Kovine, zlitine, tehnologije / letnik 27 / številka 4 / strani 283 do 288 / 1993

Relationship between Fracture Toughness and mechanical Properties of some Structural Steels at Low Temperatures

Odvisnost med lomno žilavostjo in mehanskimi lastnostmi nekaterih konstrukcijskih jekel pri nizkih temperaturah

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The effect of strain-aging on the impact toughness characteristic of Charpy specimens (CVN) and on quasi-static fracture toughness values K_{IC} of some structural steels was investigated in the temperature range of nil-ductility temperatures. Strain-aging provokes shifts of Charpy curves to higher temperatures, but it decreases the nil-ductility temperatures regarding to as purchased steels. The correlation between K_{IC} and conventional mechanical properties valid for low temperatures confirms that K_{IC} and probably also K_{arrest} of as strain-aged steels are higher than that of as purchased steels with the same Charpy energy.

Key words: fine-grain low-alloy steels, fracture mechanics, fracture toughness, drop-weight test, nil ductility temperature.

Raziskali smo vpliv deformacijskega staranja nekaterih konstrukcijskih jekel na njihovo udarno Charpyjevo žilavost (CVN) ter kvazi-statično lomno žilavost K_{IC} v temperaturnem območju ničelne duktilnosti. Deformacijsko staranje pomakne Charpyjeve krivulje k višjim temperaturam, vendar pa zniža temperature ničelne duktilnosti glede na jekla v dobavnem stanju. Korelacija med K_{IC} in konvencionalnimi mehanskimi lastnostmi, veljavna pri nizkih temperaturah, kaže, da je K_{IC} in verjetno tudi K_{arrest} vrednost staranih jekel višja kot pri jeklih v dobavnem stanju z enako Charpyjevo energijo.

Ključne besede: drobnozrnata malolegirana jekla, mehanika loma, lomna žilavost, test s padajočim bremenom, temperatura ničelne duktilnosti.

1. Introduction

The relationship of microstructure to mechanical properties in low-alloy structural steels has been the subject of considerable research. Such steels with increased yield stress are sometimes alloyed with small additions of various elements so that the characteristics and the properties of such steels are substantially affected presumably due to the reduction of the austenite and ferrite grain size and because their yield stress, strength and toughness increase while the ductile/brittle transition temperature decreases which is perhaps one of the most important aspects of microalloying. In most of the previous investigations, fracture behaviour of steels has been evaluated mainly by means of the Charpy impact test because of its convenience and familiarity. Although the material requirements for a lot of practical applications are based on concepts of fracture mechanics, they are specified in terms of Charpy V-notch impact test results (CVN). Toughness requirements for thick-walled nuclear pressure-vessel steels are based on minimum dynamic toughness values, K_{Id}. However, the actual material-toughness requirements for steels used in these pressure vessels are specified using NDT (nil-ductility transition) values and CVN impact values using lateral expansion measurements. Empirical correlations, engineering judgment and experience are thus used to translate the fracture-mechanics guidelines or controls into actual material-toughness specifications[1]. A comprehensive concept for a practical estimation of the dynamic fracture toughness from the CVN impact energy vs. temperature curve was proposed by the MPC/PVRC Working Group on Reference Toughness[2]. It was proved that lower bound curves can be derived from the CVN vs. T-curve for the quasi-static and low rate dynamic fracture toughness (K_{Ic}), dynamic and high-rate dynamic fracture toughness (K_{Id}) and crack arrest toughness (K_{Ia})[3]. Besides this, some other correlations between conventional mechanical properties and K_{IC} values for ductile/brittle transition range or for lower Charpy shelves are also well-known[4,5]. However, it is well-known too that strain-aging of several low-alloy structural steels causes some shifts along the temperature axis which is not the same for both the CVN data and the K_{Ic} data. The purpose of the present paper is therefore to determine the more relevant correlation between the conventional mechanical properties and the K_{IC} values for some structural steels in the nil-ductility temperature range.

2. Experimental procedure

Nine non-, micro- and low-alloy structural steels in the form of hot-rolled and heat-treated flats were used in this investigation. The chemical composition, the designation of the steels and the thickness of the flats are given in **Table 1**. These steels with 0.05 to 0.21 wt.% carbon were either non-alloyed or alloyed with chromium, nickel, molybdenum, niobium and vanadium in different combinations. The microstructure of the investigated steels which was hot-rolled and subsequently cooled at different cooling rates was mainly ferritic with different shares of perlite (Nioval 47, Č.0562 and Č.1204) or bainite (Niomol 490 K). Only two types of low-alloyed steels (Nionicral 70 and Nionicral 90) have a microstructure of tempered martensite. The yield stress of the investigated steels varied from 265 MPa for plain carbon steel to 1003 MPa for Nionicral 96 i.e. for submarine steel alloyed with chromium, nickel and molybdenum. All the investigated steels were tested as purchased i.e. hot-rolled and cooled at different cooling rates but they were tested also after strain-aging, i.e. after cold-rolling with a reduction in thickness of 10% and additionnally heating for 30 minutes at 250°C.

Table 1: Chemical composition of the investigated steels (weight %)

No.	Grade (thickness)	C	Si	Mn	P	S	Cr	Ni	Mo	Nb	V
1	Nioval 47 (20 mm)	0.19	0.42	1.49	0.013	0.005	0.13	0.10	0.04	0.05	0.07
2	Nioval 47 (65 mm)	0.14	0.33	1.53	0.014	0.005	0.16	0.15	0.01	0.04	0.07
3	Nionicral 70 (20 mm)	0.11	0.28	0.27	0.009	0.007	1.07	2.80	0.26		0.06
4	Nionicral 70 (50 mm)	0.11	0.37	0.34	0.009	0.003	1.03	2.63	0.27		0.08
5	Nionicral 96 (50 mm)	0.14	0.29	0.51	0.017	0.009	1.64	2.76	0.42		
6	Niomol 490 K (60 mm)	0.05	0.35	0.42	0.011	0.004	0.75	0.29	0.33	0.06	
7	Č.0562 (25 mm)	0.17	0.32	1.28	0.020	0.009	0.21	0.23	0.05		
8	Č.0562 (80 mm)	0.18	0.46	1.29	0.036	0.004	0.30	0.15	0.03		
9	Č.1204 (30 mm)	0.21	0.25	0.51	0.011	0.025	0.02	0.04	0.01		

Test specimens were cut from the plates in transverse orientation and machined to the required dimensions. Besides the standard Charpy V-notch- and Drop-weight test specimens of P3 type (15.9 x 51 x 127 mm), a large number of round-notched and prefatigue cracked tensile specimens for the low-temperature measurements of quasi-static fracture toughness K_{Ic} was made. The drop-weight test specimens were prepared in accordance with the ASTM E208-84a where the crack starter bead application is performed by the one bead technique to avoid the undesirable variation of NDT[6]. The geometry of the round-notched precracked tensile specimens, prepared according Dieter s recommendation[7] is shown in **Figure 1**.

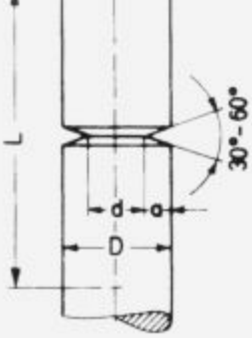

Figure 1: Geometry of a round-notched and precracked tensile specimen

Slika 1: Geometrija nateznega preiskušanca z zarezo in razpoko po obodu

At the experiments, it is essential that the fatigue annulus be of a uniform width and concentric with the outer diameter of the specimen in order to obtain a state of plain strain at fracture. The fatigue crack grew to a depth of about 0.2 mm, leaving an unfractured ligament approximately 6.5 mm in diameter.

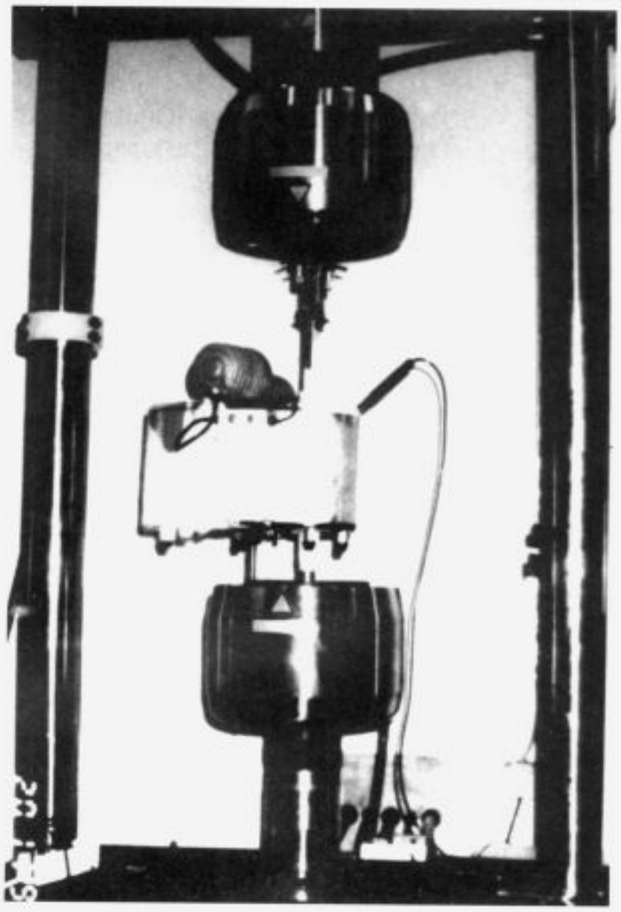

Figure 2: Experimental set-up with cryostat chamber

Slika 2: Eksperimentalna ureditev s kriostatsko komoro

An cryostat chamber filled with liquid nitrogen and petroleum ether was used during the test to control the specimen temperature range from - 140°C to room temperature and the fracture in the quasi-static test at crosshead speed of 1 mm/min was reached by using a universal testing machine (**Figure 2**). For a round-notched precracked specimen, the stress intensity factor is given by Dieter[7] as

$$K_I = \frac{P}{D^{3/2}}\ (-1.27 + 1.72\ D/d) \qquad (1)$$

where d is the radius of the uncracked ligament after fatiguing, P is the applied fracture load, and D is the outer diameter of the cylindrical specimen. In order to apply linear-elastic fracture mechanic (LEFM) concepts, the size of the plastic zone at the crack tip must be small compared with the nominal dimensions of the specimen. The size requirement for a valid K_{Ic} test is given by Shen Wei et. al.[8] as

$$D \geq 1.5\,(K_{IC}/\sigma_{ys}) \qquad (2)$$

where σ_{ys} is the initial yield stress of the material obtained at a strain rate comparable to that attained near the root of the notch in the fracture test. If the specimens did not comply with requirement **(2)** for valid fracture toughness (K_{Ic}) measurements, K_q values were obtained instead of K_{IC}, according to E399. However, the concept of the equivalent energy adopted by Wang Chang[9] enabled us to determine the virtual fracture load P^* instead of load P in equation **(1)** after the transformations of the surface under the parabolic load-displacement curve into the quantitatively equal surface of the triangle as shown on **Figure 3**.

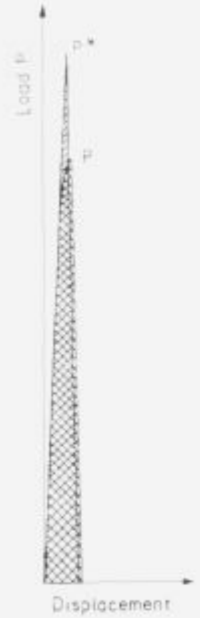

Figure 3: To the explanation of the concept of equivalent energy

Slika 3: K razlagi koncepta ekvivalentne energije

Therefore, the weak elasto-plastic fracture behaviour of the investigated steels even in the vicinity of the nil-ductility transition temperatures was approximated with linear elastic fracture behaviour.

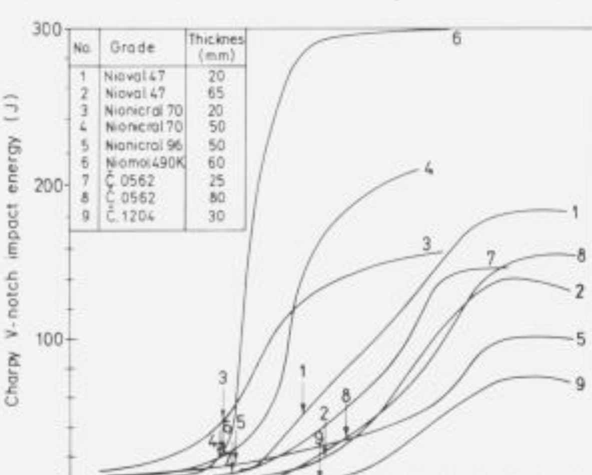

Figure 4: Charpy V-notch impact energy versus temperature behaviour of as purchased steels. Arrows indicate the NDT temperatures

Slika 4: Charpyjeve energije v odvisnosti od temperature preiskušanja jekel v dobavnem stanju. S puščicami so označene temperature ničelne duktilnosti

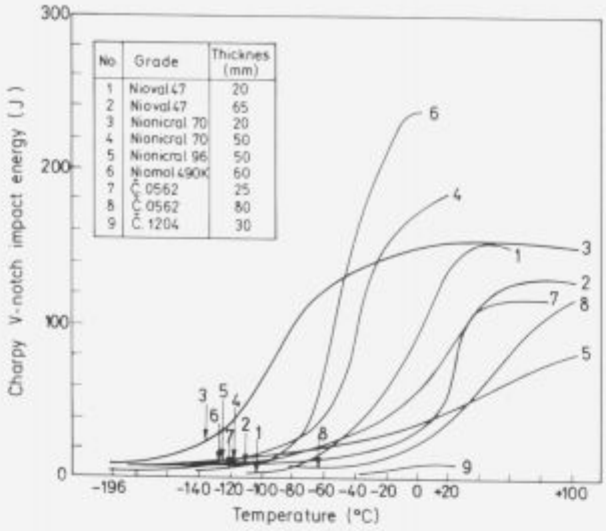

Figure 5: Charpy V-notch impact energy versus temperature behaviour of as strain-aged steels. Arrows indicate the NDT temperatures

Slika 5: Charpyjeve energije v odvisnosti od temperature preiskušanja jekel v staranem stanju. S puščicami so označene temperature ničelne duktilnosti

3. Results

Figure 4 shows the Charpy impact energy of as purchased steels as a function of the testing temperature whereas **Figure 5** shows the same relationship for investigated steels as strain-aged. The nil-ductility transition temperatures (NDT) measured at drop-weight test are also indicated in both diagrams. As may be seen, the ductile/brittle transition temperatures of the investigated steels are shifted against higher values due to strain-aging. However, the shift of nil-ductility transition temperatures nearly in all the cases shows a slightly opposite trend which is somewhat surprising.

The CVN impact energy, the yield stress σ_{ys} and the fracture toughness K_{IC} of the investigated steels measured at nil-ductility temperatures are given in **Table 2** for both as purchased and as strain-aged condition. However, because of

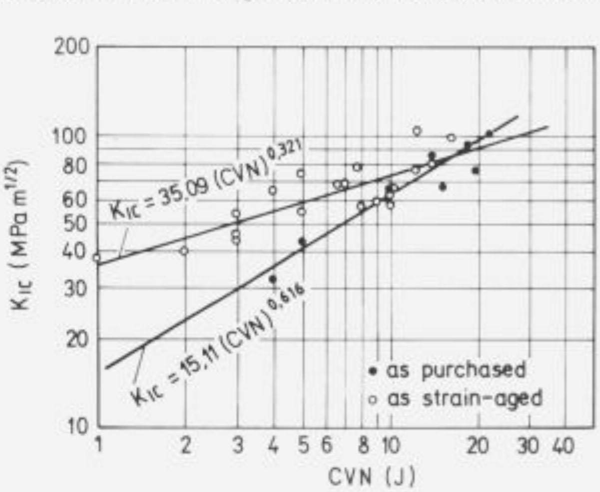

Figure 6: Relation between K_{IC} and CVN values in the nil-ductility temperature range

Slika 6: Odvisnost med K_{IC} in Charpyjevo udarno žilavostjo z V zarezo v območju temperatur ničelne duktilnosti the lack of diameter of the round-notched specimens for K_{IC} measurements, only the limited number of the entire data are taken into account, namely only data complying with the requirement **(2)**.

Table 2: Mechanical properties of the investigated steels at nil-ductility temperatures (28 valid measurements)

No.	σ_{ys} (MPa)	CVN (J)	K_{IC} (MPa $m^{1/2}$)	
			measured	calculated Eq.(5)
	As purchased			
1	908	13	68.5	75.2
2	900	19	76	80.4
3	524	5	43.5	45.1
4	354	4	31.5	34.2
5	717	10	65	62.1
6	1071	12	85	81.8
7	1056	17	91.5	86.7
8	1054	21	100.5	90.1
	As strain–aged			
9	681	7	68.5	56.3
10	780	3	53	52.0
11	780	4	63	54.9
12	745	5	73	55.7
13	803	8	56.5	63.7
14	791	10	58.2	65.9
15	781	10	65.5	65.9
16	1074	11	106	80.6
17	790	9	59	64.5
18	791	3	45	51.2
19	675	5	53	52.5
20	665	10	62.3	59.4
21	658	1	38.5	38.1
22	595	2	40	40.9
23	564	3	44.5	42.8
24	933	6.5	68.5	67.0
25	855	7.5	76.5	65.4
26	1343	11	75.5	92.2
27	1308	12	80	92.2
28	1293	14	99	94.3

The relationship between the CVN impact energy and the fracture toughness K_{IC} of the investigated steels is shown in the diagram of **Figure 6**. From the data point distribution it can be concluded that two different correlations between K_{IC} and CVN could be deduced, one for steels as purchased and another one for steels as strain-aged. Mathematical approximation with power function shows that the correlation for steels as purchased can be expressed as:

$$K_{IC} = 15.11\,(CVN)^{0.616} \qquad (3)$$

with a regression coefficient of 0.945, whereas the correlation for steels as strain-aged can be represented as:

$$K_{IC} = 35.09\,(CVN)^{0.321} \qquad (4)$$

with a regression coefficient of 0.819. As strain-aging provokes a considerable increasing of the yield stress of all the investigated steels, we tried to establish a unique correlation between K_{IC} on one side and both the properties CVN and σ_{ys} on the other side. The following correlation

$$K_{IC} = 0.776\,\sigma_{ys}^{0.60}\,(CVN)^{0.19} \qquad (5)$$

with a regression coefficient of 0.921 was deduced from the whole set of experimental data given in **Table 2**.

4. Discussion

Charpy V-notch impact toughness measurements and quasi-static fracture toughness measurements on some none- and low-alloyed structural steels in as purchased and as strain-aged condition respectively were performed over the temperature range of nil-ductility transition temperatures i.e. over the temperature range of -140°C to -40°C. The decrease of the NDT temperatures of steels as strain-aged regarding to the as purchased steels suggests that NDT temperature of steels as strain-aged is a good enough index temperature to represent the quasi-static fracture toughness transition behaviour of such steels, but it is maybe not an enough conservative estimation for the determination of the FTE temperature (NDT + 40°C). A similar ascertainment, but for dynamic fracture toughness transition behaviour of some stress-relief heat-treated steels for nuclear reactor pressure vessels, has been previously published by Tanaka and coworkers[6]. Nevertheless, it seems that the NDT temperatures, measured either in steels as purchased or after strain-aging, correspond to the adequate K_{arrest} value. Because the drop-weight test employs a sharp crack, moving rapidly from the notched brittle weld bead into the test plate, it does not come as a surprise either to find that the NDT temperature defined by this test correlates well with the beginning of an increase in fracture toughness with temperature measured in quantitative, sharp-crack tests[13].

Two different correlations between fracture toughness K_{IC} and CVN values for both groups of steels in the temperature range investigated show that steels after strain-aging have a noticeable higher fracture toughness K_{IC} than as purchased steels with the same Charpy energy. However, a very good correlation between K_{IC} and both properties, CVN and σ_{ys} was also deduced from all the data. The regression coefficient of Equation **(5)** is relatively high so that this approach seems to be relevant. Rolfe and Barsom[1] ascertained that the effects of both the notch acuity and the loading rate should be considered to establish correlations between K_{IC} and CVN test results in the transition-temperature region. They found out that K_{IC} values and CVN values in the transition-temperature region can be correlated (a) when the test results for slow-bend K_{IC} specimens are related to the test results for slow-bend fatigue-cracked CVN specimens and (b) when the test results for dynamic K_{IC} specimens are related to the test results for dynamic-cracked CVN impact specimens. The correspondence between K_{IC} and the CVN energy-absorption values obtained at a particular test temperature and the same strain-rate for both K_{IC} and CVN can be approximated by[1,10]

$$K_{IC} = A\,E\,(CVN)^{0.5} \qquad (6)$$

where A = constant of proportionality, E = Young's modulus, and K_{IC} and CVN are tested at the same temperature and strain rate.

The constant of proportionality, A, incorporates - in accordance with Rolfe and Barsom[1] - the effects of specimen size as well as notch acuity. By changing the value of A in Equation **(6)** it is then possible to correlate the K_{IC} data and the CVN energy-absorption values obtained by testing V-notched specimens. This equation suggests that the relationship between slow-bend K_{IC} and slow-bend CVN test results is the same as the relationship between the impact K_{IC} (i.e.K_{Id}) and the impact CVN results. This observation is not unexpected because it was shown[1] that a particular change in loading rate causes an equal shift along the temperature axis for both the CVN data and the K_{IC} data. Both authors also concluded that an engineering estimation of K_{IC} at any strain-rate can be predicted by using impact CVN data in conjunction with Equation **(6)** and then shifting the curve to lower temperatures. This approach has been used in investigating the effects of irradiation for steels used in nuclear reactors[11]. The magnitude of the temperature shift between dynamic and slow-bend curves was given by

$$T_{shift}(°C) = 118.4 - 0.12\,\sigma_{ys} \qquad (7)$$

and valid for steels with the yield stress σ_{ys} up to a value of 1000 MPa approximately, whereas it is diminished at steels with higher yield stresses. The general procedure to estimate K_{IC} values in the transition-temperature region from CVN impact results comprises the calculation of K_{Id} values at each test temperature using Equation **(6)** with followed shift of K_{Id} values at each temperature by the temperature shift calculated with Equation **(7)** to obtain static K_{IC} values as a function of temperature. This procedure was adopted from more recent recommendations of Rolfe and Barsom[1] and it represents a conceptual advantage compared to the previously published methods[4,5]. By comparing our Equation **(3)** for as purchased steels with the Rolfe-Barsom Equation **(6)** one can see that the exponents in both equations are relatively close. If the exponent of 0.5 is adopted also in our case owing to simplicity and considering some unaccuracy in our calculations (small number of data for relevant statistical analyse), then Equation **(3)** can be transformed into

$$K_{IC} = 20\,(CVN)^{0.5} \qquad \mathbf{(8)}$$

where the calculated constant of 19.97 was rounded up to a value of 20.

It could be assumed that Equation **(8)** represents the lower envelope of all the measured values i.e. it represents the realistic conservative estimation of the fracture toughness of the investigated steels in the temperature range of nil-ductility transition temperatures irrespective by their microstructure or prehistory. Nevertheless, at very low CVN absorbed energies our equation gives higher K_{IC} values compared with the values obtained from the previously established Barsom-Rolfe equation for the transition temperature range[4]. Namely, the mentioned authors[4] found that the plane strain fracture toughness K_{IC} in the transition region is related to the Charpy energy CVN by

$$K^2_{IC} = 0.22\,E\,(CVN)^{3/2} \qquad \mathbf{(9)}$$

where the Young modulus E is expressed in GPa, K_{IC} is expressed in MPa $m^{1/2}$, and CVN in Joules. The 54 J Charpy energy commonly used to determine the transition temperature of similar steels[12] corresponds roughly to 150 MPa $m^{1/2}$ when the relationship **(9)** is used. Quite a similar value is obtained also with Equation **(8)**, which means that both equations could be applied in the transition temperature range. It is not surprising because the loading rate and the notch acuity do not have a great influence on the fracture-toughness behaviour at slightly higher toughness values.

Besides the above mentioned equations of Barsom and Rolfe[4,10] /**(6)**,**(8)**/ there are also some other successful attempts. Namely, Begley and Logsdon[5] suggested that for low temperatures where the behaviour is predominantly brittle, the fracture toughness (in MPa $m^{1/2}$) may be related empirically to the yield stress σ_{ys} (in MPa) alone:

$$K_{IC} = 0.0717\,\sigma_{ys} \qquad \mathbf{(10)}$$

Although Equation **(10)** essentially differs either from the equations of Barsom and Rolfe[4,10] or from our equations **(3)** and **(4)**, it is not in larger disagreement with our observations since for lower Charpy shelves both approaches give a considerably higher fracture toughness for as strain-aged steels with higher yield stress. The empirical correlation **(10)** is also in good agreement with K_{Id} data[14] so our linking the Eq. **(10)** with the equation of the type $K_{IC} = A\,(CVN)^b$ into a single form **(5)** was relevant. The relatively high regression coefficient for this new correlation **(5)** i.e. a correlation which is compatible with the Barsom and Rolfe[4,10] approach as well as with the approach of Begley and Logsdon[5] confirm that Eq. **(5)** enables the best empirical estimation of the low-temperature fracture toughness K_{IC} calculated on the basis of conventional mechanical properties measured in the temperature range investigated as it is also shown in **Table 2**.

5. Conclusions

1. The fracture toughness was measured in the temperature range of nil-ductility temperatures of nine non- and low-alloy structural steels either in as purchased or as strain-aged condition and it was correlated with the Charpy V-notch impact energies. Although the strain-aging reduces the Charpy energies i.e. provokes some shifts of Charpy values to higher temperatures, it also decreases the nil-ductility temperatures of such steels.

2. The fracture toughness K_{IC} of the investigated steels in the temperature range of nil-ductility temperatures can be sucessfully predicted either by the Equation **(3)** for as purchased steels or by the Equation **(4)** for steel as strain-aged. The estimation of K_{IC}, which would be conservative enough for both states of steels can be given by the Equation **(8)** which has also a simple form.

3. In general, the most suitable and still plain procedure for obtaining the actual fracture toughness K_{IC} of structural steels in the temperature range of nil-ductility temperatures, being also compatible with various other concepts[1,4,5,10], would comprise tensile and Charpy testing at lower temperatures and further application of the generalized correlation **(5)**.

The correlation **(5)** suggests that K_{IC} and probably also K_{arrest} of as strain-aged steels would be higher than that of as purchased steels with the same Charpy energy because of the increasing yield stress at strain-aging. Consequently, strain-aged steels have lower NDT temperatures than those of as purchased steels.

REFERENCES

[1] Rolfe, S.T.; Barsom, J.M.: Fracture and Fatigue Control in Structures, Applications of Fracture Mechanics. Englewood Cliffs, New Jersey, Prentice-Hall 1977.

[2] Bamford, W.; Oldfield, W.; Marston, T.: An Improved Reference Fracture Toughness Procedure for Pressure Vessel Steels, 5th ICPVT, San Francisco, 9./14.9.1984, p. 932/65.

[3] Kussmaul, K.; Demler, T.: Steel Research 63 (1992) No. 12, p. 545/53.

[4] Barsom, J.M.; Rolfe, S.T.: Correlations Between K_{IC} and Charpy V-Notch Test Results in the Transition-Temperature Range, Impact Testing of Metals, ASTM STP 466, American Society for Testing and Materials, Philadelphia, 1970, p. 281/302.

[5] Begley, J.A.; Logsdon, W.A.: Correlation of Fracture Toughness and Charpy Properties for Rotor Steels, Scientific Paper 71-1E7-MSLRF-P1, Westinghouse Research Laboratories, Pittsburg, July, 1971.

[6] Tanaka, Y.; Iwadate, T.; Suzuki, K.: Int. J. Pres. Ves. & Piping 31 (1988), p. 221/236.

[7] Dieter, G.E.: Mechanical Metallurgy, McGraw-Hill, 1986, p. 358.

[8] Shen Wei et al.: Engng. Fracture Mech. 16 (1982), p. 69/82.

[9] Wang Chang: Engng. Fracture Mech. 28 (1987), p. 241/250.

[10] Barsom, J.M.: Engng. Fracture Mech. 7 (1975), p. 605/18.

[11] Hawthorne, J.R.; Mager, T.R.: Relationship Between Charpy V and Fracture Mechanics K_{IC} Assessments of A533-B Class 2 Pressure Vessel Steel, ASTM STP 514, American Society for Testing and Materials, Philadelphia, 1972.

[12] Faucher, B.; Dogan, B.: Metallurgical Transactions A, 19A (1988), 505/16.

[13] Langford, W.J.: Canadian Metallurgical Quarterly 19 (1980), p. 13/22.

[14] Scarlin, R.B.; Shakeshaft, M.: Metals Technology, January 1981, p. 1/9.