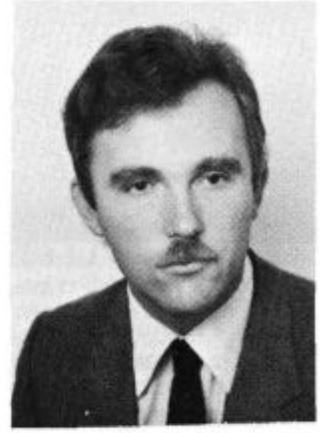

Hladno preoblikovanje konti litega jekla
Cold Working of Continuously Cast Steel

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UDK: 621.74.047-426:621.778.011:669.15-194.56
ASM/SLA: Q23q, 1—67, STb, D9q, 4—61

Postopek konti ulivanja tankih profilov jekel in drugih zlitin je novejši način izdelave predvsem specialnih in slabo preoblikovalnih materialov. Postopek bo že v kratkem uveden na Metalurškem inštitutu, v bodoče pa verjetno tudi v slovenskih železarnah.

Jeklo ima v litem stanju slabe preoblikovalne sposobnosti. V raziskavi smo ugotavljali vlečne sposobnosti konti lite avstenitne nerjavne žice. Cilj raziskave je bil ugotoviti največje deformacije, ki jih lito jeklo pri vlečenju prenese, in vpliv deformacije ter temperature na rekristalizacijo litega jekla.

1. UVOD

Postopek konti ulivanja žice je iz tehnološkega in ekonomskega stališča zelo primeren in perspektiven način izdelave tankih profilov jekel in zlitin. Iz tehnološkega zato, ker vsa vroča predelava odpade, iz ekonomskega pa, ker je konti lita žica precej cenejša od klasično izdelane. Pri postopku konti ulivanja ima jeklo oziroma žica lito mikrostrukturo, ki ima precej slabše preoblikovalne sposobnosti kot klasično izdelana, vroče valjana žica. Ker moramo tako žico zaradi nadaljnje predelave v hladnem največkrat še naprej vleči do tanjših dimenzij, smo v raziskavi ugotavljali njene preoblikovalne sposobnosti. Preizkušali smo uvoženo konti lito avstenitno nerjavno žico, vrste AISI 304, premera 8,1 mm, ki je v odstotkih vsebovala: 0,03 C, 19,1 Cr, 9,2 Ni, 0,14 Nb in 0,13 N. Preoblikovalne sposobnosti jekla smo ugotavljali s krivuljami tečenja, s preizkusi vlečenja in metalografskimi preiskavami.

2. MIKROSTRUKTURNE IN PREOBLIKOVALNE LASTNOSTI KONTI LITE ŽICE

Konti lita žica se razlikuje od klasično izdelane valjane žice po stanju površine žice, po mikrostrukturi, preoblikovalnih lastnostih jekla in poroznosti sredine litega jekla.

2.1. Površina konti lite žice

Na površini konti lite žice so vidne drobne vdolbine, podobne razpokam **(slika 1)**, ki nastanejo pri strjevanju jekla na koncu kristalizatorja. Medsebojna oddaljenost

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** Originalno publicirano: ŽZB 24 (1990)1
*** Rokopis sprejet: november 1989

Continuous casting of thin sectional steels and other alloys is a modern production process primarily for special materials with poor deformability. This process will soon be applied at the Institute of Metallurgy and probably also in Slovene steelworks in the near future.

Because the cold deformability of cast steel is limited the drawing capability of continuously cast stainless steel wire with an austenitic microstructure was examined. The aim of this was to determine the maximum strain achievable in drawing cast steel as well as the influence of strain and temperature on its recrystallization.

1. INTRODUCTION

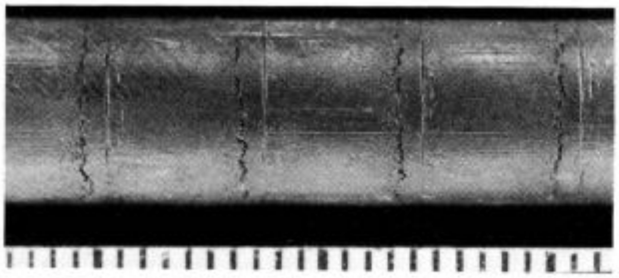
From the technological and economic point of view the production of continuously cast wire is a very suitable and prospective way of manufacturing thin sectionals steels and alloys. From the technological point of view it is suitable because hot working becomes unnecessary, and from the economic point of view, because wire cast continuously is considerably cheaper than wire produced conventionally. Steel, e. g wire produced by continuous casting, has a microstructure with essentially worse deformability than conventionally manufactured hot-rolled wire. As continuously cast wire must be additionally drawn to smaller diameters for further cold working, wire deformability was examined. Imported continuously cast wire from austenitic stainless AISI 304 steel with 0.03 % C, 19.1 % Cr, 9.2 % Ni, 0.14 % Nb and 0.13 % N with a diameter of 8.1 mm was tested. The deformability of the steel was determined by flow curves, drawing tests and by metallographic research.

2. MICROSTRUCTURE AND DEFORMABILITY OF CONTINUOUSLY CAST WIRE

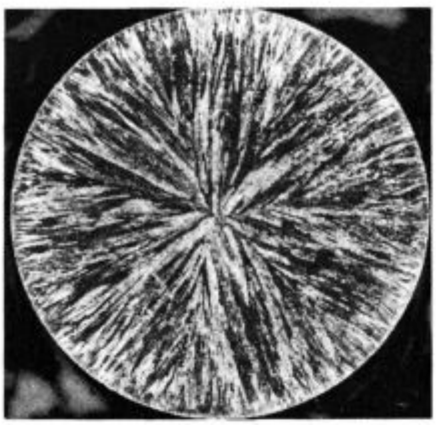
Continuously cast wire differs from conventionally made rolled wire in wire surface quality, microstructure, deformability and porosity of the cast core.

2.1 The Surface of Continuously Cast Wire

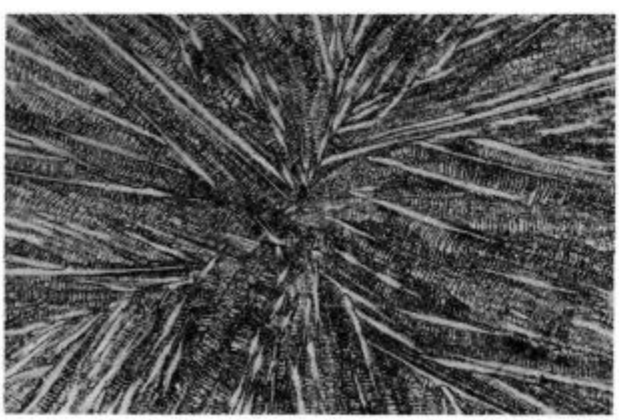
*Shallow circumferential marks are visible on the surface of continuously cast wire **(Fig. 1)**. These marks, which look like fissures, appear when steel solidifies at the end of the mould. The distance between them depends upon the stroke (frequence) of the drawing device. The circumferential marks are deeper when using older equipment with lower frequences, whereas these marks could completely disappear by using new*



Slika 1
Površina konti lite žice
Fig. 1:
Continuously cast wire surface



Slika 2:
Makroposnetek konti lite žice po litju (pov. 10 ×)
Fig. 2:
Macrostructure of continuously cast steel (magn. 10×)

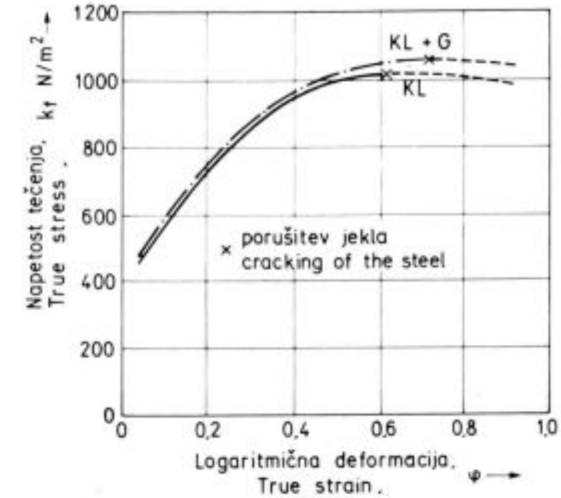


Slika 3:
Mikroposnetek konti lite žice po litju (pov. 50 ×)
Fig. 3:
Microstructure of continuously cast steel (magn. 50×)

vdolbin je odvisna od koraka (frekvence) vlečnega mehanizma. Pri starejših napravah z manjšimi frekvencami so vdolbine večje, pri novejših, tudi pri napravi, ki bo že v kratkem pričela redno obratovati na Metalurškem inštitutu, pa pri večjih frekvencah vdolbine lahko popolnoma odpravimo (2,3).

2.2. Mikrostrukturne lastnosti

Mikrostruktura konti lite žice je sestavljena iz zelo tanke plasti globulitnih kristalov in transkiristalov, ki so



Slika 4:
Napetosti tečenja konti litega jekla AISI 304 pred gašenjem in po njem (KL-konti lito, G-gašeno)
Fig. 4:
Flow stress curves of continuously cast AISI 304 steel before and after annealing (KL-continuously cast, G-annealed)

equipment with higher frequences, like that which will soon be operating at the Institute of Metallurgy (2,3).

2.2 Characteristic of Microstructure

*The microstructure of continuously cast wire consists of a very thin layer of globulitic crystal grains and columnar crystals orientated towards the centre of the wire **(Fig. 2,3)** which can be partly porous. However, this porosity is totally eliminated by further working (1).*

2.3 Deformability of Continuously Cast Wire

*Deformability of continuously cast wire was specified by yield stress curves obtained by the compression of test pieces made from continuously cast wire **(Fig. 4)**. Cast wire as well as previously quenched wire were tested in order to determine the necessity of quenching owing to improved deformability. The highest linear strains of continuously cast wire are between 40 and 45 %, which is approximately half the strain obtainable in conventionally made wire with a similar chemical composition. Continuously cast and quenched wire withstand a strain which is only a few percentage points higher than that of unquenched wire, which means that quenching after continuous casting is not essential to improve deformability. The low reduction of area which was observed during the tension test of continuously cast wire, also confirms the bad deformability of such wire. The reduction in area was only 15 %, which is considerably lower than that of conventionally made wire with a similar chemical composition which gives a reduction in area of over 60 %.*

2.4 Drawing of Continuously Cast Wire

Drawing tests were made on about 2 m long wire pieces, which were drawn from one coil to another. Before drawing, the wire surface was covered with Tehnolin and Stearat powder, which is a standard lubricant used in drawing stainless steels. The velocity of drawing was 0.24 m/s and the drawing reduction was 20 to 25 %. Continuously cast wire was drawn to the highest possible strain, i. e. until the wire split. Besides the drawing capacity of steel established in the tension test, the dis-

usmerjeni pravokotno na središčnico **(slika 2 in 3)**. Sredina konti lite žice je lahko delno porozna, ki pa jo z nadaljnjo predelavo popolnoma odpravimo (1).

2.3. Preoblikovalnost konti lite žice

Preoblikovalne sposobnosti konti lite žice smo najprej ugotavljali s krivuljami napetosti tečenja, dobljenimi s stiskanjem preizkušancev, izdelanih iz konti lite žice **(slika 4)**. Preizkušali smo žico v litem stanju brez gašenja in po gašenju z namenom, da bi ugotovili, ali je zaradi boljše predelovalnosti žico po litju potrebno gasiti ali ne. Največje specifične deformacije, ki jih konti lita žica prenese, znašajo le 40 do 45 %, kar je približno dvakrat manj kot pri klasično izdelani žici podobne kemične sestave. Gašena konti lita žica prenese le nekaj odstotkov večje deformacije kot negašena, kar pomeni, da žice po konti litju za boljšo preoblikovalnost ni potrebno gasiti. O slabih preoblikovalnih lastnostih preizkušane konti lite žice lahko sklepamo tudi iz nizke kontrakcije, ki smo jo dobili pri trgalnem preizkusu žice. Kontrakcija je znašala le 15 %, kar je precej manj kot pri klasično izdelani žici podobne kemične sestave, kjer znaša več kot 60 %.

2.4. Vlečenje konti lite žice

Preizkuse vlečenja smo naredili na približno dva metra dolgih koncih žice in z vlečenjem iz kolobarja v kolobar. Pred vlečenjem smo na površino žice nanesli Tehnolin in stearatni prašek, standardno mazivno prevleko za vlečenje nerjavnih jekel. Hitrost vlečenja je bila 0,24 m/s, redukcije pa so znašale od 20 do 25 %. Konti lito žico smo vlekli do največjih možnih deformacij, do trganja žice. Med vlečenjem smo poleg ugotavljanja vlečnih sposobnosti jekla, spremljali tudi zapolnjevanje vdolbin na površini žice in zapolnjevanje mikroporoznosti na sredini žice.

Največje deformacije, ki smo jih pri vlečenju iz kolobarja v kolobar dosegli, so znašale približno 35 % (pri vlečenju do premera 6,5 mm) in približno 45 % pri vlečenju krajših koncev žice. Dosegli smo jih pri dvakratnem vlečenju žice. Deformacije, ki smo jih pri vlečenju dosegli, so približno enake deformacijam, doseženim pri stiskanju jekla. Po vlečenju smo žico žarili pri temperaturi 1050° C in gasili. Pri omenjenem žarjenju je jeklo rekristaliziralo. O rekristalizaciji konti litega vlečenega jekla bomo podrobneje spregovorili v nadaljevanju. Rekristalizirano žico smo nadalje vlekli pri enakih redukcijah, velikih 20 do 25 %. Vlekli smo jo v štirih vlekih iz premera 6,1 do 3,5 mm. Skupna deformacija je znašala 86 %, kar je deformacija velikostnega reda vlečenja klasično izdelane avstenitne nerjavne žice, zato preizkušane žice nismo več vlekli do tanjših dimenzij. Iz omenjenih rezultatov lahko zaključimo, da ima konti lita žica po vlečenju in rekristalizacijskem žarjenju podobne vlečne sposobnosti kot klasično izdelana žica podobne kemične sestave.

Globina vdolbin, nastalih med litjem žice, se je med vlečenjem zmanjševala tako, da jih pri premeru vlečene žice 5,2 mm, pri redukciji žice $\varepsilon = 60$ %, pri metalografskem pregledu površine žice nismo več opazili. Podobno je bilo tudi z mikroporoznostjo jekla, ki je pri premeru vlečene žice 5,2 mm, pri zmanjšanju preseka žice približno za polovico, nismo več opazili.

3. REKRISTALIZACIJA KONTI LITEGA HLADNO VLEČENEGA JEKLA

Rekristalizacija konti litega hladno vlečenega jekla je odvisna od stopnje deformacije in višine temperature žarjenja. Ker konti lito jeklo prenese precej manjše

appearance of marks on the wire surface as well as the fillings of microporosity in the wire core were also determined. The highest strain attainable while drawing from one coil to another was approximately 35 % (in drawing to a diameter of 6.5 mm) and approximately 45 % in drawing shorter pieces of wire. Such strains were obtained by passing the wire twice. The strains obtained by drawing were similar to the ones obtained in steel compression tests. After drawing, the wire was annealed at 1050° C and then quenched. During annealing the steel recrystallized. Recrystallization of continuously cast steel will be treated more in detail. The recrystallized wire was further drawn in four passes with nearly the same drawing reduction of about 20 to 25 % from a diameter of 6.1 to 3.5 mm. The total drawing reduction was 86 %, which is the same order of magnitude as for conventionally made stainless steel wire. This is the reason why the tested wire was not further drawn to a smaller diameter.

On the basis of these results it could be concluded, that after drawing and recrystallization annealing, continuously cast wire has the same drawing ability as conventionally made wire with a similar chemical composition.

The depth of circumferential marks which appeared during casting decreased so much during drawing that the marks were no longer visible at metallographic examination of the wire (reduced by $\varepsilon = 60$ % from a diameter of 5.2 mm). Similarly, the microporosity of the steel was no longer observed when the cross-section of the wire with a diameter of 5.2 mm was reduced approximately by one half.

3. RECRYSTALLIZATION OF CONTINUOUSLY CAST COLD-DRAWN STEEL

Recrystallization of continuously cast cold rolled steel depends upon the degree of deformation and the annealing temperature. As continuously cast steel withstands considerably lower strains than conventionally made steel, the purpose of this investigation was to established the smallest strains and the lowest temperatures at which steel completely recrystallizes. The degree of recrystallization was determined by metallographic observations and hardness measurements. The recrystallization of steel was established at tempere-tures from 900 to 1050° C and during a drawing reduction of 9 to 44 %. The most typical microstructures of steel after recrystallization annealing are shown in ***Fig. 5****. At 900° C steel did not recrystallize until a reduction of 44 % was achieved, whereas at temperatures of 1000 and 1050° C steel recrystallized already at a reduction of 9 %. Steel drawn after recrystallization recrystallizes at the same temperatures and strains as constinuously cast drawn steel.*

4. CONCLUSIONS

The drawing ability of continuously cast AISI 304 stainless steel wire with an austenitic microstructure was examined. The aim of this was to establish its drawing ability when cast and after recrystallization anealing, as well as the influence of surface conditions and microporosity of the wire core on its drawing ability and its recrystallization properties. To summarize:

1. Before drawing for better workability it is not necessary to anneal wires from austenitic AISI 304 stainless steel produced by continuous casting process.

2. The total strain of continuously cast steel while drawing reaches 35 to 45 %, i. e. approximately less than half that of conventionally made steel.

deformacije kot klasično izdelano jeklo, smo v raziskavi želeli ugotoviti tiste najmanjše deformacije in najnižje temperature, ko jeklo še popolnoma rekristalizira. Stopnjo rekristalizacije smo ugotavljali z metalografskimi preiskavami in meritvami trdot. Rekristalizacijo jekla smo ugotavljali pri temperaturah žarjenja od 900 do 1050° C in redukcijah od 9 do 44 %. Najznačilnejše mikrostrukture jekla po rekristalizacijskem žarjenju so prikazane na **sliki 5**. Pri temperaturi 900° C je jeklo rekristaliziralo šele pri stopnji deformacije 44 %, pri temperaturah 1000 in 1050° C pa že pri stopnji deformacije 9 %. Jeklo, vlečeno po rekristalizaciji, rekristalizira pri enakih temperaturah in deformacijah kot konti lito vlečeno jeklo.

4. ZAKLJUČKI

V raziskavi smo ugotavljali vlečne sposobnosti konti lite avstenitne nerjavne žice, vrste AISI 304, ulite na napravi za konti litje žice. Cilj raziskave je bil ugotoviti njegove vlečne sposobnosti v litem stanju in po rekristalizacijskem žarjenju, vpliv stanja površine in mikroporoznosti sredine žice na njegove vlečne sposobnosti in ugotoviti njegove rekristalizacijske lastnosti. Kratki zaključki so naslednji:

1. Žice iz avstenitnega nerjavnega jekla AISI 304, izdelane po postopku konti ulivanja, pred vlečenjem za boljšo preoblikovalnost ni potrebno gasiti.
2. Preizkušano konti ulito jeklo prenese pri vlečenju 35 do 45 % skupne deformacije, kar je približno polovico manj kot pri klasično izdelanem jeklu.
3. Rekristalizirano konti lito jeklo ima podobne preoblikovalne sposobnosti kot klasično izdelano jeklo.
4. Deformirana lita mikrostruktura jekla rekristalizira pri temperaturi žarjenja 900° C pri specifični deformaciji približno 44 %, pri temperaturi 1000° C pa že pri specifični deformaciji približno 9 %. Podobno je tudi pri rekristalizirani deformirani mikrostrukturi.
5. Vdolbine, ki nastanejo pri postopku konti ulivanja na površini žice, ne vplivajo na vlečne sposobnosti preizkušanega jekla. Vdolbine in mikroporoznost jekla odpravimo s predelavo jekla na polovico preseka konti litega jekla.

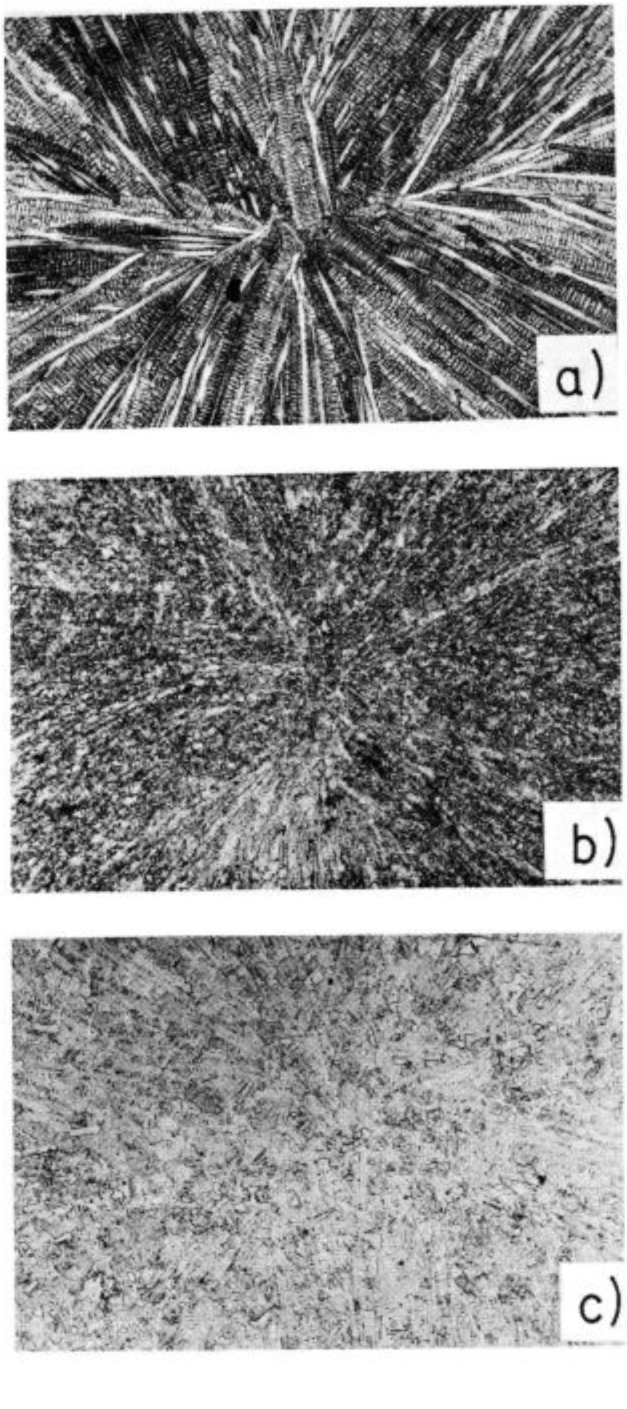
Preizkušano konti lito jeklo je bilo legirano z dušikom, saj ga je vsebovalo kar desetkrat več, kot ga vsebuje navadno jeklo AISI 304. Dušik dodajamo v jeklo za povečanje njegove trdnosti in obrabne obstojnosti. S tem zmanjšamo njegove preoblikovalne sposobnosti, zato lahko pričakujemo, da ima konti lito jeklo brez legi-

3. Recrystallized continuously cast steel has a similar workability as conventionally made steel.

4. The microstructure of cast and deformed steel recrystallizes at an annealing temperature of 900° C and a linear strain of about 44 %, whereas at a temperature of 1000° C, it already recrystallizes at a linear strain of about 9 %. This is also true for the microstructure of the steel which has been deformed after recrystallization.

5. Marks which appear on the surface of continuously cast wire do not affect a) the drawing ability of the tested steel and b) the microporosity of the core of the continuously cast wire. Marks and microporosity are eliminated by working cast steel reduced to half its initial cross-section.

The continuously cast steel was alloyed with nitrogen. In fact, it contained 10 times more nitrogen



Slika 5:
Mikrostrukture jekla AISI 304:
a) vlečenega pri stopnji deformacije 26 % in žarjenega pri temperaturi 900° C, nerekristalizirano;
b) vlečenega pri stopnji deformacije 44 % in žarjenega pri temperaturi 900° C, rekristalizirano;
c) vlečenega pri stopnji deformacije 9 % in žarjenega pri temperaturi 1000° C, rekristalizirano

Fig. 5:
Microstructure of AISI 304 steel:
a) reduced by 26 % at drawing and annealed at 900° C, unrecrystallized,
b) reduced by 44 % at drawing and annealed at 900° C, recrystallized,
c) reduced by 9 % drawing and annealed at 1000° C, recrystallized

ranega dušika boljše preoblikovalne sposobnosti. To nam potrjujejo tudi mehanski preizkusi in preizkusi vlečenja prvih vzorcev konti ulite žice iz jekla AISI 304 (z normalno vsebnostjo dušika), ulitih na napravi na Metalurškem inštitutu. Kontrakcija žice je znašala 37 %, največja deformacija, ki smo jo pri vlečenju krajših koncev žic dosegli, pa 56 %.

than ordinary AISI 304 steel. Nitrogen is added to steel in order to increase its strength and resistance to wear. In doing so the workability of steel is decreased, and that is why a better workability of continuously cast steel without alloyed nitrogen can be expected. This has also been confirmed by mechanical tests and drawing tests made on the first specimens of continuously cast wire from AISI 304 steel (with a normal content of nitrogen), which were cast at the Institute of Metallurgy. The area reduction during the wire tension test was 37 % — the highest deformation achieved in drawing shorter pieces of wire was 56 %.

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