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CHANGE OF FRACTURE MODE IN CVN TOUGHNESS TRANSITION TEMPERATURE RANGE

SPREMEMBA NA^INA PRELOMA V OBMO^JU PREHODNE TEMPERATURE CHARPY @ILAVOSTI

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Survey of ref. data on CVN fracture. Tensile and CVN tests on structural steels with yield stress 372 to 737 MPa and different microstructure in temperature interval +22°C to NDT -20°C. Tensile and CVN fracture surface micromorphology. Increase of CVN ductile fracturing temperature because of deformation generated heat. Reduction of area, CVN toughness in transition temperature range, and crack tip blunting. Change of fracture mode by fracturing of CVN specimens in transition temperature range.

Key words: steels, tensile tests, CVN tests, fracture mode, crack tip blunting, deformation generated heat

Pregled literaturnih podatkov o Charpy `ilavosti. Raztr`ni in Charpy preizkusi konstrukcijskih jekel z mejo plasti~nosti 372 do 737 MPa in razli~no mikrostrukturo v intervalu od +22°C do NDT -20°C. Morfologija raztr`nega in Charpy preloma. Sprememba morfologije preloma zaradi toplote deformacije. Kontrakcija, Charpy `ilavost in otopitev konice razpoke v obmo~ju prehodne temperature. Sprememba na~ina preloma Charpy preizku{ancev v obmo~ju prehodne temperature `ilavosti.

Klju~ne besede: jekla, raztr`ni preizkusi, na~in preloma, otopitev vrha razpoke, toplota deformacije

1 INTRODUCTION

In CVN (Charpy V notch) toughness transition temperature notch toughness is decreased by 5 times in a steel with yield stress of 265 MPa up to 30 times in a steel with yield stress 522 MPa [1]. Parallely, the fracture mode is changed from ductile dimples in upper shelf range to brittle cleavage in lower shelf range. The tensile fracture of both steels and other steels with a yield stress up to app. 1000 MPa remained ductile down to NDT (nil ductility temperature) and below the onset of brittle fracturing by CVN tests[2]. The fracture mode of three steels with yield stress levels of 377, 522 and 737 MPa was ductile on unnotched tensile specimens and mixed ductile shearing near the notch tip and brittle cleavage in the central part of the section of notched tensile specimen tested at NDT[2].

In ref.[3] it is supposed that the change of fracture mode by CVN tests is due to the change of propensity of the steel to fracture initiation. The transition behaviour is associated to the plastic straining before the onset of brittle fracture[4,5,6]. According to ref.[7] the fracture propagates in ductile mode if ahead its front a three-axial shearing zone is formed and the fracture mode is changed because a tensile stress component normal to the fracture plane arises due to an increase of three-axiality. Cleavage fracture from a crack tip assumed to be initiated when the tensile stress exceeds the critical stress on a microstructurally determined distance ahead the crack tip[22]. An intrinsic change in the matrix during the plastic deformation preceding the decohesion is essential for the transition behaviour [4,5]. The absorbed energy is also dependent the bending during the Charpy test [5]. By brittle fracturing of hardened tool steels the notch toughness energy depended mostly on the energy consumed for elastic bending prior to fracture initiation[8]. The toughness available to drive a cleavage crack is the elastic energy stored in the specimen[9]. For the propagation of brittle fracture the blunting ahead of the crack tip is essential [4,8,9,10,11,12,13]. Multiple activation of brittle crack source occurs at the ductile crack tip and the mode of fracture propagation is changed from ductile to brittle[4]. In transition zone the mechanism of ductile fracture mode is independent upon the temperature and the transition is initiated because of insufficient crack blunting[11]. Critical is the brittle crack propagation to the next grain[5,14]. The combined criterion for cleavage fracture consists of a critical strain initiating the crack nucleus, a critical three-axial stress preventing the blunting of the crack tip, and a critical normal stress allowing the propagation of cleavage[12]. The crack tip must be blunted and have a critical radius to keep stable the crack propagation mode[13,15]. The theory on of stress controlled cleavage fracture and of shear fractures controlled by three-axial plastic strain and stress ahead the cracks tip seems to be valid[16]. The fracture of tensile test is unimode, while the fracture mode by Charpy testing is multimode and several events occur in the CVN fracture- propagating layer of steel, which are competitive in terms of local stress and local strain[17]. In lower shelf range the fracture is stress controlled and in upper shelf range strain controlled[18,19]. The Charpy test specimen is too small to develop a steady state fracture mode. Hence, it is not representative of the steady state toughness of steel [20]. The energy spent for the fracture of

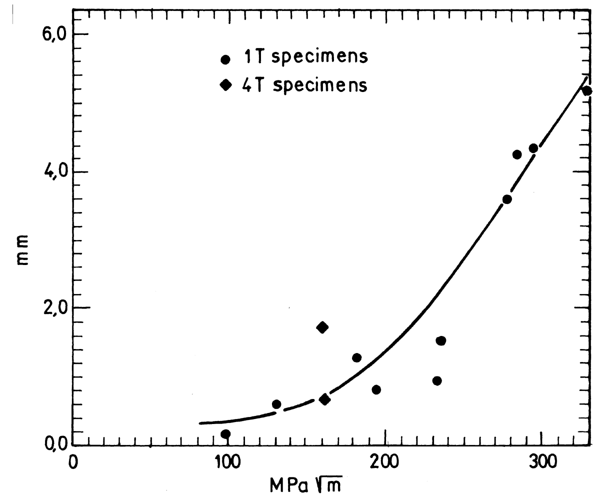

Figure 1: Relationship fracture toughness versus ductile propagation width from fatigue crack boundary to the cleavage initiation line. From ref.[23]

Slika 1: @ilavost loma v odvisnosti od oddaljenosti med mejo utrujenostne propagacije in mejo za~etnega preloma s cepljenjem. Ref.[23]

specimens is lower for low bending rate than for impact bending at the same temperature[21]. Fracture toughness is rapidly increased by increasing the ductile crack extension between the fatigue pre-crack from to the cleavage initiation boundary[23] as shown in **fig. 1**.

From this very condensed survey it is concluded that stress and strain three-axial and crack tip blunting are the perquisite for ductile crack propagation. Brittle fracture, is initiated when a new influencing factor, f.i. a mono-axial stress orthogonal to the plane of crack propagation arises or prevails, the blunting is decreased and the fracture propagation is changed from ductile to brittle. The question, why the fracture mode is changed from ductile to brittle at a specific distance from the notch tip, is not answered. In this article the answer to this question is proposed.

2 EXPERIMENTAL WORK

From 10 steel tested as delivered and after strain ageing[1], in this article the results obtained on three steels with yield stress values 377 (1), 522 (2), and 737 (3) MPa will be considered. The microstructure consisted of polygonal ferrite and pearlite grains in steel 1, of fine-grained distorted ferrite and pearlite grains in steel 2, and of tempered martensite in steel 3. Details on the composition and properties of the steels are given in ref.[1,2]. The share of different strengthening mechanisms[24], such as solid solution hardening, grain size strengthening and precipitate hardening in the yield stress is calculated. In ref.[25] a modified explanation of strain ageing is proposed, which is based on the fact that after strain ageing, the propensity of the steel to cleavage fracture is increased, while reduction of area is only slightly decreased.

The experimental work consisted of tensile tests on unnotched and notched specimens at different loading rates, CVN tests in transition temperature range, slow bending tests of unnotched and notched specimens, and SEM fracture examination[1]. Tensile and slow bending tests were carried out in ambient temperature and in the range NDT ± 20°C.

3 EXPERIMENTAL RESULTS

In **fig. 2, 3 and 4** the dependence tensile properties and CVN toughness versus testing temperature from ambient temperature to NDT -20°C is shown. By lowering the test temperature yield stress, tensile strength, and uniform elongation are increased and reduction of area (striction) is diminished. After strain ageing yield stress and tensile strength are increased, while reduction of area is slightly and uniform elongation greatly decreased. The effect of lowering temperature on steel properties after strain ageing was similar as by as delivered steels. CVN toughness was diminished in transition temperature range by app. 17 times by steel 1 (microstructure of polygonal ferrite and pearlite), by app. 12 times in steel 3 (microstructure of tempered martensite), and the most, by app. 30 times by steel 2 (microstructure of fine grained distorted ferrite and pearlite). The width of transition temperature range was in the limit of test accuracy of app. 100°C by all the steels. It ranged from + 10°C to - 90°C in steel 1 and from - 50°C to - 150°C by steels 2 and 3. This finding does not agree with the finding in ref.[26] that by higher yield stress of the same steel after different thermal treatment, independently on the microstructure, lower fracture toughness and higher transition temperature were obtained. Of the tensile properties, only reduction of area decreases by decrease of CVN toughness.

The fracture of tensile specimens tested at ambient temperature and NDTT - 20°C was ductile. The average size of dimples was smaller by steel 2 and especially steel 3 as by steel 1 **(fig. 5, 6)**. On notched tensile specimens tested at NDT the fracture consisted of a narrow band of shearing ahead the notch tip and a central area of brittle propagation[2]. The fracture of CVN specimens was ductile in upper shelf range, mixed in transition temperature and brittle in the lower shelf range. Also the average size of dimples on CVN specimens fractured in upper shelf range was smaller by steels with greater yield stress. The lower shelf fracture of CVN specimens was brittle **(fig. 7)**. Small dimpled areas were observed only on small sized slopes strongly inclined toward the crack propagation plane. On these areas cleavage micro-cracks propagating in different ferrite grains joined by shearing. By steel 2 and particularly by steel 3 cleavage facets were smaller and the stronger micro-relief showed a more frequent change of crack propagation direction **(fig. 8).** On specimens tested in the lower shelf range a few μm layer of ductile

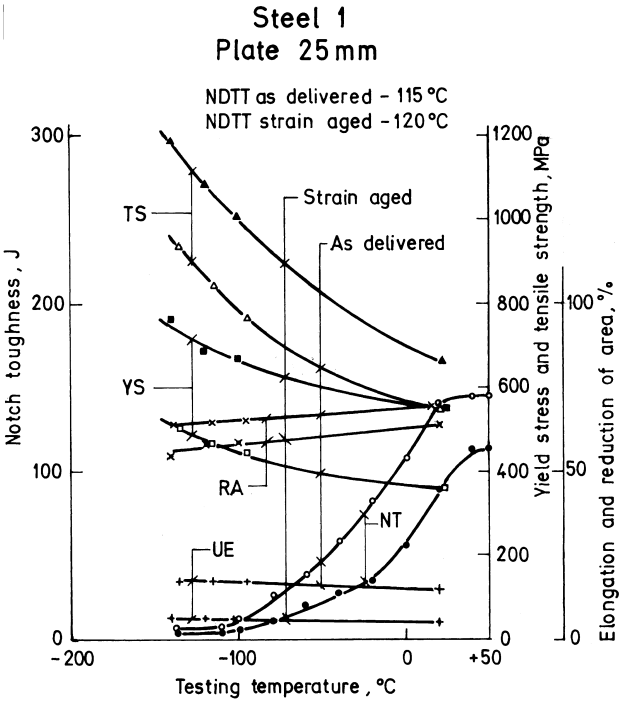

Figure 2: Effect of testing temperature on tensile properties and CVN toughness for as delivered and strain aged steel 1. From ref. [2]

Slika 2: Vpliv temperature na trdnostne lastnosti in Charpy `ilavost za dobavljeno in deformacijsko starano jeklo 1. Ref.[2]

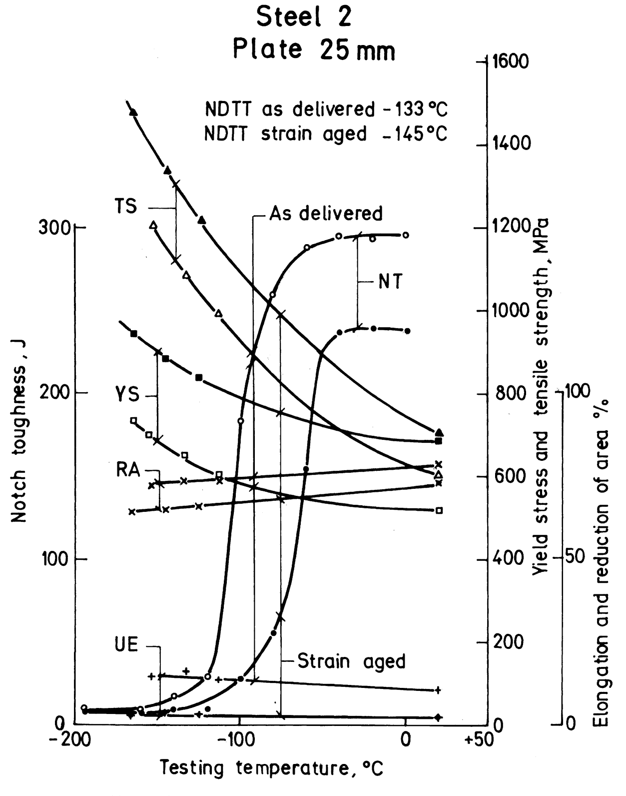

Figure 3: Effect of testing temperature on tensile properties and CVN toughness for as delivered and strain aged steel 2. From ref. [2]

Slika 3: Vpliv temperature na trdnostne lastnosti in Charpy `ilavost za dobavljeno in deformacijsko starano jeklo 2. Ref.[2]

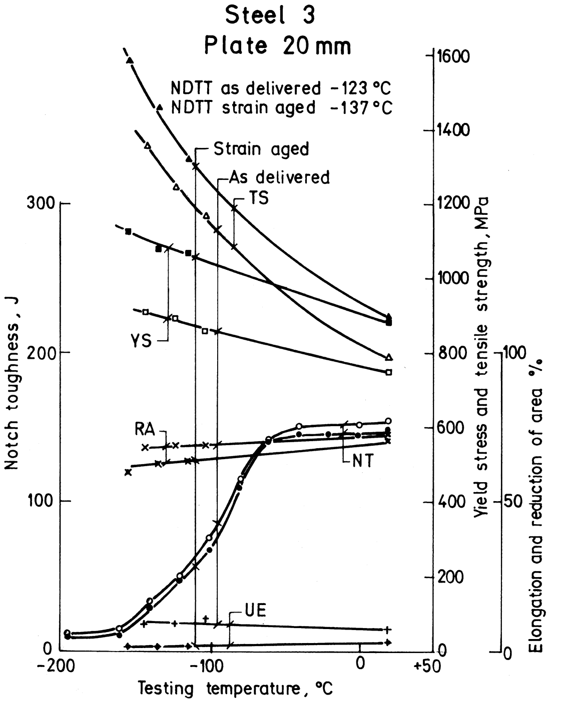

Figure 4: Effect of testing temperature on tensile properties and CVN toughness for as delivered and strain aged steel 3. From ref. [2]

Slika 4: Vpliv temperature na trdnostne lastnosti in Charpy `ilavost za dobavljeno in deformacijsko starano jeklo 3. Ref. [2]

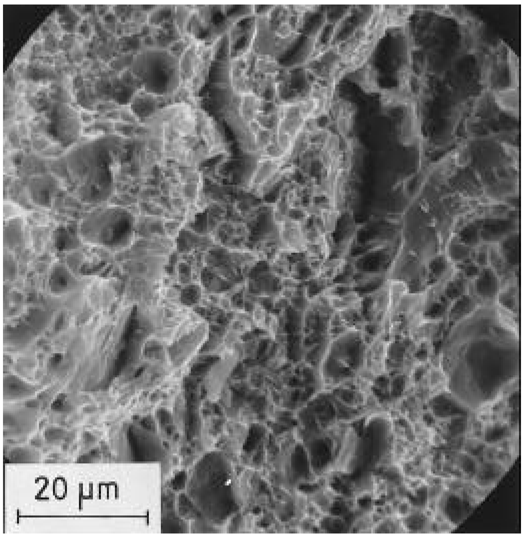

Figure 5: Dimpled ductile fracture surface of an unnotched tensile specimen of steel 1 broken at NDT (-125°C)

Slika 5: Jami~asta prelomna povr{ina nezarezanega nateznega preizku{anca iz jekla 1, ki je bil prelomljen pri NDT (-125°C)

shearing was observed immediately ahead the notch tip indicating to a thin layer of stretching before the crack initiation.

Unnotched slow bending specimens did not crack up to 170°C at ambient temperature, while at NDT brittle fracture occurred virtually without plastic deformation. Notched bending specimens fractured at NDT in similar way, while at room temperature their fracture was not

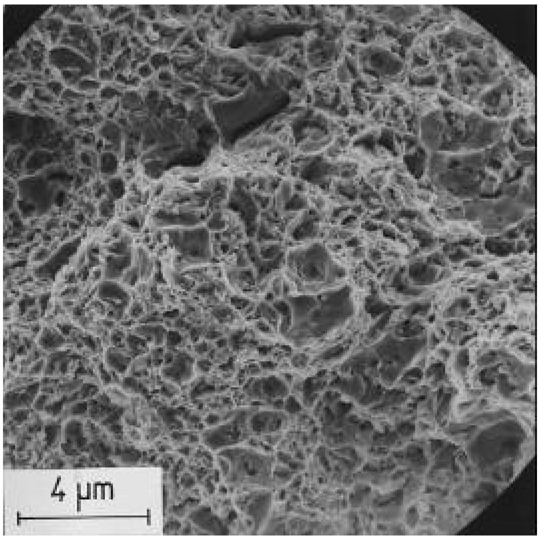

Figure 6: Dimpled ductile fracture of an unnotched tensile specimen of steel 3 broken at NDT (-145°C)
Slika 6: Jami~asta prelomna povr{ina nezarezanega nateznega preizku{anca iz jekla 3, ki je bil prelomljen pri NDT (-145°C)

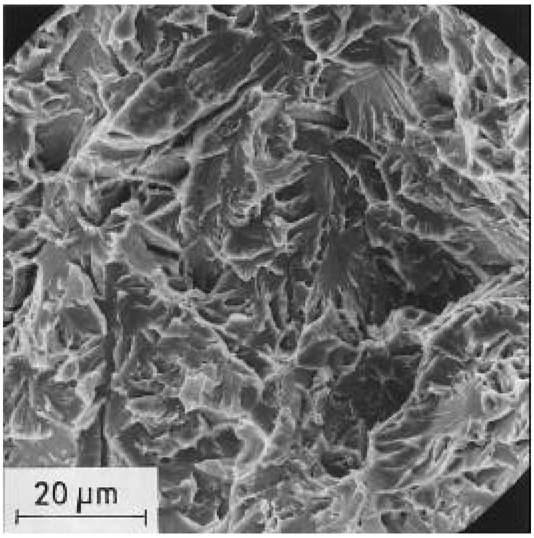

Figure 8: Cleavage fracture of a CVN specimen of steel 2 broken in lower shelf range
Slika 8: Lower shelf prelomna povr{ina Charpy preizku{anca iz jekla 2.

finished after bending to the angle of 160°C. The behaviour of steels by slow bending tests was as expected from CVN tests and show that the loading rate does not affect the mode of fracture.

4 BASIC CONSIDERATIONS ON THE CHARPY FRACTURE PROCESS

The elastic stressing state is established over the CVN specimen section instantaneously to the Charpy hammer stroke, since the rate of stress propagation is equal to the rate of sound propagation and it is independent upon the testing temperature.

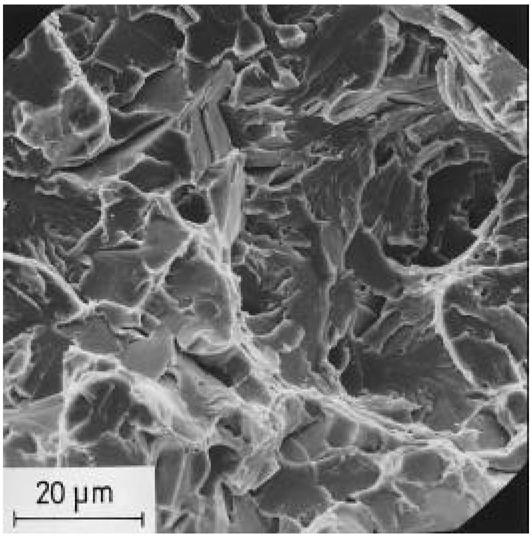

Figure 7: Lower shelf fracture surface of a CVN specimen of steel 1
Slika 7: Lower shelf prelomna povr{ina Charpy preizku{anca iz jekla 1.

The deformation rate (γ) is temperature dependent [27]:

$$\gamma = \gamma_o \exp -Q/RT \qquad (1)$$

With Q - activation energy, T - temperature in °K and R - the universal gas constant. Considering the value for activation energy given[28] for the temperature range of 50°C to 120°C it is calculated that the deformation rate is diminished by several orders of magnitude in the range of CVN transition temperature from +10°C to -150°C. Tensile tests in the range of loading rate from 0.1mm/s to 1500mm/s, thus over 4 orders of magnitude, showed virtually no rate effect on the mixed fracture mode of notched tensile specimens tested at NDT [2]. It is concluded that also by Charpy tests, which occur with an initial loading rate of 5.1m/s, the delay between the stressing and the plastic straining over the section of the CVN specimen can be neglected.

The gliding of dislocation is hindered by friction due to the presence in the metal of atom stress fields and obstacles, ev. coupled to strain fields, f.i. grain boundaries and precipitates. The force required to overcome the friction of dislocations gliding (σ_g) is defined[28] as:

$$\sigma_g = \sigma_o (T) + \sigma_2 \qquad (2)$$

and consists of one thermal and one athermal term. The size of athermal obstacles is thought to be larger than 10 interatomic distances in the metal lattice[27]. In **fig. 9** the effect of temperature on the temperature dependent friction force component is shown according to ref. [29]. This component increases from 31 MPa to app. 310 MPa in the range of transition temperature +10°C to -150°C. According to ref. [30] the friction force decreases by diminishing deformation rate. In ref. [31] it was established that by Charpy tests at strain rates 5.1m/s and $2.5 \cdot 10^{-4}$m/s the absorbed energy was smaller by smaller strain rate while the transition temperature was higher. During the plastic deformation about 90% of the energy-consumed[32] is transformed to heat. The heat generated depends on deformation rate, deformation volume, and the heat dissipation rate[28]. Assuming that for the plastic deformation and fracture of a volume of steel (V) of $0.7 \cdot 1 \cdot 0.5 = 0.35$ cm^3 an energy of E is absorbed the adiabatic increase of temperature is calculated as

$$\Delta T = 0.90 \cdot E / V \cdot c \cdot p \qquad (3)$$

with c- as specific heat and p- as specific weight.

By CVN toughness testing the share of energy consumed for the lateral contraction of specimens is the greater the greater is the ductile fracture area, while, the share of energy consumed for the elastic deformation is small, it corresponds appr. to the lower shelf notch toughness. Let us assume that by a CVN energy of 145 J, 10 J are consumed for the elastic deformation and 45% are consumed in the layer of steel directly involved in the fracturing process. Considering a specific heat of 0.448 J/g the adiabatic increase of temperature in a 5 mm thick layer of steel is calculated to $\Delta T = 53$°C.

It is clear that the process of ductile fracture by CVN tests does not occur at the nominal testing temperature, but a higher temperature corresponding to the virtually adiabatically generated heat in the fracturing layer of metal. Consequently, the inherent upper shelf threshold temperature is decreased by a value depending on the heat generated during the fracturing of CVN specimens. In lower shelf temperature the energy is consumed for the elastic deformation of specimens and, consequently, the fracturing process generates no heat, and the tests in lower shelf Charpy toughness occur at the nominal testing temperature. Thus, in transition temperature range the increase of temperature ΔT depends on the share of ductile fracture on the specimen section.

By the attempt to understand the mechanism of CVN fracturing in transition temperature range several facts and assumptions should be considered, such as:

- brittle fracturing occurs if the cleavage stress is achieved in absence of stretching of steel ahead the propagating crack and in absence of blunting;
- the ductile plastic deformation on lateral and back (hammer) sides of CVN specimens shows that by testing in transition temperature range previous plastic deformation by stretching and compression prevents the propagation of the brittle crack initiated at a specific distance from the notch tip;
- adiabatic generation of heat shifts the upper shelf threshold temperature to a lower value depending on the share of ductile fracture on the section of the CVN specimen;
- the basic difference between the unnotched tensile as well as CVN and notched tensile fracturing processes is in the fact that by unnotched tensile tests three-axial stressing and deformation occur simultaneously on the whole specimen section, while by CVN and notched tensile tests both occur only immediately ahead the notch, rsp. crack tip;

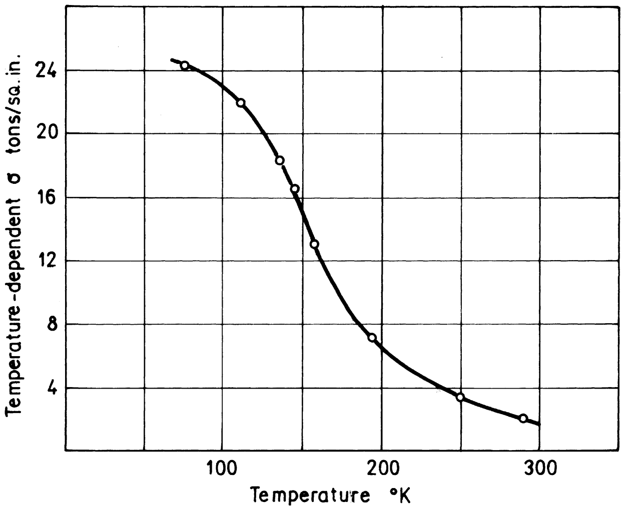

Figure 9: Effect of temperature on the temperature dependent component of the dislocation gliding friction force. From ref.[29]

Slika 9: Vpliv temperature na temperaturno odvisno komponento sile trenja pri gibanju dislokacij. Ref.[29]

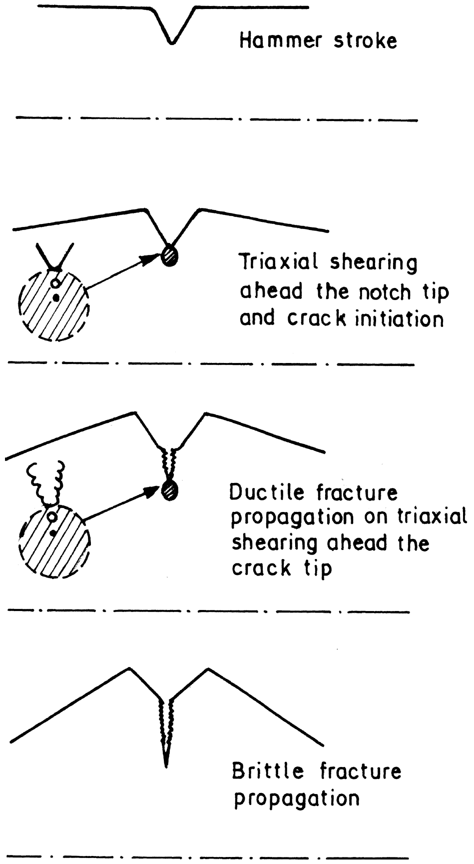

Figure 10: Scheme of CVN crack initiation and propagation in notch toughness transition temperature interval

Slike 10: Shema za~etka in {irjenja preloma Charpy preizku{anca v razponu prehodne temperature

- the loading and fracturing rates do not affect significantly the mode of fracturing of CVN specimens.

5 CHANGE OF CVN CRACK PROPAGATION MODE

In **fig. 10** the initiation and the propagation of the crack from the notch tip of a CVN specimen is shown schematically for a test in transition temperature range. The process of fracturing consists of several events

- Three-axial stressing and deformation in a band of steel ahead the notch tip,
- generation of vacancies through dislocation gliding and coalescence of vacancies to pores in the three-axially deformed band;
- growth of pores to dimples, separation of dimples ligaments by shearing to crack opening, and ductile crack propagation;
- start and propagation of cleavage at a distance the nearer to the crack tip, the lower is the nominal testing temperature.

The initial width of the three-axial deformation band ahead the notch tips depends on notch tip radius and on steel strain hardening. Since the crack tip shape is given, a sufficient steel strain hardening is needed for the going on of ductile fracturing events. However, the conditions for cleavage propagation are met at a specific distance from the crack tip by tests in Charpy transition temperature interval and the propagation mode is changed.

For ductile crack nucleation to occur, three-axial stressing and deformation ahead the notch tip are indispensable. It is therefore clear, as quoted in some references, that cleavage fracturing is initiated in absence of three-axial shearing and ahead the crack tip or when the width of the shearing band is decreased below a critical value. It is also logical to conclude that the shearing band width and the blunting do not drop at a definite distance from the notch tip, but that both decrease gradually when the ductile crack propagates from the crack tip. The change is the faster, the lower is the testing temperature in CVN transition range.

According to ref. [33] for ductile fracture propagation to occur the crack tip radius must have a size above a critical value. If not, the stability of the region ahead the crack tip is not ensured. In ref. [34] the crack tip blunting (B) is calculated from the equation:

$$B = 0.3 \cdot \sigma_y / E \cdot (1.5 \cdot E^{1+n/n} \cdot \sigma_y / E)^n \tag{4}$$

with σ_y - yield stress, E - modulus of elasticity, an n - strain hardening coefficient

The strain hardening coefficient can be calculated from the uniform tensile elongation (n_c) according to ref. [35, 36] as

$$n = \ln(1 + U_e) \text{ if } U_e = l - l_1/l \tag{5}$$

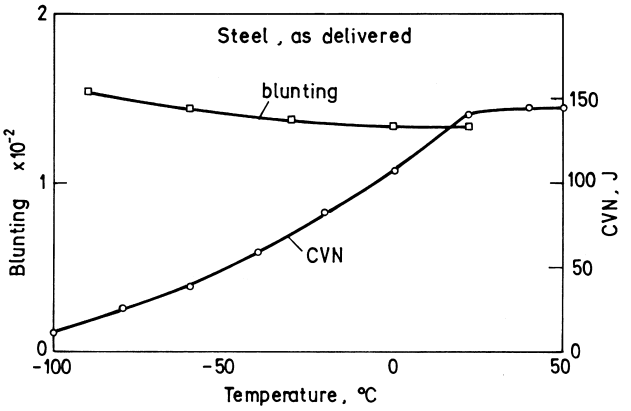

Figure 11: Notch toughness and blunting calculated according to ref. [34] in dependence of temperature in notch toughness transition temperature interval

Slika 11: Charpy `ilavost in otopitev izra~unana po ref. [34] v odvisnosti od temperature v razponu prehoda charpy `ilavosti

with l initial and l_1 the length of the tensile specimen before the necking is started.

In **fig. 11** the dependence of the calculated blunting and of the Charpy toughness on temperature is shown for the as delivered steel 1. While the toughness decreases strongly, the blunting does not change significantly in the transition temperature range. Thus, the change of blunting can not explain the change of fracturing mode. Since the stress concentration ahead the crack tip depends on crack tip acuity[3], it is clear that during the crack propagation the stress concentration could not change because of the blunting, as determined by yield stress and strain hardening of the steel.

It is stated in ref. [37] that when the temperature is raised yield stress decreases and the stress ahead the crack tip decreases also, thus, the cleavage stress would

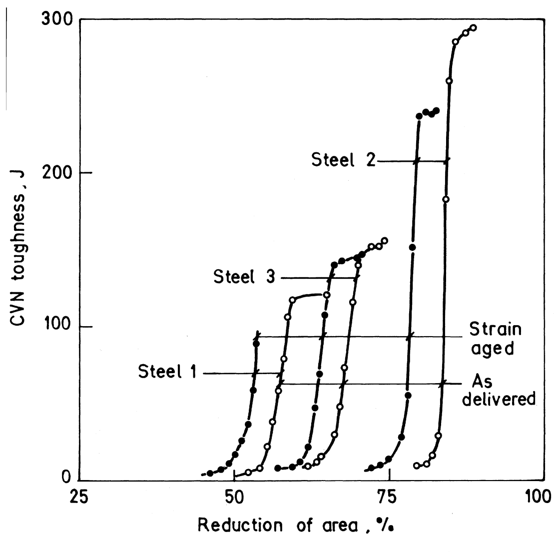

Figure 12: Relationship CVN versus reduction of area in notch toughness transition temperature interval

Slika 12: Odvisnost med kontrakcijo in Charpy `ilavostjo v razponu prehodne temperature be met only after proper work hardening. This hypothesis can not be applied to the change of CVN fracturing mode, since the change ductile cleavage propagation occurs at a nominally constant temperature and in reality on specimens, which temperature is even risen above the nominal level due to the heat generated by the previous ductile fracturing.

It was shown earlier that by lowering temperature only reduction of area decreases at decreasing testing temperature and behaves similarly to notch toughness. In **fig. 12**, notch toughness is shown in dependence of the reduction of area interpolated for the transition temperature range from room temperature and NDT ± 20°C values. Notch toughness decreases strongly by a very small decrease of reduction of area. Reduction of area is a measure of steel ductility by three-axial stressing in the volume of steel, where stretching and decohesion occur, it is also a measure of the rate of blunting decrease by crack propagation from the notch tip to the inside of the specimen. The somewhat surprising relationship in **fig. 12** could be understood considering that the three-axial shearing by CVN ductile fracturing is to be compared to the final event of ductile tensile fracturing, the discontinuance of dimples ligaments. The volume involved it at least 2 orders of magnitude smaller than the necking volume of tensile specimens. The experimental finding that the critical strain for ductile fracture decreases when the stress three-axiality in increased to a determined value[26] could be considered as an indirect corroboration of the relationship in **fig. 12**.

6 CONCLUSIONS

On the base of the survey of relevant references, experimental findings, and calculations the following conclusions are proposed.

The heat generated by plastic deformation, rsp. by the friction due to the gliding of dislocation, increases the fracturing temperature the more, the greater is the share of ductile decohesion on the fracture surface of CVN specimens. In lower shelf temperature range the fracturing temperature is virtually equal to the nominal testing temperature:

- the inherent blunting by ductile propagation is smaller than that due to the notch tip radius. Consequently, during the fracturing of CVN specimens the blunting decreases from the initial value the faster the lower is the fracturing temperature and the greater is the dislocation gliding force,
- the transition ductile decohesion to cleavage occurs in CVN specimens tested in toughness temperature range at the distance from notch tip, where the band of three-axial shearing ahead the crack tip disappears or it is diminished below a critical value,
- the decrease of the three-axial shearing band width from the value corresponding to the notch tip is gradual and occurs when the crack front propagates from the notch tip to the interior of CVN specimens,
- the change of crack propagation mode from ductile mode at the notch tip to cleavage occurs faster of lower temperature because of the increased force necessary for dislocation gliding by lower temperature,
- the decrease of the three-axial band width and of the blunting are connected to the decrease of reduction of area in the CVN toughness transition temperature range.

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