Lomna žilavost ledeburitnega kromovega jekla
Fracture Toughness of Ledeburite Chromium Steel

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UDK: 620.178:669.15—196.58
ASM/SLA: Q6, Q7, Q26q, T5h, 2 — 64

S poskusi smo ugotovili kritično vrednost faktorja intenzivnosti napetosti pri ravninski deformaciji za kromovi ledeburitni jekli Č.4150 in Č.4850. Jekli sta bili kaljeni in popuščeni pri temperaturah 180, 400 in 500 °C.

Kritično vrednost faktorja intenzivnosti napetosti K_{IC} smo določali s polempirijsko metodo. Uporabili smo CT epruvete, v katerih smo z utrujanjem ustvarili začetne razpoke. S temperaturo popuščanja se lomna žilavost obeh jekel zmanjšuje. Jeklo Č.4850 ima skozi ves interval temperatur popuščanja boljšo lomno žilavost.

The magnitude of the critical stress intensity factor in plane strain state was found out experimentally for ledeburite chromium steels Č.4150 and Č.4850. The two steel qualities were hardened and subsequently tempered to temperatures 180, 400 and 500 °C. The critical stress intensity factor K_{1C} was determined by a semi-empirical method. In the experiments CT-specimens were used which were fatigued to create initial cracks. It was found out that with increasing temperature of tempering the fracture toughness of both steel qualities decreases.

1. UVOD

Visokoogljična in mnogolegirana orodna jekla imajo praviloma mnogo slabšo udarno in lomno žilavost od konstrukcijskih jekel. Ta jekla, vgrajena v orodja, morajo imeti visoko trdoto in z njo povezano obrabno obstojnost, visoko tlačno trdnost in mnoge tehnološke lastnosti, tako, da ostanejo v jeklu zelo majhne rezerve oz. prostostne stopnje, ki naj poskrbe za žilavost.

Pri raznovrstnih orodjih, ki se izdelujejo iz teh jekel, pa so tudi odpornost proti udarcem, koncentracijam napetosti in krhkemu, nenadnemu prelomu pričakovane lastnosti. Pri tej vrsti jekel ni tako velikih absolutnih povečanj obeh vrst žilavosti, kot jih dosežejo npr. konstrukcijska jekla na račun spremenjene kemične sestave ali toplotne obdelave. Lahko pa se na podoben način dosežejo precejšnja relativna povečanja, kar znajo uporabniki teh jekel ceniti. Udarna žilavost je podatek, ki že v veliko primerih dopolnjuje tradicionalno opremo diagramov popuščanja, o lomni žilavosti pa pri tej vrsti jekel ni kaj posebej izmerjenega. Vzrok so težave pri meritvah.

Ledeburitna kromova jekla so dobro znana in uporabljena za orodja, ki delajo v hladnem. Poleg klasičnih primerov poškodb zaradi obrabe se mnogo teh orodij tudi poruši.

Podatki o žilavosti pomagajo pri načrtovanju, izbiri jekel in njihovi toplotni obdelavi. Namen tega prispevka je pokazati rezultate poskusa izmeriti lomno žilavost gradiva, ki je po svoji naravi krhko in zavoljo tega predstavlja veliko težavo pri preizkušanju.

Lomno žilavost dveh značilnih predstavnikov kromovih ledeburitnih jekel, Č.4150 in Č.4850, smo merili pri temperaturi okolice po treh temperaturah popuščanja (180, 400 in 500 °C).

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** Originalno publicirano: ZZB 22 (1988) 4
*** Rokopis prejet: avgust 1988

1. INTRODUCTION

High carbon highalloyed tool steels are characterized by a much lower impact- and fracture toughness than structural steels. As tool components, these steels have to possess a high hardness and accompanying wear resistance, a high compressive strength and many other technological properties, so that there are very few reserves left in the steel to provide it with toughness.

The variety of tools which are manufactured of these steels requires the resistance to impact, stress concentrations and sudden brittle fracture which should also be counted among the expected properties. With this type of steel there are no absolute sharp increases in both types of toughness similar to those attained by structural steels due to their changed chemical composition or heat treatment. It is, however, possible by means of similar procedures to achieve considerable relative increases in toughness, which is much appreciated by the users of these steels. Impact toughness is an item of data which has in many cases entered the traditional tempering diagrams whereas fracture toughness is not especially mentioned with this type of steel. The reason for this lies in experimental difficulties.

Ledeburite chromium steels are well known and frequently used for cold work tools. Besides the classical types of damage due to wear, many of these tools also experience fracture.

The data about toughness contribute to better planning, and selection of steels and their heat treatment. The aim of this paper is to present the results of the experiments and the measured values of fracture toughness of a material which is characterized by nature as brittle and therefore difficult to test.

The fracture toughness of two representative chromium ledeburite steel qualities Č.4150 and Č.4850 was measured at the ambient temperature after three different temperatures of tempering (180, 400 and 500 °C).

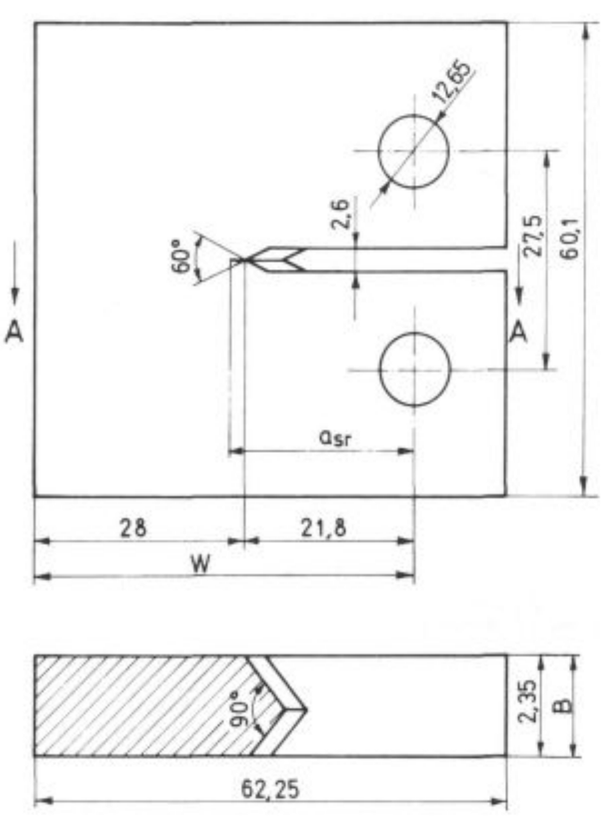
2. OPIS POSKUSOV

Preiskovani jekli sta imeli naslednjo kemično sestavo:

	(%)						
	C	Si	Mn	P	S	Cr	Mo
Č.4150 (OCRI2)	1,97	0,34	0,36	0,030	0,030	11,30	0,1
Č.4850 (OCRI2VM)	1,53	0,40	0,30	0,025	0,025	11,60	0,83
	V	Ni	Cu	Al			
Č.4150 (OCRI2)	1,53	0,19	0,15	0,016			
Č.4850 (OCRI2VM)	1,18	0,17	0,22	0,049			

Jekli smo stalili na zraku v indukcijski peči in ulili v ingote kvadratnega preseka 220 mm. S kovanjem smo dobili gredice kvadratnega preseka z robom 65 mm. Jeklo je bilo pred izdelavo epruvet mehko žarjeno.

Epruvete za mehanske preizkuse (trdnost, udarna in lomna žilavost) iz jekla Č.4150 smo kalili iz solne kopeli pri 960 °C v olje in jih dvakrat po eno uro popuščali na posameznih temperaturah; jeklo Č.4850 je bilo kaljeno na enak način s temperature 1010 °C in enako popuščano. Mikrostrukturo litega, kovanega in toplotno obdelanega jekla smo preiskali z optičnim in transmisijskim elektronskim mikroskopom, količino primarnih karbidov smo izmerili s Quantimetom 720, naravo sekundarnih karbidov z elektronsko difrakcijo, količino zaostalega avstenita pa rentgenografsko.



Slika 1
Geometrija uporabljene CT epruvete s puščičasto zarezo
Fig. 1
Geometry of the CT specimen with an arrow-like notch

2. DESCRIPTION OF EXPERIMENTS

The investigated steel qualities had the following chemical composition:

	(%)						
	C	*Si*	*Mn*	*P*	*S*	*Cr*	*Mo*
Č.4150	1,97	0,34	0,36	0,030	0,030	11,30	0,1
Č.4850	1,53	0,40	0,30	0,025	0,025	11,60	0,83
	V	*Ni*	*Cu*	*Al*			
Č.4150	1,53	0,19	0,15	0,016			
Č.4850	1,18	0,17	0,22	0,049			

The steels were melted in the air in the induction furnace and cast into ingots with square cross-sectional area (220 mm). Out of these, billets with square cross-sectional area were forged with the edge measuring 65 mm. Prior to the fabrication of the test specimens, the steel was annealed.

The specimens for mechanical testing (strength, impact and fracture toughness) made of steel quality Č.4150 were quenched from the salt bath at the temperature 960 °C into oil and tempered twice for one hour at each temperature. The steel quality Č.4850 was hardened in the same way from the temperature 1010 °C and also tempered in the same way. The microstructure of the cast, forged and heat treated steel was searched with the optical and TEM — the quantity of carbides was measured with Quantimet 720, the nature of secondary carbides was studied by electron difraction, and the quantity of residual austenite from X-ray technique.

*The magnitude of fracture toughness (stress intensity factor) was measured by means of CT-specimens, the geometry of which ensured a plane strain state. The specimens were cut out of billets so that the cut ran rectangularly to the direction of deformation and the tensile stress was acting in the direction of the deformation of the billet. The test bars were fabricated according to the ASTM E 399-83 standard, (1). The critical value of the stress intensity factor was determined semi-empirically by measuring the deformation on the CT-specimens (**Figure 1**) on which primary cracks were initiated by fatigue on the MTS 820 machine. After the fracture it was examined whether the fatigue crack fulfills the conditions of the experiment.*

After the static fracture, the length and the tip shape of fatigue crack were measured as well as the forces F_Q and F_{max}. From the force F_Q we calculated the assumed value of the factor K_Q with the help of the equation:

$$K_Q = \frac{F_Q}{B\sqrt{W}} \cdot \frac{(2 + a/W)[0,886 + 4,64\,a/W - 13,32(a/W)^2 + 14,72(a/W)^3 - 5,6(a/W)^4]}{\sqrt{(1 - a/W)^3}}$$

then the measuring conditions were controlled by calculating the following parameters:

$$B,\ a_{sr} \geq 2,5\left(\frac{K_Q}{R_{p0,2}}\right)^2, \qquad (2)$$

where B is the thickness of the specimen and a the length of the crack.

Between the maximum value of the stress intensity factor $K_{f\,max}$ in fatigue testing and the elasticity module, the following relationship has to hold true:

$$\frac{K_{f\,max}}{E} \geq 0,00032\sqrt{m}, \qquad (3)$$

Velikost lomne žilavosti (faktorja intenzivnosti napetosti) smo merili s pomočjo CT epruvet, katerih geometrija je zagotavljala ravninsko deformacijsko stanje. Epruvete smo izrezali iz gredic tako, da je bila zareza pravokotna na smer deformacije, natezna napetost pa je bila v smeri deformacije gredice. Epruvete so bile izdelane po standardu ASTM E 399-83 (1). Kritično vrednost faktorja intenzivnosti napetosti smo določali polempirično z merjenjem deformacije na CT epruvetah (**slika 1**), na katerih je bila narejena primarna razpoka z utrujanjem na stroju MTS 820.

Po prelomu smo ugotavljali, če utrujenostna razpoka izpolnjuje pogoje poskusa.

Po statičnem prelomu smo izmerili dolžino in obliko čela utrujenostne razpoke ter izmerili sili F_Q in F_{max}. Iz sile F_Q smo izračunali predpostavljeno vrednost faktorja K_Q s pomočjo enačbe:

$$K_Q = \frac{F_Q}{B\sqrt{W}} \cdot \frac{(2+a/W)\,[0{,}886 + 4{,}64\,a/W - 13{,}32(a/W)^2 + 14{,}72\,(a/W)^3 - 5{,}6\,(a/W)^4]}{\sqrt{(1-a/W)^3}}$$

nakar smo kontrolirali pogoje merjenja še z računom naslednjih parametrov:

$$B,\ a_{sr} \geq 2{,}5\left(\frac{K_Q}{R_{p0,2}}\right)^2, \qquad (2)$$

kjer sta B debelina vzorca, a pa dolžine razpoke.
Med največjo vrednostjo faktorja intenzivnosti napetosti $K_{f\,max}$ pri utrujanju in modulom elastičnosti mora veljati odnos:

$$\frac{K_{f\,max}}{E} \geq 0{,}00032\sqrt{m}, \qquad (3)$$

razmerje obremenitev: $\frac{F_{max}}{F_Q} \geq 1{,}1$ (4) in

velikost plastične cone na vrhu razpoke, ki mora biti manjša od 2 % utrujenostne razpoke:

$$r_{pl} \leq 0{,}02\,a_{sr} \qquad (5)$$

Če so izpolnjeni ti štirje pogoji, se privzame predpostavljena vrednost faktorja intenzivnosti napetosti K_Q kot dejanska, kritična vrednost tega faktorja K_{IC}.

3. REZULTATI

Mikrostrukturne sestavine obeh preiskanih jekel po toplotnih obdelavah so martenzit, primarni in sekundarni karbidi ter zaostali avstenit (**slika 2**). Količina in narava zadnjih dveh sestavin je navedena v **tabeli 2**.

Tabela 2:

		Karbidi (%)		Zaostali avstenit (%)
Jeklo	$T_{pop.}$	$M_{23}C_6$	M_7C_6	
Č.4150	180	10,5	89,5	10,2
	400	11,2	88,8	5,0
	500	11,2	88,2	0
Č.4850	180	8,8	91,40	10,9
	400	7,94	92,06	10,6
	500	7,91	92,09	7,2

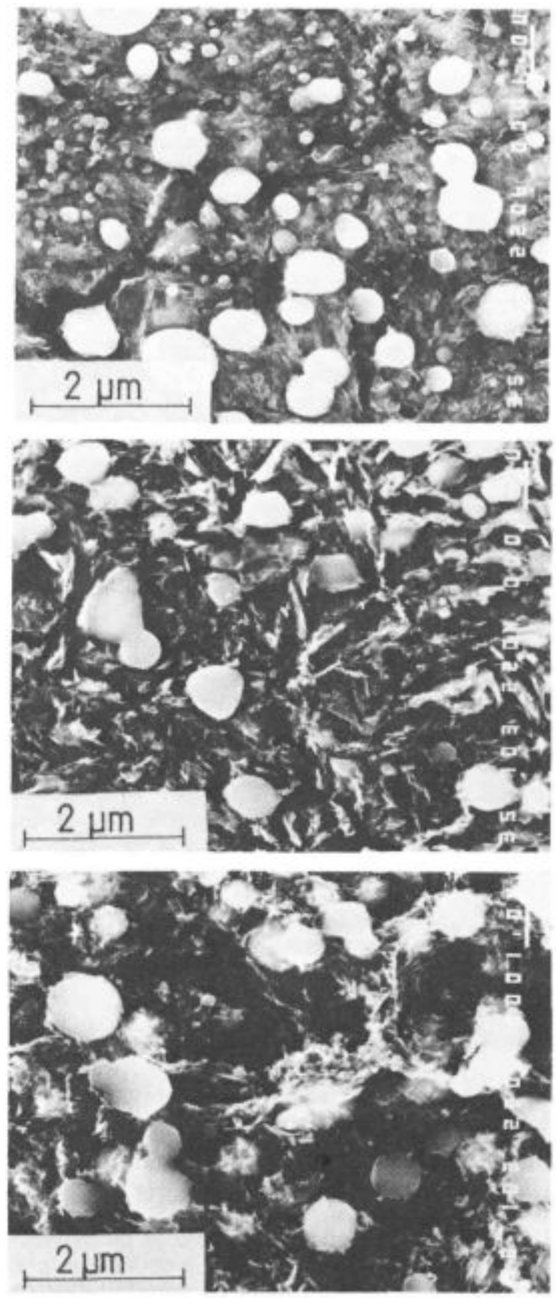
Mehanske lastnosti obeh jekel so zbrane v **tabeli 3**:

the ratio of loads: $\frac{F_{max}}{F_Q} \geq 1{,}1$ *(4) and*

the size of the plastic zone at the tip of the crack which has to be smaller than a 2 % fatigue crack:

$$r_{pl} \leq 0{,}02\,a_{sr} \qquad (5)$$

If the above four conditions are fulfilled, the assumed value of the stress intensity factor K_Q can be taken as the critical value of this factor K_{IC}.



Slika 2
Sekundarni karbidi v jeklu Č.4150 popuščenega na temperaturah a) 180, b) 400 in c) 500 °C

Fig. 2
Secondary carbides in steel Č.4150 tempered at the temperatures a) 180, b) 400 and c) 500 °C

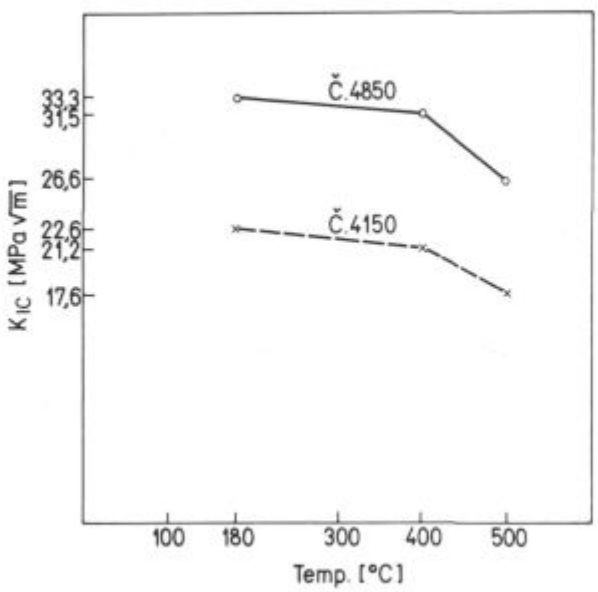
Tabela 3:

Jeklo	T_{pop}	R_m (MPa)	$R_{p0,2}$ (MPa)	E(MPa)	Trdota HRC	Žilavost MJ/m^2
Č.4150	180	1034	982	230000	62,8	0,078
	400	1024	973	230000	58,2	0,062
	500	1156	1098	230000	55	0,050
Č.4850	180	964	916	210000	62	0,075
	400	1033	981	210000	58	0,063
	500	1297	1232	210000	55	0,056

Kritične velikosti faktorja intenzivnosti napetosti K_{IC} pa so v **tabeli 4.** (**Slika 3**)

Tabela 4:

Jeklo	T_{pop} (°C)	K_Q ($MPa\sqrt{m}$)	Kontrola
Č.4150	180	22,6	$K_Q = K_{IC}$
	400	21,2	$K_Q = K_{IC}$
	500	17,6	$K_Q = K_{IC}$
Č.4850	180	33,3	$K_Q = K_{IC}$
	400	31,5	$K_Q = K_{IC}$
	500	26,6	$K_Q = K_{IC}$



Slika 3
Kritična vrednost faktorja intenzivnosti napetosti v odvisnosti od temperature popuščanja

Fig. 3
Critical stress intensity factor K_{IC} versus tempering temperature

4. Zaključek

Na način, ki je značilen za preizkušanje konstrukcijskih jekel, smo izmerili lomno žilavost dveh kromovih ledeburitnih orodnih jekel.

Osnovni problem pri preizkušanju je bil izdelati začetno razpoko z utrujanjem jekla. Izmerjeni faktorji intenzivnosti napetosti so odvisni od kemične sestave in mikrostrukture jekla.

Jeklo Č.4850 ima znatno boljšo lomno žilavost od jekla Č.4150. Pri obeh jeklih se lomna žilavost spreminja s temperaturo popuščanja jekla po kaljenju. Ta sprememba faktorja intenzivnosti napetosti je v dobri korelaciji s spremembo deleža zaostalega avstenita. Spremembe v

3. RESULTS

*The microstructural components of both investigated steels after the heat treatment procedures are: martensite, primary and secondary carbides and residual austenite (**Fig. 2**). The amount and the nature of the last two components are presented in* **Table 2**.

Table 2:

		Carbides (%)		Residual austenite (%)
Steel	T_{pop}	$M_{23}C_6$	M_7C_6	
Č.4150	180	10,5	89,5	10,2
	400	11,2	88,8	5,0
	500	11,2	88,2	0
Č.4850	180	8,8	91,40	10,9
	400	7,94	92,06	10,6
	500	7,91	92,09	7,2

*The mechanical properties of the two steel qualities can be seen in **Table 3:***

Table 3:

Steel	T_{pop}	R_m (MPa)	$R_{p0,2}$ (MPa)	*E(MPa)*	*Hardness HRC*	*Toughness* MJ/m^2
Č.4150	180	1034	982	230000	62,8	0,078
	400	1024	973	230000	58,2	0,062
	500	1156	1098	230000	55	0,050
Č.4850	180	964	916	210000	62	0,075
	400	1033	981	210000	58	0,063
	500	1297	1232	210000	55	0,056

*Finally, the critical values of the stress intensity factor K_{IC} are presented in **Table 4.** (**Fig. 3**)*

Table 4:

Steel	T_{tem} (°C)	K_Q ($MPa\sqrt{m}$)	*Control*
Č.4150	180	22,6	$K_Q = K_{IC}$
	400	21,2	$K_Q = K_{IC}$
	500	17,6	$K_Q = K_{IC}$
Č.4850	180	33,3	$K_Q = K_{IC}$
	400	31,5	$K_Q = K_{IC}$
	500	26,6	$K_Q = K_{IC}$

4. Conclusion

A method which is typically used for testing structural steels was applied to measure the fracture toughness of two chromium ledeburite tool steels. The basic problem of the testing was how to initiate a crack by fatigue. The measured stress intensity factors are in dependence on the chemical composition and microstructure of the steel. Steel Č.4850 possesses a much higher fracture toughness than steel Č.4150. With both qualities of steel the fracture toughness varies with the temperature of tempering after the hardening procedure. This variation of the factor is in good correlation with the changing percentage of the residual austenite. The changes in the magnitude of the stress intensity factor are much more selective than the values of impact toughness measured velikosti faktorja intenzivnosti napetosti so mnogo bolj selektivne od vrednosti udarne žilavosti, izmerjene po Charpyju na epruvetah z ostro V zarezo. Faktor intenzivnosti napetosti in vrednosti udarne žilavosti pri preiskanih jeklih se ne dajo povezati z znanimi empiričnimi obrazci.

Velikosti kritične vrednosti faktorja intenzivnosti napetosti za obe toplotno obdelani jekli dajejo v celotnem intervalu temperatur popuščanja prednost jeklu Č.4850. Te meritve posredno potrjujejo tudi znane vrednosti udarne žilavosti in prakso orodjarjev, ki dobro poznajo to prednost jekla Č.4850.

according to Charpy on test bars with a sharp V-notch. The stress intensity factor and the fracture toughness values of the investigated steels cannot be related to the known empirical patterns.

The magnitudes of the ultimate values of the stress intensity factor for both qualities of the heat treated steel examined over the whole temperature interval of tempering give priority to steel Č.4850. Thus these measurements are also a indirect confirmation of the known value of the impact toughness and the practical experience of tool makers who are well familiar with this advantageous feature of steel Č.4850.

LITERATURA/*REFERENCES*

1. ASTM E 399 — 83, 519—542 (1983),
2. Y. A. Geller, Tool Steels, Mir Publisher, Moscow, 132—144 (1983),
3. H. Berns, W. Trojahn. Einf. Der Warme behand. auf das ermüdung ledeb. kaltarbeits. 4 th Intern. Congr. on Heat Treatm. of Mater. Berlin, 427—439 (1985).
4. J. Rodič, Mehanizem in morfologija lomov Cr-Mo-V orodnih jekel, disertacija, Ljubljana, 1978.
5. E. Haberling, Hardenability of Ledeburitic Chromium Steels in a Vacuum Furnace, Thyssen Edelst. Techn. Ber. — 1983.