J-integral in morfologija preloma mikrolegiranih drobnozrnatih jekel Nionicral 70 ter Niomol 490

J-Integral and Fracture Morphology of Micro-Alloyed Fine-Grained Steels Nionicral 70 and Niomol 490

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Opisano je merjenje lomne žilavosti mikrolegiranih drobnozrnatih jekel z metodo J-integrala. Rezultati kažejo, da je poleg standardnih kriterijev, nanašajočih se na zahtevano velikost preizkušancev, potrebno zaradi močne strižne deformacije na bokih preizkušancev upoštevati tudi še nekatere druge empirične kriterije.

Frakturne površine preizkušancev so v vseh primerih jamičaste, duktilne, velikost jamic pa je v dobri soodvisnosti z izmerjenimi J_{IC} vrednostmi.

1. UVOD

Dolga leta so bila edina variva konstrukcijska jekla le normalizirana C-Mn jekla s feritno-perlitno mikrostrukturo. Zaradi zahtev po izboljšanju meje plastičnosti, varivosti ter žilavosti so bila pred desetletji razvita prva mikrolegirana drobnozrnata jekla. Tovrstna jekla so legirana s Ti, Nb, V, Zr oz. Mo, bodisi posamič bodisi v kombinacijah, pri čemer je povečanje meje plastičnosti doseženo deloma z izločevalnim utrjevanjem ferita, predvsem pa — in to velja še posebej za termomehansko predelana jekla — z zmanjšanjem velikosti feritnih zrn. Slednje vpliva ugodno tudi na žilavost, ker pomakne temperaturo prehoda v krhko stanje k nižjim vrednostim.

Danes od mikrolegiranih drobnozrnatih jekel zahtevamo mejo plastičnosti vsaj 500 MPa, ob tem pa mora biti Charpy-V žilavost visoka še tudi pri temperaturi −60° C. Vsebnost ogljika v novih vrstah mikrolegiranih jekel je zato nekoliko nižja, običajno med 0,03 in 0,12 %, pri čemer veljajo nižje vrednosti za termomehansko predelana jekla.

Lom konstrukcijskih jekel s povišano mejo plastičnosti je praviloma žilav in le redko polkrhek. Ker pa se takšna jekla uporabljajo za varjene konstrukcije, moramo upoštevati tudi možnost pojavljanja mikrorazpok v toplotno vplivanih conah varov, zato postane še kako pomembna izbira primernega porušitvenega kriterija. Pri kvazistatično obremenjenih konstrukcijah s planarnimi

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Measuring of fracture foughness by J-integral method is described for micro alloyed fine-grained steels. The results show that it is not enough to consider only some standard criteria related to the demanded specimen size but that some other empirical criteria must be taken into account because of a severe shear strain on the sides of the specimen.

The fracture surfaces on the specimens are in all cases of ductile type with dimples and the size of dimples are in a good correlation with the measured J_{IC} values.

1. INTRODUCTION

For many years the only weldable structure steels have been the normalized C-Mn steels with a ferritic-pearlitic microstructure. Some ten years ago the first micro-alloyed fine-grained steels were developed because of demands for better yield point, weldability and toughness. These steels are alloyed, separately or in combinations, with Ti, Nb, V, Zr and Mo. The better yield strength is partly obtained by precipitation hardening of ferrite but primarily by the reduction of ferrite grain size what is specially true for thermomechanically treated steels. Smaller grain size shows a favourable influence on toughness too, shifting the transition temperature towards lower values.

Nowadays it is required that the yield strength of micro-alloyed fine-grained steels should be at least 500 MPa and the V-notch Charpy toughness high even at the temperature of − 60°C.

The carbon content in these new micro-alloyed steels is therefore somewhat lower, commonly between 0.03 and 0.12 %, the lower values are valid for thermomechanically treated steels.

The fracture of structural steels with the increased yield strength is nearly always tough and very seldom semi-brittle. Since such steels are used for welded structures, the possibility of microcracks in the heat-affected weld zones must be considered, too. Therefore the selection of an appropriate fracture criterion appears even more important.

In quasi-statically loaded structures with planer discontinuities, i. e. with cracks in the bearing cross-sec-

diskontinuitetami, t. j. razpokami v nosilnem preseku, lahko načeloma izbiramo med dvema skupinama porušitvenih kriterijev[1]. Prva skupina teh kriterijev (koncepti K, COD, J-integral, Tearing Modulus) temelji na elasto- oziroma elasto-plastomehaniki loma ter predpostavlja napredovanje nestabilne razpoke vse do loma konstrukcije. Druga skupina pa vključuje le kriterij plastičnega kolapsa[2], ki privzema, da do porušitve pride po plastični deformaciji neto preseka kot celote še pred napredovanjem razpoke.

Za naše raziskave smo tokrat izbrali dve različni mikrolegirani drobnozrnati jekli, namreč jeklo Nionicral 70 ter jeklo Niomol 490. Obe jekli sta proizvod železarne Jesenice, v pogojih eksploatacije pa se, vse do nizkih temperatur, obnašata izrazito elasto-plastično. Za študij njunih lastnosti smo zato izbrali metodo J-integrala, ki je na Inštitutu za metalne konstrukcije v Ljubljani osvojena do praktične rabe.

2. TEORETIČNI DEL

Pri nizkih temperaturah, velikih hitrostih deformacije ter v pogojih ravninskega deformacijskega stanja, t. j. pri zadostni debelini preizkušanca, je lom jekla praviloma krhek. V takšnih primerih je velikost plastične cone ob korenu planarne diskontinuitete, namreč inicialne mikrorazpoke na preizkušancu, zanemarljivo majhna, napredovanje razpoke do loma pa lahko popišemo z linearno elastomehaniko. Pri polkrhkem ali pa pri žilavem lomu pa je velikost plastične cone znatna ter je nikakor ne smemo zanemariti. Lom moramo v takšnem primeru obravnavati z nelinearno, takoimenovano elastoplastomehaniko.

Merilo za žilavost, in s tem tudi merilo za porušitev materiala s planarnimi diskontinuitetami v nosilnem preseku je v primeru, ko pri lomu ni potrebno upoštevati vpliva velikosti plastične cone, kar kritični faktor intenzitete napetosti ali loma žilavost materiala K_{IC}, kot se tudi imenuje. Merjenje lomne žilavosti K_{IC} je že dlje časa standardizirano[3, 4].

Pri elastoplastičnem obnašanju materiala ob planarni diskontinuiteti pa zaradi učinkovanja znatne plastične cone koren diskontinuitete najprej nekoliko otopi ob sočasnem odpiranju ustja diskontinuitete. Kritična velikost odpiranja ustja neposredno pred lomom je — ob znani geometriji problema — izključno lastnost samega materiala.

Na merjenju kritičnega razmika površin razpoke je zato osnovana metoda merjenja žilavosti materiala (metoda COD). Gliha[5] v svojem preglednem članku navaja, da je kritična velikost odpiranja ustja razpoke parameter, ki se nanaša samo na plastično cono ob korenu le-te. Lastnosti znotraj plastične cone pa se spreminjajo, zato pri merjenju kritične velikosti razmika površin razpoke prihaja do znatnega razsipanja rezultatov.

Parameter, ki ne zajema le vpliva plastične cone, je kritična vrednost krivuljnega integrala J vzdolž poljubne poti, ki objame konico razpoke. Za ravninski primer, ko ima preizkušanec enično debelino, velja:

$$J = -\frac{dU_p}{da} = \int_\Gamma W\,dy - \int_\Gamma \mathbf{T}\frac{\partial \mathbf{u}}{\partial x}\,ds, \qquad (1)$$

pri čemer smo z dU_p/da označili spremembo potencialne energije na enoto podaljšanja razpoke, W je deformacijska energija na enoto volumna, **u** je vektor pomika v smeri delovanja zunanje sile **T** na konturo Γ. Člen $\mathbf{T}(\partial \mathbf{u}/\partial x)\,ds$ daje torej delež vloženega dela iz napetostnega

tions, it is principally possible to choose between two groups of fracture criteria[1]. The first group (concepts K, COD, J-Integral, Tearing Modulus) is based on elasto- or elasto-plastomechanics of the fracture and presumes an unstable crack propagation to the final fracture of a structure. The second group includes merely the criterion of plastic collapse[2], supposing that fracture occurs after the netto cross-section has been plastically deformed as a whole immediately before the crack propagation commenced.

Two different micro alloyed fine-grained steels, i. e. Nionicral 70 and Niomol 490 were chosen for our investigation. Both are manufactured by Jesenice Ironworks and they both exhibit pronounced elasto-plastic behaviour down to low temperatures during exploitation. To study their properties we therefore decided for the J-integral method which is practically applied in the Institute of metallic structures in Ljubljana.

2. THEORY

At low temperatures, at high deformation rates, and in plane-strain conditions, i. e. with sufficiently thick specimens, the fracture of steel is regularly brittle. In such cases the size of plastic zone at the root of plane discontinuity, i. e. at the initial microcrack on the specimen, is negligibly small and the crack propagation to the fracture can be described by linear elastomechanics. With semi-brittle or even tough fracture the size of plastic zone is considerably greater and therefore it should not be neglected by any means. In such cases the fracture must be analyzed by the non-linear, so-called elasto-plastomechanics.

When the influence of the plastic zone size needs not be considered, the toughness criterion and thus the criterion for fracture of material containning plane discontinuities in the bearing cross-section is represented by the critical stress intensity factor, also called the material fracture toughness K_{IC}. The method of K_{IC} measurement has been standardized[3, 4] for quite a long time.

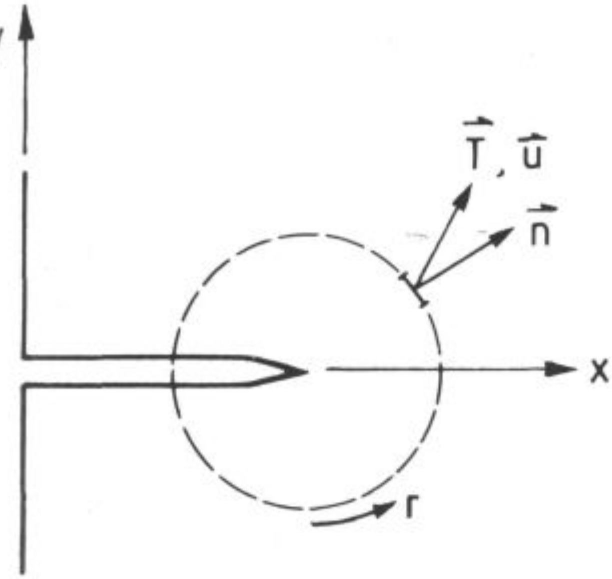
When material with plane discontinuities behaves elasto-plastically, the root of the discontinuity is initially blunted due to the influence of a considerable plastic zone and the crack starts simultaneously to open. The critical size of the crack opening displacement immediately before fracture occurs is — at the known geometry of problem — exclusively a material property.

Material toughness measurement (COD method) is therefore based on the method of measuring the critical displacement of the crack surface. Gliha[5] quotes in his review paper that the critical size of a crack opening displacement is a parameter related only to the plastic zone at its root. The properties within the plastic zone are changing and thus we have to do with a considerable scatter of results when the critical size of the crack surface displacement is measured.

The parameter which does not include only the influence of plastic zone is the ciritical value of the curved J-integral along any arbitrary path, enclosing the crack tip. For the case that the specimen has unit thickness, it can be writen as:

$$J = -\frac{dU_p}{da} = \int_\Gamma W\,dy - \int_\Gamma \mathbf{T}\frac{\partial \mathbf{u}}{\partial x}\,ds, \qquad (1)$$

*dU_p/da stands for the change of potential energy per unit crack propagation, W is deformation energy per unit volume, **u** is the displacement vector in the direction of external force action **T** on the contour Γ. The term $\mathbf{T}(\partial \mathbf{u}/\partial x)\,ds$ represents the rate of work input form the stress*



Slika 1
Integracijska pot krivuljnega integrala J je kontura Γ, ki objema plastično cono ob korenu razpoke

Fig. 1
Integrating path of the curve J-integral is the contour Γ, surrounding the plastic zone at the crack root.

polja v področje, obdano s konturo Γ. Več o J-integralu najde bralec v zelo razširjeni tozadevni literaturi[6,7], pomen simbolov v enačbi (1) pa je sicer razviden tudi s **slike 1.**

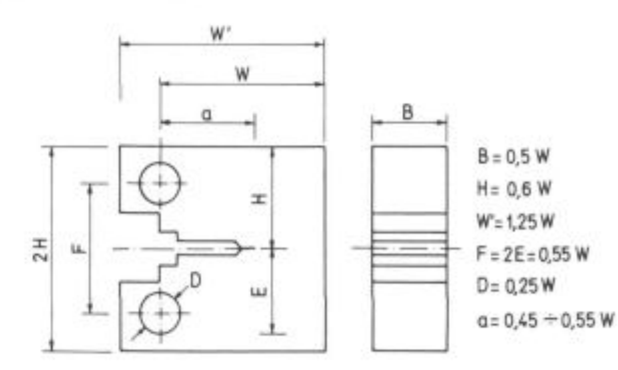
Metoda J-integrala je torej zasnovana na energijskem modelu loma, pri čemer je kritična vrednost J_C definirana kot vrednost J integrala tik pred lomom. Rice[8] je dokazal, da je J-integral od poti neodvisen, zato lahko za njegovo izračunavanje, t. j. za vrednotenje elastoplastičnega sproščanja energije namenoma izberemo takšno konturo, ki vključuje le bremena s pripadajočimi elastičnimi pomiki. Običajno je takšna kontura kar obris preizkušanca, za katerega so bremena in pomiki poznani, namreč izmerjeni.

Kako pa eksperimentalno določimo kritično vrednost J-integrala? V ta namen izdelamo večje število takoimenovanih CT preizkušancev, kakršen je prikazan na **sliki 2.** Ti preizkušanci imajo to posebnost — za razliko od podobnih CT preizkušancev za določevanje K_{IC} vrednosti — da lahko merilec hoda tzv. clip-gauge pozicioniramo natančno v linijo delovanja obremenitve. Zato, da dobimo dovolj oster koren razpoke, preizkušance predhodno pulzirajoče obremenjujemo z določeno, ne preveliko obremenitvijo.

Določevanje J_C vrednosti nato izpeljemo v pogojih kontroliranega pomika, t. j. pogojih kontroliranega odpiranja ustja razpoke, kar daje stabilno napredovanje razpoke. S sočasnim beleženjem obremenitve P ter odpiranja ustja razpoke δ dobimo opravljeno delo U enostavno s planimetriranjem zapisa P-δ. Ob tem merimo še dolžino razpoke a, kot tudi njeno napredovanje Δa, kar predstavlja določen eksperimentalni problem. Vsakokratnemu napredovanju razpoke Δa ustreza odgovarjajoče opravljeno delo oz. energija U, s pomočjo katere izračunamo pripadajočo J vrednost v skladu z enačbo:

$$J = \frac{2\,U}{B\,(w-a)}\,f\,(a/w), \qquad (2)$$

pri čemer je funkcija f (a/w) odvisna od neto preseka preizkušanca. Najdemo jo v ustreznem standardu[9].



Slika 2
Compact Tension (CT) preiskušanec za določevanje J integrala

Fig. 2
A compact tension (CT) specimen for determination of J-integral.

field into the area enclosed by the contour Γ. Detailed information about J-integral can be found in references[6,7] and while the meaning of symbols used in equation (1) evident from ***Fig. 1.***

This J-integral method is based on the fracture-energy model, the critical value J_C being defined as the value of J-integral immediately before the fracture sets in. Rice[8] proved that J-integral is independent of the path. For its calculation, i. e. for the evaluation of elasto-plastic release of energy it is therefore possible to choose intentionally a contour including only loads with corresponding elastic displacements. Such a contour is usually represented by the very outline of the specimen for which loads and displacements are known, that is measured.

How can the critical J-integral value experimentally be defined?

In order to define it experimentally a great number of the so-called CT specimens ***(Fig. 2)*** *was prepared. The peculiarity of these specimens is that the clip gauge can be positioned exactly in the line of load action in which they differ from the CT specimens used to determine K_{IC} values. In order to get a sufficiently sharp crack root the specimens are cycle loaded with a certain but not too heavy load.*

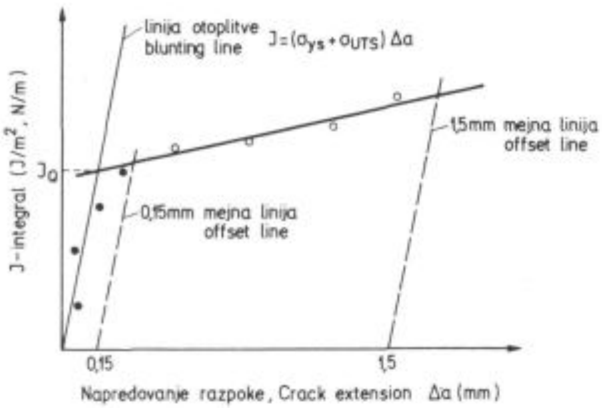
The J_C values are then determined under conditions of controlled displacement, i. e. under the conditions of controlled crack opening displacement, providing a stable crack propagation. By recording in the load P and the crack opening displacement δ, the work done U is obtained by planimetric treatment of the record P-δ plot. Simultaneously the crack length a and its propagation Δ a are measured, which represents some experimental problem. Each crack propagation step Δ a corresponds to an adequate work done or energy U. With the help of U it is possible to calculate the corresponding J-value according to equation:

$$J = \frac{2\,U}{B\,(w-a)}\,f\,(a/w), \qquad (2)$$

The function f (a/w) depends on the netto cross-section of a specimen and can be found in an adequate standard[9].

The first measured J value is applied to determine the conditional J_Q value which must meet the following conditions:

$$B \text{ and also } (w-a) > \frac{25\,J}{\sigma_o}, \qquad (3)$$



Slika 3
Odvisnost J integrala od napredovanja razpoke pri določevanju J_{IC} vrednosti

Fig. 3
Relationship between the J-integral and the crack extension in determining the J_{IC} values.

Prva izmerjena vrednost J služi za določevanje pogojne J_Q vrednosti, ki mora zadostiti zahtevam:

$$B, \text{ kot tudi } (w-a) > \frac{25\,J}{\sigma_o}, \tag{3}$$

pri čemer smo s σ_o označili napetost tečenja, ki je tu določena kot srednja vrednost med mejo plastičnosti σ_{ys} ter natezno trdnostjo σ_{uts}. S tako definirano napetostjo tečenja zajamemo namreč tudi deformacijsko utrjevanje materiala.

Minimalna debelina CT preizkušanca $B > 25\,J/\sigma_o$ zagotavlja, da bo daljšanje razpoke Δa opravljeno pod pogoji ravninskega deformacijskega stanja, minimalna dolžina ligamenta $b=(w-a) > 25\,J/\sigma_o$ pa preprečuje »tečenje« neto preseka preizkušanca.

Postopek določevanja veljavne J_{IC} vrednosti je prikazan na **sliki 3.** Postopek vključuje takoimenovano »blunting line procedure«, ki je uvedena za oceno navideznega napredovanja razpoke zaradi otopitve njenega korena. To navidezno napredovanje razpoke, merjeno z odpiranjem njenega ustja δ, bo manjše ali kvečjemu enako otopitvenemu radiusu korena, ki pa je enak polovici odpiranja, torej: $\Delta a \leq 0{,}5\,\delta$. Upoštevaje odvisnost $\delta = J/\sigma_o$, dobimo končno za enačbo linije otopitve naslednji izraz:

$$J = 2\sigma_o \Delta a = (\sigma_{ys} + \sigma_{uts})\,\Delta a \tag{4}$$

Omenimo naj še pomen obeh mejnih linij na sliki 3. Linija, označena kot 0,15 mm — mejna linija, zagotavlja, da bo napredovanje razpoke Δa vsaj 0,15 mm, da ga lahko dovolj natančno izmerimo. Linija, označena kot 1,5 mm — mejna linija, pa zagotavlja, da bo Δa v splošnem manjši od 6 % preostale dolžine ligamenta $(w-a)$, saj do te vrednosti ostane v veljavi enačba (2).

Veljavne vrednosti med obema linijama povežemo z regresijsko premico, katere presečišče z linijo otopitve daje J_Q vrednost. Tako določena pogojna J_Q vrednost je, ako sta izpolnjena pogoja (3), že tudi J_{IC} integral.

3. EKSPERIMENTALNI DEL Z REZULTATI

3.1 Določevanje J_{IC}-integrala

Za preiskave smo izbrali dva kosa jeklene pločevine, in sicer pločevino, debeline 40 mm, izdelano iz jekla Nionicral 70, ter pločevino, debeline 25 mm, izdelano iz jekla Niomol 490.

σ_o indicates the yield stress, defined as the mean value of the yield point σ_{ys} and the ultimate stress σ_{UTS}. Yield stress defined in this way includes the strain hardening of the material, too.

The minimal thickness of a CT specimen $B > 25\,J/\sigma_o$ guarantees that the crack propagation Δa will proceed under plane strain conditions and the minimal length of ligament $b=(w-a) > 25\,J/\sigma_o$ prevents the yielding of the netto cross-section of the specimen.

*The method to determine the valid J_{IC} value is shown in **Fig. 3.** It includes the so-called »blunting line procedure« which has been introduced in order to estimate the apparent crack propagation due blunting of its root. This apparent crack propagation measured by the crack opening displacement δ will be smaller or at least equal to the blunted root radius which itself is equal to one half of the opening: $\Delta a < 0.5\,\delta$. Considering that $\delta = J/\sigma_o$, the following expression is obtained for the blunting line equation:*

$$J = 2\sigma_o \Delta a = (\sigma_{ys} + \sigma_{UTS})\,\Delta a \tag{4}$$

The meaning of both offset lines in Fig. 3 should specially be eyplained. The 0.15 mm offset line guarantees that the crack propagation Δa must be at least 0.15 mm in order to enable accurate measurement. The 1.5 mm offset line, on the other hand, guarantees that Δa will on the whole be less than 6 % of the remaining ligament length $(w-a)$ because equation (2) is only valid up to this value.

The valid values between both lines can be connected by a regression straight line. Its intersection with the blunting line represents the J_Q value. In a case that both conditions (3) are fulfilled, the J_Q represents the J_{IC} integral as well.

3. EXPERIMENTS AND RESULTS

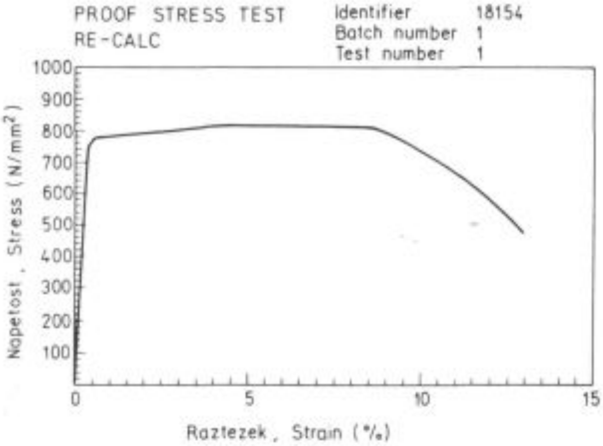
3.1 Determination of J_{IC} integral

For our investigation two pieces of steel sheet were chosen: a 40 mm thick sheet of Nionicral 70 and a 25 mm thick sheet of Niomol 490.

Nionicral 70 is a micro-alloyed steel applicable for dynamically loaded structures on low temperatures, containing 0.15 % C, 1.2 % Cr, 2.6—2.8 % Ni, 0.3 % Mo and 0.07 % V. With an ultimate tensile strength of 740—940 MPa, the yield strength of this steel with tempered martensitic microstructure achieves the value of at least 690 MPa. At a temperature of $-60^\circ C$ the V-notch Charpy toughness in longitudinal direction is still 94 J and in transversal direction 47 J. In welding conventional thicknesses, this steel must be preheated to $120^\circ C$.

Niomol 490 is of more recent date and it belongs to the group of micro alloyed steels which needn't be preheated in welding. It contains up to 0.10 % C, 1.2 % Mn, 0.3 % Mo and 0.04 % Nb and has a bainitic microstructure with a yield strength of at least 490 MPa at an ultimate tensile strength of 560—740 MPa. The V-notch Charpy toughness measured at $-60^\circ C$ is somewhat lower than in Nionicral, being at least 39 J in longitudinal and 31 J in transversal direction.

*Of both steels a greater number of CT specimens was made with the characteristic dimension w= 36,50 or 100 mm in longitudinal as well as in transversal direction. Besides, some cylindrical specimens were made for determination of conventional mechanical properties. The results of tensile tests are shown in plots in **Figures 4 and 5.** In Nionicral 70 the yield strength of 748 MPa and*



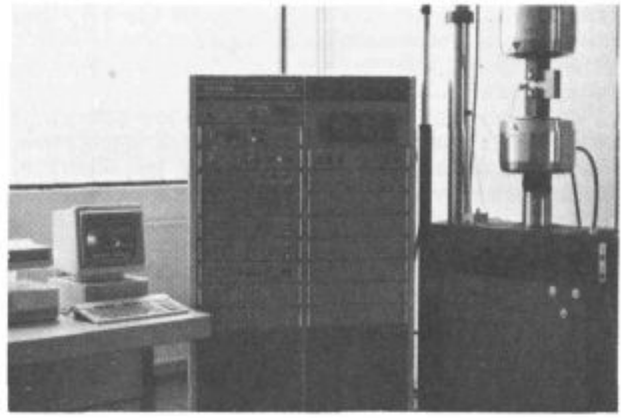
Slika 4
Zapis nateznega preiskusa jekla Nionicral 70
Fig. 4
Record of the tensile test for Nionicral 70.

Slika 5
Zapis nateznega preiskusa jekla Niomol 490
Fig. 5
Record of the tensile test for Niomol 490.

Nionicral 70 je mikrolegirano jeklo, uporabno za dinamično obremenjene konstrukcije pri nizkih temperaturah. Vsebuje od 0,15 % C, 1,2 % Cr, od 2,6 do 2,8 % Ni, 0,3 % Mo ter 0,07 % V. Pri trdnosti 740 do 940 Mpa dosega meja plastičnosti tega jekla z mikrostrukturo popuščenega martenzita vsaj 690 MPa. Žilavost Charpy-V je pri temperaturi −60°C v vzdolžni smeri še vedno 94 J ter v prečni še vedno 47 J. Pri varjenju običajnih debelin moramo to jeklo predgrevati do temperature 120°C.

Jeklo Niomol 490 je novejšega izvora ter spada v skupino mikrolegiranih jekel, ki jih pri varjenju ni potrebno predgrevati. Vsebuje do 0,10 % C, do 1,2 % Mn, 0,3 % Mo ter 0,04 % Nb. Ima bainitno mikrostrukturo z mejo plastičnosti vsaj 490 MPa pri trdnosti od 560 do 740 MPa. Žilavost Charpy-V, merjena pri temperaturi −60°C, pa je nekoliko slabša kot pri Nionicralu. V vzdolžni smeri dosega vsaj 39 J, v prečni pa vsaj 31 J.

Iz obeh kosov pločevine smo izdelali večje število CT preizkušancev s karakteristično dimenzijo w = 36, 50 oziroma 100 mm, in sicer tako v vzdolžni kot tudi v prečni smeri. Poleg teh smo izdelali še tudi nekaj cilindričnih preizkušancev za določevanje konvencionalnih mehanskih lastnosti. Rezultati nateznih preizkusov so prikazani



Slika 6
Preiskuševalni stroj INSTRON 1343
Fig. 6
»INSTRON 1343« testing machine.

the ultimate tensile strength of 823 MPa were measured. The corresponding values for Niomol 490 were 533 MPa and 618 MPa respectively.

*J-integral was determined with the help of the static/dynamic testing machine INSTRON 1343 with the capacity of 500/250 kN, controlled by a HP 9000/310 computer. The testing machine shown in **Fig. 6** is used at Inštitut za metalne konstrukcije in Ljubljana and is of a hydraulic type with a closed control system.*

*For specific testing requirements a series of clip gauges was made to measure the crack opening displacements. In **Fig. 7** a 15 mm clip gauge is shown. Its accuracy is 0.5 %. It is mounted on a CT specimen in the line of load action.*

The fatigue crack was initiated in all specimens by a dynamic load of a sine shape in the range of stress intensity factor $\Delta K = 1000\ Nmm^{-3/2}$ by 850 cycles per mm of crack propagation increment. All measurements were made at 20°C.

J-integral was determined in two ways, either with several specimens or with a single one. In the case of several-specimens method the crack extension was marked by thermal etching. In the case of a single specimen, however, the crack length was determined from the deflection of the specimen at partial unloading. The deflection of the specimen determined from the unloading line slope is directly related to the length of the crack.

Not fulfilling the size criterion (3) CT specimens with characteristic dimension w = 36 mm were found unsuitable. Results obtained on specimens with w = 50 mm were much better. Specimens with w = 100 mm are tested now.

*Plot in **Fig. 8** shows the results for Nionicral 70 measured by the method of unloading of a single specimen in transversal direction.*

After a series of repeated measurements the following values were obtained:

		J_{IC} (kJ/m²)
Nionicral 70	*in longitudinal direction*	*810—1020*
	in transversal direction	*290— 460*
Niomol 490	*in longitudinal direction*	*1570—1680*
	in transversal direction	*700— 990*

v diagramih na **slikah 4 in 5.** Pri jeklu Nionicral 70 smo namerili mejo plastičnosti 784 MPa ter trdnost 823 MPa, pri jeklu Niomal 490 pa mejo plastičnosti 533 MPa ter trdnost 618 MPa.

Za določevanje J-integrala smo uporabili statični/dinamični preizkuševalni stroj INSTRON 1343, zmogljivosti 500/250 kN, upravljan preko računalnika HP 9000/310. Preizkuševalni stroj, prikazan na **sliki 6**, je montiran na Inštitutu za metalne konstrukcije v Ljubljani in je hidravličnega tipa z zaprtim kontrolnim sistemom.

Za specifične potrebe preizkušanja smo izdelali serijo merilcev hoda (clip gauge) za merjenje odpiranja ustja razpoke. Na **sliki 7** je prikazan merilec hoda 15 mm točnosti 0,5 %, montiran na CT preizkušancu v liniji delovanja obremenitve.

Vnašanje utrujenostne razpoke je pri vseh preizkušancih potekalo z dinamično obremenitvijo sinusne oblike v območju faktorja intenzitete napetosti $\Delta K = 1000\ Nmm^{-3/2}$ z 850 cikli na mm prirastka razpoke. Vsa merjenja so bila opravljena pri temperaturi 20°C.

J-integral smo določali na dva načina, bodisi z več preizkušanci, pri katerih smo nato napredovanje razpoke markirali s toplotnim jedkanjem, bodisi z enim samim preizkušancem, kjer smo dolžino razpoke določili iz podajanja preizkušanca pri delnem razbremenjevanju. Iz naklona razbremenilne linije določena podajanost preizkušanca je namreč v neposredni zvezi z dolžino razpoke.

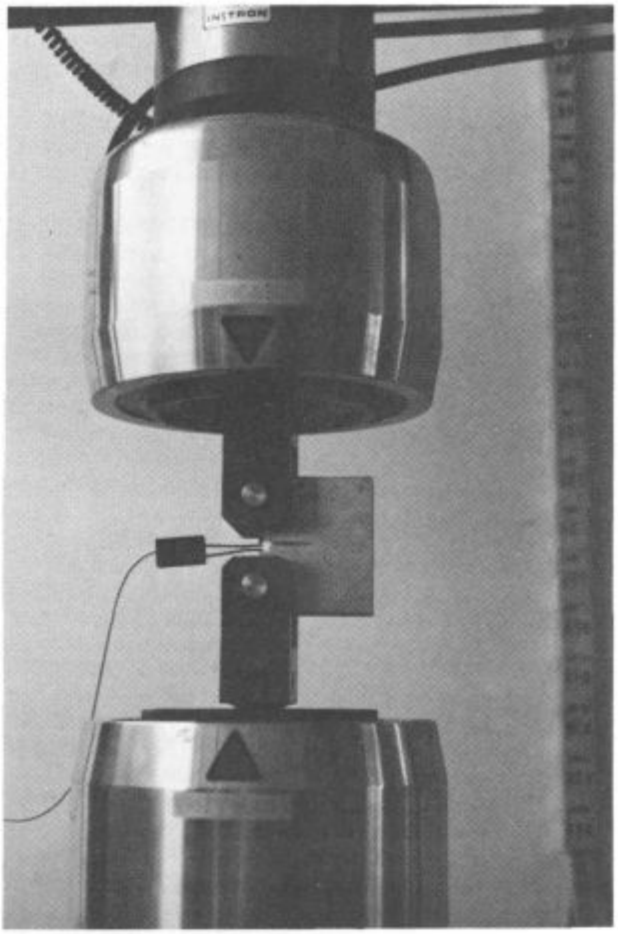
CT preizkušanci karakteristične dimenzije w = 36 mm so se že po prvih testih izkazali za neuporabne, ker ne zadovoljujejo velikostnega kriterija (3). Boljši so bili rezultati, dobljeni na preizkušancih s karakteristično dimenzijo w = 50 mm, v teku pa so preizkusi na preizkušancih s karakteristično dimenzijo w = 100 mm.

V diagramu na **sliki 8** so zbrani rezultati merjenja z metodo enega preizkušanca z razbremenjevanjem, veljajo pa za jeklo Nionicral 70 v prečni smeri.

Po velikem številu ponovljenih merjenj imamo končno:

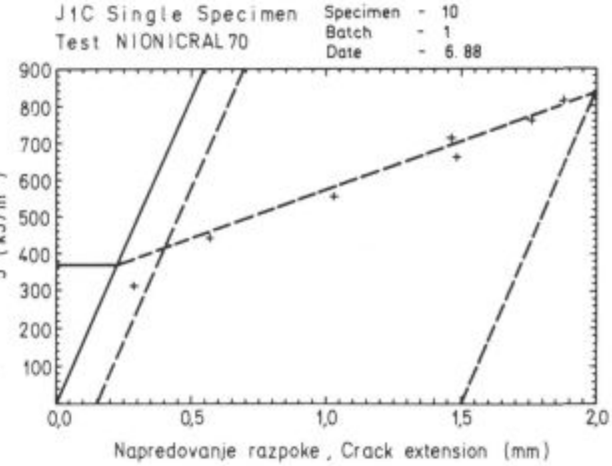
		J_{IC} (kJ/m²)
Nionicral 70	vzdolžno	810—1020
	prečno	290— 460
Niomol 490	vzdolžno	1570—1680
	prečno	700— 990

Na **sliki 9** je prikazana serija uporabljenih CT preizkušancev različnih debelin. Za polkrožno utrujenostno razpoko je možno na vsakem preizkušancu opaziti s toplotnim jedkanjem obarvano temnejšo frakturno površino, ki označuje med preizkušanjem napredovalo razpoko. Preseneča pa močna lateralna kontrakcija bokov preizkušancev ter s tem povezana strižna ustnica na frakturnih površinah celo največjega od uporabljenih preizkušancev, kar govori v prid domnevi, da je velikost plastične cone znatna v primerjavi z dimenzijami preizkušancev. Literatura[10, 11] navaja, da pri merjenju odvisnosti lomne žilavosti (določene preko J-integrala) od temperature preizkušanja dosežemo določeno žilavost, ki jo pri višjih temperaturah preizkušanja nič več ne presežemo, pač pa žilavost le še pada. Govorimo o takoimenovanem platoju žilavosti, ki pa je odvisen od debeline CT preizkušanca. Plato se pojavi, ko postane velikost plastične cone ravninskega napetostnega stanja r_p primerljiva z debelino preizkušanca B. V teh pogojih pride do močne plastične deformacije pred korenom razpoke in merjenje žilavosti ni več veljavno.



Slika 7
Obremenjen CT preiskušanec z montiranim merilcem hoda v liniji delovanja obremenitve

Fig. 7
Loaded CT specimen with a clip gauge mounted in the line of load action.



Slika 8
Diagramski prikaz določevanja J_{IC} vrednosti za jeklo Nionicral 70 v prečni smeri

Fig. 8
Diagramatical presentation of determining J_{IC} values in transversal direction for Nionicral 70

Slika 9
Serija uporabljenih CT preiskušancev različnih debelin. Na sliki je za primerjavo še škatlica vžigalic.

Fig. 9
A series of used CT specimens of various thicknesses. For comparison's sake there is a box of matches.

Velikost plastične cone za ravninsko napetostno stanje določimo z enačbo:

$$r_p = \frac{1}{2\pi}\left(\frac{K_{IC}}{\sigma_{ys}}\right)^2 \qquad (5)$$

Ker je med faktorjem intenzitete napetosti ter J-integralom naslednja zveza:

$$J = \frac{K_{IC}^2}{E'} \qquad (6)$$

pri čemer je: $E' = E$ za ravninsko napetostno stanje
ter $E' = E/(1-\nu^2)$ za ravninsko deformacijsko stanje, dobimo končno rezultat, da pri meji plastičnosti 600 MPa, ki je na primer zgornja vrednost za Niomol 490, ter debelini preizkušanca 25 mm, lahko pravilno izmerimo le žilavost v območju do največ 240 $MNm^{-3/2}$, kar ustreza J_{IC} vrednosti največ 260 kJm^{-2}. Celo pri vzorcu dvojne debeline bi še vedno lahko pravilno merili le do 370 kJm^{-2}.

Milne in Chell[12, 13] sta na primer pokazala, da testi s CT preizkušanci, ki sicer zadovoljujejo velikostne kriterije (3), lahko dajajo rezultate K_J (torej lomno žilavost izračunano preko J integrala), ki so tudi za faktor 2,5 večji od dejanske K_{IC} vrednosti.

Omenimo naj še empirično določen kriterij, ki so ga Bergerjeva in sodelavci[14] našli za minimalno debelino CT preizkušancev za merjenje J-integrala. Kriterij v obliki:

$$B > 0{,}35\left(\frac{K_J}{\sigma_{ys}}\right)^2 \qquad (7)$$

predpisuje še dosti večje debeline preizkušancev, kot pa je to določeno s standardnim kriterijem (3).

Na osnovi povedanega lahko zaključimo, da so bile v okviru opravljenega eksperimentalnega dela izmerjene le okvirne vrednosti J_{IC} in da je pri korektnem merjenju J-integrala potrebno upoštevati poleg s standardom predpisanih kriterijev (3), nanašajočih se na debelino preizkušanca ter dolžino ligamenta, še tudi nekatere druge bolj ali manj empirične kriterije[11, 14].

3.2 Mikrofraktografske preiskave

Mikrofraktografske preiskave prelomnih površin CT preizkušancev so bile opravljene s scanning elektronskim mikroskopom na Metalurškem inštitutu v Ljubljani.

Fig. 9 *shows several CT specimens of various thicknesses. For a semicircular fatigue crack it is possible to note a darker fracture surfase coloured by thermal etching which denotes crack extension. Surprising is a severe lateral contraction of the sides and the shear lip on fracture surfaces even on the greatest specimens. It speaks in the favour of the hypothesis that the size of plastic zone is considerably great in comparison to the dimensions of specimens.*

As cited in references[10, 11], a certain toughness is obtained when measuring the fracture toughness in relation (determined over a J-integral) to the testing temperature. At higher temperatures this toughness is not exceeded, it even tends to be reduced. We have to do with the so-called toughness plateau, depending on the thickness of the CT specimen. This plateau occurs when the size of plastic zone in the plane stress r_p becomes comparable to the thickness of the specimen B. Under these conditions a severe plastic deformation takes place in front of the crack root, making all subsequent toughness measurements non-valid.

The plane-strain plastic-zone-size-factor can be determined by the equation:

$$r_p = \frac{1}{2\pi}\left(\frac{K_{IC}}{\sigma_{ys}}\right)^2 \qquad (5)$$

There is the following connection between the stress intensity factor and the J-integral:

$$J = \frac{K_{IC}^2}{E'}, \qquad (6)$$

where $E' = E$ for plane stress and
$E' = E/(1-\nu^2)$ *for plane strain*
Thus it becomes evident that with the yield strength of 600 MPa, which is e. g. the peak value for Niomol 490, and with the sample thickness of 25 mm it is only possible to measure correctly the toughness values within the range up to 240 $MNm^{-3/2}$, which corresponds to a J_{IC} value of utmost 260 kJm^{-2}. Even with a specimen of a twofold thickness it could be measured correctly only up to 370 kJm^{-2}.

Milne and Chell[12, 13] have shown that tests with CT specimens which actually satisfy all size criteria (3) can give results for K_J (i. e. for fracture toughness calculated from J-integral being even 2.5 times higher than the actual K_{IC} values.

Let us mention here the empirically defined criterion for minimal thickness of CT specimens, found by Berger and his colleagues[14], which is suitable for measuring the J-integral. According to the criterion in the form of:

$$B > 0.35\left(\frac{K_J}{\sigma_{ys}}\right)^2 \qquad (7)$$

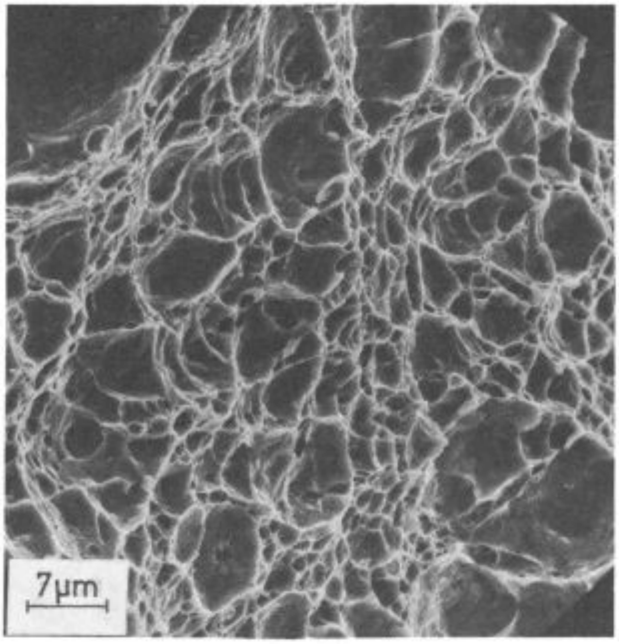
far greater thicknesses are demanded than those determined by the standard criterion (3).

It can be concluded that only approximate J_{IC} values were measured. For correct measuring of J-integral it is necessary to consider not only the standard criteria (3) referring to the thickness of a specimen and to the length of the ligament but also some other more or less empirical criteria[11, 14].

3.2 Microfractographic investigations

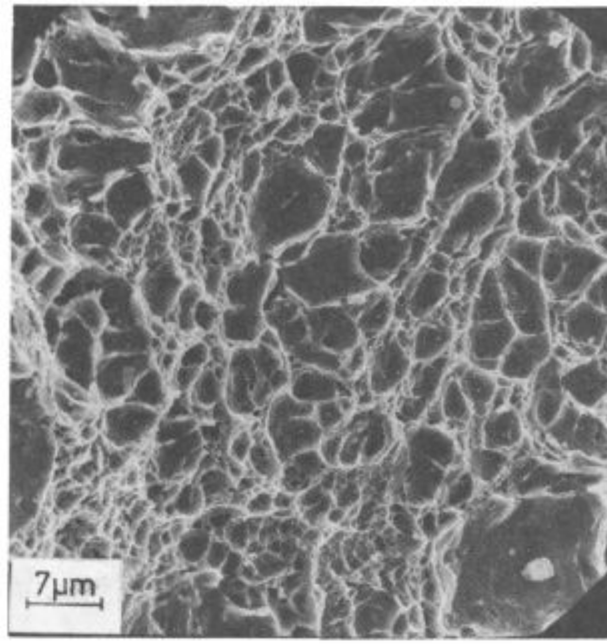
The fracture surfaces of CT specimens were investigated by a scanning electron microscope at the Institute of Metallurgy in Ljubljana.

In Fig. 10 there is a dimpled fracture surface (Niomol 490) which corresponds to a ductile type of fracture. The



Slika 10
Jamičasta frakturna površina CT preiskušanca iz jekla Niomol 490, sicer značilna za duktilno obliko loma

Fig. 10
Dimpled fracture surface of a CT specime of Niomol 490, normally characteristic for a ductile fracture.



Slika 11
Podobna kot na sliki 10 je tudi frakturna površina CT preiskušanca iz jekla Nionicral 70

Fig. 11
The fracture surface of a CT specimen of Nionicral 70, similar to that shown in Fig. 10.

Na sliki 10 je prikazana jamičasta prelomna površina pri jeklu Niomol 490, ustrezna duktilnemu tipu preloma. Premer jamic se giblje v mejah od 1,3 do 5 µm. Zelo podobna je prelomna površina pri jeklu Nionicral 70, prikazana na sliki 11, čeprav je premer jamic v tem primeru nekoliko manjši, vsega 0,5 do 3,5 µm. Ti podatki se dobro ujemajo z rezultati merjenj J_{IC} vrednosti. Premer jamic na frakturni površini je namreč v določeni soodvisnosti z volumnom plastično deformiranega materiala neposredno ob frakturni površini, torej tudi v soodvisnosti z izmerjeno žilavostjo jekla. Vendar pa ta soodvisnost ni trdna, ker k žilavosti jekla, merjeni z metodo J-integrala, prispeva prvenstveno energija, nakopičena v plastični coni, in le v manjši meri energija, potrebna za neposredno formiranje novonastalih frakturnih površin. Vsekakor je velikost plastične cone pred korenom razpoke za več velikostnih redov večja od velikosti jamic na frakturnih površinah.

4. ZAKLJUČKI

Merjenja J_{IC} integrala drobnozrnatih mikrolegiranih jekel Nionicral 70 ter Niomol 490 kažejo, da je žilavost Niomola, merjena pri temperaturi 20 °C, znatno boljša od žilavosti Nionicrala, čeprav so bile lahko izmerjene le orientacijske vrednosti. Močna lateralna kontrakcija bokov preizkušancev ter s tem povezana strižna ustnica na frakturnih površinah celo največjih CT preizkušancev namreč pomeni, da je velikost plastične cone primerljiva z debelino preizkušancev ter so zato izmerjene vrednosti vprašljive. Čeprav preizkušanci zadovoljujejo standardne velikostne kriterije (3), pa je pri korektnem merjenju potrebno upoštevati tudi še kriterij na osnovi velikosti plastične cone (5), kot je to opisano v članku, pa tudi empirični kriterij Bergerjeve[14] (7), ki se zdi še ostrejši.

Mikrofraktografske preiskave potrjujejo rezultate merjenj žilavosti. Frakturne površine so v vseh primerih

diameter of dimples ranges within 1.3 and 5 µm. The fracture surface for Nionicral 70 shown in Fig. 11 is very similar to the previous one although the diameter of dimples was slightly smaller — 0.5 to 3.5 µm. These results are in a good agreement with results obtained by J_{IC} measurements. The diameter of dimples on a fracture surface is namely to some extent related to the volume of plastically deformed material in the surrounding of the fracture surface and therefore also to the measured toughness of a steel too. But this relation is not fixed, as the energy accumulated in the plastic zone contributes much more to the steel toughness measured by J-integral method than to the energy needed for direct formation of newly initiated fracture surfaces. In any case the size of plastic zone in front of the crack root is for several orders of magnitude greater than the size of dimples on fracture surfaces.

4. CONCLUSIONS

Measurements of J-integral in fine-grained micro-alloyed steels Nionicral 70 and Niomol 490 indicate that the toughness of Niomol 490 measured at 20 °C is much better than that of Nionicral, although only approximate values could be measured. A severe lateral contraction of the sides of specimens and the corresponding shear lip on the fracture surfaces of even the greatest CT specimens mean that the size of plastic zone is comparable to the thickness of a specimen, thus the measured values are questionable. Although the specimens satisfy the standard size criteria (3) it is necessary for obtaining correct results to consider the criterion based on the size of plastic zone (5) as described in the paper, as well as the empirical Berger's criterion[14] (7) which seems even more rigid.

Microfractographic investigations confirm the results of toughness measurements. Fracture surfaces are in all jamičaste, duktilne, vendar pa je volumen jamic pri Niomolu opazno večji od volumna jamic pri Nionicralu. Zveza med velikostjo jamic na frakturnih površinah ter izmerjeno žilavostjo pa ni preveč trdna zaradi dominantnega prispevka plastične cone — slednja je za več redov velikosti večja od velikosti jamic — k izmerjeni žilavosti jekla.

cases of ductile type with dimples, though the volume of dimples in Niomol is notably greater than that in Ninicral. The relation between the size of dimples on fracture surfaces and the measured toughness is no very reliable due to the dominating contribution of the plastic zone — the latter is for several orders of magnitude greater than the size of dimples — to the measured steel toughness.

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SLOVENSKE ŽELEZARNE

ŽELEZARNA ŠTORE

ŠTORE

PROIZVODNI PROGRAM

Toplo valjani profili

- kvalitetno in plemenito ogljikovo jeklo ter
- kvalitetno in plemenito nizko legirano jeklo v okrogli, ploščati in kvadratni obliki,
- specialni profili po načrtih

Hladno oblikovani profili

- vlečeno in brušeno jeklo v vseh kvalitetah v okrogli, ploščati in specialni izvedbi

Livarski proizvodi

- ulitki iz sive litine,
- ulitki iz nodularne (KGR) litine,
- kontinuirno liti profili,
- litoželezni valji,
- jeklarske kokile,
- priklopna sedla,
- mehanski sklopi,
- strmoramenska platišča

Industrijska oprema

- industrijski gorilniki, industrijske peči za ogrevanje, žarenje itd.,
- indukcijske peči,
- rekuperativna toplotna tehnika,
- plinski oskrbovalni sistemi za ZP in zamenljive mešanice

Vlečene palice kakovostnega jekla