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Resistance of Structural Steel to Crack Formation and Propagation

Odpornost gradbenih jekel proti nastanku in širjenju razpoke

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Parameters of linear fracture mechanics can be a useful measure for selection of steel with various strength and yield stress (in limits 200 to 1000 MPa). They determine also influence of purity (non-metallic inclusions) and of thermal or thermomechanical treatment.

These parameters are effective only if they are measured in the conditions when the plastic deformation at the initial crack growth is limited to minimal value. This happens in corrosion media by measuring K_{IC}^{c} *and especially in impact loading by measuring* K_{IC}^{d}*. These parameters are closely connected with the microstructure and structure of steel. They are suitable for designing structures resistant to brittle fracture if operational (destruction) conditions of those structures are seized, since they occur at high preceeding plastic deformations.*

V članku razpravljamo o načinih zboljšanja efektivnih parametrov linearne mehanike loma, ki so merilo kvalitete gradbenih jekel in osnova za izračun konstrukcij odpornih proti krhkemu prelomu. Predmet raziskave je bila skupina malooglјičnih in malolegiranih jekel z napetostjo tečenja 200–1000 MPa. Po kemični sestavi spadajo ta jekla v štiri skupine: malooglјična, mangan silicijeva, manganova mikrolegirana jekla in kompleksno legirana jekla z 0.2–0.6% Mo.

Po trdnosti lahko omenjena jekla razdelimo v tri skupine: v skupino z napetostjo tečenja do 290 MPa (normalna trdnost); v skupino z napetostjo tečenja do 390 MPa (povišana trdnost) in v skupino jekel z napetostjo tečenja več kot 390 MPa (visoka trdnost).

Lomne karakteristike smo raziskovali pri statičnih in dinamičnih obremenitvah ter v korozijskem mediju. Raziskave smo opravili v skladu z GOST in mednarodnimi standardi, pa tudi po originalni metodiki. Največ smo uporabljali epruvete z ekscentrično obremenitvijo (CTS) (sl. 1), dvojno konzolno vpeto klinasto epruveto (sl. 2) in cilindrične preizkušance s koncentrično krožno zarezo z utrujenostno razpoko kot koncentratorjem napetosti (sl. 3). Pri statičnih obremenitvah smo ugotovili pomembne posebnosti v rasti vrednosti K_{IC} *s trdnostjo jekla takrat, ko je imelo valjano jeklo "racionalno" mikrostrukturo. Ugotovili smo tudi, da raste vrednost* K_{IC} *v jeklih s povišano in visoko trdnostjo s čistostjo jekla. Istočasno pa ti parametri niso zelo tesno povezani z mikrostrukturo jekla. Njihova uporaba v inženirskih izračunih pa omogoča oceniti velikost nevarnih napak v konstrukcijah. V članku je tudi pokazano, kako je moč z omejitvijo obsega plastične deformacije (pri dinamičnih preizkusih ali v korozijskih medijih) povečati občutljivost parametrov linearne mehanike loma od mikrostrukture jekla. Te parametre je moč privzeti kot efektivne, kar je na koncu članka prikazano s primerom izračuna primarnega dela plinovoda iz malolegiranega jekla.*

1 Introduction

In steel structures good weldable low-carbon and low-alloyed steel with yield stress 200 to 800 MPa are used. In the recent time the resistance of those steels to brittle fracture is more frequently estimated by parameters which caracterize the crack stability[1,2]. Steel resistance to brittle fracture is highly dependant on its microstructure. Thus the mechanical properties of steel, especially the parameters determining the crack stability, are useful in estimating the resistance to brittle fracture. This is especially valid when the value of those parameters is microstructurally a highly sensitive value.

It is very advantageous if those parameters are applicable in designing structures. This condition is fulfilled the more completely the better description of fracture conditions is achieved in this way.

Paper describes the decisive effective parameters of crack stability which are highly dependent on microstructures as a measure of useful properties of structural steel, and they can be also simply applied in engineering design of structures which must be resistant to brittle fracture.

2 Testing of Steel

Plates of all structural steel types being used in former Soviet Union were investigated with a special emphasis on those standardized in GOST 27772-88. Steels differ by their composition, strength, and way of manufacturing.

Steels with yield stresses 230 to 285 MPa are characterized as steel with standard strength, while higher-strength steels had yield stresses 290 to 375 MPa, and high-strength ones above 390 MPa. According to chemical composition the treated steels can be divided in four groups:

- low-carbon steels with up to 0.22% carbon,
- low-alloyed steels, mainly manganese-silicon ones (12G2S, 09G2S, 14G2),
- manganese microalloyed steels (14G2AF, 09G2FB,...),
- complex molybdenum-alloyed steels (12GN2IFAJU).

Classification and composition of those steels is particularly described in ref.[2]. The guaranteed values of yield stresses of the discussed steels after standard working or heat-treatment processes are described in **Table 1.**

Table 1. Guaranteed values of yield stresses of investigated structural steels

Steel	Guaranteed yield stress (MPa)		
	Hot rolled	Normalized	Hardened and tempered
Low-carbon	230–285	230–285	285
Manganese-silicon	335–375	335–375	390
Manganese microalloyed	-	390–440	490
Complex molybdenum alloyed	-	-	590–740

(-) due to low resistance to brittle fracture, the steel is not used in such a state

Steels of the third group (e.g. 09G2FB) are used either as controlled by rolled, or like some others of that group as thermomechanically treated by various processes detailed described elsewhere[2].

3 Investigation Methods

Estimation of the crack stability in ductile structural steel has some specialties. Increase of nominal stress can exceed the yield stress on the crack front in these steels. In all cases it happens before the stress intensity factor reaches its critical value.

At that time plastic deformation takes place at the crack tip in the zone of r_T size (Fig. 4). The size of r_T zone is for the case of plane-stressed state equal to:

$$r_T = \frac{1}{2\pi} \cdot \frac{K_{IC}^2}{\sigma_T}, \tag{1}$$

and in the case of plane-strain state equal to:

$$r_T = \frac{1}{6\pi} \cdot \frac{K_{IC}^2}{\sigma_T}, \tag{2}$$

In the conditions of actual stress and strain states during the testing, the size of plastic deformation zone is between the two extremes. The conditions in our testing corresponded to the following size of plastic deformation zone:

$$r_T \approx 0.1 \cdot \frac{K_{IC}^2}{\sigma_T}$$

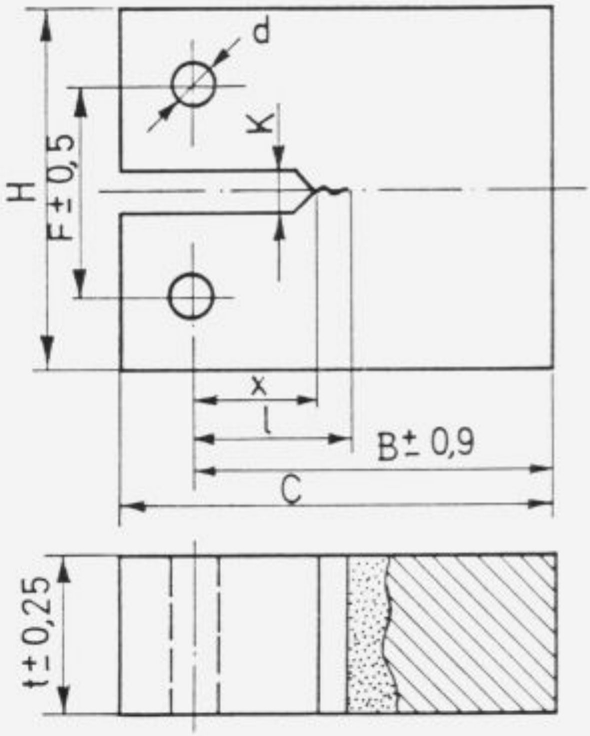

Figure 1. CTS test probe (type 3 according to GOST 25.506-85) for determining crack stability parameters in structural steel.
$l = (0.45 \text{ to } 0.55)B$, $t = 0.5B$, $C = 1.25B$, $d = 0.25B$, $K \leq 0.05B$, $F = 0.55B$, $H = 1.2B$

Slika 1. Epruveta CTS (tip 3 po GOST 25.506-85) za merjenje parametrov stabilnosti razpoke v jeklih za gradbene konstrukcije.
$l = (0.45 \text{ do } 0.55)B$, $t = 0.5B$, $C = 1.25B$, $d = 0.25B$, $K \leq 0.05B$, $F = 0.55B$, $H = 1.2B$

Correct determination of the fracture toughness value (stress intensity factor) is possible only if the size of r_T plastic deformation zone is essentially smaller than the crack length and effective test probe cross section. In structural steel such a ratio (r_T/l) cannot be easily achieved since they have low yield stresses and high fracture toughnesses K_{IC}. Based on numerous tests detailed described elsewhere[2] some general recommendations for selection of test-probes for static testing depending on plate thickness and steel strength were given. For 40 to 60 mm plates of low-alloyed steel the K_{IC} parameter can be correctly determined at temperatures below −40°C with CTS probes (**Fig. 1**). For 20 to 40 mm plates the contoured double-cantilever doubleaxially notched probe (**Fig. 2**) gives good results since plastic deformation at crack front is highly reduced in it. In many cases, especially in industrial testing, the cylindrical probes with concentric peripheral notch (**Fig. 3**) gave good results.

Measurements were made correspondingly to GOST 25506-85 standard (Determination of characteristics of crack stability in static loading) and to ASTM standards. Rupture conditions were intensified by dynamic loading and using corrosion media. Dynamic tests were made according to ASTM standards5 and to RD50-344-82 instructions for method selection (Determination of characteristics of fracture toughness in dynamic loading). Test were made both with CTS and Charpy probes with fatigue crack according to GOST 9454-78. Influence of corrosive medium on the crack stability was studied with probes according to

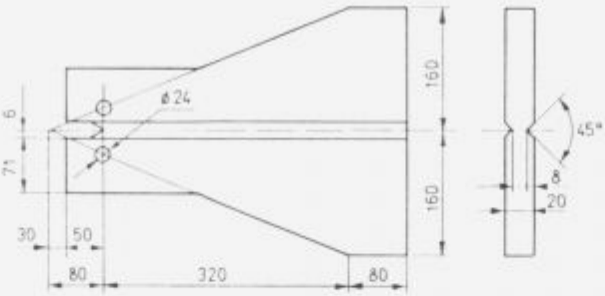

Figure 2. Contoured double-cantilever double axially notched probe.
Slika 2. Dvojno konzolno vpeta klinasta epruveta z dvema osnima zarezama.

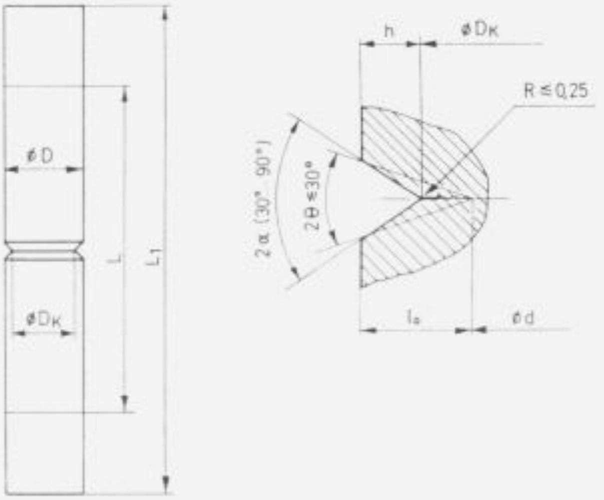

Figure 3. Cylindrical probe with concentric fatigue crack—(type 2 according to GOST 25.506-85). L = length between the clamped parts of probe in the tensile testing machine. $L = 5D$; $d = (0.6 \text{ to } 0.7)D$; $L_1 \geq 7D$; $I_0 = 0.5(D - d) \geq h + 1.5$ mm; $l_0 \geq 3.7 \operatorname{tg} \alpha$; $D_K = D - 2h = (0.65 \text{ to } 0.85)D$.
Slika 3. Cilindrična epruveta s koncentrično utrujenostno razpoko—(tip 2 po GOST 25.506-85). L = razdalja med deloma epruvete, ki se vpneta v trgalni stroj $L = 5D$; $d = (0.6 \text{ do } 0.7)D$; $L_1 \geq 7D$; $I_0 = 0.5(D - d) \geq h + 1.5$ mm; $l_0 \geq 3.7 \operatorname{tg} \alpha$; $D_K = D - 2h = (0.65 \text{ do } 0.85)D$.

Figure 4. Scheme of crack tip with the zone of plastic deformation.
Slika 4. Shema razpoke s cono plastične deformacije.

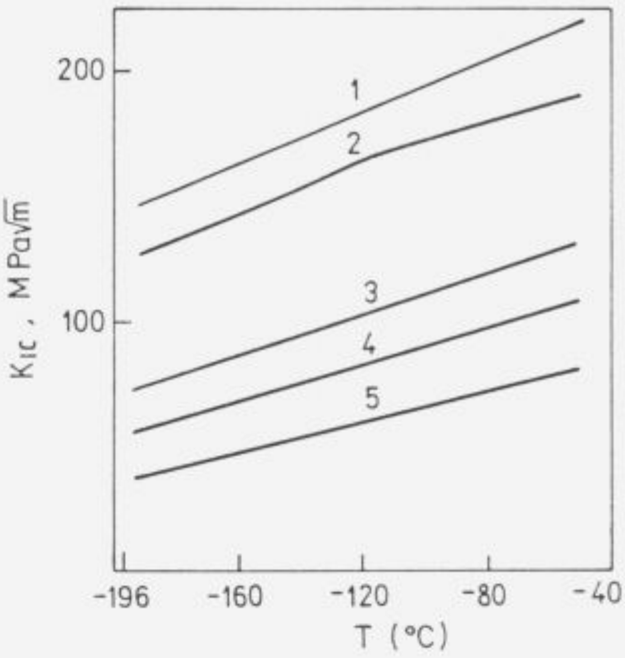

Figure 5. Fracture toughness of structural steel plate. Dependance of K_{IC} on temperature, plate thickness 20 mm. Probe from Fig. 2. 1) Hardened and tempered molybdenum-alloyed steel: 0.12% C, 0.54% Si, 1.05% Mn, 0.5% Cr, 1.47% Ni, 0.12% V, 0.24% Mo, 0.011% Al, 0.022% N, 0.025% S 2) The same steel, plate thickness 40 mm, $R_p = 710$ MPa 3) Hardened and tempered manganese-silicon steel (0.1% C, 1.48% Mn, 0.9% Si, 0.031% S, 0.021% P); $R_p = 435$ MPa 4) Steel above, rolled; $R_p = 350$ MPa 5) Hot rolled low-carbon steel (0.16% C, 0.24% Si, 0.65% Mn, 0.025% S, 0.025% P); $R_p = 265$ MPa.
Slika 5. Lomna žilavost pločevine iz jekla za gradbene konstrukcije. Odvisnost K_{IC} od temperature, debelina pločevine 20 mm. Epruveta slika 2. 1) Poboljšano legirano jeklo z molibdenom: 0.12% C, 0.54% Si, 1.05% Mn, 0.5% Cr, 1.47% Ni, 0.12% V, 0.24% Mo, 0.011% Al, 0.022% N, 0.025% S 2) Isto jeklo, debelina pločevine 40 mm, $R_p = 710$ MPa 3) Poboljšano mangan-silicijevo jeklo (0.1% C, 1.48% Mn, 0.9% Si, 0.031% S, 0.021% P); $R_p = 435$ MPa 4) Jeklo (3) valjano; $R_p = 350$ MPa 5) Vročevaljano maloogljično jeklo (0.16% C, 0.24% Si, 0.65% Mn, 0.025% S, 0.025% P); $R_p = 265$ MPa.

GOST 9454-77 in distilled water and in 3% NaCl water solution according to RM SEV method (Corrosion protection in building engineering. Corrosion cracking of high-strength armature steel. Investigation methods, 1986).

Moving rate of the tensile-tester clamping jaws was $2 \cdot 10^{-8}$ mm/min which was sufficient for completing test in one day. Also impact toughness with U and V-notched probes (according to GOST 9454-78) was measured simultaneously with the uniaxially loaded tensile tests according to GOST 1797-84 with flat probes of the same thickness as investigated plate.

4 Results of Tests

Static testing gave a series of relations valid for the crack stability in structural steel (Figs. 5 to 8). It shows that in steel of standard purity and rational microstructure the fracture toughness value increases with the increased strength and with the transition from ferrite-pearlite microstructure

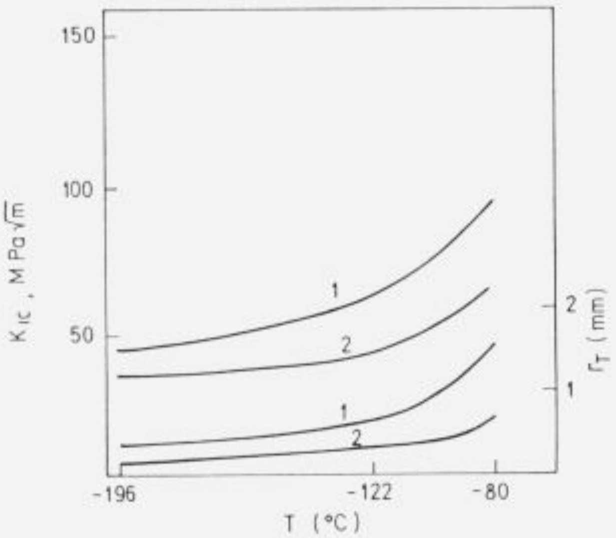

Figure 6. Fracture toughness and the size of plastic deformation zone in normalized steel (0.17% C, 1.56% Mn, 0.4% Si, 0.11% V, 0.015% N, 0.008% S, 0.07% P). Sulphide inclusions are modified by addition of RE, curve (1) vacuum treated steel; $R_p = 460$ MPa.

Slika 6. Lomna žilavost in velikost cone plastične deformacije v normaliziranem jeklu (0.17% C, 1.56% Mn, 0.4% Si, 0.11% V, 0.015% N, 0.008% S, 0.07% P). Sulfidni vključki so modificirani z dodatkom RZ, (1) jeklo vakuumirano; $R_p = 460$ MPa.

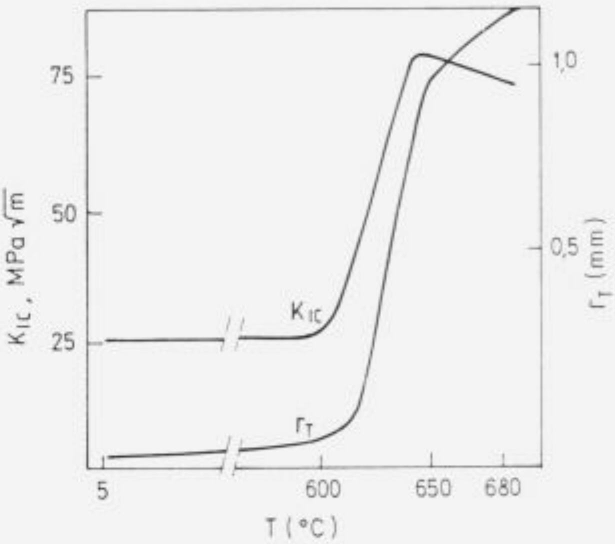

Figure 7. Dependance of fracture toughness and the size of plastic deformation zone on tempering temperature for molybdenum-alloyed steel (0.10% C, 0.37% Si, 1.16% Mn, 3.1% Cr, 1.0% Ni, 0.34% Mo, 0.016% S, and 0.04% P), plate thickness 20 mm, probe type from Fig. 3.

Slika 7. Odvisnost lomne žilavosti in velikosti cone plastične deformacije od temperature popuščanja za jeklo legirano z molibdenom (0.10% C, 0.37% Si, 1.16% Mn, 3.1% Cr, 1.0% Ni, 0.34% Mo, 0.016% S in 0.04% P) debelina pločevine 20 mm, epruveta sl. 3.

to microstructures obtained by hardening and tempering (**Fig. 5**).

Plate thickness reduces the K_{IC} value (Fig. 5) due to the reduced plastic deformation zone (r_T). The investigation results also indicate that fracture toughness of high-strength steel depends on type, amount and distribution of non-metallic inclusions, mainly sulphides (**Fig. 6**). Pure steel (0.008% S) excells the steel with standard amount of sulphur both in the respect of fracture toughness and in size of plastic deformation zone at crack tip (r_T). This confirms the influence of inclusions, on which decohesion takes place (formation of voids), on the conditions of crack initiation[3].

In heat-treated steels the fracture toughness K_{IC} is abruptly reduced if tempering temperature is reduced from 650 to 600°C (Fig. 6). The reason is in changed mechanism which controls the crack initiation. The two-stage process connected to formation of microvoids is substituted by an energy undemanding mechanism of local destruction which is detailed described elsewhere[4].

The reduced tempering temperature reduces the K_{IC} value measured by static loading (**Figs. 6** and **7**) which is in contradiction with the hitherto ideas, especially with the changed size of plastic deformation zone r_T.

This can be explained by applied testing methods which did not allow a suitably high microstructural sensitivity of parameters describing the crack stability in ductile steel with rational microstructure. This is confirmed with two additional cases of unsufficient microstructural sensitivity in estimating K_{IC} value with static tests. **Table 2** presents the relation between the fracture toughness of manganese-silicon steel and the chemical composition and the hardening temperature. Steel samples with various chemical compositions were hardened at optimal temperature of 930°C, and at 1050°C. This temperature was chosen in order to determine the influence of overheating. In all the cases the steel samples were tempered at 650°C.

Investigation results indicated that concentrations of alloying elements had a small influence on mechanical properties. Overheating of steel highly deteriorates the Charpy-test values, transition the impact toughness value which was practically halved. K_{IC} value is not extra highly influenced by overheating; the obtained differencies were below 5% and they are in the region of measuring errors.

The second case is connected to the selection of thermomechanical treatment in manufacturing 50 mm plate with yield stress $R_p \geq 450$ MPa made of microalloyed manganese steel (**Table 3**). Steel was quenched from the rolling temperature and tempered at 650°C. Initial and final rolling temperatures, and the quenching temperature (i.e. interval between finished rolling and quenching in water) were varied. Specifications TMT 1, 2, 3, and 4 in the mentioned table represent various regimes of thermomechanical treatment. K_{IC} values were measured with CTS probes (Fig. 1) having plate thickness. The highest temperature at which the K_{IC} value was correctly measured was −40°C. Table gives the dissipation of results of three tests. Table also suggests the selection of optimal regime of treatment which enables the yield stress above 490 MPa at simultaneously the highest toughness transition temperature, i.e. TMT-1.

Simultaneously it is evident that fracture toughness values ($K_{IC,-40}$ and $K_{IC,-70}$) do not enable to judge which thermomechanical treatment is optimal. These measurements only reliably indicate that TMT-4 treatment (hot rolling) is the most unusitable one. The mentioned cases show that parameters of linear fracture mechanics are microstructurally not enough sensitive to enable the regarding selection of tested steels.

The most probable reason is the high ductility of structural steel; in this case the ductility of high-strength steel which have oversized plasticity zone at crack tip in static

Table 2. Some parameters of brittle-fracture resistance of manganese-silicon steels with yield stress $R_p \geq 390$ MPa, plate thickness 20 mm

Chemical composition of steel %					Quenching temperature	Mechanical properties			
C	Mn	Si	S	P	(°C)	R_p (MPa)	KCV^{-70} (J/cm^2)	T^{50x} (°C)	K_{IC}^{-70xx} (MPa m$^{1/2}$)
0.09	1.42	0.28	0.030	0.022	930	429	64	-20	165
0.09	1.42	0.28	0.030	0.022	1050	432	29	+20	160
0.09	1.30	0.60	0.022	0.019	930	417	84	-40	180
0.09	1.30	0.60	0.022	0.019	1050	414	41	+20	175
0.09	1.42	1.03	0.030	0.023	930	435	69	-20	175
0.09	1.42	1.03	0.030	0.023	1050	445	41	+20	170

x—Toughness transition temperature determination was based on 50% tough fracture
xx—Probe in Fig. 2. -70°C was the highest temperature on which K_{IC} could be estimated

Table 3. Mechanical properties of 50 mm thick plate of microalloyed manganese steel (0.19% C, 1.58% Mn, 0.48% Si, 0.07% V, 0.024% S)

Steel treatment	R_p (MPa)	T_1^{xxx} (°C)	T^{50} (°C)	KCV^{-70} (J/cm^2)	K_{IC}^{-40} (MPa m$^{1/2}$)	K_{IC}^{-70} (MPa m$^{1/2}$)
Hot rolled	420	-70	-20	49	55–76	42–55
Hardened and tempered	500	-60	+20	31	61–82	52–67
TMT 1	520	-100	-40	92	67–103	52–64
TMT 2	570	-60	-20	38	52–91	42–64
TMT 3	620	-40	0	32	64–106	39–67
TMT 4	635	-20	+20	28	45–64	27–48

xxx—Determined by impact toughness criterion 39 J

loaded probes though all the testing conditions described by corresponding standards were fulfilled.

Microstructural dependance of investigated parameters becomes more pronounced in more severe testing conditions which reduce the extent of plastic deformation and the size of plastic deformation zone at the crack tip. This occurs during testing in corrosive media (**Fig. 7**). In these tests the K_{IC} value increases with the increased tempering temperature of steel. The obtained result is the consequence of a high density of disordered dislocation loops. Such a structure is essentially less resistant to stress corrosion[2], especially if hydrogen embrittlement is developed. In steel with such a structure, the KC_{IC} value is essentially lower than the K_{IC} one (Fig. 8).

Behaviour of hardened and tempered steel during loading is characterized by its substructure which is formed in recovery of ferrite and in the beginning of recrystallization. Materials with such a structure are not sensitive to stress corrosion; therefore there it is valid: $K_{IC} = K_{IC}^c$ (**Fig. 8**).

Another way to increase the structural sensitivity of K_{IC} are the impact tests where loading rates are increased for six orders of magnitude. In this case the extent of plastic deformation is reduced to suitable amount, also size of plastic deformation zone at the crack tip is abruptly reduced, and it becomes dependant on steel microstructure. This finding can be confirmed with the investigations of steel of big pipelines which measured K_{IC} values were close to the K_{IC} values determined by static testing (Table 4).

In static loading the CTS probe was applied while for impact tests Charpy test probe with fatigue crack was used.

Steels with equal K_{IC} values exhibit the same sequence

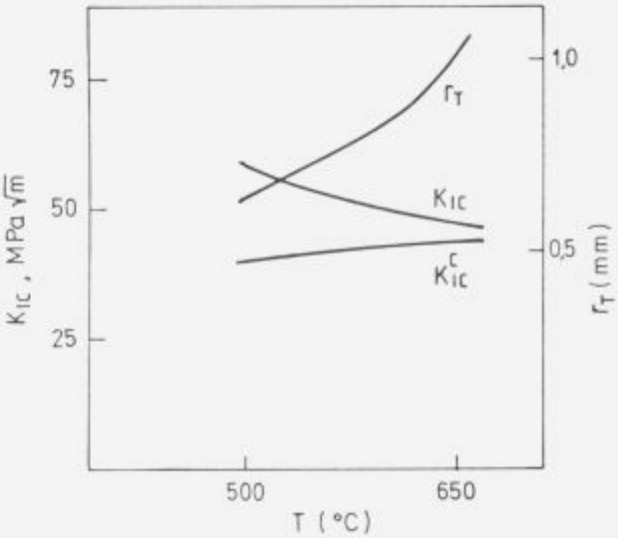

Figure 8. Dependance of fracture toughness and the size of plastic deformation zone on tempering temperature for microalloyed manganese steel (0.14% C, 1.64% Mn, 0.52% Si, 0.07% V, 0.007% N, 0.031% S, 0.013% P). K_{IC}^c—fracture toughness for tests in corrosive medium.

Slika 8. Odvisnost lomne žilavosti in velikosti cone plastične deformacije od temperature popuščanja za mikrolegirano manganovo jeklo. (0.14% C, 1.64% Mn, 0.52% Si, 0.07% V, 0.007% N, 0.031% S, 0.013% P). K_C^c—lomna žilavost pri preizkusih v korozijskem mediju.

Table 4. Fracture toughness and the size of plastic deformation zone on crack tip

Steel treatment	Plate thickness (mm)	Chemical composition		Grain size (μm)	R_p MPa	K_{IC} MPa$^{1/2}$	r_T mm	K^d_{IC} MPa$^{1/2}$	r^d_T mm
		C	S						
		(%)							
Microalloyed Mn steel, hardened with AlN, normalized	12	0.17	0.012	9	418	80	4.2	13.7	0.15
Microalloyed Mn steel, hardened with VN, normalized	12	0.13	0.011	6	425	80	4.1	22.6	0.14
Mn steel alloyed with small amounts of Mo and Nb, controlled rolled	16	0.13	0.011	4	590	84	3.1	37	0.29

after impact testing. Investigations also showed the advantage of controlled rolled plates. Microstructural sensitivity of fracture parameters was also essentially increased, especially the K^d_{IC} and r^d_T values which are in a good correlation with the grain size.

5 Analysis of Results

The described testing results show that the K_{IC} value measured at static loading is not sufficiently microstructurally sensitive property (Figs. 6 and 7, Tables 2 and 3). The needed sensitivity can be achieved by increased test severity or with more demanding tests applying corrosive media or impact loads (Fig. 7, Table 4). Microstructural sensitivity was increased if the extent of plastic deformation was reduced. As a rule, at least three of the following conditions must fulfilled in that case: temperature below 0°C, dynamic tensile load, stress raisers must be present in structure, dimensional factor (great cross section, and the like), and unsuitable steel microstructure. In these cases the parameters of crack stability measured in the conditions of highly limited plastic deformation give good description of fracture conditions.

These parameters were well applied in engineering design of structures. As an example, the crack propagation in the wall of main pipeline will be described. Crack was initiated in the weld on the line of fusion penetration inside the pipeline, and then it propagated towards the external surface. The K^d_{IC} values and the critical crack lengths l_c in the heat affected zones for various steel are reviewed in **Table 5.**

Critical size of defect was calculated by expression[5]:

$$K_{IC} = \frac{pR}{t}\sqrt{\pi l_c}\left(1 + 1.6\frac{l_c^2}{r_T}\right)$$

where p is pressure, R pipe radius, and t wall thickness.

The obtained results show that crack in manganese-silicon steel becomes unstable at low temperatures, and it starts spontaneously to propagate in the axial direction at relatively small penetration into the pipe wall. At those temperatures the use of pipes made of the mentioned steel is not allowed. After controlled rolling the critical size of crack becomes greater than the wall thickness. Thus the stable crack which reaches the pipe surface hinders the spontaneous propagation of crack. At the given temperature the pipe made of the third steel (cited in Table 5) is safe.

Table 5. Fracture characteristics of steel in heat affected zone of pipeline weld

Steel treatment	Plate thickness (mm)	$K^{d(-60)}_{IC}$ (MPa m$^{1/2}$)	$l_c^{(-60)}$ (mm)
Mn-Si steel, normalized	12	24	3
Microalloyed (V) Mn steel, controlled rolled	17	81	24
Mn steel, microalloyed with V and Nb, controlled rolled	14	97	32

Fatigue crack was normal to the plate surface

Determination the fracture toughness at static load at -60°C ($K_{IC} > 100$ MPa m$^{1/2}$) for manganese-silicon steel indicates the safety of that steel, but unfortunately the practical experiences did not confirm it. Thus the parameters of linear fracture mechanics measured in the conditions of very limited plastic deformation did not exhibit only high structural sensitivity but they are also useful in engineering design of brittle-fracture resistance in the cases when they enough accurately describe the mechanism and conditions for brittle fracture of certain steel.

6 References

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