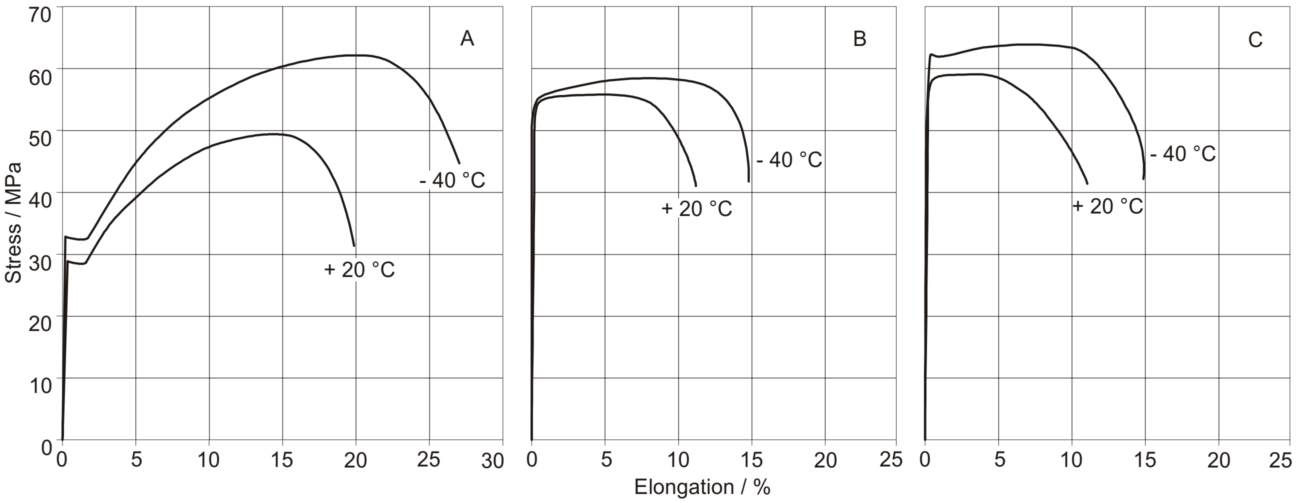

Figure 3. **Dependence load versus elongation at two temperatures for a structural steel after normalisation (A), after 10 % plastic deformation (B) and after strain ageing (C) [16]**

Slika 3. **Sila u ovisnosti od deformacije kod dviju temperatura za konstrukcijski čelik poslije normalizacije (A), poslije 10 % plastične deformacije (B) i poslije deformacijskog starenja (C) [16]** ing at 250 °C, of 499 MPa after 10 % of plastic deformation and of 510 MPa after strain ageing [17]. Earlier data [16] are confirmed and it is shown that the ageing at 250 °C is without significant effect on the yield stress.

Uniform elongation is a measure of the uniaxial deformation and it is related to the strain hardening propensity of the steel. This property is strongly decreased after strain ageing, as shown in relation (2). For the steel with the yield stress of 347 MPa the uniform elongation was of 22,5 % after normalisation, of 22,6 % after ageing at 250 °C, of 6,7 % after 10 % of cold deformation and 7,4 % after strain ageing [17]. Uniform elongation is decreased lesser for high yield stress steels with a smaller uniform elongation in as delivered condition [18] and with a smaller grains sized microstructure. Considering these experimental findings it is justified to conclude, that the smaller uniform elongation is related to the strain hardening propensity of the steel. Accordingly, the smaller uniform elongation after strain ageing is due to the fact that part of the strain hardening capacity is consumed allready in the steel 10 % plastic deformation.

With difference to uniform elongation, the effect of strain ageing on reduction of area is very small, it amounts to approximately 10 % of the as delivered value for the whole tested temperature range and for all tested steels in Figure 1. In the zone of uniform elongation the deformation is uniaxial and it is triaxial in the zone of reduction of area. No experimental finding indicates to the possibility, that the intrinsic effect of strain ageing could be different for uniaxial and triaxial deformation, since the basic mechanism of plastic deformation is the same in both cases. It is assumed, therefore, that the difference in the extent of the effect of strain ageing on uniform elongation and reduction of area could be explained with the local increase of temperature generated with the greater rate of deformation in the reduction of area part of a tensile specimen. Above 90 % of the deformation energy is dissipated as heat [19] and the inherent steel deformability is greater for higher temperature. Consequently, it is possible that on the same specimen the deformation related to the uniform elongation and that related to the reduction of area occurr at different temperature.

CHARPY NOTCH TOUGHNESS

Experimental results obtained with testing of 6 steels with the three typical microstructures and different plate thickness show that after strain ageing the upper shelf notch toughness is slightly lower, the upper shelf temperature is increased differently and it depends on steel microstructure rsp. yield stress [18]. The NDT temperature is slightly increased after strain ageing [20] and considering the procedure for the determination of NDT it was proposed that the decrease of NDT after strain ageing was related to the greater yield stress.

The lower and upper shelf temperature is increased for all steels, again the most for the steel with a microstructure of polygonal ferrite and pearlite. From engineering point of view the must deleterious effect of strain ageing is the increase of temperature of change of fracture mode from ductile dimpled to brittle cleavage crack propagation, termed as Charpy toughness transition temperature. For this temperature (T_{tr}), defined as the temperature for 50 % of upper shelf notch toughness, in dependence of the yield stress of as deliverd steels the following relationship was deduced [14].

$$T_{tr} = 27 \text{ Arcsh } [-0.016\,(YS-410)] - 35 \qquad (4)$$

with Arc sh = $\ln(YS + YS^{1/2} + 1)$.

In Figure 4. the relationship Charpy notch toughness versus testing temperature is given for the same steel after different treatments: normalisation, normalisation + strain ageing, normalisation + 10 % plastic deformation, normalisation + annealing at 500 rsp. 400 °C, normalisation + annealing at these temperatures + strain ageing, quenching from normalisation temperature and quenching + stran

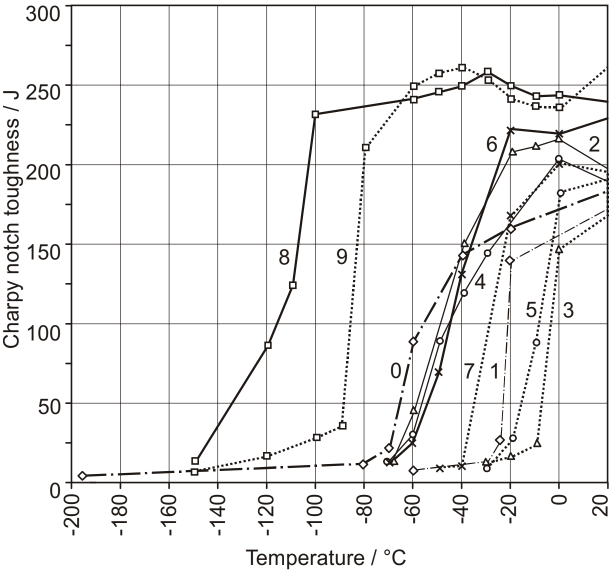

Figure 4. **Charpy notch toughness versus the testing temperature for the same steel after different treatments [21]: 0 - normalisation, 1 - norm. + strain ageing, 2 - norm. + 2 hr. 550 °C + def. ageing, 3 - norm. + 2 hr. 550 °C, 4 - norm.+ 2 hr. 400 °C, 5 - norm. + 2 hr. 400 °C + def. ageing, 6 - norm. + 2 hr. 550 °C + def., 7 - norm. + 2 hr. 550 °C + 30 min. 250 °C, 8 - quenching + 2 hr. 550 °C, 9 - quenching + 2 hr. 550 °C + def. ageing**

Slika 4. **Charpy žilavost u ovisnosti od temperature za isti čelik poslije različitih postupaka [21]: 0 - normalizacija, 1 - norm. + deformacijsko starenje, 2 - norm. + 2 s. 550 °C + def. starenje, 3 - norm. + 2 s. 550 °C, 4 - norm. + 2 s. 400 °C, 5 - norm. + 2 s. 400 °C + def. starenje, 6 - norm. + 2 s. 550 °C + def., 7 - norm. + 2 s. 550 °C + 30 min. 250 °C, 8 - kaljenje + 2 s. 550 °C, 9 - kaljenje + 2 s. 550 °C + def. starenje**

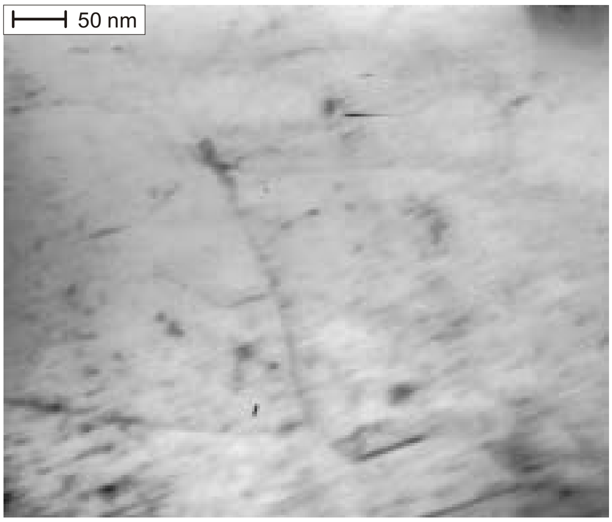

Figure 5. **TEM of the strain aged steel 1. Elongated dark spots showing periodical elastic stress fields in the (011) plane**

Slika 5. **TEM deformacijski starenog čelika 1. Izdužene tamne točke pokazuju periodičko elastično polje naprezanja u (011) ravnini**

ageing [21]. With regard to the normalised steel, the change of 50 % upper notch toughness transition temperature after plastic deformation and ageing is up to +8 °C and it is +30 °C and more after strain ageing, independently of the previou treatment of the steel.

The content of carbon in solid solution in ferrite is probably above 100 ppm after normalisation. According to the solubility product [22]: wt. % C = 240 exp (–77300/*RT*) the solubility it is of 2,4 ppm after annealing at 400 °C and it is below 1 ppm after ageing at 250 °C. The carbon solubility in ferrite and the results in Figure 4. lead to the following conclusions [21]:

- for the same steel the strain ageing propensity is not related to the content of carbon in solid solution in ferrite in the range from above 100 ppm to below 1 ppm C (from 0,01 to 0,001 wt. %);
- the transition temperature is virtually independent upon the plastic deformation and ageing annealing and it is increased only after strain ageing, as a joint effect of plastic cold deformation and annealing and
- for the same steel the change of transition temperature is independent of the microstructure, since it is virtually the same for the normalised steel with a microstructure of polygonal ferrite and pearlite and the steel quenched from the normalisation temperature with a microstructure acicular ferrite and pearlite with a much smaller linear intercept size.

The experimental findings in Figure 4. vere confirmed with control tests on steel normalised, normalised and annealed at 250 °C, normalised and 10 % plaştically deformed and strain aged [23]. A very careful examination of thin foils in transmission electron microscope showed after strain ageing periodic elastic stress maxima between rows of atoms in the {011} plane (Figure 5.). The mechanims of the increase of transition temperature was explained in terms of diminished cleavage strength in {011} planes due to elastic stresses generated with the interplanar segregation of carbon atoms in solid solution [23]. The interaction energy E_C for the introdution in the lattice of an interstitial carbon atom, which causes a volume change of ΔV is [24]:

$$E_C = K\theta \cdot \Delta V \tag{5}$$

with

K - bulk modulus and
θ - the local strain.

It was deduced that the decrease of free energy was smaller in case of segregation of carbon atoms, than in

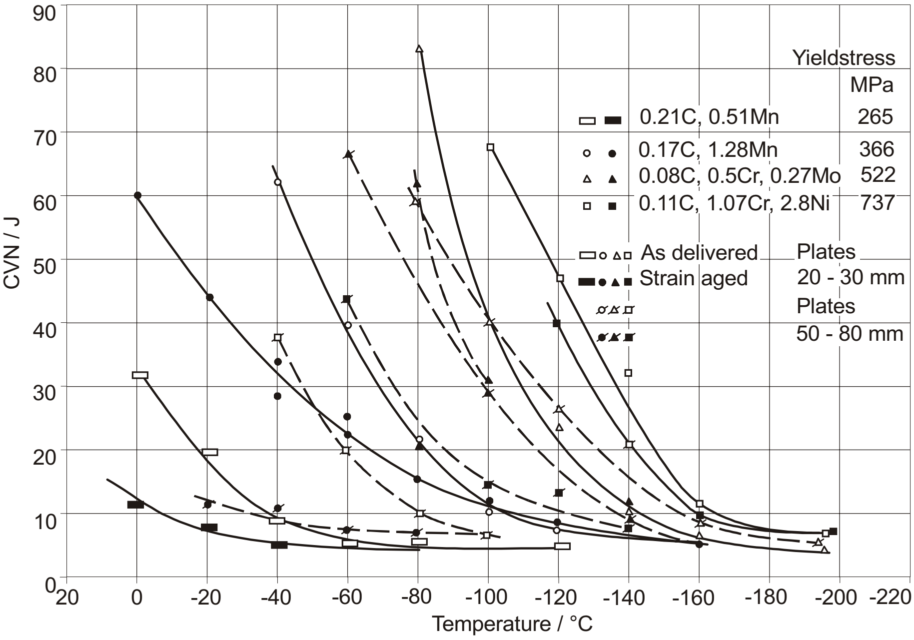

Figure 6. **Charpy notch toughness for different steels in as delivered and strain aged condition both sides the lower tough-ness tempereture threshold [21]**

Slika 6. **Charpy žilavost za različite čelike u početnom i deformacijskom starenom stanju na obje strane praga potpuno krtog prijeloma [21]** case of binding of the same number of carbon atoms to cementite [23].

The lower shelf notch toughness at a temperature of 10 to 20 °C below the lower shelf threshold is in the range from 8 to 12 J for as delivered and strain aged steels with yield stress in a wide range and the microstructure of polygonal ferrite and pearlite, quenched and tempered pearlite and ferrite and tempered martensite [25] (Figure 6.). In lower shelf range the fracture occurs with clevage in the ferrite matrix. According to the explanation proposed for the increase of notch toughness transition temperature[23], the lower shelf notch toughness should be lower for the strain aged than for the same as delivered steel. In the lower shelf the differences in Figure 6. are small and unsystematic. A difference in clevage behaviour would be reliably detected only with very careful, possibly non standard tests.

Also in fracture toughness tests the fracture occurs with cleavage of ferrite. From tests on 10 steels in as delivered and strain aged state the dependence on Figure 7. fracture toughness (K_{IC}) versus versus Charpy notch toughness (CVN) was derived [13]. In the limit of experimental error all obtained data fit acceptably to the relationship $K_{IC} = K + CVN^n$. No significant difference was detected between as deliverd and strain aged steels. The differences are, as for lower shelf notch toughness, probably smaller than the experimental error in the standard testing procedure.

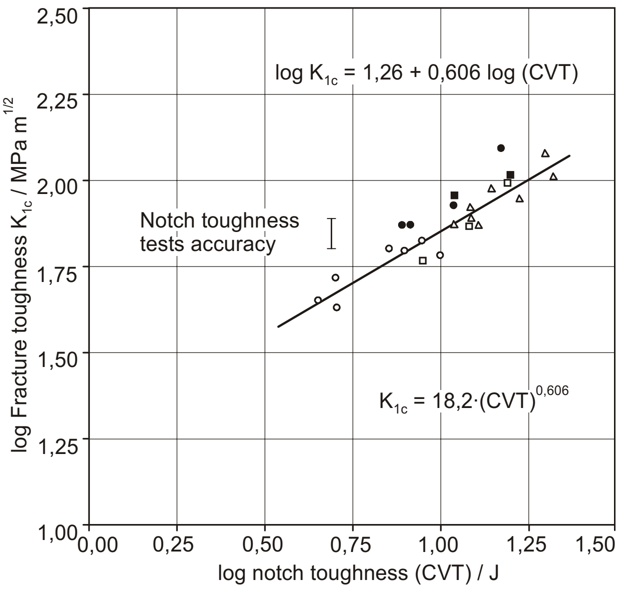

Figure 7. **Relationship fracture toughness - Charpy notch toughness for different structural steels [13]**

Slika 7. **Ovisnost žilavosti loma - Charpy žilavost za različite konstrukcijske čelike [13]**

CONCLUSIONS

A short survey is given on the effect of strain ageing on tensile properties and the Charpy notch toughness of three types of structural steels. It is shown that strain ageing affects the properties of all tested steels inspite of their different microstructure. Tensile properties are affected to a different measure: yield stress and tensile strength are strongly increased, while, reduction of area is slightly and uniform elongation is strongly decreased. The increase of yield stress is greater for lower as delivered yield stress, while the effect on uniform elongation is smaller with higher yield stress steel.

The change in tensile properties is due mostly to the effect of strain hardening after 10 % of plastic cold deformation. After 10 % plastic deformation and after ageing at 250 °C the Charpy notch toughness transition temperature is not changed, in comparison to that for the normalised steel. This temperature is increased only as the effect of synergy of deformation and ageing producing an interplane segregation of carbon atoms whic decreases the ferrite cleavage strength.

REFERENCES

[1] F. R. N. Nabarro: Report on Strength of Solids, p. 38, The Physical Society, London, 1948. Loc. cit.: ref 4.
[2] J. L. Snoek: Physica 1941, 8, 711, 741. Loc. cit. ref. 4
[3] A. H. Cottrell: Report on Strength of Solids, p. 30. The Physical Society, London, 1948. Loc. cit. ref. 4.
[4] D. V. Vilson: Acta Metallurgica, 1959, 5, 293.
[5] A. H. Cottrell: Dislocations and Plastic Flow in Crystals, p. 134, Oxford Un. Press, 1953,. Loc. cit. ref. 7.
[6] A. H. Cottrell: J. Iron and Steel Institute, 1952,172, 301.
[7] D. V. Vilson, B. Russell, J.D. Eshelby: Acta Metallurgica, 1959, 7, 628.
[8] C. Zener: Elasticity and Anelasticity of Metals, 1948, p. 122, Univ. of Chicago Press. Loc. cit. ref. 7.
[9] D. V. Vilson, B. Russell, Acta Metallurgica, 1960, 8, 36.
[10] W. R. Thomas, G.M. Leak: J. Iron and Steel Institute, 1955, 180, 155.
[11] D. V. Vilson, B. Russell: Acta Metallurgica, 1960, 8, 468.
[12] F. Vodopivec, J. Vojvodič-Tuma, M. Lovrečič-Saražin: Kovine Zlitine Technologije, 1998, 32, 463.
[13] 12. J. Vojvodič-Tuma: Nucl. Eng. Des., 2002, 211, 105.
[14] F. Vodopivec, J. Vojvodič-Tuma, M. Lovrečič-Saražin: Metalurgija, 38 (1999), 127.
[15] J. Vojvodič-Tuma: J. Materials Processing Technology, 2002, 121, 323.
[16] W. Dahl, H. Henstemberg, H. Behrens: Stahl u. Eisen, 1967, 87, 1030.
[17] B. Breskvar. Unpublished experimental findings.
[18] J. Vojvodič-Gvardjančič: Ph. D, Thesis, FAGG, Univ. Ljubljana, 1993.
[19] T. Tani, M. Naguno: Metal. Mater. Trans. A, 1994, 26 A, 391.
[20] B. Ule, J. Vojvodič-Gvardjančič, M. Lovrečič-Saražin: Can. Metal. Quart., 1996, 35, 159.
[21] F. Vodopivec, B. Breskvar, J. Vojvodič-Tuma, B. Arzenšek, S. Spaić, B. Markoli, D.A. Skobir: Materiali in Tehnologije, 2002, 36, 25.
[22] J. Chipman: Metall. Trans., 1972, 55.
[23] F. Vodopivec, B. Breskvar, S. Spaić, B. Markoli: Mat. Sci. Techn., submitted for publication.
[24] M. Nacken, J. Jargon: Arch. Eisenh., 1966, 37, 989.
[25] F. Vodopivec, J. Vojvodič-Tuma: M. Tokuda, B. Xu: Mechan. Prop. of Advanced Materials, Mie Univ. Press, Tsu, 2001, 187.