ŽELEZARSKI ZBORNIK
IZDAJAJO ŽELEZARNE JESENICE, RAVNE, ŠTORE IN METALURŠKI INŠTITUT
LETO 21 LJUBLJANA DECEMBER 1987

Strjevanje jekla v kokili

Solidification of Steel in a Mould

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UDK: 669.18:669.112.223:620.192.43
ASM/SLA: N21, M28h, E25n, D9p, 9—69

UVOD

Proces strjevanja jekla v kokili je opisan že v najrazličnejši strokovni literaturi[1–10] s področja metalurgije in matematične fizike.

Pritem pa ne gre zgolj za samo opisovanje pojavov, ki nastopajo pri strjevanju. Tu mislimo predvsem na izceje[11], notranje napetosti[12, 13] in lunker. Vedno več je poskusov, da te pojave razložimo in jih opišemo z enačbami matematične fizike.

Pri računalniški simulaciji strjevanja jekla v kokili, pri kateri smo raziskovali vpliv eksotermnih plošč na obliko primarnega lunkerja, smo namreč dobili zanimive rezultate, ki so nam dali ideje za nadaljnje raziskovalno delo.

Tako se nam je z rekonstrukcijo kokile OK 650 posrečilo, da smo bistveno vplivali na porazdelitev izcej v prerezu strjenega bloka. Uspelo nam je zmanjšati sekundarni lunker in prišli smo do novih spoznanj o samem procesu strjevanja — da je namreč mogoče vplivati tudi na strukturo strjenega bloka.

V nadaljevanju je natančneje opisan sam poskus in dobljeni rezultati.

Gre za novo gledanje na pojav strjevanja, ki je morda nekoliko neobičajno. Prvi poskusi pa so dali odlične rezultate in odpirajo se nove možnosti v prizadevanjih za izboljšanje kvalitete strjenih blokov tudi drugačnih oblik.

VPLIV EKSOTERMNIH PLOŠČ NA VELIKOST PRIMARNEGA LUNKERJA

Izolacijske eksotermne plošče, ki jih montiramo v zgornji del kokile, služijo za to, da ohranimo zgornji del taline čim dalj v tekočem stanju. Pri strjevanju se pa volumen zmanjša približno za 4 %. Želimo, da bi bilo to zniževanje gladine taline čimbolj počasno in na čim večjem prerezu. Tako bi dosegli najmanjšo globino primarnega lunkerja.

Na tržišču se pojavljajo vedno nove kvalitete izolacijskih plošč z vedno boljšimi izolacijskimi sposobnostmi, pa tudi z novo ceno. S pomočjo poenostavljenega modela smo želeli oceniti, kako vplivajo te lastnosti na globino primarnega lunkerja.

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INTRODUCTION

The process of solidification of steel in a mould is described elsewhere in various textbooks and in professional literature[1–10] from the metallurgical science and the mathematical physics. Usually it is not limited only to phenomenological descriptions of the effects observed with solidification. Here we mean especially the appearance of segregations[11], the internal stresses[12, 13] and the shrinkage holes. There are more and more efforts to explain these effects and to describe them by the equations of the mathematical physics.

With the computer simulation of solidification of steel in a mould where special exothermic plates were used to reduce the primary shrinkage hole, very interesting results were obtained that gave us new ideas for the further research work.

By the reconstruction of the mould OK 650 we succeeded in influencing the distribution of various segregations in the middle of the cross-section of the ingot and in reducing the secondary shrinkage hole. So we came to a new knowledge — how the structure of the solidified ingot could be modified. In the due text the experiment itself is described thoroughly together with the most important results. The idea about our vision of the process of solidification is perhaps a little unusual. But our first experiments gave us exellent results and new possibilities in improving the quality of solid ingots of different forms were opened.

INFLUENCE OF EXOTHERMIC PLATES UPON THE PRIMARY SHRINKAGE HOLE

The isolating exothermic plates that are usually mounted at the top of the mould are supposed to enable the upper part of the liquid steel to stay liquid as long as possible. By the process of solidification the liquid shrinks for about 4 %. It is desired to lower the level of the liquid steel as slow as possible and to keep it in the largest possible cross-section. In this way the smallest depth of the primary shrinkage hole is obtained.

On the market there are permanently new qualities of isolating plates available with better isolating properties and naturally with new prices.

V ta namen smo izdelali matematični model, s katerim smo simulirali proces strjevanja, in pri tem izhajali iz naslednjih predpostavk:

— kokila ima obliko pokončnega valja z enakomerno debelo steno,

— kokila stoji na debeli livni plošči iz podobnega materiala,

— velikost kokile, debelino stene in plošče lahko poljubno spreminjamo, prav tako tudi fizikalne lastnosti, kot sta specifična toplota in toplotna prevodnost strjenega bloka in kokile,

— talina se pri vlivanju v kokilo dviga enakomerno z določeno hitrostjo,

— gladina jeklene taline je idealno izolirana: toplotna prevodnost praška za posipanje je enaka 0,

— temperatura taline je enaka temperaturi tališča, strjevati se začne, ko je kokila nalita do vrha,

— latentna toplota ni vključena v specifično toploto, strjevaje v celoti poteče pri temperaturi tališča,

— toplotni stik med talino in kokilo naj bo ves čas idealen: strjeni blok je ves čas v tesnem stiku s kokilo,

— na zunanji steni kokile predpostavljamo ohlajanje s konvekcijo s konstantnim konvekcijskim koeficientom,

— v zgornjem delu kokile imamo izolacijske plošče z znanimi lastnostmi, ki segajo od vrha kokile do določene globine.

Za takšen poenostavljen primer smo izdelali računalniški program, s katerim smo lahko izračunali temperaturni profil v prerezu kokile in bloka in pri tem spremljali ugrezanje gladine in napredovanje meje med tekočo in trdno fazo.

Variirali smo lastnosti materiala, iz katerega so izdelane eksotermne plošče, dimenzije plošč in hitrost ulivanja. Poročilo o tej raziskavi je shranjeno v strokovni knjižnici Železarne Jesenice.

Računalniški program smo uspešno uporabili tudi pri študiju strjevanja valjavniških valjev[14], ki so bili uliti v železarni Štore, in se prepričali, kolikšna je upravičenost omenjenih predpostavk.

Prišli smo še do naslednjih spoznanj:

— če bi ulivali brez eksotermnih plošč, bi dobili zelo globok primarni lunker, ki bi segal skoraj do polovice višine bloka,

— pri vsakem ulivanju z eksotermnimi ploščami pa opazimo pojav »mostu« iz strjenega jekla, ki nastane nekje na 3/4 višine bloka.

V trenutku, ko nastane most, se pač en del taline nahaja pod njim, drugi del taline pa nad mostom. Delež taline nad mostom je tem večji, čim boljše izolacijske sposobnosti imajo eksotermne plošče in čim hitreje se dviga talina v kokili.

Most nastane v vsakem primeru.

Pojavlja pa se drugo vprašanje: Kaj se zgodi z mostom in kako se talina pod njim strjuje, če upoštevamo, da se pri nadaljnjem strjevanju volumen ujete taline zmanjša za 4 %.

Odgovore na to vprašanje je mogoče najti v različnih člankih, ki govorijo o rahli sredini v bloku, o notranjih razpokah, luknjicah, različnih vrstah poroznosti[15], sekundarnem lunkerju in podobno.

Mnogi avtorji trdijo, da pri tem pride do ugrezanja strjenega dela mostu.

Po naših izračunih in po natančnejšem ogledu Baumannovega odtisa prerezanega bloka iz avtomatnega jekla Č3990[16] smo ugotovili, da je verjetno res šlo za ugrezanje strjenega mostu oziroma za vdiranje nečistoč, ki se nabirajo v glavi, v notranjost bloka.

Using the simplified mathematical model we wished to estimate how all these different properties influence the depth of the primary shrinkage hole.

For this purpose the mathematical model is made to simulate the process of solidification based on the following assumptions:

— the mould has the form of a cylinder with a uniform thick wall,

— the mould is put upon a thick casting plate made of the same material,

— the dimensions of the mould, the thickness of the wall and of the casting plate can be varied together with the physical properties of the material like specific heat, the thermal conductivity of the solid ingot and of the mould,

— the level of the liquid steel is isolated perfectly: the thermal conductivity of the isolating powder on the top is equal zero,

— the temperature of the liquid steel is equal to the melting point, the solidification starts to proceed in the moment when the mould gets completely filled,

— the latent heat of the liquid steel is not included into the specific heat and the solidification is proceeded at the melting point,

— the thermal contact between the liquid and the mould is ideal all the time, even the solid ingot stays attached to the wall of the mould, there is no air gap,

— at the outer surface of the mould the convective heat transfer with a definite coefficient of convection is assumed,

— inside in the upper part of the mould the exothermic isolating plates are mounted extending from the top of the mould to a certain depth into the liquid steel.

For such a simplified case the computer program is made for calculation of the temperature profile in the cross-section of the mould and in the ingot. It is possible to follow the lowering of the liquid metal and to study the improving of the boundary between the solid and the liquid phase.

The properties of the isolating plates were varied together with the dimensions and with the casting speed.

The detailed report of this research work could be obtained at Strokova knjižnica Železarne Jesenice.

The computer program was also successfully applied to the study of solidification of the steel cylinder[14] for the rolling mill, cast in Železarna Štore, and the validity of the suppositions mentioned above could be verified.

The following conclusions were found:

— casting without exothermic plates would cause very deep primary shrinkage hole extending nearly to the half height of the ingot,

— with any case where exothermic plates were used, the formation of a "bridge" of the solid steel could be observed at about 3/4 of the ingot height.

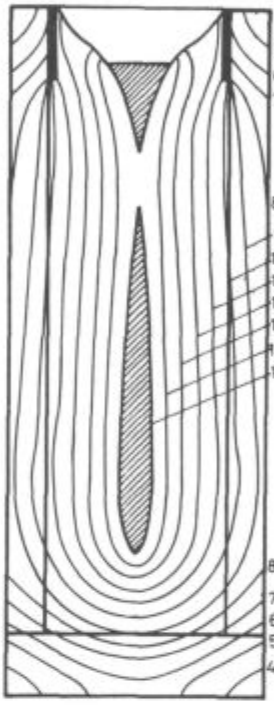
In the moment of the formation of the bridge one part of the liquid steel remains above the bridge, the second part gets caught under the bridge. The amount of the liquid metal under the bridge is somehow proportional to the isolating properties of the isolating plates and to the speed of raising of the liquid metal in the mould.

The bridge is formed in any case.

Now a new question arises.

What happens to the bridge and how is the solidification improving when the reduction of the volume (4 %) of the caught liquid metal is taken into account.

The answer to this question could be found in the articles describing the formation of the "soft middle" in the ingot, the internal cracks, the holes and various types of



Slika 1:

Izoterme v prerezu bloka v kokili. Toplotna prevodnost eksotermnih plošč 1.563 W m^{-1} K^{-1}, hitrost dviganja taline 200 mm/min, stanje po 106 minutah.

Fig. 1:

Isotherms in the cross-section of the ingot and the mould. Thermal conductivity of the exothermic plates 1.5 W m^{-1} K^{-1}, the speed of raising of the liquid steel 200 mm/min, the situation after 106 minutes.

Izračunani potek meje med trdno in tekočo fazo v simulaciji strjevanja bloka pa nas je napeljal še na novo idejo.

Slika 1 prikazuje izoterme v trenutku, ko je pri omenjeni simulaciji nastal most.

Ali se morda meja med trdno in tekočo fazo ne ujema s črtami, ki na odtisih po Baumannu običajno pomenijo izceje MnS v obliki črke A?

Izredna podobnost v poteku linij izcej MnS v obliki črke A in izračunanih izoterm nas je silila v iskanje dokaza za tako predpostavko.

Po nekaterih razlagah[17, 18] naj bi bila za to kriva koničnost kokile. V svojih izračunih pa smo predpostavljali, da kokila ni konična.

Kasneje smo našli poročilo, ki opisuje enake oblike izcej pri kokili, ki je celo širša v zgornjem delu[19, 20]. To je bil dokaz, da so razlage, ki se pojavljajo tudi v metalurških učbenikih, včasih zelo pomanjkljive.

Če so izceje v obliki črke A zares slike trenutne meje med tekočo in trdno fazo v prerezu bloka, ki naj bi nastale ob strjevanju, bi bilo mogoče na to porazdelitev vplivati, če bi lahko vplivali na hitrost strjevanja.

Z omenjenim računalniškim programom smo naredili simulacijo, pri kateri smo pogoje ohlajanja spreminjali.

Tako smo si »izmislili« dodatno plast iz šamotne opeke, ki naj bi bila pritrjena na zunanji strani v zgornji polovici kokile. Izračunali smo, kako bi se spremenil potek strjevanja v takem primeru. Ugotovili smo, da bi to prav nič ne vplivalo na hitrost strjevanja in da bi bile razlike v temperaturni porazdelitvi v trenutku, ko bi nastal most, zanemarljivo majhne. Seveda nismo naredili nobenega praktičnega poskusa, saj ni bilo potrebno.

Druga ideja je bila, da bi kokilo »postavili« na vodno hlajeno bakreno livno ploščo. Tudi ta simulacija je pokazala, da s tem ne bi prav nič vplivali na tvorbo mostu.

V vsakem primeru je bila stena kokile predebela, da bi bilo mogoče kakorkoli vplivati na potek strjevanja v notranjosti oziroma na potek meje med trdno in tekočo fazo v trenutku, ko nastane omenjeni most.

porosity[15], secondary shrinkage holes and similar things. Many authors are suggesting the lowering of the solidified bridge.

According to our calculations and after a thorough examination of the sulphur prints in the cross-section of the ingot[16], it was found out that in fact the lowering of the bridge and the penetration of impurities from the top into the middle of the ingot could be assumed.

The calculated course of the boundary between the liquid and the solid phase in the simulation of solidification of a steel ingot led us to a new idea.

Fig. 1 is represeting the isotherms in the moment of the formation of the bridge according to our simulation.

Is it possible to assume that the boundary between the solid and the liquid phase were equal to the lines that correspond to the segregations of MnS in the sulphur prints in the form of the letter A?

The outstanding similarity in the course of the lines corresponding to segregations of MnS in the form of the letter A with the calculated isotherms forced us to look for the confirmation of our assumptions.

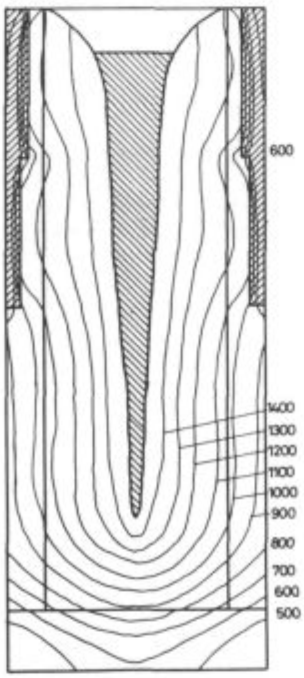
According to some interpretations[17, 18] about the process of solidification this effect could be explained simply by the conicity of the mould.

In our calculations, however, it was assumed that the mould was not conical. Later we found the articles where the same form of segregations were reported[19, 20] even in the moulds that were wider at the top. It was the proof that explanations appearing in metallurgical textbooks are sometimes too superficial.

If the so called A-segregates are really corresponding to the boundaries between the liquid and the solid phase in the cross-section of the ingot that should be formed at solidification it would be possible to influence them if we could influence the speed of solidification.

With the computer program different simulations were made with different cooling conditions.

An additional layer of recovery that would be "fixed" at the outer side of the upper half of the mould was simulated. It was calculated how the solidification would be changed in such case. It was found out that it would



Slika 2:

Izoterme pri simuliranem primeru brez mosta. Toplotna prevodnost zunanje obloge 1.5 W m^{-1} K^{-1}, hitrost dviganja taline 200 mm/min, stanje po 109 minutah

Fig. 2:

Isotherms in the cross-section of the simulated case. The thermal conductivity of the isolating layer outside 1.5 W m^{-1} K^{-1}, the speed of raising of the liquid steel 200 mm/min, the situation after 109 minutes.

Ostala nam je torej samo še ena možnost:

v zgornjem delu »stranjšati« steno kokile in jo še dodatno izolirati z zunanje strani.

V omenjenem programu za simulacijo strjevanja smo postopoma »tanjšali« steno kokile in »dodajali« izolator toliko časa, da smo prišli do zaželenega rezultata.

Rezultat þa je bil takle: **(slika 2)**.

Jeklena talina se je strjevala tako, da se most sploh ni pojavil. Meje med tekočo in trdno fazo so dobile obliko črke U. V sredini je sicer prišlo do primarnega lunkerja, o sekundarnem lunkerju, ugrezanju mostu oziroma o vdiranju nečistoč iz glave v notranjost pa ni bilo sledu.

Seveda je bilo vse to izračunano na matematičnem modelu.

Model sam je temeljil na razmeroma hudih poenostavitvah[21] glede stika med kokilo in talino, vendar pa nam je dal ideje za nadaljnje raziskovalno delo. Na osnovi rezultatov omenjene simulacije smo naredili praktični poskus s tako imenovano rekonstruirano kokilo.

REKONSTRUIRANA KOKILA

Odločili smo se za stanjšanje stene kokile tako, kot prikazuje **slika 3**. Zgornjo polovico smo konično posneli z zunanje strani in preostalo debelino nadomestili z izolatorjem. Potrebna je bila posebna konstrukcija, ki je omogočala stripanje in polnjenje zgornjega dela z izolacijskim sredstvom. Na ta način smo hoteli zmanjšati toplotno kapaciteto zgornjega dela kokile v primerjavi s spodnjim delom in dodatno zmanjšati hitrost strjevanja v glavi bloka. Zaradi primerjave rezultatov smo ulili en blok v klasično kokilo.

Odločili smo se za format OK 650 (650 × 650 × 2000) in za jeklo, kvalitete Č 3990. Pri tem jeklu je namreč mogoče opazovati izredno intenzivne izceje MnS in je zato tudi primerjava med različnimi bloki lažja.

Napravili smo 4 poskuse:

1. jeklo ulito v klasično kokilo (A)
2. jeklo ulito v kokilo d = 40 mm izolacija: livarski pesek (B)

not influence the solidification at all and that the temperature differences in the moment of the formation of the bridge would be negligibly small.

The second idea was to "put" the mould upon a water-cooled casting plate made of copper. Also the results of this simulation showed that this would not influence the formation of the bridge at all.

In all cases the wall thickness seemed to be too large to be able to influence the process of solidification inside, especially the course of the bundary between the solid and the liquid phase in the moment of the formation of the bridge.

There was only one possibility still left.

To lessen the thickness of the wall in the upper part of the mould and to isolate it additionally from the outside. In the program for the simulation of solidification the thickness of the wall was gradually "thinned" and an isolator was "added" till the final result was obtained.

The final result was the following **(Fig. 2)**.

The liquid steel became solid in such a way that the bridge was not formed at all. The boundaries between the solid and the liquid phase got the form of the letter U. In the middle the primary shrinkage hole could be calculated, but there was no secondary shrinkage hole, no lowering the bridge or penetrating impurities from the top into inside.

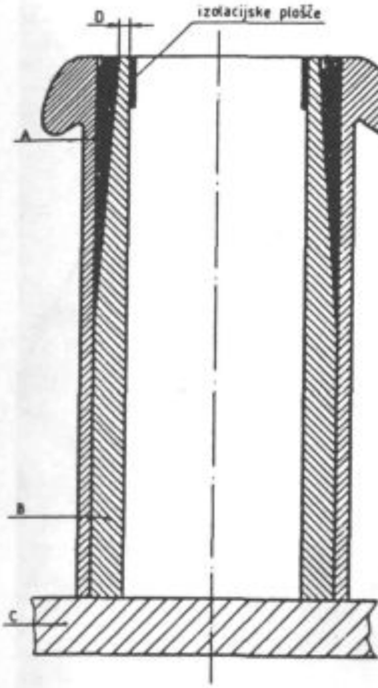
Naturally all this was calculated according to mathematical model.

The model itself based on rather severe simplifications concerning the thermal contact[21] between the mould and the liquid steel but it gave us anyway the ideas for the further research work. On basis of these simulations we performed the experiment with the so-called reconstructed mould.

RECONSTRUCTED MOULD

We decided to thin the mould wall according to **Fig. 3**.

The upper part was taken off conicaly and the remaining thickness was replaced by the thermal isolator.



Slika 3:
Prerez rekonstruirane kokile:
A izolator
B kokila
C livna plošča

Fig. 3:
The cross-section of the reconstructed mould:
A isolator
B mould
C casting plate

3. jeklo ulito v kokilo d = 40 mm izolacija: perlit (C)
4. jeklo ulito v kokilo d = 20 mm izolacija: perlit (D).

(V primeru 4 je bil perlit posebej sušen.)

Na **slikah 4, 5, 6 in 7** so prikazani odtisi po Baumannu za vse 4 primere obenem z ustrezno sliko jedkane površine prereza.

POJASNILO K POSAMEZNIM SLIKAM

Slika 4 je zelo podobna sliki iz leta 1973[16]. Prav lepo se vidijo izceje v obliki črke A in v sredini izceje MnS v obliki črke V. Na fotografiji jedkane površine se zelo lepo vidijo vzdolžne razpoke, ki potekajo praktično po vsej dolžini bloka.

Blok B na **sliki 5** je bil pa ulit v rekonstruirano kokilo. Očitno je število razpok v področju sekundarnega lunkerja bistveno manjše, potek izcej v obliki črke A pa ni bistveno drugačen, kot pri bloku A. Ta ugotovitev nas je v prvem trenutku nekoliko razočarala, saj smo pričakovali znatnejše razlike v poteku teh izcej. Pojav smo si razložili s tem, da so izolacijske sposobnosti livarskega peska verjetno razmeroma majhne.

Pri bloku C smo namesto livarskega peska uporabili perlit (U2), ki se uporablja za izolacijo fasad na zgradbah. Pokazalo se je, da smo vendarle na pravi poti.

S **slike 6** se jasno vidi, da je izcej v obliki črke V v sredini prereza manj in praktično tudi ni več razpok v sredini prereza v področju sekundarnega lunkerja. Glava je nekoliko bolj čista, robne izceje v obliki črke A potekajo nekoliko bolj pokončno, kot pri bloku A, nečistoče v obliki črke V v sredini prereza so manj izrazite.

Opazili pa smo nekaj, kar nam prej ni zbudilo pozornosti.

Osrednji del v glavi, v katerem sicer vidimo mnogo izcej V, (primerjaj blok A!), je tu najširši, če med seboj primerjamo prereze blokov A, B in C. To področje je omejeno nekako z dvema paralelnima navpičnima črtama.

A special construction was necessary to enable the stripping of the ingot and the filling of the isolating material.

Tha thermal capacity of the upper part of the mould in comparison with the bottom part was reduced and we hoped that the speed of solidification in the top would be additionally reduced too. To make the comparison among different experiments easier one ingot was cast into the ordinary mould.

For our practical experiment the mould OK 650 (65 × 650 × 2000) and the quality of the free-cutting steel Č 3990 were chosen. With this type of steel very intense segregates of MnS could be detected so that the comparison among different ingots is easier.

The following experiments were performed:

— steel cast into an ordinary mould (A)

— steel cast into the reconstructed mould with D = 40 mm and with the casting sand used as the isolating material (B)

— steel cast into the reconstructed mould with D = 40 mm and with the pearlite used for the thermal isolation (C)

— steel cast into the reconstructed mould with D = 20 mm and with the pearlite used for the thermal isolation (D)

In the last case the pearlite was specially dried.

The **Figs. 4, 5, 6 and 7** show the sulphur prints for all the four cases together with the corresponding photos of the etched surfaces of the cross-sections.

COMMENTS TO THE FIGURES

Fig. 4 is very similar to the figure from the year 1973[16]. The segregations in the from of the latter A are clearly seen and the V-segregations of MnS in the middle of the cross-section are evident. From the photos of the etched surface the longitudinal cracks are shown, being practically distributed all along the length of the ingot.

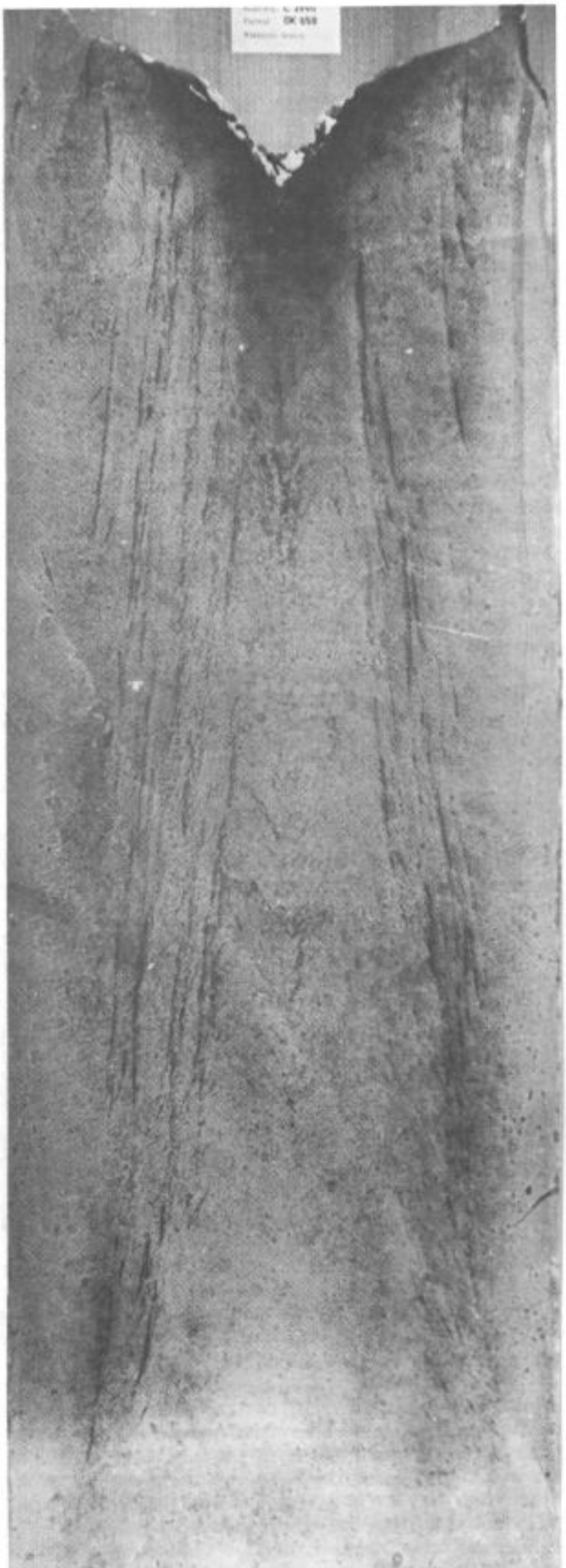
The ingot B from **Fig. 5** was cast into the reconstructed mould. It is evident that the number of cracks in the region of the scondary shrinkage hole is significantly smaller and the course of the segregates in the form of the letter A is not much different from that one of the ingot A.

This effect disappointed us at the first moment since considerable differences in the course of these segregates were expected. This could be explained by the fact that the isolating properties of the casting sand were not good enough.

With the casting of the ingot C instead of casting sand the pearlite (U2) was used. This is the same material that is so often used for the thermal isolation of façades of houses. It was shown at once that we were nevertheless on the right way.

From **Fig. 6** it can be easily seen that there are not so many V-segregates just in the middle of the cross-section and that there are not so many cracks in the region of the secondary shrinkage hole. The top of the ingot is a little cleaner, the A-segregates are a little more steep than they are in the case of the block A. The impurities in the form of the letter V are less expressed.

But we observed something what was not evident at the first moment. The middle top region (Fig. 6), where there are normally many V-segregates, is the largest if the ingots A, B and C are compared. This region is somehow limited by two vertical parallel lines of segregates. We wished to increase the isolating properties of the upper part of the mould. So the thickness of the wall



Slika 4:

Ingot A — odtis po Baumannu
sulphur print

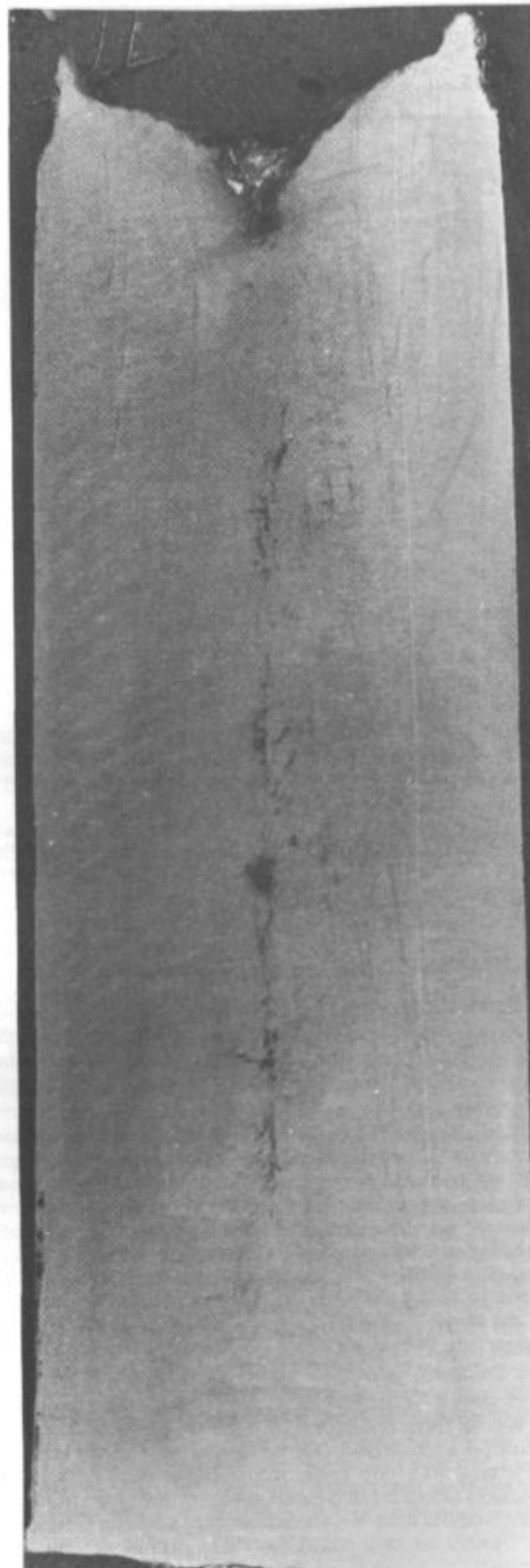
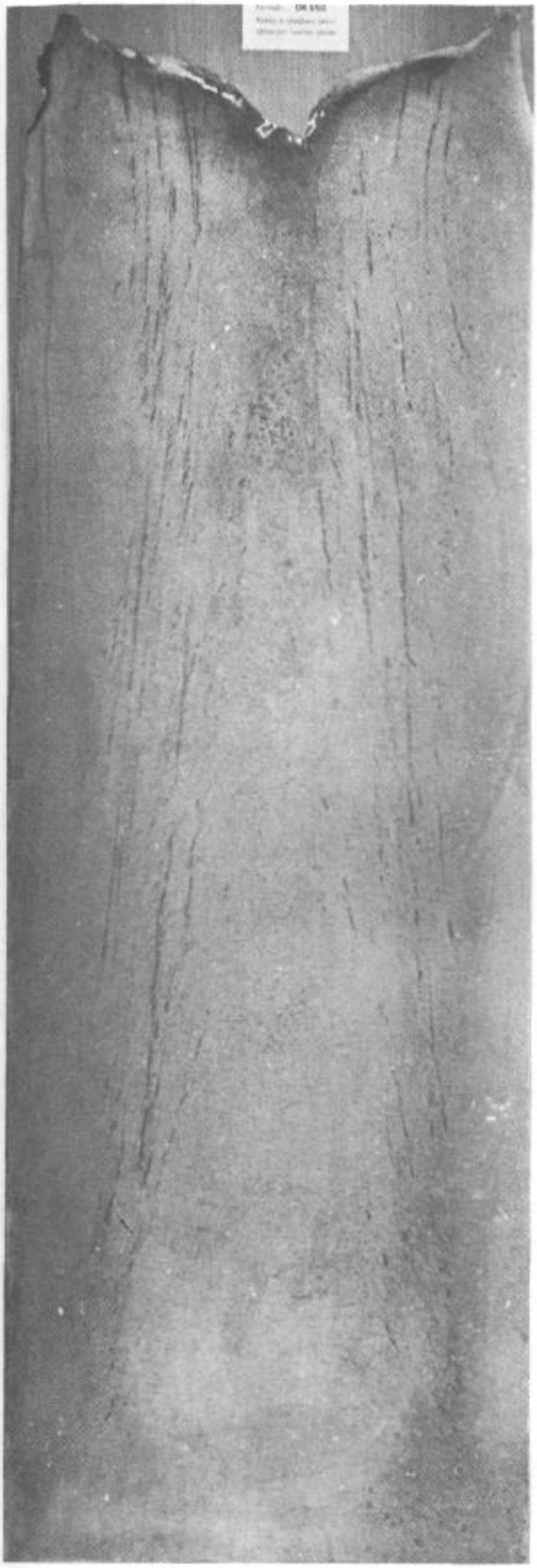


Fig. 4:

Ingot A — jedkana površina prereza
the etched surface of the cross-section



Slika 5:
Ingot B — odtis po Baumannu
sulphur print

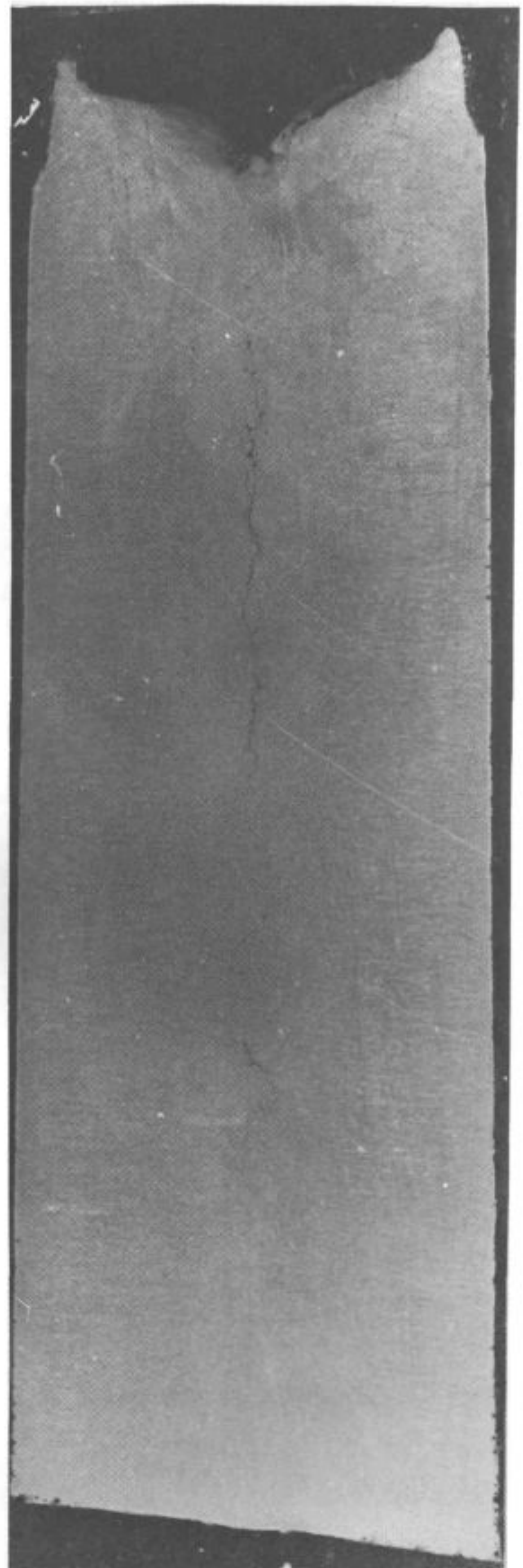
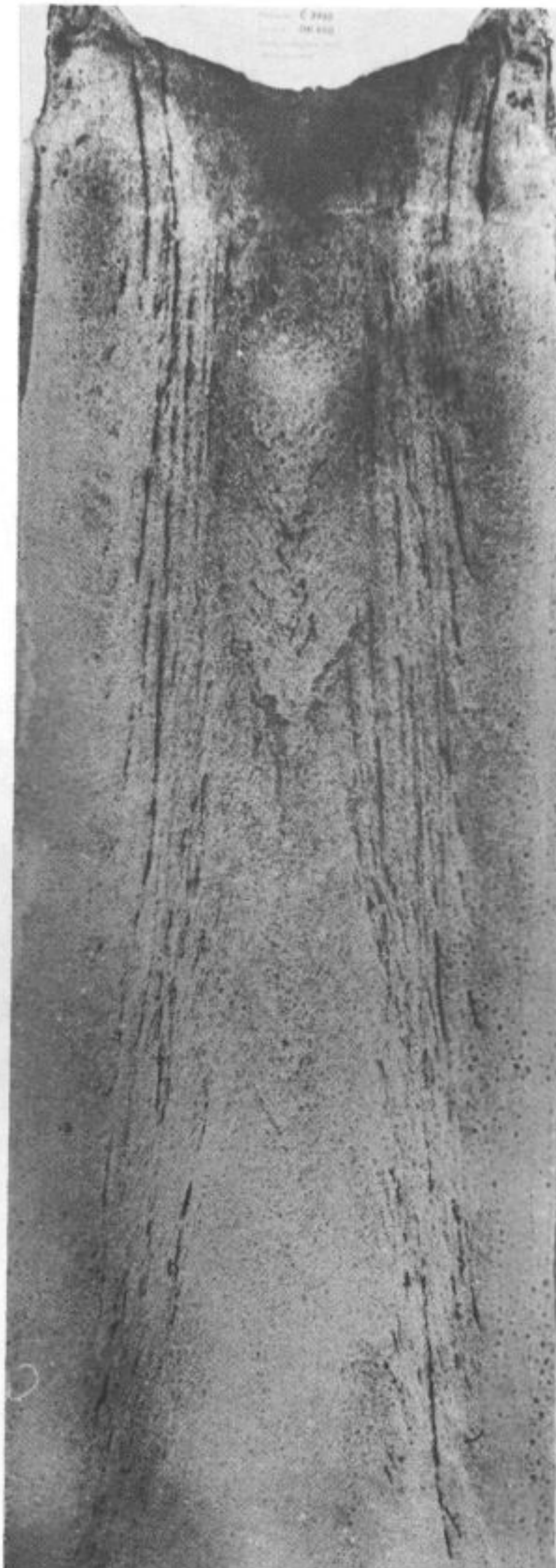
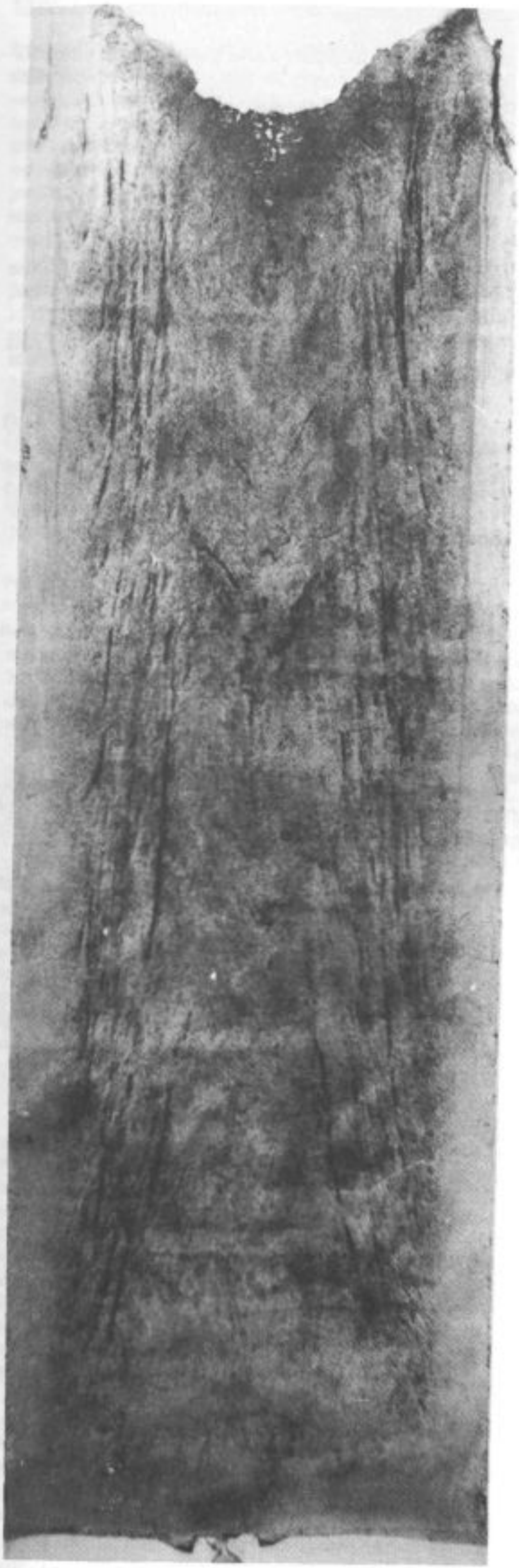


Fig. 5:
Ingot B — jedkana površina prereza
the etched surface of the cross-section



Slika 6:
Ingot C — odtis po Baumannu
sulphur print

Fig. 6:
Ingot C — jedkana površina prereza
the etched surface of the cross-section



Slika 7:
Ingot D — odtis po Baumannu
sulphur print

Fig. 7:
Ingot D — jedkana površina prereza
the etched surface of the cross-section

Hoteli smo še bolj povečati izolacijske sposobnosti v zgornji polovici kokile, zato smo dodatno stanjšali steno kokile in spet uporabili perlit. V tem primeru smo namenoma šli v skrajnost glede debeline stene kokile. Po pričakovanju se je ta stena zelo močno ogrela, ponekod celo nad tališče perlita, zaradi česar smo morali perlit med samim strjevanjem dodajati. (Končno nam ga je celo nekoliko zmanjkalo). Stena kokile pa se je v zgornjem stanjšanem delu toliko ogrela, da se je nekoliko usločila (napihnila se je) in smo jo morali končno razrezati, da smo dobili blok iz kokile.

Rezultat na **sliki 7** pa je tisto, kar smo pričakovali.

V tem primeru je področje homogene strukture med obema paralelno potekajočima izcejama še širše, kot v primeru C. Če gledamo od roba proti sredini prereza, potem končne izceje, ki so še jasno izražene, nimajo več oblike črke A, ampak opazujemo namesto konice pri A dvoje paralelnih navpičnih črt. Izceje bi laže opisali z dvema polovicama na glavo postavljene črke Y, ki sta nekoliko razmaknjeni.

Razlika med slikama 4 in 7 je očitna.

Nekoliko pa nas je vseeno razočaral »V« v sredini prereza, saj ga v tem primeru nismo pričakovali. Pozneje smo našli razlago tudi za ta pojav.

NAŠA HIPOTEZA STRJEVANJA JEKLA V KOKILI

Na osnovi rezultatov predhodnih računalniških obdelav in proučevanja slik 4—7 smo postavili naslednjo hipotezo o poteku strjevanja:

Problem prehoda toplote med talino in kokilo opisuje več avtorjev. Nekateri govorijo o tanki plasti strjenega jekla, ki se tvori ob stiku taline s hladno kokilo. Ker se strjena »srajčka« skrči, odstopi od kokile. To pa povzroči, da se toplotni tok iz taline zmanjša in zato se »srajčka« ponovno pretali itd. To naj bi se periodično ponavljalo toliko časa, dokler se ne bi »srajčka« toliko zdebelila, da se ne bi več pretalila in bi že vzdržala hidrostatični tlak.

Težko verjamemo, da bi prišlo do take periodične tvorbe »srajčke«, ki se enkrat dotika kokile, drugič pa spet ne.

Gre za neke vrste neidealen kontakt. Po naše narašča koeficient prenosa toplote od zgoraj navzdol zaradi večjega ferostatičnega tlaka. Iz taline torej odteka toplota v stene kokile, tako da se stene intenzivneje ogrevajo spodaj kot pa zgoraj. Talina se pri tem meša zaradi temperaturnih razlik. To pomeni, da se, po našem mnenju, vsa toplota, ki je shranjena v talini zaradi pregretja, odteče v stene kokile in jih neenakomerno ogreje (spodaj bolj, zgoraj manj), tako da temperatura stene kokile približno linearno narašča od zgoraj navzdol.

Pričakujemo, da ni bistvenih razlik v debelini »srajčke« zgoraj in spodaj v trenutku, ko ingot odstopi od stene kokile v celoti. Zgoraj se sicer zelo hitro naredi, vendar je tanka, saj je tudi ferostatični tlak manjši. Spodaj pa mora biti debelejša, saj blok kasneje odstopi od stene.

Ko blok po vsej višini odstopi od stene kokile, pa zaradi nadaljnjega odtekanja toplote narašča debelina strjene »srajčke«. To pa poteka v vsakem primeru hitreje v zgornjem delu kot pa v spodnjem.

Če namreč pomislimo, kolikšna je temperatura onstran zračne reže v steni kokile v zgornjem delu, je takoj jasno, da mora potekati strjevanje zgoraj hitreje. Spodnji deli kokile so se le precej bolj ogreli v tistem času, ko je bilo odtekanje toplote v steno kokile zaradi nastajajoče »srajčke« intenzivnejše. Zato trdimo, da v nada-

was additionally reduced and the pearlite was used for the thermal isolation again. In this case we deliberately decided for an extreme situation concerning the thickness of the wall. As expected the wall became very hot and the temperature raised somewhere even above the melting point of the pearlite so that pearlite had to be added continously during the process of solidification. (Before the end of the experiment practically all the isolating material available was used).

Due to rather high temperatuers the wall of the mould became deformed in the upper thinner region so that the ingot had to be cut out of it.

The results shown in **Fig. 7** are something what was expected before.

The region of the homogenous structure between both parallel flowing segregates is still larger than it is in the case C. Looking towards the center the final still recognizable A-segregates are no more of the form of the letter A. Instead of the top of A, two parallel vertical lines could be observed. The segregations could be better described by two separated halves of the inverted letter Y.

The differences between the **Figs. 4 and 7** are evident. However the "V" in the middle of the cross-section in such an extreme case was not expected any more. An explanation also for this effect was found later.

OUR HYPOTHESIS OF SOLIDIFICATION OF STEEL IN A MOULD

On the basis of the results of the computer simulations made before and from the careful examination of **Figs. 4 to 7** the following hypothesis seems to be valid for the process of solidification.

The problem of the heat transfer between the mould and the liquid metal was described by several authors. Some of them suggest the formation of a very thin layer of solid steel (shell) formed at the contact of the liquid steel with the cold mould. Because the solid shell shrinks, an air gap is formed and it prevents the further heat flux from the inside of the liquid pool. The shell melts again and this process is supposed to be continued so long until the shell gets so thick that is does not melt any more and until it can endure the ferrostatic pressure of the liquid steel inside.

It can be hardly believed in the periodic formation of the shell that once sticks to the mould and then melts again. We mean that there must be some kind of non-ideal thermal contact. According to our vision we have to do with an increasing coefficient of the heat transfer when looking from the top to the bottom of the mould due to increasing ferrostatic pressure. From the liquid metal the heat flux flows into the mould so that the walls become more intensively heated at the bottom than at the top. We suppose that the liquid is mixing all the time due to temperature differences. It means that according to our idea all the superheat that is stored in the liquid metal, flows to the walls of the mould and warms them non-uniformly (more at the bottom and less at the top) so that the temperature of the mould wall increases approximately linearly from the top to the bottom.

We expect that there are not great differences between the thickness of the shell formed at the bottom and at the top in the moment of the formation of the air gap all along the length of the ingot. At the top a thin shell is formed very quickly together with the air gap because of very small ferrostatic pressure. At the bottom ljevanju strjevanja debelina stene narašča linearno od spodaj navzgor.

Tudi izceje v obliki črke A so v področjih bliže steni kokile praktično ravne črte, ki so enako strme v vseh štirih primerih.

To si razlagamo tako, ker mislimo, da v začetku strjevanja različna debelina stene v posameznih področjih kokile še ne pride do izraza. Kasneje pa se slika spremeni.

Zmanjšana toplotna kapaciteta in povečana izolacija v primerih blokov B, C in D lahko znatno vplivata šele proti koncu strjevanja. Pri rekonstruirani kokili dobi torej talina proti koncu strjevanja obliko prisekanega stožca, ki se nadaljuje v valj. Širina tega valja se veča od slike 4 proti sliki 7. Kljub temu, da pri sliki 7 nismo pričakovali mostu, pa je vseeno mogoče videti, da se je del izcej v obliki črke A v sredini ugreznil v obliki črke V, čeprav ne posebno globoko (manj, kot je pa to razvidno s slike 4). Tudi za to smo našli razlago, ki je opisana v nadaljevanju.

KAKO SI ZAMIŠLJAMO NASTANEK IZCEJ MnS

Ob fronti dendritov, ki rastejo pravokotno na mejo med tekočim in trdnim, se bogati talina z vsebnostjo MnS, tako da ni mogoče več »tolerirati« tolikšne koncentracije. Čisti kristali potiskajo pred seboj talino, ki postane prenasičena. Zato naenkrat pride do izločanja MnS v obliki izcej, kar pa verjetno sprosti nekaj toplote. To pomeni, da se v nadaljevanju prodiranje dendritov proti sredini nekoliko zaustavi, saj odtekanje te reakcijske toplote ne povzroči rasti strjene plasti. V tem času ima tisti del taline ob strjeni steni možnost, da se v njem ponovno izenači koncentracija MnS. Pri tem ima odločilno vlogo temperatura oziroma konvekcijski in difuzijski procesi.

Ko reakcijska toplota odteče, se vse skupaj ponovi.

Tako si razlagamo nastanek izcej MnS v obliki črke A — nastanejo paralelne črte, pri katerih se medsebojna razdalja manjša, če gremo od roba proti sredini prereza.

Omenjena oblika »taline« v obliki prisekanega stožca, ki se nadaljuje v valj, pa po našem mnenju dobi lastnosti težko se premikajoče »marmelade«, ki se pri nadaljnjem odvajanju toplote pretvori v plastično maso, podobno pudingu in se krči kot celota.

Predstavljamo si, da je ta plastična talina nekako »obešena« na stene, ki so se že prej strdile.

Ko se sama skrči, potegne za seboj navzdol tudi dele stene, ki so že prej nastali, pa še niso dovolj trdni. Nastnejo izceje v obliki črke V.

Na to idejo nas je navedlo dejstvo, ki smo ga lahko opazovali pri vseh odtisih po Baumannu na slikah 4 do 7, da so namreč praktično pri vseh blokih tudi 0.5 metra nad osnovno ploskvijo bloka kristali deformirani, zavihani navzdol, podobno kot se to vidi v področju izcej V.

V primeru D, ko imamo nad prisekanim stožcem izrazito širok valj, pa se kljub temu nismo mogli izogniti izcejam v obliki črke V v sredini prereza.

Na jedkanem obrusu pa se vidi, da je v tistem področju glave, ki je po navadi kritičen, v primeru D izredno homogena struktura. Trdimo, da smo v zgornjem delu glave dosegli, da je material izredno homogen in čist in zanj ni mogoče več trditi, da je prišlo pri krčenju do vdiranja nečistoč iz glave v sredino prereza. Edino izcejo v obliki črke V v sredini pri bloku D pa lahko razložimo takole:

the thickness is larger but the air gap is formed much later.

After the air gap is formed completely, the further heat flux into the mould causes the increasing of the thickness of the solid shell. This process is improving more quickly in the upper part than in the lower part of the ingot.

If we just consider the temperature of the mould wall across the air gap in the upper part, it becomes quite evident that the solidification must proceed more quickly there. The bottom of the mould accepted much more heat, because the heat flux into the wall due to higher ferrostatic pressure with the formation of shell, was more intense. We say that after the air gap is formed in the further process of solidification the thickness of the shell increases linearly from the bottom to the top of the ingot.

Even the A-segregations in the region closer to the wall are practically straight lines with nearly the same steepness in all four cases. This could be explained by the fact that at the beginning of solidification the influence of the different thick walls in different heights with the reconstructed mould can not play its role yet.

In the cases of ingots B, C and D the influence of the smaller thermal capacity of the wall and the increasing thermal isolation of the mould become considerable only at the end of the solidification process.

With the reconstructed mould towards the end of solidification the liquid gets the form of a truncated cone that is continuing into a cylinder. The diameter of this cylinder is increasing if Figs. 4 to 7 are compared.

Although with the ingot D (Fig. 7) no bridge is expected, it is possible to see one part of an A-segregate in the middle of the cross-section is bent down in the form of the letter V, but not so deeply as it could be seen in **Fig. 4**. The explanation to this effect is also found and it is given later.

HOW WE IMAGINE THE FORMATION OF THE SEGREGATIONS OF MnS

With the growth of the dendritic crystals rectangularly to the boundary between the liquid and the solid phase, the liquid gets richer on MnS so that once it is not possible to tolerate such concentration any more. Pure crystals are pushing the oversaturated liquid in front of them. At a certain moment the MnS starts to segregate and it causes most probably the generation of a small amount of heat. This would mean that in due course the growth of dendrites towards the center stops a little, because the reaction heat that flows into the mould does not cause further growth of crystals.

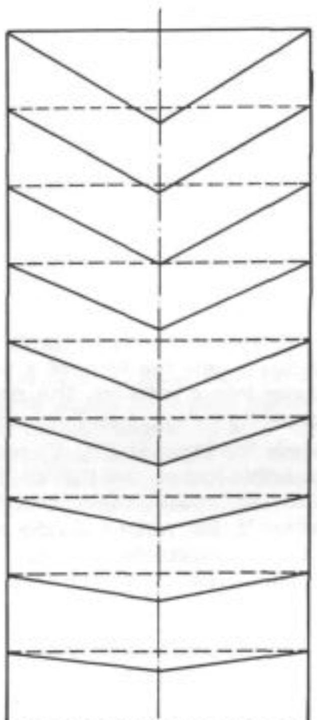
In this moment in the liquid region close to the solid shell the concentration of MnS equalizes again. Different diffusion and convective processes due to temperature differences are playing the most important role. When the flow of the reaction heat is finished, the whole story is repeated.

So we are explaining the formation of the A-segregates of MnS. The parallel lines can be observed and their mutual distance is decreasing when moving towards the center of the cross-section. The form of the liquid metal mentioned above in the form of a truncated cone continuing into a cylinder attains according to our assumptions the property of a very slowly moving "jam" that with the further cooling gets the properties of a

IZCEJE V OBLIKI ČRKE V

Mislimo si, da ima talina obliko valja in da so stene tega valja trdne, narejene iz iste snovi. Ker se pri strjevanju zmanjšuje volumen, se pač lahko ugreza le sredina.

Predpostavljajmo, da valj razrežemo enakomerno na valjaste plasti po **sliki 8**. Volumen vsake od teh plasti se pri strjevanju zmanjša za 4 % in zgornja ploskev naj se ugrezne tako, da dobi obliko navzdol obrnjenega stožca. Na **sliki 8** so s črtkano črto označene valjaste plasti taline, s polnimi črtami pa plasti, ki bi jih dobili po strjevanju. Takšno sliko bi dobili, če bi želeli, da ostane talina nekako »privezana« na stene valja.



Slika 8:
Strjevanje taline valjaste oblike
Fig. 8:
Solidification of a cylindrcal liquid.

Drugi primer:

Mislimo si, da imamo namesto valjaste taline talino v obliki prisekanega stožca, ki pa naj ima, kot prej, trdno steno. Spet ga razrežemo na enako debele plasti in poskušajmo določiti, kako bi se morale ploskve med posameznimi plastmi deformirati, da bi talina ostala privezana na stene stožca. S **slike 9** se vidi, da bi se morala potem ugrezniti v sredini v zgornjem delu (9. plast na **sliki 9**) zgornja ploskev valjaste plasti bolj, kot se je ugreznila spodnja ploskev te plasti ali talina se ne more strjevati tako, kot smo predpostavili, če naj bo »obešena« na stene stožca. Nujno potegne del strjene plasti na steni stožca navzdol, v sredino prereza bloka.

Če gre za konično obliko taline, je mogoče celo izračunati, na kateri višini bi se to zgodilo, če bi šlo za krčenje v stožec.

plastic material similar to a jelly that shrinks as a whole in one piece.

We suppose that such a plastic "metal" is somehow hung on its boundary to the walls that have been solidified previously. When it shrinks, it pulls down also some parts of the wall, that are still plastic. So the V-segregates are formed.

This idea is supported by the fact that with all the sulphur prints from Figs. 4 to 7 in the structure found about 0.5 m above the basis of the ingot, the crystals are deformed similarly, as it can be seen in the region of the V-segregations above.

In the case of the ingot D where we have to do with a cylinder with a rather large diameter above the core the appearance of V-segregations could not be avoided. From the photo of the etched surface it could be seen that in the region that is normally critical, in the case of the ingot D the structure is extremely homogenous.

It could be stated that in the upper part of the ingot an extremely good and homogenous structure is achieved and it is no more possible to say that there are any impurities penetrating from the top into the middle of the ingot.

The only V-segregate in the middle of the ingot D can be explained in the following way.

V-SEGREGATIONS

Let us suppose the liquid metal is of the form of a cylinder and the walls of this cylinder are solid, made of the same material. Due to shrinkage the volume gets smaller and the upper level moves down in the middle. Let us further suppose that the cylinder is cut uniformly to smaller equidistant layers according to **Fig. 8.** Due to solidification each layer shrinks for 4 % so that the upper flat circular surface moves down and it attains the form of an inverted cone. In Fig. 8 the subsequent cylindrical layers are indicated by dotted lines. The full lines indicate the form of these layers after the solidification. Such picture would be obtained if the liquid stays attached to the walls of the cylinder.

Another example:

If instead of a cylinder we have to do with a conical form of the liquid steel attached to solid walls of the same material. Let us again cut it into parallel layers of equal thickness and let us try to find out, how the flat basic surfaces of these layers would be deformed at solidification, if the liquid stays attached to the conical walls.

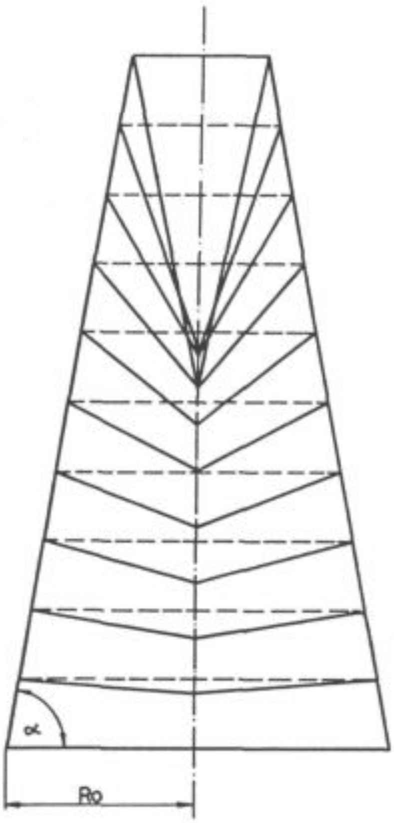
From **Fig. 9** it can be seen that something new must happen if we want to fulfil previous condition.

According to **Fig. 9** the upper surface of the 9th layer should move towards the center much deeper than the lower surface. With the other words:

The liquid metal can not be solidified in this way. It necessarily pulls a piece of the solid wall down into the middle of the cross-section of the ingot.

If the form of the liquid metal is conical, it is possible to evaluate also mathematically where it happens, if the basic surfaces of the subsequent layers get the form of an inverted cone.

Let the volume of the liquid steel of the form of a truncated cone with the radius Ro and with the angle α **(Fig. 9)** be reduced for η in the process of solidification. The upper level is supposed to be lowered so that it stays attached to the conical wall. In the middle it attains the form of an inverted cone. The critical height, where



Slika 9:
Strjevanje taline konične oblike
Fig. 9:
Solidification of a conical liquid.

Pri talini, ki ima obliko pokončnega prisekanega stožca, pri katerem je kot med stranskim robom osnega prereza in radijem α in polmer osnovne ploskve R_o, naj se volumen pri strjevanju zmanjša za η. Gladina naj se ugrezne tako, da ostane na robu »privezana« na steno stožca, v sredini pa naj dobi obliko stožca, ki je z vrhom obrnjen navzdol. Kritična višina, pri kateri se v takem primeru prvič »strga« stena in ugrezne navzdol, se izračuna po formuli:

$$H = R_o \cdot tg\alpha \cdot \left(1 - \sqrt[3]{\frac{2\eta}{1-\eta}}\right)$$

Če se to ne bi zgodilo, bi se sicer morala zgornja ploskev 9. valjaste plasti po sliki 9 ugrezniti bolj kot spodnja. S slike 4 lahko ocenimo, da je približno $tg\,\alpha \approx 10$ in če je $\eta = 0.04$, lahko ocenjujemo, da se bo pojavil prvi ugrez približno 1.5 metra nad osnovno ploskvijo ingota.

Natančnejši izračuni pa kažejo, da se pri pogojih strjevanja valjasta plast taline v sredini ugrezne celo nekoliko bolj, kot če bi šlo za ugrezanje v obliki stožca.

V primeru D opazujemo le eno večjo izcejo v obliki črke V v zgornjem delu prereza bloka, nekako tam, kjer se stožčasti del konča in začenja valjasti del. To je razumljivo, saj smo s stanjšano steno kokile dosegli, da se stožec nadaljuje v dosti širok valj.

ZAKLJUČEK

1. Na potek izcej in na strukturo v prerezu jeklenega bloka, ki je bil ulit v kokilo, lahko vplivamo s primerno regulacijo hitrosti strjevanja.

2. Z rekonstruirano kokilo smo nakazali, kako je mogoče odpraviti sekundarni lunker, rahlo sredino in povečano koncentracijo nečistoč v sredini bloka.

the boundary tears off and slips down, can be calculated from the following relationship:

$$H = R_o \cdot tg\,\alpha \cdot \left(1 - \sqrt[3]{\frac{2\eta}{1-\eta}}\right)$$

If it does not happen, the upper surface of the 9th layer according to **Fig. 9** should be lowered deeper than the bottom surface of the same layer. From **Fig. 4** it can be estimated that $tg\,\alpha \approx 10$ and if $\eta = 0.04$ we can calculate the position of the first V-segregate. It would appear approximately 1.5 m above the basis of the ingot.

From more precise calculations it is evident that the lowering of the middle of the surface of a layer would be even deeper than it is the case with the inverted cone, if the real shrinkage is taken into account.

In the case of the ingot D only one V-segregate in the upper part of the ingot can be observed just in the place where the cone starts to continue into the cylinder. The thinner wall in the upper part of the mould thus enables the formation of a cylinder with a large diameter.

CONCLUSION

1. The course of segregates and the structure in the cross-section of a steel ingot cast into a mould can be modified by a proper regulation of the speed of solidification.

2. With the reconstructed mould it is shown how the secondary shrinkage hole can be suppressed together with the "soft middle" and with the increased concentration of impurities in the middle of ingot.

3. Since with a proper form of the mould wall the homogeneity of the upper part of the ingot can be considerably increased it could be expected that difficulties

3. Ker znamo s primerno obliko kokile znatno povečati homogenost v zgornjem delu bloka, pričakujemo, da bi s tem odpravili težave, ki se pojavljajo pri valjanju nekaterih kvalitet zaradi nehomogenosti v sredini (dvoplastnost in podobno).

4. To trditev bo treba še praktično preveriti. Nova oblika kokile bo seveda nekoliko drugačna. Opisani poskusi bodo služili za izhodišče za delo v proizvodnji.

5. Odpirajo se možnosti za razvoj računalniškega krmiljenja in avtomatizacijo ohlajanja tudi ulitih blokov drugačnih oblik, kar je še posebno pomembno v livarstvu.

appearing with the rolling of some qualities of steel slabs due to inhomogeneities in the middle could be avoided.

4. This statement must be also verified practically. The form of the reconstructed mould for practical purposes will be a little different. The results of the experiments discussed above will be starting point for the practical measures.

5. New possibilities in the development of the computer regulation and automation of process of cooling of the cast steel ingots of different forms seem to be opened. It would be very important especially for the technological development in foundries.

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