Vpliv vroče predelave na drobljenje karbidov in lomno žilavost

Influence of Hot Working on Carbide Crushing and Fracture Toughness

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Lastnosti ledeburitnih orodnih jekel za delo v hladnem so odvisne od mikrostrukturnih značilnosti. Rezultati raziskave kažejo vpliv pogojev vročega valjanja na velikost ledeburitnih karbidov. Lomna žilavost jekla je izračunana po korelaciji Hahn-Rosenfield.

1. UVOD

Ledeburitna orodna jekla za delo v hladnem imajo pred drugimi orodnimi jekli nekatere določene prednosti. Izdelana so na osnovi kroma in so zato sorazmerno poceni. Od teh jekel ima jeklo Č.4150 (OCR 12) zaradi visoke vsebnosti kroma (12 %) in ogljika (2 %) zelo dobro obrabno odpornost, visoko trdoto, dobre rezne lastnosti in orodja so dimenzijsko stabilna. Poleg teh lastnosti je za orodja kot merilo odpornosti proti nenadnemu lomu zelo pomembna žilavost jekla.

S klasičnim Charpyjevim preizkusom ni mogoče eksaktno opredeliti krhkosti loma ledeburitnih jekel. V linearni elastomehaniki je razvitih več metod za določitev kritične intenzitete napetosti, ki jo imenujemo lomna žilavost K_{1C}. Lomna žilavost materiala kaže povezavo med napetostmi v materialu in velikostjo napak. Zato so za lomno žilavost jekla Č.4150 zelo pomembne mikrostrukturne značilnosti. V poboljšanem stanju ima jeklo v matici iz popuščenega martenzita in zaostalega avstenita ledeburitne karbide M_7C_3 in drobne sekundarne karbide.

Jeklo se vroče preoblikuje predvsem s kovanjem, za večje orodne plošče pa je z ekonomskega stališča ustreznejše valjanje. Velikost in razporeditev ledeburitnih karbidov v matici je odvisna od pogojev litja, strjevanja in termomehanskih pogojev vroče predelave.

2. EKSPERIMENTALNO DELO

2.1. Značilnosti vroče valjanega jekla

Jeklo Č.4150 ima v litem stanju zelo nehomogeno mikrostrukturo z izrazito mrežo ledeburitnih karbidov, ki je nastala v meddendritskih prostorih. Med vročim kovanjem in nadaljnjim valjanjem se povprečna velikost ledeburitnih karbidov zaradi drobljenja zmanjšuje, delno pa se tudi prerazporedijo.

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The properties of ledeburitic cold work tool steels depend upon the characteristics of the microstructure. The results of the investigation confirm the influence of hot-rolling conditions on the size of massive carbides. Fracture toughness of steel is calculated according to the Hahn-Rosenfield correlation.

1. INTRODUCTION

Ledeburitic cold work tool steels have some advantages in comparison with other tool steels. The base of ledeburitic cold work tool steels is chromium which makes them relatively cheap to produce. One of them, the steel Č.4150 (OCR 12), due to its high content of chromium (12 %) and carbon (2 %), has a very good wear resistance, a great hardness and good cutting properties, and the dimensions of the tools are stable. Besides these properties, the toughness of steel is very important for tools as a criterion of resistance to fast fracture.

The brittleness of ledeburitic tool steels cannot be exactely established by the classical Charpy test. In linear elastomechanics several methods were developed to calculate the critical stress intensity factor called fracture toughness K_{1C}. The fracture toughness of the material is related to the stresses and the size of defects within the material. The microstructure characteristics are therefore very important for the fracture toughness of steel Č.4150. In quenched and subsequently tempered state this steel shows massive carbides M_7C_3 and small-sized secundary carbides in a matrix of tempered martensite and retained austenite.

Steel is hot worked, primarily by forging, whereas from the economic point of view rolling is more suitable for larger tool plates. The size and the distribution of massive carbides in the matrix depend upon the conditions of casting, solidification and upon the thermomechanical conditions of hot working.

2. EXPERIMENTAL

2.1. Characteristics of Hot-Rolled Steel

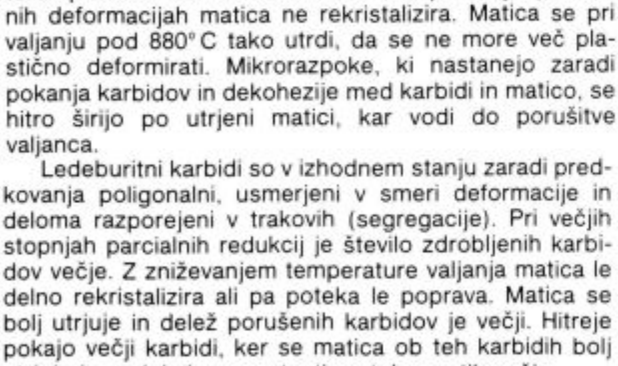
The steel Č.4150 as cast has a very non-homogeneous microstructure with a marked network of massive carbides occurring in interdentritic spaces. In hot forging and subsequent rolling the average size of massive carbides decreases due to crushing and a rearrangement of carbides also occurs. In hot-rolling the differences between the mechanical properties of the matrix and the carbide phase are heightened (1, 2). Massive carbides

Pri vročem valjanju pridejo do izraza razlike v mehanskih lastnostih med matico in karbidno fazo (1, 2). Ledeburitni karbidi so zelo trdi in krhki, imajo visoko trdnost in visok modul elastičnosti. Matica ima precej manjšo trdoto, trdnost in modul elastičnosti. V temperaturnem področju vroče predelave se mehanske lastnosti matice in karbidov spreminjajo (4). Na drobljenje karbidov pa vpliva predvsem utrjevanje matice zaradi plastične deformacije. Sicer pa je drobljenje karbidov odvisno od več dejavnikov: od mejne površinske napetosti, velikosti karbidnih zrn, razdalje med njimi, njihove orientacije in termomehanskih pogojev valjanja (temperatura, velikosti parcialnih deformacij in skupne deformacije, hitrost deformacije). Med valjanjem delujejo največje napetosti pravokotno na silo valjanja, to je v smeri valjanja. Zato karbidi najpogosteje pokajo na smer največje napetosti.

Na **sliki 1** je prikazana odvisnost srednje preoblikovalne trdnosti od temperature valjanja in specifične stopnje parcialnih deformacij. Srednjo deformacijsko trdnost smo izračunali iz meritev sile valjanja, višine valjčne reže, električne obremenitve motorja in momenta na gredi pogonskih valjev. Hitrost deformacije je bila $\dot{\varphi} = 5s^{-1}$. Odpor proti deformaciji se do temperature 1050° C malo razlikuje glede na 15 in 30 % stopnjo parcialnih deformacij. Pri nadaljnjem zniževanju temperature valjanja se jeklo pri 15 % parcialnih deformacijah hitreje utrjuje in ima zato večjo preoblikovalno trdnost. V matici poteka le poprava, pri večjih parcialnih deformacijah pa poteka tudi rekristalizacija. Odpor proti deformaciji pri temperaturah pod 900° C zelo hitro raste. Tudi pri večjih parcialnih deformacijah matica ne rekristalizira. Matica se pri valjanju pod 880° C tako utrdi, da se ne more več plastično deformirati. Mikrorazpoke, ki nastanejo zaradi pokanja karbidov in dekohezije med karbidi in matico, se hitro širijo po utrjeni matici, kar vodi do porušitve valjanca.

Ledeburitni karbidi so v izhodnem stanju zaradi predkovanja poligonalni, usmerjeni v smeri deformacije in deloma razporejeni v trakovih (segregacije). Pri večjih stopnjah parcialnih redukcij je število zdrobljenih karbidov večje. Z zniževanjem temperature valjanja matica le delno rekristalizira ali pa poteka le poprava. Matica se bolj utrjuje in delež porušenih karbidov je večji. Hitreje pokajo večji karbidi, ker se matica ob teh karbidih bolj utrjuje in so lokalne napetosti na teh mestih večje.

Na **sliki 2** je prikazana povprečna velikost ledeburitnih karbidov v odvisnosti od končne temperature



Slika 1

Odvisnost srednje preoblikovalne trdnosti od temperature valjanja

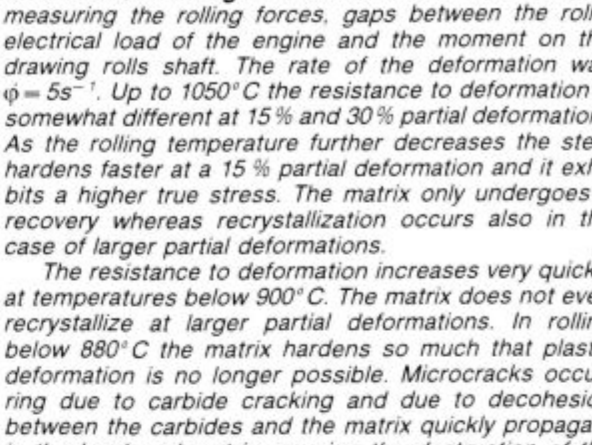
Fig. 1:

Dependence of mean true stress upon rolling temperature.

are very hard and brittle, besides they have a high strength and a high Young's modulus. The matrix has a substantially lower hardness, strength and Young's modulus. The mechanical properties of the matrix and of the carbides are modified in the hot working temperature range (4). Carbide crushing is affected primarily by the matrix hardening due to plastic deformation. In fact, carbide crushing depends upon several factors: the interface surface tension, the size of carbide grains and the distance between them, their orientation and the thermomechanical rolling conditions (the temperature, the step of partial deformations and of total deformation). In rolling the highest stresses act perpendicularly upon the rolling force i. e. in the rolling direction. That is why carbides crack most frequently in the direction of the highest stress.

The relationship between the true stress, the rolling temperature and the specific steps of partial deformations is shown in ***Fig. 1****. True stress was calculated by measuring the rolling forces, gaps between the rolls, electrical load of the engine and the moment on the drawing rolls shaft. The rate of the deformation was* $\dot{\varphi} = 5s^{-1}$*. Up to 1050° C the resistance to deformation is somewhat different at 15 % and 30 % partial deformation. As the rolling temperature further decreases the steel hardens faster at a 15 % partial deformation and it exhibits a higher true stress. The matrix only undergoes a recovery whereas recrystallization occurs also in the case of larger partial deformations.*

The resistance to deformation increases very quickly at temperatures below 900° C. The matrix does not even recrystallize at larger partial deformations. In rolling below 880° C the matrix hardens so much that plastic deformation is no longer possible. Microcracks occurring due to carbide cracking and due to decohesion between the carbides and the matrix quickly propagate in the hardened matrix, causing the destruction of the rolled workpiece. At initial state the massive carbides have a polygonal shape due to preforging, they line themselves in the deformation direction and they are distributed in a discontinuous chain type (segregations). The number of crushed carbides is greater resulting on



Slika 2

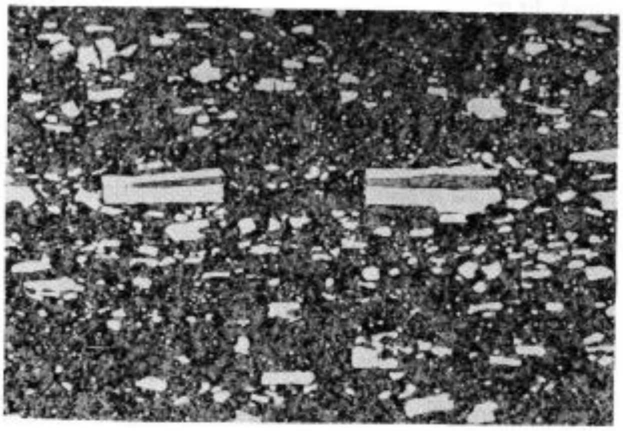
Povprečna velikost ledeburitnih karbidov v odvisnosti od končne temperature valjanja. Parcialne redukcije so različne, celotna redukcija je približno enaka

Figure 2:

Dependence of average size of massive carbides upon finish rolling temperature. Partial deformations are different, total deformation is approximately the same.

valjanja za vzorce, deformirane z različnimi parcialnimi deformacijami. Celotna deformacija je bila približno enaka. Povprečno velikost karbidov smo določili na metalografskih posnetkih s pomočjo digitalne tablice in računalniškega programa za vzorčenje likov. Zaradi ročnega očrtovanja drobnih karbidov nismo upoštevali. Menimo, da s tem nismo naredili večje napake, ker ti karbidi ne sodelujejo v procesu drobljenja (3). Na porazdelitev karbidov v trakovih, kar je posledica karbidne mreže, nastale pri strjevanju jekla, s pogoji valjanja ne moremo bistveno vplivati. Opazi pa se, da so karbidi v trakovih drobnejši. Matica se v ozkih pasovih med karbidi hitreje utrjuje in drobljenje je intenzivnejše.

Pri višjih temperaturah valjanja matica hitro zapolnjuje mikropraznine, ki nastajajo zaradi pokanja karbidov **(slika 3)**. Pri nižjih temperaturah valjanja se plastičnost matice zmanjšuje in matica zato slabše zapolnjuje mikropraznine **(slika 4)**. Mikropraznin, nastalih zaradi dekohezije med karbidnimi zrni in matico, je malo in smo jih opazili na koncih večjih karbidnih zrn. Imajo značilno trikotno obliko.



Slika 3:
Matica je zapolnila mikropraznine, nastale pri pokanju karbidov. Končna temperatura valjanja je bila 1080° C (pov. 200×)

Figure 3:
Microvoids occurring at carbide cracking are filled with the matrix. The finish rolling temperature was 1080° C (magnification 200×).

2.2. Lomna žilavost jekla

Mehanske lastnosti smo določili na vzorcih, zvaljanih s petimi 25 % parcialnimi redukcijami v intervalu končnih temperatur valjanja med 1060 in 890° C. Vzorce smo kalili v olju s temperature 960° C in nato popuščali pri 210° C. Zaradi precejšnjega deleža zaostalega avstenita ima jeklo boljšo žilavost, kot če je popuščeno pri višjih temperaturah. Rezultati meritev so prikazani v **tabeli 1**.

Izmerjene vrednosti Charpy — V žilavosti ne kažejo večje odvisnosti od velikosti ledeburitnih karbidov in so prenizke, da bi lahko določili vrednosti K_{1C} s korelacijo Rolfe-Novak. Lomno žilavost smo določili na osnovi rezultatov nateznih preizkusov s korelacijo Hahn-Rosenfield. Ta je podana z izrazom:

$$K_{1C} = (0{,}05 \cdot \varepsilon_f \cdot n^2 \cdot E \cdot \sigma_{0,2}/3)^{1/2}$$

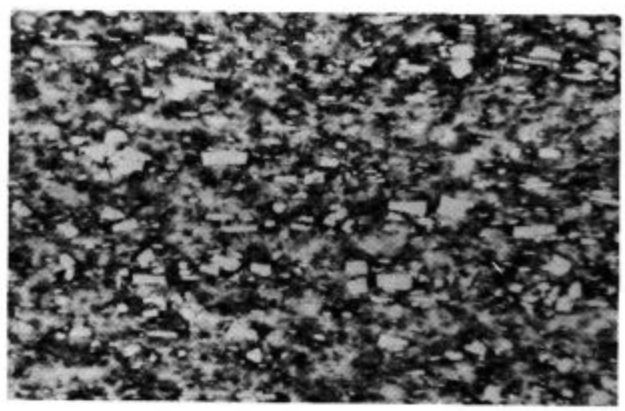
V njem je ε_f lomna duktilnost jekla. Določena je s kontrakcijo nateznega preizkušanca ($\varepsilon_f = \ln A_o/A_f$). Z n je označen eksponent utrjevanja in je določen z izrazom $n = \ln(1 + e_u)$, kjer je e_u maksimalni enakomerni raztezek, ki ga običajno izražamo kot $e_u \times 100$ v odstotkih. E je

higher partial deformation step. As the rolling temperature decreases there is either a partial recrystallization of the matrix or a recovery. The matrix hardens more and the number of crushed carbides is greater. The larger carbides crack faster because the matrix around these carbides hardens more and because of the higher local stresses.

Fig. 2 *illustrates the relationship between the average size of massive carbides and the finish rolling temperature of specimens with different partial deformations. The whole deformation was approximately the same in all the cases. The average size of carbides was determined on metallographical snap-shots by digital figure analysis equipment. Small carbides were not taken into consideration because of hand outlining. It is believed that no essential error was done as these carbides do not participate in the crushing process (3).*

The rolling conditions cannot essentially affect the distribution of the chain type carbides which result from the carbide network formed during the solidification of steel. However it is observed that the chain type carbides are smaller. The matrix hardens faster in the narrow bands between carbides and crushing is more intensive.

At higher rolling temperatures the matrix rapidly fills the microvoids which occur due to carbide cracking ***(Fig. 3)****. At lower rolling temperatures the deformability of the matrix is decreased and therefore it cannot fill the microvoids so well* ***(Fig. 4)****. Only a few microvoids occur due to decohesion between the carbide grains and the matrix; these are observed at the edges of larger carbide grains. They are typically triangular in shape.*



Slika 4:
Matica ni zapolnila mikropraznin, nastalih pri pokanju karbidov. Končna temperatura valjanja je bila 890° C (pov. 200×)

Figure 4:
Microvoids occurring at carbide cracking are not filled with the matrix. The finish rolling temperature was 890° C (magnification 200×).

2.2. Fracture Toughness of Steel

The mechanical properties were determined on rolled workpieces with five partial deformations of 25 % each within finish temperature intervals between 1060 and 890° C. Specimens were quenched in oil at 960° C and subsequently tempered at 210° C. The toughness of steel is better, owing to the substantial quantity of retained austenite, as when tempered at higher temperatures. The results of measurements are shown in ***Table 1****.*

The measured Charpy-V notch impact values do not wholly depend upon the size of massive carbides and

Tabela 1: Rezultati metalografskih in mehanskih preiskav

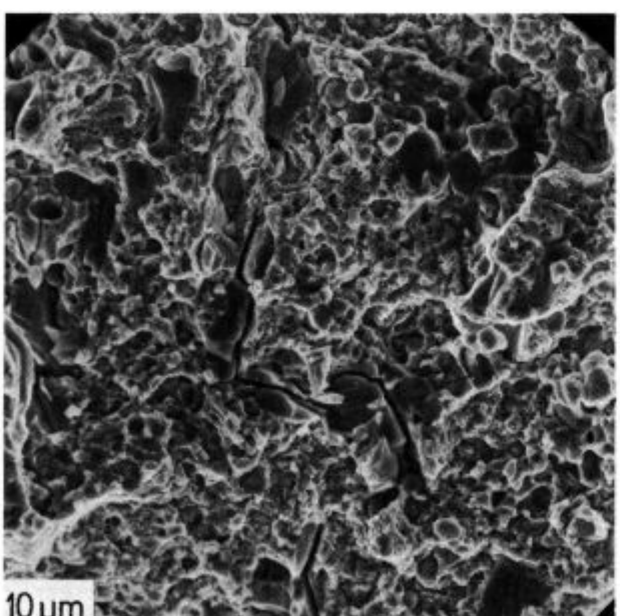
Končna temperatura valjanja (°C)	Povprečna velikost ledeburitnih karbidov (μm²)	Maksimalna velikost ledeburitnih karbidov (μm²)	Meja plastičnosti (MNm⁻²)	Kontrakcija (%)	Maksimalni enakomerni raztezek (%)	Eksponent deformacijskega utrjevanja	Charpy-V žilavost (J)	Lomna žilavost (MNm⁻³ᐟ²)
1060	80	450	1480	4	0.0087	4	3.9	
1010	62	250	1380	5	0.98	0.0098	4	4.8
950	43	180	1460	5	1.5	0.0149	5	7.5
890	32	140	1470	5	1.7	0.0169	5	8.6

***Table 1:** Results of metallographical and mechanical tests*

Finish rolling temperature (°C)	*Massive carbides average size (μm²)*	Massive carbides maximum size (μm²)	Yield point (MNm⁻²)	Reduction of area (%)	Maximum uniform elongation (%)	Strain hardening exponent	Charpy V-notch impact energy (J)	Fracture toughness (MNm⁻³ᐟ²)
1060	80	450	1480	4	0.0087	4	3.9	
1010	62	250	1380	5	0.98	0.0098	4	4.8
950	43	180	1460	5	1.5	0.0149	5	7.5
890	32	140	1470	5	1.7	0.0169	5	8.6

modul elastičnosti jekla in $\sigma_{0.2}$ meja plastičnosti jekla (8). Rezultati lomne žilavosti, ki smo jih dobili s to korelacijo, so dovolj točni. Vrednosti smo določili mnogo enostavneje, kot pa če bi merili K_{1C} s standardnimi CT (compact tension) preizkušanci. Iz rezultatov se vidi, da lahko s pogoji vroče predelave vplivamo na velikost ledeburitnih karbidov in s tem na lomno žilavost jekla.

Pri vrednotenju rezultatov pa ne smemo zanemariti vpliva pogojev litja, strjevanja in toplotne obdelave. Boljšo lomno žilavost jekla Č.4150, ki bi se približala vrednostim, ki jih imajo druga orodna jekla, bi dosegli le z bistveno manjšo povprečno velikostjo ledeburitnih karbidov, brez velikih karbidov in homogenejšo porazdelitvijo po matici.



Slika 5
Mikrorazpoka v nizu ledeburitnih karbidov

Figure 5:
Microcrack in chain-type massive carbide bands.

they are too low to determine K_{1C} values using the Rolfe-Novak correlation. Fracture toughness was calculated by means of the Hahn-Rosenfield correlation on the basis of tensile tests as follows:

$$K_{1C} = (0.05 \cdot \varepsilon_f \cdot n^2 \cdot E \cdot \sigma_{0.2}/3)^{1/2}$$

where ε_f is the fracture ductility of steel. It was calculated from the reduction of area as a proportion between the initial cross-section and the fracture cross-section of the tensile specimen ($\varepsilon_f = \ln a_o/A_f$). The strain hardening exponent is calculated by the equation $n = \ln(1+e_u)$ where e_u is the maximum uniform elongation, usually expressed in percentage as $e_u \times 100$. E is the Young's modulus of steel and $\sigma_{0.2}$ is the yield point of steel (8). The results for fracture toughness given by this correlation are sufficiently accurate. The values for K_{1C} were much easier determined in this way than using standard compact tension specimens. The results show that the size of massive carbides and therefore the fracture toughness of steel, can be affected by the conditions of hot working.

The influence of casting, solidification and thermal treatment conditions are not to be neglected when evaluating the results. A better fracture toughness of steel Č.4150, such as to be closer to the values of other tool steels, could be obtained only by essentially smaller average sized massive carbides, and a homogeneous distribution in the matrix, without any large carbides.

2.3. Morphological Characteristics of Fracture Surfaces

The fracture surface morphology depends upon the characteristics of microstructure phases in steel and their mechanical properties (7). In tempering at low temperatures the matrix retains more austenite and has therefore a better toughness. Due to rough massive carbides, morphological characteristics of fracture surfaces of ledeburitic steels cannot be compared with fracture surfaces of other tool steels.

The density of dislocations in the matrix around larger carbide grains and in narrow matrix bands between chain type carbides is essentially increased due to plastic deformation. Larger massive carbides crack at critical stress below the yield point of the matrix. Besides the larger carbide grains, microvoids

2.3. Morfološke značilnosti prelomov

Morfologija prelomov je odvisna od značilnosti mikrostrukturnih faz v jeklu in njihovih mehanskih lastnosti (7). Matica ima pri nizkih temperaturah popuščanja večji delež zaostalega avstenita in zato boljšo žilavost. Zaradi grobih evtektičnih karbidov morfoloških značilnosti prelomnih površin pri ledeburitnih jeklih ne moremo primerjati s prelomi drugih orodnih jekel.

Zaradi plastične deformacije se v matici okoli večjih karbidnih zrn in v karbidnih nizih, kjer so med karbidnimi zrni le ozki pasovi matice, zelo poveča gostota dislokacij. Pri kritični napetosti, ki je nižja od meje plastičnosti matice, večji ledeburitni karbidi pokajo. Poleg večjih karbidnih zrn so iniciali za nastanek začetnih razpok tudi mikropraznine, ki so nastale pri pokanju karbidov med vročim valjanjem in jih matica ni zapolnila. Pogoji za združevanje začetnih razpok v mikrorazpoke so ugodnejši v karbidnih nizih, kjer je matica močno utrjena in je manj možnosti, da se mikrorazpoke ustavijo v večjih področjih matice, ki imajo boljšo plastičnost (**slika 5**). Matica se sicer lomi duktilno, deformacija matice pa je zelo majhna, kar je sicer značilno za prelome visokolegiranih orodnih jekel. Martenzit z visoko vsebnostjo ogljika je trši in ima slabšo žilavost.

3. ZAKLJUČEK

Povprečna velikost ledeburitnih karbidov je v jeklu Č.4150 manjša pri valjanju z večjimi parcialnimi redukcijami in pri nižjih končnih temperaturah valjanja. Pri temperaturah valjanja pod 890°C poteka le poprava in matica se tako utrdi, da ni sposobna za nadaljnjo plastično predelavo.

Lomno žilavost smo določili po korelaciji Hahn-Rosenfield iz rezultatov nateznih preizkusov. Rezultati, ki kažejo odvisnost lomne žilavosti od velikosti ledeburitnih karbidov, so bistveno bolj selektivni kot rezultati žilavosti, izmerjeni s Charpy-V preizkušanci.

Grobi ledeburitni karbidi imajo dominanten vpliv na morfologijo loma. Boljšo lomno žilavost, s katero bi se približali vrednostim drugih orodnih jekel, bi lako dobili le z bistveno manjšo povprečno velikostjo ledeburitnih karbidov. Zato bi moralo imeti že jeklo v litem stanju drobnejše evtektične karbide.

*occuring at carbide cracking and not being filled with the matrix at hot-rolling, also initiate crack nucleation. Initial cracks find better conditions to join into microcraks in chain type carbide bands where the matrix has hardened a great deal and microcraks have therefore less opportunity of arresting in larger matrix areas which have a better deformability **(Fig. 5)**). Although the matrix undergoes a ductile fracture, its deformation is very small which is typical of fractures of high alloyed tool steels. Martensite with a high content of carbon is harder and exhibits a worse toughness.*

3. CONCLUSION

In steel Č.4150 the average size of massive carbides is smaller when rolling with larger partial deformations at lower finish rolling temperatures. At rolling temperatures below 890°C only a recovery occurs and the matrix hardens to such a degree that it is no longer suitable for further plastic deformation.

Fracture toughness was calculated on the basis of tensile tests according to the Hahn-Rosenfield correlation. The results which illustrate the relationship between fracture toughness and the size of massive carbides are far more selective than those for toughness measured with Charpy-V specimens.

Rough massive carbides have a dominant influence on fracture morphology. A better fracture toughness, which would be closer to the values of other tool steels, could be obtained only by essentially lower average size of massive carbides. Therefore steel should present smaller massive carbides already as cast.

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