Fracture Mechanics Investigations of Structural Steels with the Yield Stresses between 265 and 1000 MPa

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ABSTRACT. *Knowledge of mechanical properties and fracture behaviour of fine-grained low-alloyed and structural steels in wide range of yield stresses is important from the manufacturer, as well as user point of view. Especially, the behaviour of steels below the nil ductility temperature (NDT±20 °C) is very important. Mechanical properties of selected structural and fine-grained low-alloy steels were determined in as delivered and as strain-aged condition. In the present paper for selected steels the following characteristics are given: chemical compositions, impact Charpy toughness in temperature region between 80°C and -196 °C, nil temperature ductility* T_{NDT} *determined by drop weight test, tensile properties at room temperature and at temperatures ±20°C higher and lower than* T_{NDT}*, respectively. For selected steels fracture toughness* K_{IC} *in nil ductility temperature region, as well as J-integral were determined.* K_{IC} *was determined with cylindrical V-notched precracked tensile specimens and J-integral was determined with CT samples by a modified chevron notch. Detailed microstructure characterisation and fractography of fractured samples were also performed. The effect of strain-aging on the impact Charpy toughness and quasy-static fracture toughness of ten structural steels was investigated in the nil-ductility temperature range. Strain–aging provokes shifts of Charpy curves to higher temperatures, but it decreases the nil-ductility temperatures regarding to as-received steels. The correlation between* K_{IC} *and conventional mechanical properties valid for low temperatures confirms that* K_{IC} *values of as strain-aged steels are higher than those in as received condition at the same Charpy energy level.*

1. INTRODUCTION

Fine-grained micro-alloyed structural steels are commonly used as structural elements of complex constructions which operate in low temperature region, usually between -20 and -60 °C. Although, such constructions are designed with computer supported numerical calculations such as finite element methods (FEM) considering geometrical non-linearity, starting geometrical imperfections, materials inhomogeneity, retained stresses etc. they have to be considered also from the fracture-mechanics point of view because of the risk that brittle fracture can occur.

Our preliminary investigations showed [1] that strain ageing processes of fine-grained micro-alloyed structural steels cause expected shift of Charpy impact energy curves to higher temperatures, but measured T_{NDT} of strain-aged steels determined with Drop Weight Test are lower than T_{NDT} of as-received steels. Now the question is if the nil temperature ductility is a safe enough criterion for the selection of low-temperature limit and usability of strain-aged steels with predominantly ferrite microstructure. The correct answer is very important, because a prehistory of steel is generally unknown, and therefore, it is unknown the actual condition of steel to be used, e.g.: non-strain-aged or perhaps partially strain-aged steel. On the other hand, steels used for different structures (for example pipe lines, high-pressure vessels etc.) are frequently strain-aged already during their manufacture because of cold plastic deformation (bending, forming) followed by the rapid heating in the cold weather conditions (welding).

2. EXPERIMENTAL PROCEDURE

The chemical compositions of investigated steels are collected in Table 1. Charpy V-notched (CVN) test samples, plain tensile samples P-3 type in accordance with ASTM E 208 with dimensions 15,9 x 127 mm with brittle surface weldments for T_{NDT} with Drop Weight test and large number of cylindrical tensile test specimens with diameter of 10 mm for determination of conventional mechanical properties, as well as V-notched precracked cylindrical tensile test specimens for K_{IC} determination at low temperatures were cut of and machined from selected steels.

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

GRADE THICKNESS	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Nb	V	Al
NIOVAL 47 (20 mm)	0,19	0,42	1,49	0,013	0,005	0,13	0,10	0,04		0,050	0,07	0,087
NIOVAL 47 (65 mm)	0,14	0,33	1,53	0,014	0,005	0,16	0,15	0,01		0,042	0,07	0,026
NIONICRAL 70 (20 mm)	0,11	0,28	0,27	0,009	0,007	1,07	2,80	0,26	0,20		0,06	0,043
NIONICRAL 70 (50 mm)	0,11	0,37	0,34	0,009	0,003	1,03	2,63	0,27	0,17		0,08	0,050
NIONICRAL 96 (20 mm)	0,14	0,29	0,51	0,017	0,009	1,64	2,76	0,42	0,21		0,01	0,054
NIOMOL 490 K (25 mm)	0,08	0,34	0,36	0,011	0,004	0,54	0,17	0,27	0,36	0,058		0,052
NIOMOL 490 K (60 mm)	0,05	0,35	0,42	0,011	0,004	0,75	0,29	0,33	0,40	0,058		0,057
Č.0562 (25 mm)	0,17	0,32	1,28	0,020	0,009	0,21	0,23	0,05	0,35	0,003		0,045
Č.0562 (80 mm)	0,18	0,46	1,29	0,036	0,004	0,30	0,15	0,03	0,22	0,001		0,043
Č.1204 (30 mm)	0,21	0,25	0,51	0,011	0,025	0,02	0,04	0,01	0,009	0,050		0,027

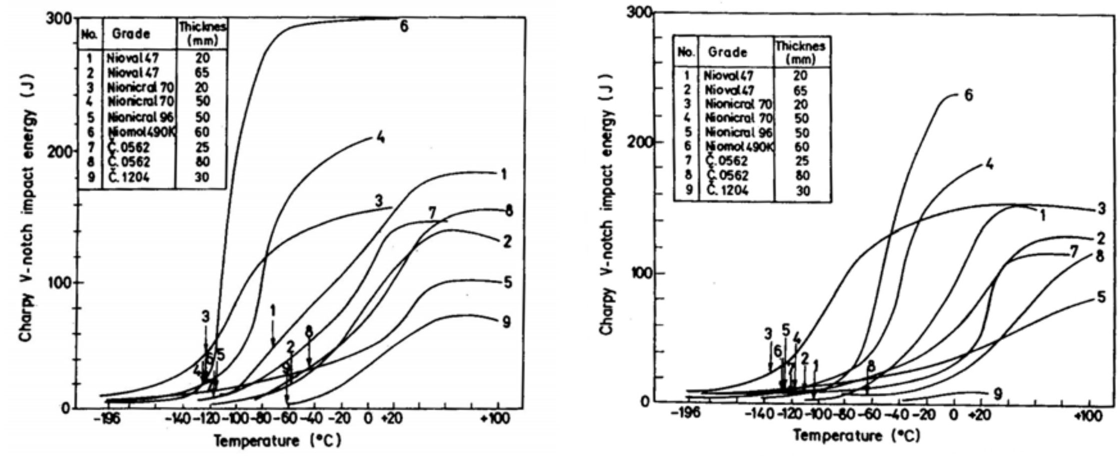
CT samples with modified notch in accordance with ASTM E 399-83 were also made for determination of fracture toughness. The orientation of all samples was perpendicular to the rolling direction. Notches on Drop Weight Test specimens were made on the upper and lower surfaces of plates and not laterally as at samples for fracture toughness determination. K_{IC} was determined in the nil temperature ductility regions with cylindrical V-notched precracked tensile specimens. Diameter of fatigue precracked region *d* was determined after tensile test by scanning electron microscope (SEM) at low magnification (Fig. 1) and fracture toughness was calculated by Heckel's equation [2, 3, 4].

Figure 1. Fractured surface of cylindrical tensile test specimen with precracked circumferential V notch, SEM micrograph, magnification 10 x

3. RESULTS

Figure 2a shows the Charpy impact energy of as-received steels as a function of a testing temperature whereas Figure 2b shows the same relationship for investigated steels in as-strain-aged condition. The nil-ductility transition temperatures are also indicated in both diagrams. As can 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 almost in all cases shows a slightly opposite trend which is surprising.

The Charpy impact energy (CVN), 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.



a) b)

Figure 2. Charpy V-notch impact energy versus temperature behaviour of a) as delivered steels and b) of as strain-aged steels; arrows indicate the NDT

Table 2. Mechanical properties of the investigated steels at nil-ductility temperatures

No.	σ_{ys} (MPa)	CVN (J)	K_{IC} (MPa $m^{1/2}$) measured
	As received		
1	908	13	68.5
2	900	19	76
3	524	5	43.5
4	354	4	31.5
5	717	10	65
6	1071	12	85
7	1056	17	91.5
8	1054	21	100.5
	As strain-aged		
9	681	7	68.5
10	780	3	53
11	780	4	63
12	745	5	73
13	803	8	56.5
14	791	10	58.2
15	781	10	65.5
16	1074	11	106
17	790	9	59
18	791	3	45
19	675	5	53
20	665	10	62.3
21	658	1	38.5
22	595	2	40
23	564	3	44.5
24	933	6.5	68.5
25	855	7.5	76.5
26	1343	11	75.5
27	1308	12	80
28	1293	14	99

In table 2 the obtained results are given for both as received and as strain-aged condition. However, because of the small diameter of the round-notched specimens for K_{IC} measurements, only the limited numbers of the entire data are taken into the account. Namely, only the data complying with the requirement given by Shen Wei [5] as: $D \geq 1,5\ (K_{IC}/\sigma_{ys})$, 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.

The relationship between the CVN impact energy and the fracture toughness K_{IC} of the investigated steels is shown on the diagram in Figure 3. From the data point distribution it can be concluded that two different correlations between K_{IC} and CVN could be deduced [6], one for steels as received and another one for steels as strain-aged:

steel in as-received condition: $K_{IC} = 15,11 \cdot (CVN)^{0,62}$ (1)

steel in as-strain-aged condition: $K_{IC} = 35,10 \cdot (CVN)^{0,32}$ (2)

Both correlations agree well with experimental data; equation (1) has regression coefficient r = 0,945 and equation (2) has regression coefficient r = 0,819

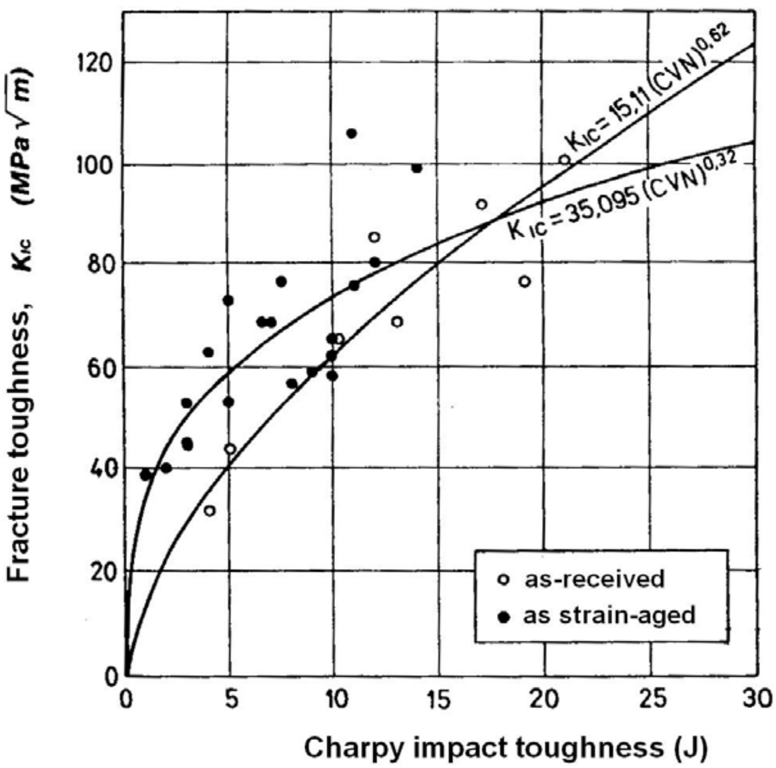
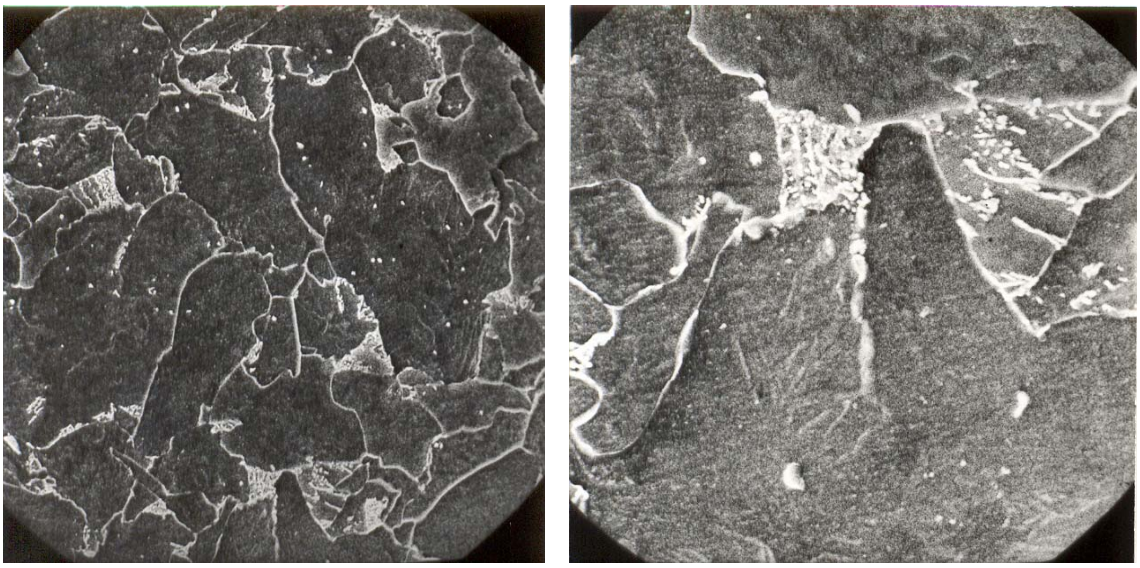


Figure 3. Relation between K_{IC} and CVN values in the nil ductility temperature range

The microstructure of steel Niomol 490 K (steel plate with thickness of 25 mm), visible under SEM microscope is shown on Figures 4a and 4b. It is a ferrite-bainite structure without martensite. In the microstructure of this steel prevail ferrite and two-phase (α'+carbides) microstructure constitution as a result of tempering.



a) b)

Figure 5. Microstructure of steel Niomol 490 K, SEM micrograph, longitudinal section: a) magnification 2000 x and b) magnification 6000 x

4. DISCUSSION

Charpy V-notch impact toughness measurements and static fracture toughness measurements on ten structural and fine-grained low-alloy steels in as delivered and as strain-aged condition, respectively, were performed over the temperature range of nil-ductility transition temperatures; i.e. over the temperature range of -145 °C to -45 °C. The decrease of nil ductility temperatures T_{NDT} of steels as strain-aged regarding to the as delivered steels suggests that T_{NDT} temperature of steels as strain-aged is good enough index temperature to represent the quasy-static fracture toughness behaviour of such steels, but it is maybe not a conservative enough estimation for the determination of the *FTE* temperature (T_{NDT} + 40 °C).

Two different correlations between fracture toughness K_{IC} and Charpy V-notch impact toughness values (*CVN*) for both groups of steels in the temperature range investigated show that steels after strain-aging have a significant higher fracture toughness K_{IC} than as delivered steels with the same Charpy energy. However, a very good correlations between K_{IC} and both properties, *CVN* and σ_{YS} was also deduced from all the data. The regression coefficient of both equations (1) and (2) is relatively high so that this approach seems to be relevant. Rolfe and Barsom 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 when the test results for slow-bend K_{IC} specimens are related to the test results for slow-bend fatigue-cracked CVN specimens and 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 [7] :

$$K_{IC} = A \cdot E \cdot (CVN)^{0,5} \tag{3}$$

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

5. CONCLUSIONS

Ten steel plates with the thicknesses of 20 to 60 mm were investigated in the range from room temperature to the NDT –20 °C. The microstructure of investigated steels is polygonal ferrite and pearlite, quenched-and-tempered ferrite and pearlite, and tempered martensite. Depending on microstructure and heat-treatment, yield stresses of investigated steels are between 265 and 1003 MPa. Tensile properties, notch toughness, fracture toughness, nil temperature ductility, as well as crack-initiation and propagation energies were determined. All these steels were investigated in as received and as strain-aged condition. As-aged condition is understood artificially aged (heat-treated) steel. The specimens of steel sheets were firstly cold rolled with 10 % reduction (deformation) and then heated at 250 ºC for ½ hour. On the basis of our experimental investigations the following conclusions are made:

- The result of strain-ageing of investigated micro-alloyed steels is shift of ductile-to-brittle transition (measured by Charpy impact energy) to higher temperatures and decrease of nil-ductility temperature T_{NDT}.
- The analysis of instrumented Charpy impact toughness measuring results showed that strain-ageing of investigated steels significantly decreases its crack initiation energy, but it has negligible effect on the crack propagation energy.
- Charpy impact toughness of strain-aged steel is consequently lower than Charpy impact toughness of steels in as-received condition in the whole temperature range.
- Dependence fracture toughness K_{IC} vs. Charpy impact energy *CVN* is different for strain-aged steels compared to steels in as-received condition in the temperature range close to nil-ductility temperature. It was found out that two empirical relationships are valid in the nil-ductility temperature range T_{NDT}.

From the results of our empirical equations one can conclude that the fracture toughness of strain-aged steel is higher than the fracture toughness of as-received steel at equal value of Charpy energy in the region of very low temperatures. In the literature one can find different empirical correlations valid in this temperature region. The Barsom-Rolfe-Novak's equation takes into the account only the dependence between K_{IC} and *CVN*. The equation Begley-Logsdon considering yield stress enables calculation of K_{IC} at very low temperatures only. However, our correlations overcome both difficulties.

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