O strukturi in vroči krhkosti litega jekla z 0,16 % C in dodatki aluminija, mangana, dušika in žvepla

On the structure and hot brittleness of as cast 0.16 % C steel with aluminium, nitrogen, manganese and sulphur additions

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Aluminij in dušik sta med elementi, ki povzročajo vročo krhkost jekla v začetku valjanja, ko se ruši lita struktura jeklenih ingotov. Ta oblika vroče krhkosti je drugačna od vroče krhkosti, ki jo pripisujemo povečani količini žvepla v jeklih. Dokaz za to je dejstvo, da se pojavlja pri zelo različnih količinah žvepla in le pri zadostni množini aluminija in dušika v jeklu. Sestava nekaterih jekel, ki so se pokazala kot krhka v začetku valjanja, je prikazana v tabeli 1[1]. V industrijskem preizkusu so bili vroče založeni 4 ingoti jekla 10, trije pa mrzli. Izplena 45 in 85 % jasno kažeta, da hladno zalaganje in transformacija jekla pomembno zmanjšata vročo krhkost.

Iz valjarniške prakse je znano, da se vroča krhkost ne pojavlja pri valjanju slabov, ki so bili

Aluminium and nitrogen belong to those elements which cause hot brittleness in the beginning of rolling when the as cast structure of steel ingots is being broken. This type of hot brittleness is different from the brittleness attributed to the increased sulphur content in steel. It is prooved by the fact that it can be observed at very different sulphur contents and only at sufficient aluminium and nitrogen contents in steel. The compositions of some steels which displayed hot brittleness at the start of hot rolling is given in table 1[1]. In one industrial test four ingots of the steel 10 were hot and three cold soaked. The recoveries 45 % and 85 % respectively showed clearly that cold soaking and transformation resulted in a significant reduction of the hot brittleness. From rolling practice it is known that hot brittleness does not appear at

Tabela 1: Sestava in podatki o ogrevanju za jekla, občutljiva na vročo krhkost
Tab. 1: Composition and heating data for steels subjected to hot brittleness

Jeklo Steel	Element %							Temperature °C			
No	C	Si	Mn	P	S	Al	N	1	2	AlN(3)	4
1	0,15	0,42	1,18	0,011	0,008	0,052	0,0086	1050	1250	20	1280
2	0,15	0,35	1,10	0,015	0,020	0,047	0,0116	1070	1300	5	1314
3	0,22	0,35	1,30	0,022	0,017	0,055	0,0107	880	1300	12	1319
4	0,21	0,29	1,20	0,013	0,009	0,036	0,0100	920	1300	0	1250
5	0,16	0,39	1,25	0,02	0,016	0,046	0,0096	1070	1300	0	1278
6	0,16	0,19	0,68	0,011	0,009	0,043	0,0077	900	1300	0	1239
7	0,16	0,38	1,29	0,015	0,014	0,040	0,0107	960	1300	0	1274
8	0,17	0,38	1,27	0,013	0,010	0,036	0,0112	850	1300	0	1266
9	0,15	0,35	1,07	0,011	0,023	0,046	0,0105	950	1300	0	1290
10	0,14	0,33	1,13	0,017	0,019	0,032	0,0091	900	1250	0	1222
10a								20	1250	0	1222

1 — Temperatura ingota ob zalaganju. Ingot temperature at soaking.

2 — Začetna temperatura valjanja. Starting rolling temperature.

3 — Količina neraztopljenega AlN pred valjanjem, izračunano po ref. 13. Content of unsolved AlN before rolling — calculated according to ref. 13.

4 — Temperatura topnosti AlN, izračunana po ref. 13. Solution temperature of AlN — calculated according to ref. 13.

Šarže 1 do 9 so bile izmeček zaradi površinskih razpok. Heats 1—9 were discarded due to surface cracks.

Štirje ingoti šarže 10 so bili založeni vroči — izplen 45 %. Four ingots of heat No 10 were hot soaked — recovery 45 %.

Trije ingoti iste šarže so bili založeni hladni (s črno površino) — izplen 85 %. Three ingots of the same heat were soaked with black surface — recovery 85 %.

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izvaljani iz ingotov, ki so ob valjanju pokazali pomembno vročo krhkost.

V literaturi je precej podatkov o vroči krhkosti maloogljičnega jekla s povečano vsebnostjo aluminija in dušika. Majhno deformabilnost jekla so pripisali raztapljanju in izločanju aluminijevega nitrida (AlN) in njegovi volumski in interkristalni prisotnosti v jeklu[2, 3, 4, 5]. Izločki niobijevega karbonitrida imajo podoben vpliv[6].

Nekateri viri zagovarjajo mnenje, da je potrebno vročo krhkost pripisati prisotnosti sulfidnih vključkov v trdnem in staljenem stanju po kristalnih mejah[7, 8, 9, 18]. Oslabitev interkristalne kohezije zaradi penetracij (zaves) škaje je bila tudi ena izmed razlag krhkosti[10, 11].

V nadaljevanju dajemo bolj detajlen pregled različnih razlag vroče krhkosti, pri čemer posebno upoštevamo lito strukturo ingotov in sestavo jekla.

Tvorba izločkov AlN po mejah avstenitnih zrn zmanjša hladno plastičnost jeklene litine z visokim aluminijem. To je verjetno osnova za predpostavko, da je vroča krhkost neposreden rezultat zmanjšanja interkristalne kohezije zaradi precipitacije AlN. Notranje razpoke po kristalnih mejah, obeleženih s kolonijami evtektika Fe-NbC, nastajajo med valjanjem mikrolegiranih jekel[12]. Čeprav je ta razlaga o vplivu Al nitrida privlačna, je ne moremo sprejeti. Podatki v tabeli 1 namreč kažejo, da se vroča krhkost pojavlja tudi v jeklih, v katerih je ob začetku valjanja AlN v raztopini v avstenitu. To je mogoče izračunati iz podatkov o topnosti[13] in je bilo eksperimentalno potrjeno za nekatera jekla iz tabele[14].

Izločke AlN so opazili po kristalnih mejah pod 1050 °C, in to je zmanjšalo deformabilnost jekla, ki je bilo ohlajeno s temperature strjevanja na temperaturo predelave[5, 29]. Pri precipitaciji AlN med ohlajanjem je velika histereza[15, 16]. Vroča deformacija poveča hitrost precipitacije[17], vendar le pod temperaturo topnosti. Število vrtljajev jekla z 0,07 Al in 0,01 N je večje, če izločanje poteka med deformacijo, kot če so bili izločki v jeklu že ob začetku vroče deformacije[17]. Ni verjetno, da bi deformacija z valjanjem sprožila tako izločanje AlN, da bi bile lahko kristalne meje pomembno oslabljene že med nadaljevanjem valjanja.

Z upoštevanjem teh dejstev lahko zaključimo, da vroče krhkosti pri valjanju ne moremo pripisati neposredno škodljivemu učinku izločkov AlN. Razumljivo pa je, da interkristalna precipitacija pred deformacijo ali med njo lahko sproži interkristalno krhkost.

Med strjevanjem konstrukcijskih jekel s povečano količino Al in N se preostala talina med dendritnimi vejami bogati z žveplom. Končno stanje strjevanja pokaže evtektične kolonije manganovega sulfida po dendritnih mejah. To zmanjša deformabilnost jekla, ki je izrezano iz stebrastega sloja ingotov[9], in vročo preoblikovalnost jekla, ki je bilo strjeno v napravi za preizkušanje[18, 26]. Zmanjšanje vroče in hladne preoblikovalnosti je

rolling slabs obtained from ingots which showed considerable hot brittleness.

There are many data on hot deformability of low carbon structural steel with increased aluminium and nitrogen content. Poor deformability has been ascribed to solution and precipitation of aluminimum nitride (AlN) and his bulk and intergranular presence in steel[2, 3, 4, 5].

Niobium carbonitride precipitates exibit a similar influence[6].

Some references hold that hot brittleness should be attributed to the presence of sulphide inclusions in solid or liquid state along the grain boundaries[7, 8, 9, 18]. The weakening of intergranular cohesion because of scale curtains (penetrations) has been also considered[10, 11].

In the following a more detailed survey of different explanations for the hot brittleness is presented with special regard to as cast structure of ingots and steel composition.

Precipitation of AlN particles along grain boundaries of austenite reduces the cold plasticity of cast steel with high aluminium content. That is probably the base for the supposition that hot brittleness is a direct result of the decrease in intergranular cohesion due to AlN precipitates. Core cracks along grain boundaries marked by eutectic Fe-NbC colonies appear during the rolling of slabs of microalloyed steels[12]. Although attractive, a similar interpretation of the influence of AlN precipitates could not be accepted. Data given in table 1 show that hot brittleness occurs also in steels with AlN in solution in austenite at the starting rolling temperature as calculated from solubility data[13] and experimentally confirmed for some steels in table 1[14].

AlN precipitates have been observed along austenite grain boundaries below 1050 °C and that lowered the deformability of steel cooled from solidification to deformation temperature[5, 29]. A strong hysteresis was observed in the precipitation of AlN during cooling[15, 16]. Hot deformation increases the rate of AlN precipitation[17] but only below the temperature of solubility. The number of revolutions of steel with 0.07 % Al and 0.01 % N is higher when precipitation takes place during straining than if AlN precipitates were present in steel already before deformation[17]. It is not likely that rolling deformation could provoque such precipitation of AlN that austenite grain boundaries could be significantly weakened already during the continuation of the rolling.

Considering these facts it may be concluded that hot brittlenes at rolling could not be attributed to a direct harmfull action of AlN precipitates. Intergranular precipitation of AlN before the deformation during the straining could naturally induce intergranular brittleness.

During solidification of structural steels with increased Al and N content the residual melt between branches of dendrites is gradually enriched in sulphur. The final stage of solidification opazno, če se jeklo segreje na temperaturo delne topnosti MnS v avstenitu in ohladi tako, da nastanejo MnS precipitati po avstenitnih mejah[18, 19]. Povečano deformabilnost po ohladitvi in ponovnem ogrevanju na temperaturo preoblikovanja pripisujejo sferoidizaciji vključkov manganovega sulfida pri ogrevanju in povečanju razdalje med njimi[18]. Te razlage ne moremo uporabiti, da bi pojasnili vročo krhkost malooglјičnih jekel s povečano vsebnostjo aluminija in dušika, in sicer iz naslednjih treh razlogov: vroči krhkosti so podvržena tudi jekla z nizkim žveplom (glej tabelo 1); vroči krhkosti niso podvržena jekla z nizkim aluminijem in dušikom, kljub višjemu žveplu; in končno, ohladitev ingotov pred prvo valjalniško deformacijo ne dovoljuje precipitacije MnS po mejah avstenitnih zrn, čeprav se seveda lahko precipitacija izvrši pri ohladitvi s temperature strjevanja jekla na temperaturo valjanja.

O tem vprašanju bomo razpravljali kasneje.

V jeklih, ki so podvržena vroči krhkosti, je večina manganovega sulfida kristalizirana v evtektični obliki[20] in lahko si predstavljamo, da ni pomembne razlike v obliki sulfidnih vključkov med jeklom z 0,015 % Al in jeklom z 0,03 % Al, čeprav je zadnje mnogo bolj krhko v vročem. Pri nizkem dušiku so jekla kljub visoki vsebnosti aluminija manj krhka v vročem[1]. Zato lahko zaključimo, da se vroča krhkost jekel s povečano količino aluminija in dušika razlikuje od krhkosti, ki jo povzročajo sulfidni vključki. Jasno je, da se obe obliki krhkosti lahko združita in povzročita resno pokljivost jekla v vročem. Po tretji razlagi je pokljivost v vročem posledica slabljenja kohezije kristalnih mej zaradi zaves škaje, oz. penetracij škaje vzdolž kristalnih mej. Globina teh zaves naj bi bila neodvisna od termične zgodovine jekla[11]. Ta razlaga je enostavna in privlačna, vendar sta za njen sprejem dva pomembna zadržka: zakaj so zavese škaje škodljive v jeklu z 0.03 % Al, niso pa škodljive v jeklu z 0,015 % Al in zakaj so zavese škodljive v jeklu, ki je bilo ohlajeno na temperaturo valjanja, niso pa škodljive v jeklu, ki je bilo na isto temperaturo segreto. O tej razlagi vroče pokljivosti bomo razpravljali kasneje, ko bomo tudi pokazali, da imajo zavese škaje zanemarljiv pomen.

Kritična ocena razpoložljivih podatkov pokaže, da so resni pomisleki za sprejem razlag vroče pokljivosti litega malooglјičnega jekla s povečano količino aluminija in dušika. Nasprotno, dosedanje eksperimentalne ugotovitve niso v nasprotju s hipotezo, po kateri je poreklo vroče krhkosti v vplivu aluminija in dušika na strukturo ob površini litega jekla, najverjetneje v vplivu obeh elementov na globularen sloj ob površini jekla, ki je odvisen od podhladitve jeklene taline pred strjevanjem[21].

Ta hipoteza logično razlaga zmanjšanje vroče krhkosti, če se ingoti ogrevajo na temperaturo valjanja izpod temperature transformacije. Transformacija namreč ustvari v jeklu enakomerno globularno strukturo.

shows eutectic colonies of manganese sulphide inclusions along dendrite boundaries. This reduces the deformability of steel cut from the layer of columnar grains of ingots[9] and the hot deformability of steel solidified in the testing machine[18, 26]. A decrease in hot and cold deformability is observed if steel is heated to the temperature of partial solution of MnS in austenite and cooled to produce MnS precipitates at austenite grain boundaries[18, 19]. Improved deformability after cooling and reheating to deformation temperature is attributed to spheroidisation of sulphide inclusions at reheating and to increased distance between them[18].

This can not explain the hot brittleness of low carbon steel with increased aluminium and nitrogen content because of the three following reasons: hot brittleness is observed also on steels with low sulphur (see data in table 1), brittleness is not observed on steels with low aluminium and nitrogen contents in spite of the higher sulphur content and finally the cooling of ingots before the first rolling passes does not allow the precipitation of MnS at austenite grain boundaries although precipitation could occurr at cooling from solidification to rolling temperature. This question will be discussed later.

In steels subjected to hot brittleness the major part of manganese sulphide is solidified in eutectic form[20] and it can be supposed that there is no significant difference in the form of sulphide inclusions in a steel with 0.015 % Al as compared to that with 0.03 % Al although hot brittleness of the last steel is significantly higher. At low nitrogen content steels display less hot brittleness in spite of higher aluminium content[1]. It can be consequently concluded that hot brittleness of low carbon steel with increased aluminium and nitrogen content differs of the brittleness caused by sulphide inclusions. It is however quite clear, that both types of brittleness could associate resulting in severe hot shortness.

According to the third viewpoint the hot brittleness is a result of weakening of grain boundaries cohesion force caused by scale curtains, i. e., scale penetrations with depth independent on thermal history of steel before deformation[11]. This explanation is rather simple and attractive, however two meaningfull objections could be found. First, why scale curtains are harmfull on steel with 0.03 % Al and not on steel with 0.015 % Al and secondly why are harmfull in steel cooled to rolling temperature and not harmfull in steel heated to rolling temperature. This subject will be discussed also in the following section where it will be shown that scale penetrations along grain boundaries are of minor importance only.

A critical survey of available data shows that neither of the mentioned explanations for hot brittleness of as cast low carbon steel with increased aluminium and nitrogen content could with-

Kristalne meje v avstenitu, ki je bil ogret na temperaturo vroče deformacije, ne ustrezajo več strjevalnim mejam, ki so obogatene z vključki in izločki manganovega sulfida in celo pregrade škaje ne nastajajo več vzdolž teh mej. Zato je manjša verjetnost, da bi bile oslabljene kristalne meje, ki so nastale pri strjevanju, podvržene natezni deformaciji.

V tem prispevku obravnavamo nekatere izsledke iz dela, ki ga opravljamo s ciljem, da bi našli povezavo med vročo pokljivostjo, strukturo in sestavo jekla ter da bi preverili predpostavke, za razlago vpliva aluminija in dušika na vročo krhkost litega jekla.

B. MATERIAL IN EKSPERIMENTALNO DELO

Vse raziskave smo izvršili na jeklih, ki so bila izdelana v 20-kilogramski indukcijski peči. Osnovna sestava jekla je bila: 0,16 % C in 0,3—0,4 % Si. Mangan in žveplo sta bila v intervalih 0.13 do 1,18 % in 0,013 do 0,05 %, aluminij in dušik pa v intervalu 0 do 0,1 % in 0,006 do 0,02 %. Količina aluminija je bila često nad tisto, ki jo najdemo v industrijskih jeklih, medtem ko so bile vsebnosti drugih elementov v normalnih mejah. Željene sestave smo dosegli tako, da smo v osnovno jeklo dodajali ferolegure, aluminij, kromov nitrid in železov sulfid. Preverjanje vroče krhkosti je sledilo dvem načinom segrevanja: hlajenje s temperature kristalizacije na temperaturo deformacije (oznaka A) in ogrevanje na isto temperaturo deformacije 1200 °C (oznaka B). Vročo krhkost smo preverjali z vročim upogibom, ki smo ga pred tem uspešno uporabili pri preverjanju vpliva bakra in kositra na vročo pokljivost[22]. Natezna deformacija je znašala 20 %. Vsak preizkušanec smo vzeli iz žarilne peči, upognili in kalili v vodi v največ 5 sekundah. Zato lahko predpostavimo, da med deformacijo ni bilo zaznavne precipitacije AlN ali MnS. Preizkušanci s prerezom 40 × 20 mm so se strdili v ogreti kovinski kokili. Drugi preizkušanci s presekom 30 × 30 mm in 60 × 60 mm so bili vliti v pesek in često tudi kaljeni v vodi po strjevanju, da bi se jasneje razločila struktura ob površini.

C. REZULTATI, OPIS IN RAZPRAVA

1. Vroča pokljivost, vpliv ogrevanja

Nekatere rezultate prikazujemo v tabeli 2. Površinske razpoke smo opazili le na jeklih z visokim aluminijem in dušikom. Pod 0.007 % N tudi v jeklu z 0,1 % Al ni bilo razpok.

Industrijska valjalniška praksa pove, da jekla niso podvržena vroči pokljivosti, če vsebujejo pod 0,007 % dušika, ne glede na vsebnost aluminija[1]. To ujemanje je lahko slučajno, vendar to ni bistveno.

stand serious objections. On the contrary up to now experimental findings are not in disagreement with the hypothesis according to which the hot brittleness arises from the influence of aluminium and nitrogen on the surface structure of the as cast steel, most probably of their influence on the thickness of the globular layer at the surface of steel which depends upon the undercooling of the steel melt before the solidification[21].

This hypothesis logically accounts for the reduced hot brittleness of ingots heated to rolling temperature from below the transformation temperature. The transformation produces an uniform globular structure at the surface of steel. Grain boundaries of austenite reheated to deformation temperature do not correspond to solidification boundaries enriched in inclusions and precipitates of manganese sulphide and even oxide curtains are not formed along these boundaries. Hence, there is a lower probability that solidification grain boundaries will be subjected to tensile deformation.

The present communication deals with some of the findings of the work being carried out in order to find a correlation between hot brittleness, solidification structure and composition of steel and to verify the proposed explanation of the influence of aluminium and nitrogen upon the hot brittleness of as cast steel.

B. MATERIALS AND EXPERIMENTAL

All investigations were carried out on steels melted in a 20 kg induction furnace. Basic steel composition was 0.16 % C and 0.3—0.4 % Si. Manganese and sulphur varied within 0.13—1.5 % and 0.013—0.049 % range resp. and aluminium and nitrogen varied from 0 to 0.1 % and 0.006 to 0.02 % resp. The content of aluminium was often above that in industrial steels, while the content of other elements was within the normal limits. Desired compositions were attained by adding to the same base steel ferroalloys, aluminium, chromium nitride and iron sulphide. The testing of hot brittleness followed two thermal cycles, i. e., cooling from solidification to deformation temperature (designation A) and cooling from solidification to room temperature and heating to the same deformation temperature 1200 °C (designation B). Hot bending of cast samples was applied to check the hot brittleness because it has been successfully tested in the investigation of the influence of copper and tin on the hot shortness[22]. The tensile strain amounted to 20 %. Each sample was taken from the heating furnace, bent and quenched in water in maximally 5 seconds. Therefore, it can be assumed that no significant precipitation of AlN or MnS occured during the deformation. Samples of steel of 40 × 20 mm cross section were solidified in a heated mould. Samples of the same

Tabela 2: Število razpok v odvisnosti od načina ogrevanja
Osnovna sestava jekla: 0,16 % C, 0,28 % Si in 0,52 % Mn

Tab. 2: Number of cracks in dependence on thermal cycle
Basic composition of steel: 0.16 % C, 0.28 % Si and 0.52 % Mn

Jeklo Steel No	Način ogrevanja Thermal cycle	Al %	N %	S %	Nr*	Nm* cm—1	N_2* cm—1	G_2 mm	AlN** %
1	A	0,10	0,0083	0,017	—	12	8	0,035	38
2	B	0,086	0,0076	0,017	—	26	7	0,039	21
3	A	0,072	0,0132	0,017	70	14	10	0,044	45
4	B	0,083	0,0156	0,017	14	20	16	0,042	60
5	A	0,076	0,0142	0,017	100	16	15	0,040	52
6	B	0,079	0,0150	0,017	—	24	14	0,036	56
7	A	0,025	0,0060	0,054	101	80	72	0,050	0
8	B	0,025	0,0060	0,054	36	21	18	0,040	0
9	A	0,070	0,015	0,054	115	40	35	0,055	51
10	B	0,070	0,015	0,054	37	18	15	0,040	51

* Povprečje 3 meritev na 4 preizkušancih. Average value of 3 measurements on four specimens.

** Količina neraztopljenega AlN, izračunana iz topnostnega produkta po viru 13. Content of unsolved AlN calculated from the solubility product, according to ref. 13.

Nr — Število razpok na upognjeni površini. Number of cracks on bent surface.

Nm — Število zrn pri oddaljenosti 0,1 mm od površine. Number of grains 0.1 mm under surface.

N_2 — Število kristalnih mej s pregradami škaje. Number of grain boundaries with scale curtains.

G_2 — Globina najglobljе zavese škaje. Depth of biggest scale curtain.

Nm, N_2 in G_2 so bili določeni na nedeformiranem prerezu. Nm, N_2 and G_2 were determined on nondeformed section.

Način ogrevanja. Thermal cycle.

A — Litje, strjevanje, ohladitev do 1200 °C, držanje 0,5 ure, upogib. Casting, solidification, cooling to 1200 °C, holding 0.5 hour and bending.

B — Litje, strjevanje, ohladitev na 20 °C, ogrevanje na 1200 °C, držanje 0.5 ure, upogib. Casting, solidification, cooling to 20 °C, heating to 1200 °C, holding 0.5 hour and bending.

no za naš namen, ker iščemo relativne razlike med jekli z različno sestavo, ki so bila enako pripravljena in deformirana.

Po ogrevanju A je nastalo pomembno več razpok kot po ogrevanju B, ne glede na sestavo jekla. Število razpok je večje pri večji količini žvepla in dušika, ki sta povzročila tudi finejšo strjevalno strukturo ob površini jekla (sl. 1). Podatki v tabeli 2 ne pokažejo nobene povezave med številom razpok in količino AlN pri temperaturi upogiba, izračunano iz topnostnega produkta za AlN. V soglasju z virom[11] je globina zaves škaje po mejah neodvisna od načina ogrevanja. Ni jasne povezave med številom zaves po obeh ogrevanjih in številom poklin. To jasno pove, da zavese škaje niso primarni vzrok za vroče razpokanje. Globina razpok je bila v poprečju 1,5 mm po ogrevanju A in 1,0 mm po ogrevanju B, brez jasne korelacije z velikostjo zrn ob površini preizkušancev.

Števila razpok tudi ni mogoče neposredno povezati z velikostjo avstenitnih zrn ob površini pred deformacijo. Vse to kaže, da je treba iskati razlago za vročo krhkost v specifičnosti strukture, ki je nastala pri strjevanju jekla ali ohlajanju do

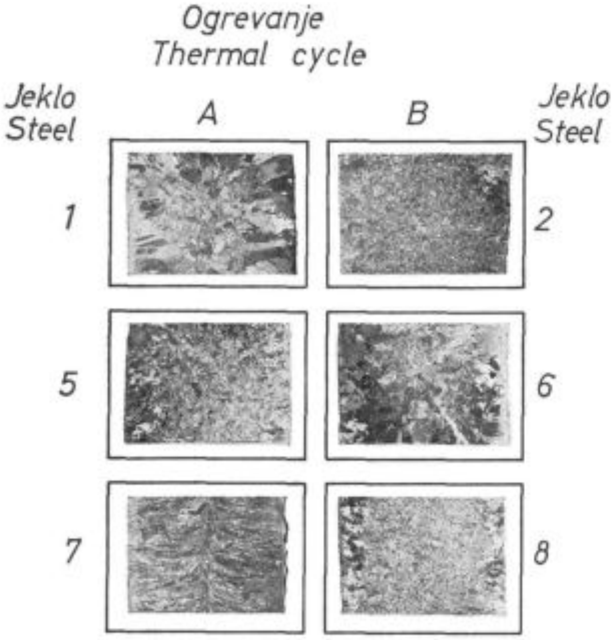
steels were solidified in sand in sections 30 × 30 mm and 60 × 60 mm and frequently quenched in water after solidification in order to show more clearly the structure at the surface.

C. RESULTS, PRESENTATION AND DISCUSSION

1. Hot brittleness, influence of heating

Some results of tests are given in table 2. Surface cracks were observed only on steels with high aluminium and nitrogen content. Below 0.007 % N cracks were not observed in steel up to 0.1 % Al.

Industrial rolling practice shows also that steels are not inclined to hot brittleness if the content of nitrogen is below 0.007 % irrespectively to the increased content of aluminium[1]. This agreement can be accidental, however, that is not essential for our purpose since we look for relative differences only between steels of different composition prepared and deformed in identical manner.



Slika 1
Makrostruktura nekaterih jekel iz tabele 2.

Fig. 1
Macrostructure of some steels in table 2.

1200 °C, pa so izginile ali postale zanemarljive po ohladitvi pod temperaturo transformacije.

Sodeč po topnostnem produktu, je del AlN ostal neraztopljen pri temperaturi deformacije. Zaradi histereze v precipitaciji iz trdne raztopine v avstenitu lahko celo pričakujemo več neraztopljenega AlN po ogrevanju B kot po ogrevanju A. Mikroskopska opazovanja jekla, ki je bilo kaljeno s temperature vročega upogiba, so pokazala, da so izločki AlN enakomerno porazdeljeni in da ni zaznavnih obogatitev po mejah avstenitnih zrn.

Našo razpravo lahko na tem mestu zaključimo z ugotovitvijo, da je uporabljena preizkuševalna metoda primerna za preverjanje občutljivosti jekla za vročo krhkost. Rezultati uvodnih preizkusov so potrdili sklepe, ki smo jih izoblikovali na osnovi pregleda literature.

Potrjeno je, da lahko povežemo vročo krhkost konstrukcijskih jekel s povečano količino dušika in aluminija s strukturo, ki se razvije pri strjevanju jekla in pri njegovem ohlajanju na temperaturo deformacije.

2. **Vroča krhkost, vpliv vsebnosti mangana in žvepla**

Pri hitrem strjevanju v kokili nastane ob površini preizkušancev plast stebrastih kristalnih zrn. Zato lahko preverimo z upogibom le krhkost, ki je povezana s stebrasto strukturo. To je zahtevalo, da bolj sistematično preverimo vpliv mangana in žvepla na strukturo in krhkost.

Izdelali smo jekla z različnim razmerjem Mn/S, jih vlili v kokilo in jih podvrgli upogibu po ogrevanju A. Makrostrukturo jekel, ki so bila ka-

Thermal cycle A produced an explicitely higher number of surface cracks than thermal cycle B irrespectively from the steel composition. The number of cracks increased at higher sulphur and nitrogen contents which caused also a finer solidification structure at the surface of steels (fig. 1). Data in table 2 show no correlation between the number of cracks and the content of AlN at deformation temperature 1200 °C calculated from solubility product. In accordance to ref. 11 the depth of scale curtains along austenite grain boundaries is independent of the thermal cycle. There is no correlation between the number of scale curtains after both thermal cycles and the number of cracks. That clearly shows that the effect of scaling could not be the primary cause for hot cracking. The depth of cracks was on average 1.5 mm after thermal cycle A and 1.0 mm after thermal cycle B and without clear correlation to the grain size at the surface of specimens.

The number of cracks could not be related also to the austenite grain size at surface before the deformation. Consequently, one should look for the explanation that hot brittleness resulted from peculiarities of structure developed at solidification or at cooling to 1200 °C which disappeared or became negligeable at cooling below the transformation temperature.

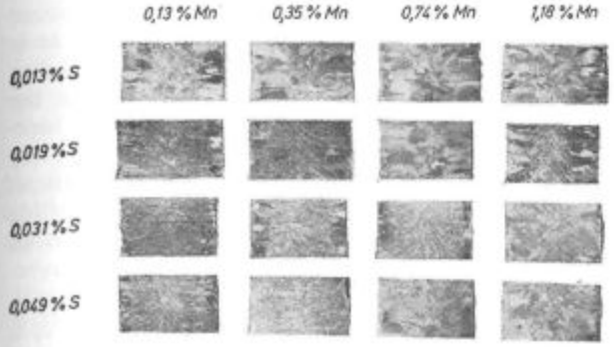
According to solubility product part of AlN remained unsolved at deformation temperature. Because of the hysteresis in precipitation from solid solution in austenite we could even expect more AlN after thermal cycle B than after cycle A. Microscope observation of steel quenched from deformation temperature showed a uniform distribution of AlN precipitates without notable enrichment at austenite grain boundaries.

We can conclude at this point that the applied testing method is suitable to check the sensitivity of as cast steel to hot cracking. The results confirm the conclusions derived on the ground of the survey of references. It seems confirmed that the hot brittleness of structural steel with increased contents of aluminium and nitrogen should be associated with the structure developped at solidification of steel and at cooling to deformation temperature.

2. **Hot brittleness, influence of manganese and sulphur contents**

At fast solidification a layer of columnar grains is formed at the surface of steels. Consequently with bending deformation only the hot brittleness related to columnar structure could be tested. That called for a more systematic checking of the influence of manganese and sulphur on structure and brittleness.

Steels with different Mn/S ratio have been melt, cast in mould and submitted to bending deformation after thermal cycle A. The macrostructure of steels quenched from the deformation



Slika 2

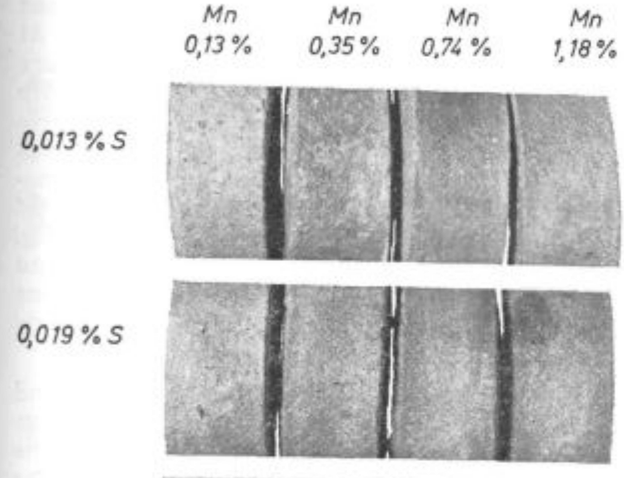
Makrostruktura jekel z okoli 0,16 % C in 0,35 % Si ter naraščujočimi količinami žvepla in mangana.

Fig. 2

Macrostructure of steels with appr. 0.16 % C and 0.35 % Si and increasing contents of manganese and sulphur.

ljena s temperature deformacije, kaže slika 2, deformirano površino preizkušancev pa slika 3. Kot že v tem prispevku omenjeno, žveplo zmanjšuje velikost zrn pri kristalizaciji, mangan pa ima nasproten učinek.

V ref.[23] smo našli podatek, da je velikost primarnih dendritskih vej (ta ustreza debelini zrn v stebrastem sloju preizkušancev, ki so bili vliti v

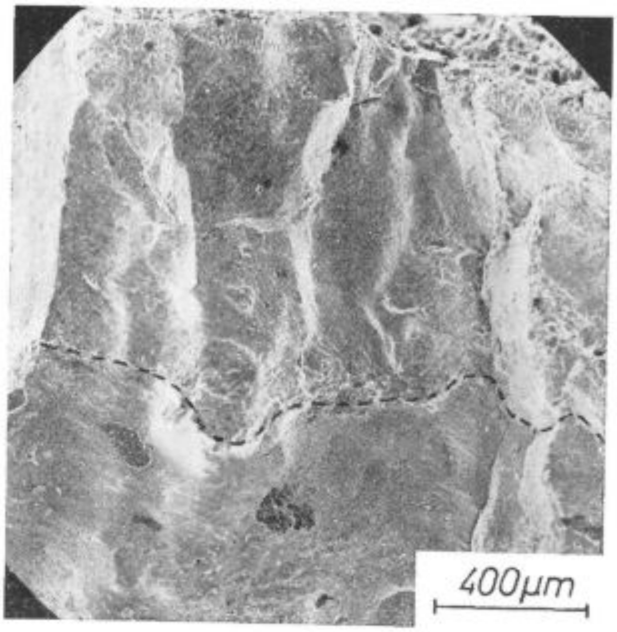


Slika 3

Upognjena površina jekel s slike 2.

Fig. 3

The bent area of samples in fig. 2.



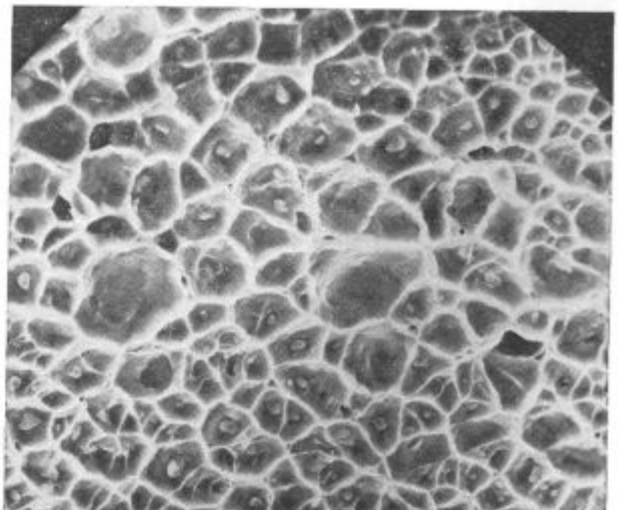
Slika 4

Nad črtkano črto vroč in pod njo hladen zlom. Jeklo z 0,031 % S in 0,13 % Mn ohlajeno s temperature strjevanja na 1200 °C, zadržano 30 min., upognjeno, kaljeno in hladno prelomljeno.

Fig. 4

Hot fracture above and cold fracture below the dotted line, resp.. Steel with 0.031 % S and 0.13 % Mn cooled from solidification to deformation temperature 1200 °C, hold 30 mins., bent, quenched and cold fractured.

temperature is shown in fig. 2 and deformed surface in fig. 3. As shown in the previous section the grain size in the columnar layer decreases with

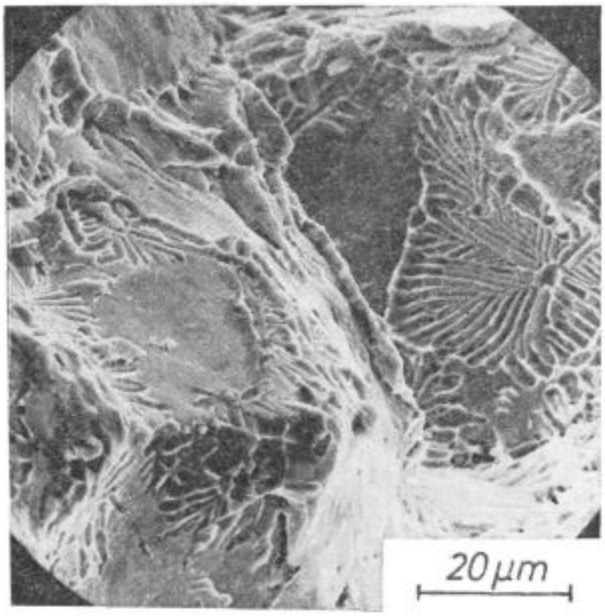


Slika 5

Drobno jamičast interkristalen hladen prelom s slike 4.

Fig. 5

Small dimpled intergranular cold fracture of the sample in fig. 4.



Slika 6
Mešan jamičast in gladek hladen interkristalen prelom jekla z 0,031 % S, 1,2 % Mn in 0,048 % Al.

Fig. 6
Mixed small dimpled and smooth brittle cold intergranular fracture of steel with 0.031 % S, 1.24 % Mn and 0.048 % Al.

kokilo) neodvisna od količine žvepla. Vzrok za nesoglasje bi lahko bil v sestavi jekla ali v hitrosti strjevanja. Vprašanje za naše delo ni pomembno, zato ga bomo zanemarili. Površinske pokline so nastale v jeklih z 0,013 in 0,019 % S le pri 0,13 in 0,24 % Mn, jekla z višjim ogljikom so pokazala površinske razpoke pri vseh količinah mangana. Mikrostruktura in deformacija torej kažeta, da se vroča krhkost poveča in zmanjša velikost zrn, ko se v jeklo dodaja žveplo, mangan pa ima nasproten učinek.

Zaradi hitrega ohlajanja po upogibu deli vročih prelomov (površina vročih razpok) niso toliko oksidirali, da bi bilo nemogoče opazovanje v raster elektronskem mikroskopu. Taki prelomi so bili interkristalni (sl. 4) in so napredovali brez spremembe pri hladnem upogibu v jeklih z malo mangana. Pri večji povečavi je razpoka pokazala duktilno širjenje z majhnimi globularnimi vključki v jamicah (sl. 5). Opazovanja na presekih so potrdila interkristalni značaj razpok. Ko je mangan v jeklu rastel, je ostajal vroč prelom interkristalen, pri hladnem upogibu pa se je pojavilo več in več intrakristalnega preloma. V jeklih z aluminijem je bila vroča površina razpoke tudi interkristalna (sl. 6). Pri zadostnem žveplu so nastali v takih jeklih pri hladnem upogibu deli interkristalne površine s tipično porazdelitvijo paličastih evtektično strjenih vključkov manganovega sulfida. Deli površin z gladkim krhkim napredovanjem so bili redkejši. Interkristalno širjenje vročih razpok in prisotnost sulfidnih vključkov na prelomu sta potrdila, da je krhkost povezana s prisotnostjo teh vključkov po kristalnih mejah, kot je omenjeno

the increasing sulphur content, while manganese produces an inverse effect. In reference 23 it is quoted that the size of primary dendrite branches (that correspond to the thickness of grains in the columnar layer on steels cast in mould) was independent of the content of sulphur. The cause for disagreement could be in the composition of steels or in the rate of solidification. The question is not important for our subject and it will be therefore neglected.

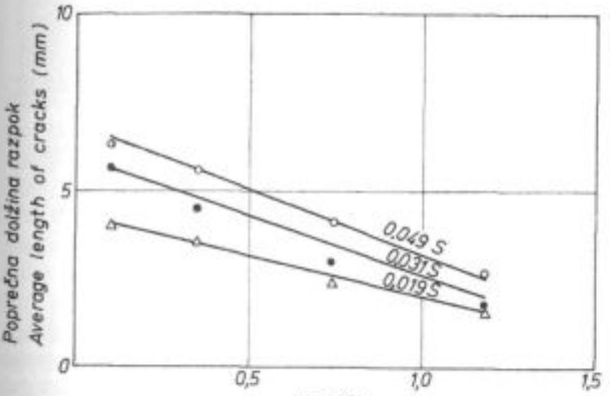
Surface cracks occurred on steels with 0.013 % S and 0.019 % S containing 0.13 % Mn and 0.39 % Mn. Steels with higher sulphur showed surface cracks at all manganese contents. Microstructure and deformation show therefore that at increasing sulphur, brittleness is increased and grain size diminished, on the contrary, at increasing manganese, brittleness is diminished and grain size coarsened.

Because of fast cooling after bending parts of hot fractures did not oxidize in such extent as to prevent observation in scanning electron microscope. Such fractures were intergranular (fig. 4) and propagated at cold bending without modification in steel with low content of manganese. At higher magnification ductile propagation with small globular inclusions in dimples can be seen (fig. 5). Observation on cross-sections confirmed the intergranular propagation of hot cracks. At increasing manganese content hot fracture remained intergranular, but at cold bending more and more transgranular brittle and ductile propagation was observed. In steels containing also aluminium the hot fracture was also intergranular. At sufficient sulphur cold bending produced in such steel intergranular areas of fracture (fig. 6) with dimples showing typical distribution and rod-like form of eutectically solidified inclusions of manganese sulphide. Smooth areas with brittle intergranular propagation were found also.

Intergranular propagation of hot cracks and the presence of sulphide inclusions on the fracture confirm that the brittleness is related to the presence of these inclusions at grain boundaries as quoted in some references[7, 8, 9, 21].

Let us try to explain the beneficial influence of manganese on hot brittleness. Supposing that sulphide inclusions are enriched along grain boundaries, these should be the more weakened the coarser is the grain size at equal content of sulphur in steel. However, that is not the case. In fact, increasing grain size with increasing manganese results in reduced brittleness. Anormal growth of large cracks does not permit an exact evaluation of the hot brittleness on the ground of the number and length of cracks. It can be shown in spite of this, that the average length of cracks increases at constant manganese with increasing sulphur and it is diminished proportionally to the manganese content in steel (fig. 7).

v nekaterih virih[7, 8, 9, 21]. Poskusimo sedaj razložiti pozitiven vpliv mangana na vročo krhkost! Če predpostavimo, da so sulfidni vključki obogateni po mejah avstenitnih zrn, bi morale te meje biti tem bolj oslabljene, čim večja so avstenitna zrna pri enaki količini žvepla v jeklu. To ne drži, krhkost se celo zmanjšuje, ko raste velikost zrn z dodatkom mangana v jeklo. Anormalna rast posamičnih velikih razpok ne dovoljuje, da bi se vedno ovrednotila vroča krhkost na osnovi števila in dolžine razpok. Kljub temu se pokaže, da povprečna dolžina razpok raste, ko raste količina žvepla pri stalnem manganu in se proporcionalno zmanjša s povečanjem mangana v jeklu (sl. 7).

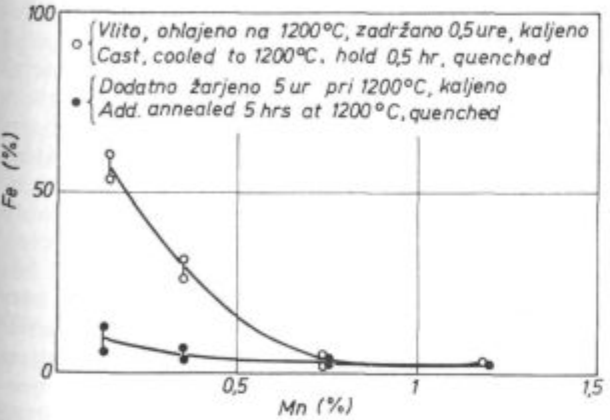


Slika 7

Razmerje med količino mangana v jeklih z različno vsebnostjo žvepla in poprečno dolžino razpok na preizkušancih na sl. 3.

Fig. 7

Relationship between manganese content in steel with different sulphur level and the average length of cracks on fig. 3.



Slika 8

Vpliv količine mangana v jeklih na vsebnost železa v sulfidnih vključkih, ki so nastali pri kristalizaciji jekla. Jeklo z 0,049 % S s slike 2 in po dodatnem ogrevanju 5 ur pri 1200 °C.

Fig. 8

Relationship between the manganese content in steel and the iron content in sulphide inclusions in 0.049 % S steel after additional annealing at 1200 °C. The same steel as in fig. 2.

Data in table 3 show that the content of iron in sulphide inclusions is independent on the content of aluminium, nitrogen and sulphur in steels and depends in as cast state on the content of manganese (fig. 8). Over 0.7 % Mn the content of iron in inclusions is within the range 3 to 5 % and independent on the content of manganese in steel. This iron level is obtained at heating the cast steel at 1200 °C already at much lower manganese in steel.

Tabela 3: Vsebnost mangana in železa v sulfidnih vključkih v različnih jeklih.

Tab. 3: Content of iron and manganese in sulphide inclusions in different steels.

Jeklo Steel No	Sestava jekla Steel composition[1] %			Sestava sulfidnih vključkov Composition of sulphide inclusions %	
	Mn	S	Al	Fe	Mn
1	0,13	0,049[2]		56 —57	2,5— 3,5
				ind.32 —36	25 —31
2	0,13	0,049[3]		6 —13	47 —51
3	0,35	0,049		26 —31	28 —33
				ind.56	3
6	0,35	0,049[3]		4 — 7	53 —59
7	0,74	0,049		2,5— 5,5	53 —59
8	0,74	0,049[3]		3 — 4	55 —58
9	1,18	0,049		2,5— 3	57 —60
10	1,18	0,049[3]		2,5— 3	57 —60
11	0,13	0,012	0,03	20 —33	22 —31
12	1,18	0,012	0,03	3 — 3,5	58 —61
13	0,35	0,019	0,03	7 —13	44 —53
14	1,18	0,019	0,1	2 — 5	56 —60
15	0,35	0,019	0,03	9 —14	44 —52
16	1,18	0,049	0,1	2,5— 3,5	56 —60

1 — V jeklih 1—14 je bilo 0,01 % N, v jeklih 15 in 16 pa 0,015 % N. Steels 1—14 contained 0.01 % N while steels 15 and 16 contained 0.015 % N.

2 — Vsa jekla so bila ohlajena s temperature strjevanja na 1200 °C, zadržana 30 min. in kaljena. All steels were cooled from solidification temperature to 1200 °C, hold 30 mins and quenched.

3 — Dodatno ogrevana 5 ur pri 1200 °C in kaljena. Additionally annealed 5 hrs at 1200 °C and quenched.

On the ground of these observation we can conclude that grain size and iron content in sulphide inclusions, which is related to their melting point[10], could not be connected to the hot brittleness of as cast steel.

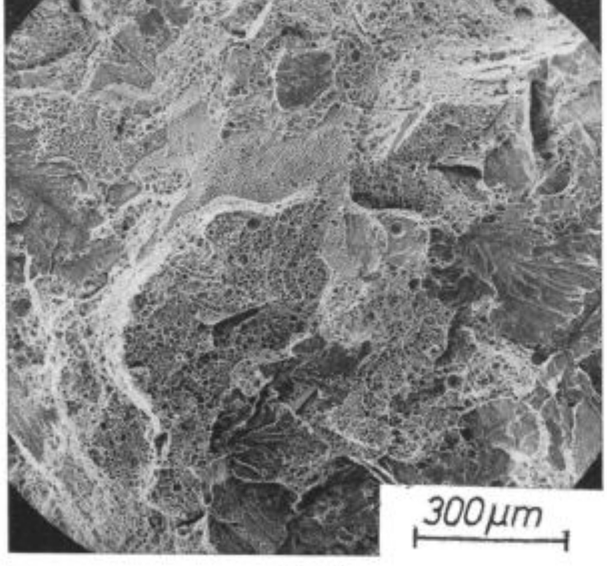
The examination of the fractures shows two types of sulphide inclusions: small spherical or platelet inclusions produced by the precipitation

Podatki v tabeli 3 pokažejo, da je količina železa v sulfidnih vključkih, ki so nastali pri strjevanju, neodvisna od količine aluminija, dušika in žvepla v jeklu in je v tem stanju odvisna le od količine mangana v jeklu (sl. 8). Nad 0,7 % Mn je vsebnost železa v vključkih v območju 3 do 5 % in neodvisna od naraščanja količine mangana v jeklu. To količino železa v vključkih dosežemo, ko jeklo žarimo pri 1200 °C, že pri mnogo nižjem manganu v jeklu.

Na osnovi teh ugotovitev lahko sklepamo, da velikosti zrn in vsebnosti železa v sulfidnih vključkih, ki je povezana z njihovim tališčem[10], ni mogoče povezati z vročo krhkostjo jekla z lito strukturo.

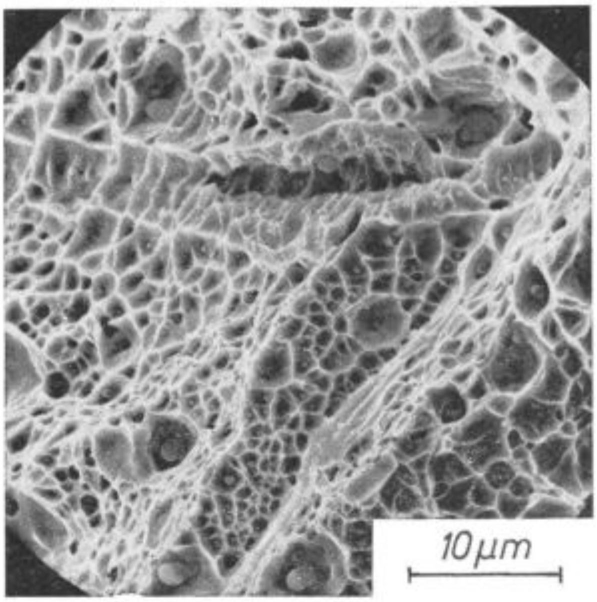
Opazovanja prelomov pokažejo dve vrsti sulfidnih vključkov: majhne globularne ali ploščičaste vključke, ki so nastali z izločanjem iz trdne raztopine žvepla v avstenitu pri ohladitvi s temperature strjevanja na temperaturo deformacije jekla, in večje v jeklih z aluminijem, paličaste vključke evtektičnega porekla. Ob upoštevanju vseh eksperimentalnih dognanj se zdi logična dvojna razlaga vpliva mangana: z zmanjšanjem topnosti žvepla v avstenitu[26] (to zmanjša količino vključkov, ki nastanejo z izločanjem iz trdnega avstenita) in z zmanjšanjem števila vključkov, ki nastanejo z evtektično kristalizacijo manganovega sulfida.

Jeklo z malo mangana (sliki 4 in 5) smo segrevali pri 1200 °C, kalili v vodi in prelomili s hladnim upogibanjem. Nastal je drobni jamičast prelom, ki kaže na posamičnih področjih značilno interkristalno napredovanje (sl. 9). V jamicah so sulfidni vključki podobne velikosti kot v jeklih, ki so



Slika 9
Mešan interkristalen hladen prelom jekla s slike 4 po segrevanju na 1200 °C, držanju 1 uro in gašenju v vodi.

Fig. 9
Cold fracture of steel from fig. 4 after heating to 1200° C, holding 60 mins. and water quenching



Slika 10
Detajl sl. 9.

Fig. 10
Detail of fig. 9.

from solid solution of sulphur in austenite at cooling from solidification to deformation temperature and bigger spherical or rodlike inclusions produced at solidification. Considering all experimental data it seems logical to explain the role of manganese in two ways: in reducing the solubility of sulphur in austenite[26] (that decreases the quantity of inclusions produced by precipitation from austenite) and in diminishing the number of inclusions produced at the solidification of steel.

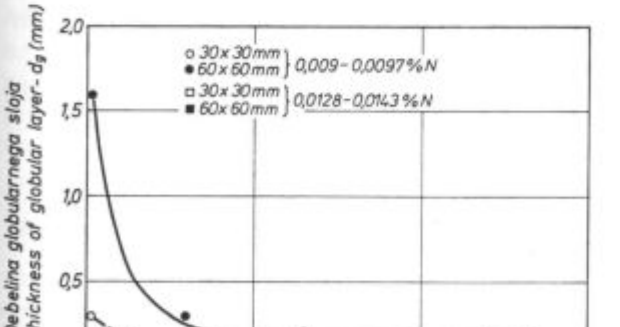
Low manganese steel from fig. 4 and 5 was submitted to heating at 1200 °C, water quenched and fractured by cold bending. A small dimpled fracture was obtained showing in some areas typical intergranular propagation (fig. 9). Sulphide inclusions of similar size as in steel cooled from solidification to deformation temperature were observed (fig. 10). That shows that reheating the steel to the deformation temperature and short retaining at this temperature does not modify notably the size and mutual distance of sulphide precipitates. It seems therefore, that the diminished hot brittleness, which is observed at reheating the cast steel to the deformation temperature, in comparison to the same steel cooled from solidification to deformation temperature, could not be connected to the modification of inclusions, as reported[21]. An alternative explanation could be in the fact that after transformation the grain boundaries of austenite do not correspond to the solidification grain boundaries weakened by sulphide precipitates.

3 Globular layer at the surface of steel

In all cases so far discussed no globular layer was observed at the surface of samples. That is bila ohlajena s temperature kristalizacije na temperaturo deformacije (sl. 10). To pove, da ogrevanje jekla na temperaturo deformacije in kratko zadržanje na tej temperaturi ne spremenita zaznavno velikosti in medsebojne oddaljenosti sulfidnih izločkov. Zato kaže, da zmanjšanja vroče krhkosti, katerega opazimo, če jeklo ogrejemo na temperaturo deformacije, v primerjavi z ohlajanjem na enako temperaturo deformacije ni mogoče povezati s spremembo oblike vključkov, kot navaja vir [21]. Alternativna razlaga bi bila lahko v tem, da se po transformaciji meje avstenitnih zrn ne prekrivajo z mejami, ki so nastale pri kristalizaciji jekla in ki so oslabljene s sulfidnimi izločki.

3. Globulitni sloj ob površini jekel

V vseh primerih, o katerih smo razpravljali dosedaj, ni bilo nobenega globulitnega sloja ob površini preizkušancev. To se dobro razloči tudi na posnetkih. Opazovanje v mikroskopu je pokazalo, da s pasovi ferita označene meje kristalnih zrn dosegajo površino preizkušancev. Zato so vsi izsledki o korelaciji med vročo krhkostjo in strukturo veljavni le za jeklo s stebrasto kristalizacijo. Pri tem je potrebno poudariti, da imajo meje zrn v jeklih, ki so bila najprej ohlajena pod temperaturo transformacije avstenita in nato ponovno ogreta na temperaturo deformacije, pri podobni velikosti boljšo vročo preoblikovalnost kot meje v jeklih, ki so ohlajena s temperature kristalizacije na temperaturo deformacije.



Slika 11

Vpliv količine aluminija v jeklu na debelino globulitnega sloja ob površini blokov z različnim presekom, ki so se strdili v pesku.

Fig. 11

Relationship between the aluminium content of steel and the thickness of globulitic layer at surface of blocks of different section solidified in sand moulds.

Da bi napredovali v preverjanju razlage, da je vročo krhkost maloogljičnih jekel s povečano količino aluminija in dušika potrebno povezati z vplivom teh dveh elementov na strjevalno strukturo ob površini, smo pripravili jekla, ki so zaradi manjše hitrosti strjevanja pokazala globularni sloj ob površini.

easy to verify on the pictures. Observation in microscope showed the boundaries of columnar grains, marked by ferrite bands, reaching the surface of specimens. Hence, all observations regarding the correlation between structure and hot brittleness refer to steel with columnar structure. It is important to underline that the grain boundaries in steels cooled below the transformation temperature of austenite and subsequently heated to the deformation temperature display better hot workability at similar grain size than the grain boundaries in steel cooled from solidification to deformation temperature.

To progress in the verification of the explanation that hot brittleness of low carbon steel with increased content in aluminium and nitrogen should be associated with the influence of these two elements on the solidification structure, steels were prepared which due to slower solidification showed a globular layer at the surface. Microstructure examinations of these steels have been carried out to the present.

The relationship in fig. 11 shows that at increasing content of aluminium the thickness of globular layer is decreased. At approximatively 0.03 % Al the thickness is within a value which remains independent on further increase in aluminium. The initial thickness of the globular layer is smaller in steels with higher nitrogen level.

The relationship in fig. 11 supports the hypothesis that the hot brittleness of low carbon steel with increased content in aluminium and nitrogen is associated with the influence of aluminium and nitrogen on the solidification structure at the surface of the steel. If there is no globular layer at the surface of blocks, or a thin globular layer was destroyed by scaling of steel at soaking before rolling, the solidification structure with columnar grains is exposed to severe straining. Boundaries of such grains, weakened with inclusions, precipitates of manganese sulphide and scale curtains, can not bear tensile deformation vertical to them. In this way different phenomena collaborate to increase the intergranular brittleness of steel causing a severe hot shortness of the steel cooled from solidification to rolling temperature.

D. SUMMARY

In the first part of this communication a survey of the data related to the hot brittleness of low carbon steels with increased contents of aluminium and nitrogen is presented. Serious objections can be made to the hypothesis which associate the hot brittleness with a direct influence of aluminium nitride, manganese sulphide inclusions produced at the solidification of steel and scale curtains along austenite grains boundaries. Hot bending tests of as cast specimens of

Odvisnost na sliki 11 pove, da se s povečanjem količine aluminija v jeklu zmanjšuje debelina globulitnega sloja ob površini jekla. Pri približno 0,03 % Al debelina doseže vrednost, ki se ne spreminja, ko znova zraste količina aluminija. Začetna debelina globularnega sloja je manjša v jeklih z manjšo vsebnostjo dušika. Odvisnost na sliki 11 potrjuje hipotezo, da je vroča krhkost maloogljičnega jekla s povečano količino aluminija in dušika povezana z vplivom, ki ga imata ta dva elementa na strjevalno strukturo ob površini jekla. Če ob površini jekla ni globularnega sloja ali je tanek globularni sloj uničilo škajanje jekla med ogrevanjem pred valjanjem, je močni deformaciji podvržena strjevalna struktura s stebrastimi zrni. Meje takih zrn, oslabljene z vključki in precipitati manganovega sulfida in zavesami škaje, ne prenesejo natezne deformacije, ki je nanje pravokotna. Na ta način sodeluje več fenomenov v povečanju interkristalne krhkosti jekla in povzroča močno vročo pokljivost jekla, ki je ohlajeno s temperature strjevanja na temperaturo valjanja.

D. REZIME

V prvem delu tega prispevka smo obravnavali literaturne podatke o vroči krhkosti maloogljičnega jekla s povečano količino aluminija in dušika. So resni pridržki, da bi sprejeli hipoteze, ki povezujejo vročo krhkost z neposrednim vplivom aluminijevega nitrida, zavesami škaje in vključki manganovega sulfida po avstenitnih mejah, ki so nastali pri strjenju jekla. Vroči upogibni preizkusi jekel z lito strukturo potrjujejo vprašljivost teh razlag in kažejo, da predstavlja vroča krhkost značilno lastnost strjevalne strukture jekla. Razpoložljivi literaturni podatki in izvršeni preizkusi niso v nasprotju s hipotezo, po kateri je vroča krhkost povezana z vplivom teh dveh elementov na nastanek in debelino globulitnega sloja ob površini jekla, ki je bilo ohlajeno s temperature kristalizacije na temperaturo deformacije. Neprimerna strjevalna struktura se superponira z interkristalno krhkostjo zaradi sulfidnih izločkov in povzroča resno vročo pokljivost jekla z okoli 0,16 % C in povečano količino aluminija in dušika, ki je bilo ohlajeno s temperature kristalizacije na temperaturo deformacije.

RAZPRAVA

A. Fuchs Hoesch Hüttenwerke AG, Bochum

Govorili ste o dveh mehanizmih krhkosti pri visoki temperaturi: krhkost zaradi precipitacije (MnFe) S in zaradi AlN. V vašem jeklu z 1,2 Mn prva oblika krhkosti ni močneje izražena in je pomembno izločanje AlN. Med obema vrstama

steel confirmed the questionability of these interpretations and show that hot brittleness in this type of steel represents a characteristic property of the solidification structure of steel. The available reference as well as performed tests and investigations do not oppose to the hypothesis that hot brittleness is associated with the influence of aluminium and nitrogen on the formation and the thickness of globular layer at the surface of steel cooled from solidification to rolling temperature. Unsuitable solidification structure at surface of blocks and the integranular brittleness due to sulphide precipitates cause a severe hot shortness of rd. 0.16 % C steel with increased contents of aluminium and nitrogen cooled from solidification to rolling temperature.

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DISCUSSION

A. Fuchs, Hoesch Hüttenwerke AG, Bochum

You spoke about two high temperature embrittlement mechanisms: embrittlement due to precipitation of (MnFe) S and due to AlN. In your steels with 1,2 Mn I think the first type is not very pronounced and the precipitation of AlN is very imkrhkosti je važna razlika; prva se pojavlja med valjanjem in hitrim upogibom, druga pa potrebuje mnogo časa za precipitacijo AlN. Uspelo nam je dokazati, da razpoke niso posledica krhkosti, ki je nastala med valjanjem. Majhne razpoke so bile že na ingotih zaradi termičnih napetosti in mogoče tudi zaradi napetostno induciranega izločanja AlN. Ali soglašate s takim mogočnim učinkom AlN?

F. Vodopivec

Strinjam se s prvim delom Vašega komentarja in z idejo, da majhne, predhodno nastale razpoke lahko povzročajo vročo krhkost. Nimamo nobenih izkušenj z majhnimi razpokami na površini blokov. Vendar bi s takimi razpokami težko razložili dejstvo, da je vroča krhkost močnejša, če se jeklo založi vroče, kot če se založi hladno; prej bi pričakovali nasprotno.

Ph. Aubrun, Sollac, Florange

Ne verjamem, da bi bila lahko uporaba topnostnega produkta za AlN primerna za analizo izločkov.

F. Vodopivec

Strinjam se, vendar je analiza AlN draga in često podvržena nezanemarljivim analitskim napakam. Zato verjamem, da se lahko produkt topnosti uporabi, da bi dobili splošno predstavo o količini AlN pri določeni temperaturi. Podatki v razpravi ne pomenijo realne vsebnosti AlN, temveč da realna vsebnost ne more biti večja od tiste, ki jo predvideva produkt topnosti za jeklo s podobno osnovno sestavo.

H. J. Grabke, MPI, Düsseldorf

Pred kratkim sem slišal za možnost, da se poveča vroča deformabilnost jekla, ki vsebuje baker z dodatkom približno 0,2 % Ni. To se zdi razumno. Ni in Cu se oba obogatita pod oksidnim slojem, ki nastane med ogrevanjem. Če je prisoten samo Cu, je tališče železa, obogatenega z bakrom, okoli 1080 °C; talina prodira po kristalnih mejah, zato pride do pokanja površine. Če pa je obogaten tudi Ni, je tališče kovine, obogateno s Cu in Ni, višje in se vroča krhkost lahko ne pojavi.

F. Vodopivec

Poznano je, da se zaradi prisotnosti niklja v železu spremenita sestava in tališče sloja kovine, ki je obogatena z rezidualnimi elementi. Zato se strinjam z Vašim komentarjem. Dodatek niklja je lahko koristen, vendar je malo verjetno, da bi postal splošna praksa. Mislim, da se lahko dodatek niklja upošteva kot posebnost, ki pa potrebuje skrbno preverjanje.

portant. But there is an important difference between these two embrittlement mechanisms, while the first one will be active during rolling or fast bending, the second needs much more time for the precipitation of AlN. We were able to prove that cracks of rolled products were not the consequence of the embrittlement during rolling. Small cracks were already present in the ingot due to thermal stresses and possible stress induced AlN precipitation. Do, you agree with this possible effect of AlN?

F. Vodopivec

I agree with the first part of your comment and with the idea that small preexisting cracks could cause hot brittleness. We do not have any experience with small cracks on the surface of blocks. However, such cracks could hardly explain the fact that hot brittleness is stronger if the blook is soaked hot than if is soaked cold, the contrary would be expected more probably.

Ph. Aubrun, Sollac, Florange

I dont believe that the solubility product of AlN could be utilised to analyse the AlN precipitates.

F. Vodopivec

I agree, however the analysis of AlN is rather expensive and frequently subjected to non negligible analytical errors. I believe that the solubility product could be used to get a general idea about the possible quantity of AlN at a fixed temperature. Data in the paper do not signify real contents of AlN but rather that the real contents could not be higher than the values predicted by the solubility product for a steel with a similar basic composition.

H. J. Grabke, MPI, Düsseldorf

I recently read about the possibility to improve the hot deformability of a steel containing copper by an addition of about 0.2 % Ni. This seems reasonnable. The Cu and Ni will both be enriched below the oxide layer which is formed during heating. In the case of only Cu present, the melting point of the Cu enriched in Fe is about 1080 °C the melt is intruding the grain boundaries and surface cracking occurs. However when Ni is also enriched the melting point of the Cu and Ni enriched metal phase will be higher and no hot shortness may occur.

F. Vodopivec

It is known that the presence of nickel in steel modifies the composition and the melting point of the metal layer enriched in residuals. I agree therefore with your comment. The addition of nickel could be useful, it is however hard to believe that it could be introduced as general practice. I think that the addition of nickel should be considered as a measure for specials cases and only after careful checking.