Platiranje orodnih jekel na konstrukcijska jekla
Plating Tool Steel on Structural Steel

D. Kmetič*, J. Gnamuš**, F. Vodopivec*, B. Ralić*

UDK: 621.771.8:669.14.018.23/29
ASM/SLA: L22, F23, K5j, TSb, SGBs

V Železarni Ravne uspešno platirajo z vročim valjanjem orodna jekla na nosilno konstrukcijsko jeklo. Za nekatere pare jekel je postopek platiranja osvojen in poteka z ustreznim izkoristkom.

O poteku ogrevanja in valjanja je bilo na voljo premalo podatkov, da bi se lahko projektirala tehnologija izdelave različnih parov orodno jeklo — nosilno konstrukcijsko jeklo. Raziskave naj bi omogočile boljše poznavanje fizikalno-metalurških procesov vročega preoblikovanja compound jekel.

UVOD

Vedno več industrijskih nožev in drugih orodij se izdeluje po postopku vročega platiranja. Tako izdelana orodja imajo pri ustreznih mehanskih lastnostih precejšnje ekonomske prednosti zaradi prihranka dragih legiranih jekel, saj je iz orodnega jekla izdelan le koristni del orodja. Prednost je tudi v lažji mehanski obdelavi in v veliko lažjem doseganju dimenzijskih toleranc.

Program preiskav je bil obširen in je potekal v več fazah:

— priprava parov orodno jeklo-konstrukcijsko jeklo iz različnih jekel, ki pridejo v poštev za program platiranih orodij, pri čemer smo veliko pozornost posvetili pripravi stičnih površin in varjenju paketov;

— ogrevanje vzorcev;

— valjanje vzrocev pri različnih termomehanskih pogojih (temperatura, parcialna in skupna redukcija);

— metalografske preiskave vzrocev s ciljem, da opredelimo mikrostrukturne značilnosti na stiku orodno jeklo-konstrukcijsko jeklo po žarjenju, po valjanju in po toplotni obdelavi. Opredelili smo porazdelitev legirnih elementov v prehodni coni med obema jekloma;

Osikro spec.:	0,8 % C, 0,4 % Si, 0,4 % Mn, 1 % Cr, 2 % W, 0,3 % V
BRM 2:	0,9 % C, 4 % Cr, 6,5 % W, 5 % Mo, 1,9 % V
OSV 1:	1,5 % C, 4,5 % Cr, 6,5 % W, 3,5 % Mo, 5 % V, 5 % Co
OCR 12 spec.:	2,1 % C, 0,3 % Si, 0,3 % Mn, 12 % Cr, 0,7 % W
OCR 12 extra:	1,65 % C, 0,3 % Si, 0,3 % Mn, 12 % Cr, 0,5 % W, 0,6 % Mo, 0,1 % V
OCR 12 VM:	1,55 % C, 0,3 % Si, 0,3 % Mn, 12 % Cr, 0,9 % Mo, 1 % V
Utop Mo 4:	0,5 % C, 1 % Si, 0,3 % Mn, 5 % Cr, 1,5 % Mo, 1 % V

* SŽ Metalurški inštitut Ljubljana
** SŽ Železarna Ravne

** Originalno publicirano: ZZB 22 (1988) 4
*** Rokopis prejet: avgust 1988

In Ravne Ironworks the process of plating tool steel on bearing structural steel by hot rolling is successfully applied. For some steel pairs the plating process is mastered and it is carried out with a suitable yield.

There was not sufficient data on heating and rolling conditions to prepare the technology of manufacturing various tool steel/bearing structural steel pairs. The investigation should enable a better knowledge of physico-metallurgical processes during the hot working of compound steel.

INTRODUCTION

Various cutting and other tools in industry are manufactured by hot plating. So made tool saves expensive tool steel which is used only for the working part of the tool which does not loose its original mechanical properties. Further advantage is easier machining and easier achieving dimensional tolerances.

Program of investigations was extensive and they were made in several steps:

— preparation of tool steel/structural steel pairs, applying steels suitable for plating tools. Great attention was given to the preparation of contact surfaces, and to welding the packs,

— heating of samples,

— rolling of samples at various thermomechanical conditions (temperature, partial and overall reduction),

— microstructural investigations of samples in order to determine microstructural characteristics on the contact tool steel — structural steel after annealing, after rolling, and after heat treatment. The distribution of alloying elements in the transition zone between the two steel was determined,

Osikro spec.:	*0,8 % C, 0,4 % Si, 0,4 % Mn, 1 % Cr, 2 % W, 0,3 % V*
BRM 2:	*0,9 % C, 4 % Cr, 6,5 % W, 5 % Mo, 1,9 % V*
OSV 1:	*1,5 % C, 4,5 % Cr, 6,5 % W, 3,5 % Mo, 5 % V, 5 % Co*
OCR 12 spec.:	*2,1 % C, 0,3 % Si, 0,3 % Mn, 12 % Cr, 0,7 % W*
OCR 12 extra:	*1,65 % C, 0,3 % Si, 0,3 % Mn, 12 % Cr, 0,5 % W, 0,6 % Mo, 0,1 % V*
OCR 12 VM:	*1,55 % C, 0,3 % Si, 0,3 % Mn, 12 % Cr, 0,9 % Mo, 1 % V*
Utop Mo 4:	*0,5 % C, 1 % Si, 0,3 % Mn, 5 % Cr, 1,5 % Mo, 1 % V*
OH 49:	*0,6 % C, 3,3 % Cr, 1,1 % Mo, 0,15 % V*
145 V 33:	*1,45 % C, 0,3 % Si, 0,4 % Mn, 3,2 % V*
Ck 15:	*0,12—0,18 % C, 0,15—0,35 % Si, 0,30—0,60 % Mn*
EC 80:	*0,14—0,19 % C, 0,15—0,40 Si, 1—1,3 % Mn, 0,8—1,1 % Cr*
EC 100:	*0,17—0,22 % C, 0,15—0,40 % Si, 1,1—1,4 % Mn, 1—1,3 % Cr*

OH 49:	0,6 % C, 3,3 % Cr, 1,1 % Mo, 0,15 % V
145 V 33:	1,45 % C, 0,3 % Si, 0,4 % Mn, 3,2 % V
Ck 15:	0,12—0,18 % C, 0,15—0,35 % Si, 0,30—0,60 % Mn
EC 80:	0,14—0,19 % C, 0,15—0,40 Si, 1—1,3 % Mn, 0,8—1,1 % Cr
EC 100:	0,17—0,22 % C, 0,15—0,40 % Si, 1,1—1,4 % Mn, 1—1,3 % Cr

— mehanske preiskave z opredelitvijo trdnosti vezi med orodnim in konstrukcijskim jeklom.

Navedene preiskave smo naredili na parih iz orodnih jekel, kvalitete Osikro spec. (Č.6445), BRM 2 (Č.7680), OSV 1 (Č.9880), OCR 12 spec. (Č.4650), OCR 12 extra (Č.4750), OCR 12 VM (Č.4850), Utop Mo 4 (Č.4757), OH 49 (Č.7440), 145 V 33 (Č.8140), in konstrukcijskih jekel Ck 15 (Č.1221), EC 80 (Č.4320) in EC 100 (Č.4321). Preiskave smo naredili tudi na nekaterih parih iz konstrukcijskih jekel in na vzrocih, platiranih iz štirih vrst različnih jekel. Približna kemična sestava navedenih jekel je naslednja:

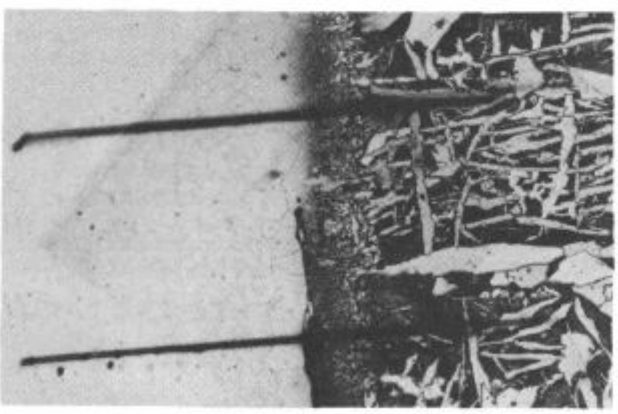
EKSPERIMENTALNO DELO

Žarjeni vzorci

Vzorce paketov, zvarjenih iz orodnega in konstrukcijskega jekla, na katerih smo naredili preiskave po žarjenju, smo ogrevali skupno z vzorci, ki smo jih valjali. Vzorce smo po predgrevanju žarili 1, 3 in 6 ur v temperaturnem intervalu od 900 do 1300 °C.

V mikrostrukturi stičnih površin orodnega in konstrukcijskega jekla se vidi, da so med ogrevanjem potekali difuzijski procesi. Koncentracijske profile legirnih elementov Cr, V, Mo, W, Si in Mn v prehodni coni smo naredili v elektronskem mikroanalizatorju. Analizo C smo naredili le na nekaterih vzorcih s kvantometrom, tako da smo na stični površini jekel postopno odbrusili tanke plasti. Meritve sicer niso tako točne kot meritve v elektronskem mikroanalizatorju, se pa dobro ujemajo s koncentracijskimi profili ostalih legirnih elementov in z mikrostrukturnimi značilnostmi prehodne plasti.

Stične površine jekel so bile različno obdelane, skoblane, brušene in polirane. V nobenem primeru pa obdelava površin in zavaritev paketa ni bila tako popolna, da bi stični površini popolnoma nalegali, pač pa se stikata le na določenih mestih. Preko teh stičnih mest pričnejo potekati difuzijski procesi **(sl. 1)**. Potek difuzije je odvisen



Slika 1
Mikrostruktura prehodne plasti na vzorcu BRM 2/Ck 15 žarjenjem 6 ur na 1200 °C (pov. 200 ×)

Fig. 1
Microstructure of the transition zone in sample BRM 2/Ck 15, annealed 6 hours at 1200 °C (magn. 200×)

— mechanical investigations in order to determine the strength of bond between tool and structural steel.

The mentioned investigations were made with the following tool steels: Osikro spec. (Č.6445), BRM 2 (Č.7680), OSV 1 (Č.9880), OCR 12 spec. (Č.4650), OCR 12 extra (Č.4750), OCR 12 VM (Č.4850), Utop Mo 4 (Č.4757), OH 49 (Č.7440), 145 V 33 (Č.8140), and the following structural steel: Ck 15 (Č.1221), EC 80 (Č.4320), and EC 100 (Č.4321). Investigations were made also with some pairs of structural steels, and with plated samples made of four various steels. Approximate chemical composition of mentioned steels is the following:

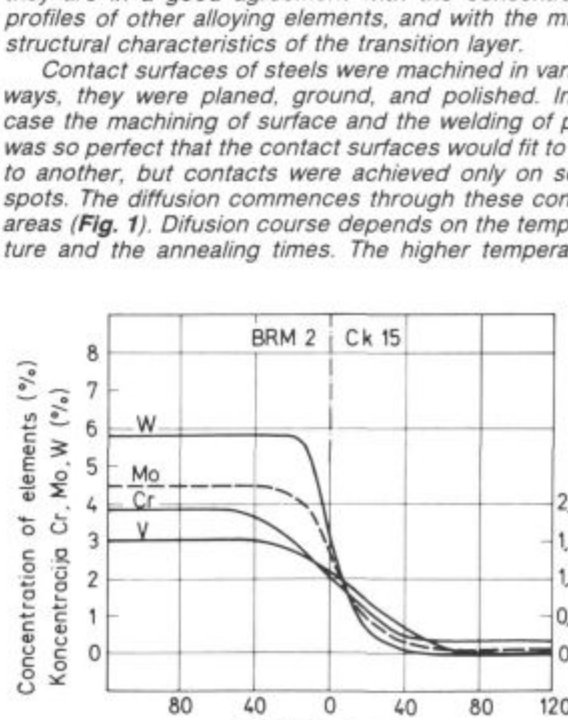
EXPERIMENTAL WORK

Annealed samples

Samples of packs where tool and structural steel were welded, and which were investigated after annealing, were heated together with the samples for rolling. After preheating the samples were annealed 1, 3, and 6 hours in the interval between 900 and 1300 °C.

The microstructure of contact surfaces between tool and structural steel revealed that diffusion occured during the heating. Concentration profiles of alloying elements (Cr, V, Mo, W, Si, and Mn) in the transition zone were made by electron microprobeanalyzer. Carbon was analyzed only in some samples by quantometer. The analysis was made so that gradually thin layers on contact surface were ground off. These measurements are not as accurate as those by electron mictroanalyzer but they are in a good agreement with the concentration profiles of other alloying elements, and with the microstructural characteristics of the transition layer.

*Contact surfaces of steels were machined in various ways, they were planed, ground, and polished. In no case the machining of surface and the welding of pack was so perfect that the contact surfaces would fit to one to another, but contacts were achieved only on some spots. The diffusion commences through these contact areas (**Fig. 1**). Difusion course depends on the temperature and the annealing times. The higher temperature*

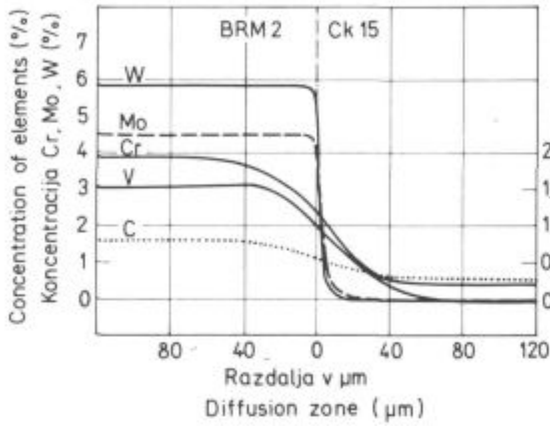


Slika 2
Koncentracijski profili legirnih elementov na vzorcu BRM 2/Ck 15 (1200 °C, 6 ur) na mestu kjer se jekli stikata (mikroposnetek na sl. 1)

Fig. 2
Concentration profiles of alloying elements in sample BRM 2/Ck 15 (1200 °C, 6 hours) on the contact between the two steels (microscopic picture in Fig. 1)

od temperature in časa žarjenja. Čim višja je temperatura in daljši so časi žarjenja, širša je cona, v kateri potekajo difuzijski procesi. Sicer pa poteka difuzija dovolj hitro, da lahko govorimo o difuzijskem spoju, pri temperaturah $T > 0,5 T_m$, pri čemer je T_m absolutna temperatura tališča kovine (1).

Iz diagramov na **sliki 2 in 3** se vidi, da poteka difuzija zelo hitro preko stičnih točk in na teh mestih je nastal



Slika 3
Koncentracijski profili legirnih elementov na vzorcu BRM 2/Ck 15 (1200 °C, 6 ur) na mestu kjer je med jekloma reža (mikroposnetek na sl. 1)

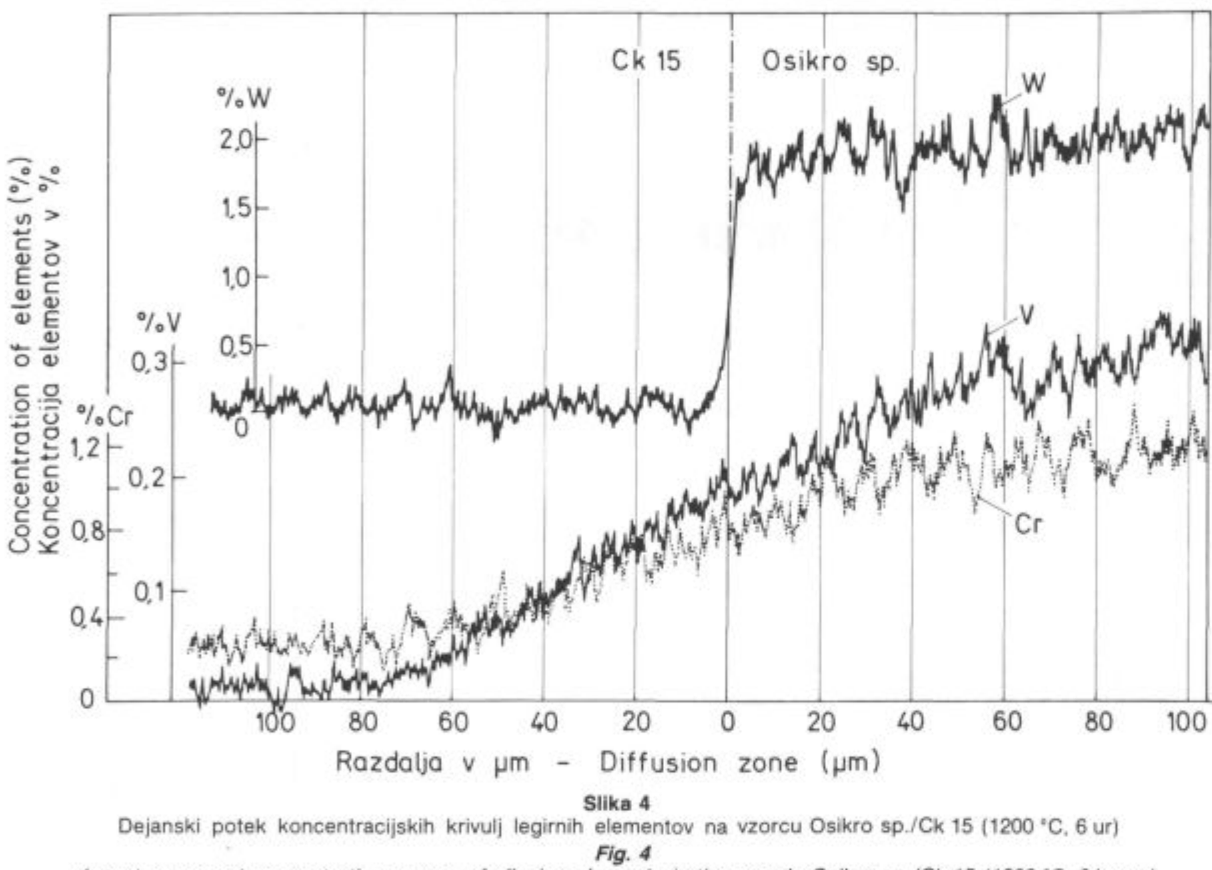
Fig. 2
Concentration profiles of alloying elements in sample BRM 2/Ck 15 (1200 °C, 6 hours) around the gap between the two steels (microscopic picture in Fig. 1)

and the longer annealing times the deeper is the zone into which the action of diffusion was felt. Anyhow, the diffusion is fast enough that we can speak about diffusion bond at temperatures $T > 0,5 T_m$, where T_m is the melting point of metal in absolute temperature (1).

*Plots in **Fig. 2 and 3** show that diffusion through contact points is very fast, and on these spots a solid bond was formed between the tool and the structural steel. Diffusion of Cr, V, Si, Mn, and C from tool into structural steel is very fast while the diffusion of Mo and W is rather slow. Also surface diffusion of Cr, V, Si, Mn, and C from contact proints is very fast. Thus the course of concentration curves for those elements is continuous also on the areas where a gap exists between the tool and the structural steel. Depth of diffusion is greater on the contact areas. Diffusion of Mo and W is slower to such an extent that the concentration curves are continuous on the contact areas and in the samples which were annealed for a longer time (3 and 6 hours) at temperatures 1200 °C or more. On the areas where a gap exists a stepwise concentration variation of the two elements was found.*

***Figs. 4 and 5** present the actual course of concentration curves for Osikro spec. and OCR 12 VM tool steels in combination with Ck 15 structural steel. The curves reveal the influence of inhomogeneities, and of carbide grains.*

Diffusion processes took place under isothermal conditions in austenite, but in cooling a new microstructure was formed, thus it is not possible to find how the diffusion acted on grain boundaries. Diffusion of carbon is the fastest since it is dissolved in iron interstitially. In the couples where Osikro spec. is the tool steel, the diffusion of carbon was the fastest. Though steel OCR 12



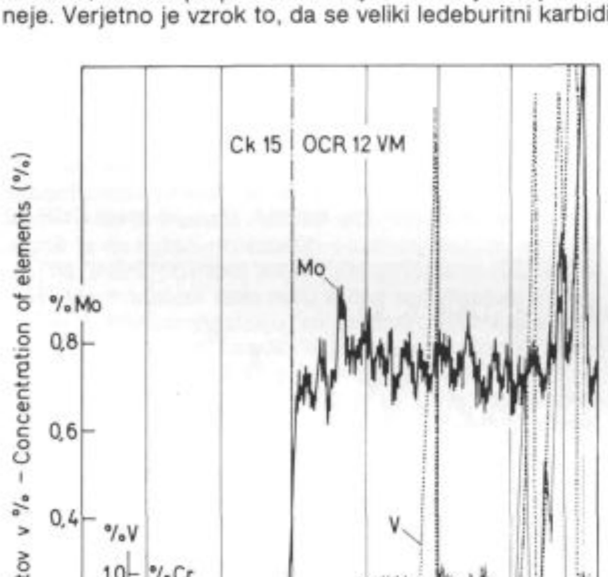
Slika 4
Dejanski potek koncentracijskih krivulj legirnih elementov na vzorcu Osikro sp./Ck 15 (1200 °C, 6 ur)

Fig. 4
Actual course of concentration curves of alloying elements in the sample Osikro sp./Ck 15 (1200 °C, 6 hours)

med orodnim in konstrukcijskim jeklom trden spoj. Difuzija Cr, V, Si, Mn in C poteka iz orodnega v konstrukcijsko jeklo zelo hitro, difuzija Mo in W pa je precej počasnejša. Tudi površinska difuzija Cr, V, Si, Mn in C s stičnih točk poteka zelo hitro. Potek koncentracijskih krivulj je zato za te elemente zvezen tudi na mestih, kjer je med orodnim in konstrukcijskim jeklom sicer reža. Globina, do katere je potekala difuzija, pa je večja na stičnih mestih. Difuzija Mo in W je toliko počasnejša, da so koncentracijske krivulje zvezne na stičnih mestih in na vzorcih, žarjenih dalj časa (3 in 6 ur) pri temperaturah 1200 °C ali več. Na mestih, kjer je med jeklom reža, je koncetracijski prehod za ta dva elementa sicer skokovit.

Na **slikah 4 in 5** je prikazan dejanski potek koncentracijskih krivulj za orodni jekli Osikro spec. in OCR 12 VM v paru s konstrukcijskim jeklom Ck 15. Na krivuljah se vidi vpliv nehomogenosti in karbidnih zrn.

Difuzijski procesi so potekali pri izotermnih pogojih v avstenitu in pri ohlajanju je nastala nova mikrostruktura, zato ne moremo opredeliti, kako je potekala difuzija po kristalnih mejah. Difuzija ogljika je najhitrejša, ker je ta v železu raztopljen intersticijsko. Pri parih, pri katerih je kot orodno jeklo Osikro spec., je difuzija ogljika najhitrejša. Jekla, vrste OCR 12, imajo sicer višjo vsebnost C, vendar pa poteka difuzija C v teh jeklih počasneje. Verjetno je vzrok to, da se veliki ledeburitni karbidi



Slika 5

Dejanski potek koncentracijskih krivulj legirnih elementov na vzorcu OCR 12 VM/Ck 15 (1200 °C, 6 ur)

Fig. 5

Actual course of concentration curves of alloying elements in the sample OCR 12 VM/Ck 15 (1200 °C, 6 hours)

has higher carbon content, the diffusion of carbon in this steel was slower. The explanation could be, that big ledeburite carbides dissolve less easily in annealing, but the other possibility is that higher concentration of Cr retards the diffusion of carbon. Diffusion of carbon is the slowest in pairs Utop Mo 4—Ck 15 (EC 80) where the difference in C content between the tool and the structural steel is the smallest. The other elements form a substitutional solution with iron, and the diffusion processes takes place through vacancies, by rotational mechanism, or by exchange of two atoms (5). Diffusion of Si, and Mn due to small concentration differencies between the tool and the structural steel is not essential for formation of transition zone between the two steels. Formation of transition zone is the most influenced by C, Cr, and V. Diffusion of alloying elements on the contact surface is fast also because the surface is thermodynamically less stable due to numerous defects (vacancies, dislocations). A relatively low diffusion of Mo and W corresponds to the fact that the activation energy of diffusion is proportional to the melting point of metal.

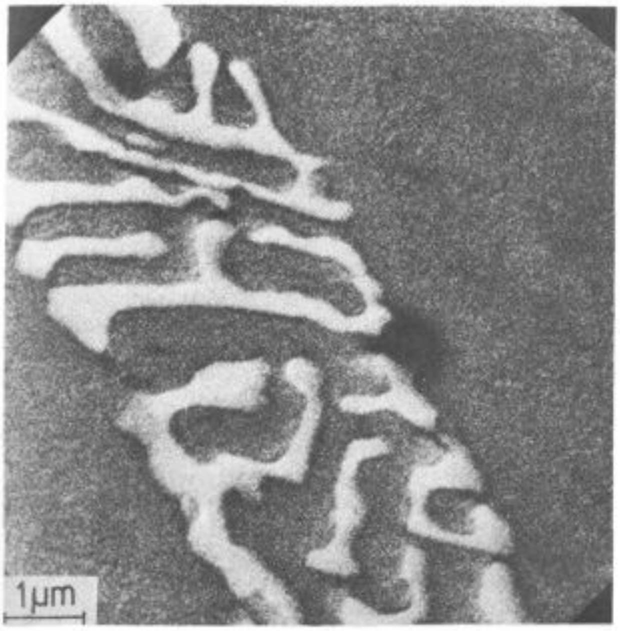
*The size of crystal grains in tool and structural steel depends on the conditions of annealing. Tool steel has martensitic micro structure, while structural steel has ferritic pearlitic bainitic microstructure. Due to concentration variations a transition layer is formed at the contact of tool and structural steel, and its microstructural characteristics depend on the steels used in couples and thus also on the concentration of alloying elements and the conditions of cooling. In pairs Osikro spec. — Ck 15 (EC 80) a fine lamellar pearlite was found in the transition zone, in some cases there was bainite. In other pairs we have found that the intermediate layer was composed of two phases and it well differs from that of structural steel. Transition into tool steel is not distinct. Microscopic pictures of the transition layer made by SEM (**Fig. 6**) reveal precipitated carbides in the matrix. As already mentioned, the transition layer is the*

Slika 6

Mikrostruktura prehodne plasti na vzorcu OCR 12 VM/Ck 15 (1200 °C, 6 ur)

Fig. 6

Microstructure of the transition layer in the sample OCR 12 VM/ Ck 15 (1200 °C, 6 hours)



Slika 7
Začetna faza nastajanja mikropor med eutektičnimi karbidi po kristalnih mejah na vzorcu BRM 2/Ck 15 (1200 °C, 3 ure)

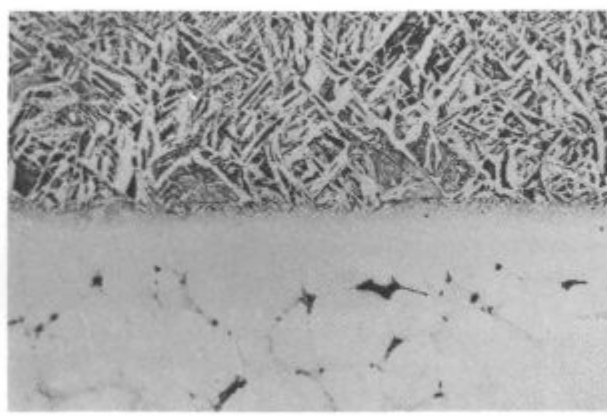
Fig. 7
Initial phase of formation of micropores between eutectic carbides on the crystal boundaries in the sample BRM 2/Ck 15 (1200 °C, 3 hours)

Slika 8
Mikroporozno mesto na kristalni meji po kateri so izločeni eutektični karbidi na vzorcu OCR 12 VM/Ck 15 (1200 °C, 6 ur)

Fig. 8
Microprorous area on the crystal boundary where eutectic carbides in the sample OCR 12 VM/ck 15 are formed (1200 °C, 6 hours)

pri žarjenju težje raztapljajo, možno pa je tudi, da visoka koncentracija Cr zavira difuzijo C. Difuzija C je najpočasnejša pri parih Utop Mo 4/Ck 15 (EC 80), kjer je razlika med vsebnostjo C v orodnem in konstrukcijskem jeklu najmanjša. Ostali elementi so raztopljeni v železu substitucijsko in difuzijski procesi potekajo preko praznin, po rotacijskem mehanizmu ali z menjavo dveh atomov (5). Difuzija Si in Mn zaradi majhnih koncetracijskih razlik med orodnim in konstrukcijskim jeklom za nastanek prehodne cone med jekloma ni pomembna. Na izoblikovanje prehodne plasti imajo tako največji vpliv C, Cr in V. Difuzija legirnih elementov je na stični površini hitra tudi zaradi tega, ker je površina zaradi številnih napak (praznine, dislokacije) termodinamično manj stabilna. Sorazmerno počasna difuzija Mo in W se ujema z dejstvom, da je aktivacijska energija, potrebna za difuzijo, sorazmerna temperaturi tališča kovine.

Velikost kristalnih zrn v orodnem in konstrukcijskem jeklu je odvisna od pogojev žarjenja. Orodna jekla imajo martenzitno mikrostrukturo, konstrukcijska pa feritnoperlitno-bainitno mikrostrukturo. Zaradi koncentracijskih sprememb nastane na stiku orodnega jekla s konstrukcijskim prehodna plast, katere mikrostrukturne značilnosti so odvisne od vrste jekel v paru in s tem od koncentracij legirnih elementov in pogojev ohlajanja. Pri parih Osikro spec./Ck 15 (EC 80) smo v prehodni coni opazili drobno lamelaren perlit, v nekaterih primerih pa tudi bainit. Pri ostalih parih pa smo opazili, da je vmesni sloj dvofazen in se dobro loči od konstrukcijskega jekla. Prehod v orodno jeklo je zabrisan. Na mikroposnetku prehodne plasti, narejene v SEM, se na **sliki 6** vidijo v matici izločeni karbidi. Kot smo že omenili, je prehodna plast širša, čim višja je temperatura in daljši je čas žarjenja; s tem je tudi večja gostota in velikost karbidnih delcev. Najbolj je izrazita ta plast pri parih, kjer je orodno jeklo iz vrste OCR 12.



Slika 9
Mikroposnetek pozornosti po kristalnih mejah zaradi difuzije legirnih elementov na vzorcu BRM 2/Ck 15—1300 °C, 1 ura (pov. 100 ×)

Fig. 9
Microscopic picture of the porosity on crystal boundaries due to diffusion of alloying elements in the sample BRM 2/Ck 15—1300 °C, 1 hour (magn. 100×)

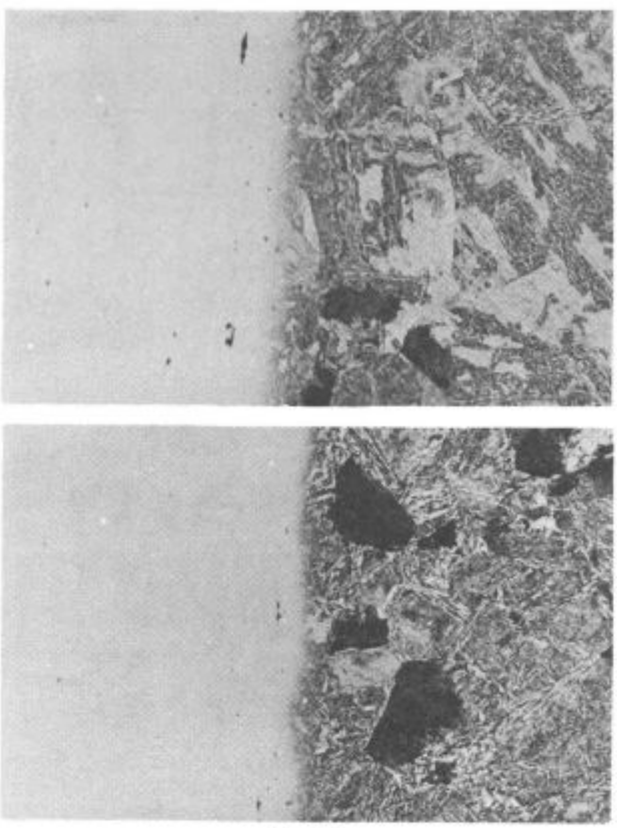
wider the higher is the temperature and the longer is the time of annealing, and thus also the density and the size of carbide inclusions is increased. The most pronounced is this layer in pairs where tool steel is of OCR 12 type.

At annealing temperatures 1200 °C or higher a very fast diffusion was found with OCR 12 and BRM 2 steels. The concentration of alloying elements on the grain boundaries is increased to such an extent that boundaries start to melt (4) which accelerates the diffusion of alloying elements into structural steel, and it becomes faster than the flow of new atoms. During the solidifica-

Pri temperaturah žarjenja 1200 °C in več smo pri jeklih, vrste OCR 12 in BRM 2, opazili zelo hitro difuzijo. Po kristalnih mejah pride do take koncentracije legirnih elementov, da se te natalijo (4), kar pospeši difuzijo legirnih elementov v konstrukcijsko jeklo v taki meri, da je ta hitrejša od dotoka novih atomov na njihova mesta. Med strjevanjem nataljenih mej, po katerih nastanejo evtektični karbidi, se zato pojavijo zaradi praznin mikroporozna mesta. Linija cone, v kateri nastanejo mikropore, se s časom žarjenja oddaljuje od mejne površine orodno jeklo/konstrukcijsko jeklo **(sl. 7, 8 in 9).**

Valjanje klinastih vzorcev

Orodna in konstrukcijska jekla imajo različne fizikalne lastnosti (modul elastičnosti, toplotna prevodnost, temperaturni razteznostni koeficient) in različno deformacijsko trdnost (meja tečenja, utrjanje). Tudi fazne premene, ki potekajo pri različnih temperaturah, so povezane z volumskimi spremembami. Zaradi tega nastanejo med jekloma pri ogrevanju, med valjanjem in pri ohlajanju precejšnje notranje napetosti. Zvar med ogrevanjem ne sme popustiti, sicer se zaradi oksidacije stičnih površin jekli med valjanjem ne zavarita. To lahko prepreči tudi prisotnost varilne žlindre. Zaradi različnih lastnosti jekel se med valjanjem ustvarijo med jekloma take napetosti, da se valjanci krivijo. Krivljenje se nadlajuje tudi med ohlajanjem. S padajočo temperaturo valjanja se razlike v lastnostih jekel večajo, zato je krivljenje intenzivnejše pri



Slika 10
Mikrostruktura valjanega vzorca OCR 12 VM/Ck 15, predhodno 30 min. žarjenega na 1160 °C, pri 15 (zgoraj) in 40 % (spodaj) redukciji (pov. 200 ×)

Fig. 10
Microstructure of rolled sample OCR 12 VM/Ck 15, initially annealed 30 mins at 1160 °C at 15 % (above) and 40 % (below) reduction (magn. 200×)

tion of partially melted boundaries where eutectic carbides are formed microporous areas are formed due to vacancies. Line of zone where micropores are formed moves away from the tool steel/structural steel boundary surface with the time of annealing ***(Figs. 7, 8, and 9)****.*

Rolling of Wedge Samples

Tool and structural steel have different physical properties (modulus of elasticity, thermal conductivity, expansion coefficient), and different deformation strength (yield strength, hardening). Also phase transformations occuring at various temperatures are connected with the volume changes. Thus rather high internal stresses appear between the two steel during heating, in rolling, and during cooling. The weld during heating must not break, since the contact surfaces do not weld again in rolling because the surfaces are oxidized. The same effect can have the presence of welding slag. Due to different properties of steel such stresses appear between the two steel in rolling that the rollings are buckled. Further buckling occurs in cooling. Reduced rolling temperature increases the differences in steel properties, and buckling is more intensive at lower rolling temperatures. By a certain shape of welded packs the buckling can be avoided to a considerable extent.

By wedge samples rolled in the interval of specific reduction between 0 and 40 % the influence of the degree of deformation on the formation of transition diffusion layer and on the strength of bond between the two steel could be more accurately determined.

Tool and structural steel in all cases sticked well together at the 15 % degree of reduction. At lower reductions various defects are influencial though the bond can also be good.

The transition zone is the narrower the higher is the degree of reduction. Temperature does not influence the adherence of steel if the degree of reduction is high enough, but it influences only the thickness of the layer in which the diffusion processes took place ***(Fig. 10)****.*

Measuring forces in rolling, the degree and the rate of deformation enables us to calculate the yield stresses. They are regardless to the temperature and the degree of reduction between 80 and 190 N/mm². *These values correspond to the yield strengths of tool steel which shows that structural steel has small influence on the workability of compound steel. But rolling of such steel has specific demands.*

Rolling with many passes

Test samples were rolled in six passes at most with 12, 20, and 25 % degree of partial deformation. Temperature of samples was measured at the beginning and at the end of rolling.

The same findings as given for the annealed samples are also valid for the diffusion of alloying elements. Alligatoring was observed only at the first pass, and the reasons for it could be exactly determined. If the two steels adhered in this step the alligatoring practically could not occur in further rolling. Thus we are of opinion that higher degree of reduction is needed in the first pass (at least 15 %) to prevent alligatoring. Recrystallization taking place in rolling and in the intervals between single passes contributes to the bond between the tool and the structural steel.

Comparison of the thicknesses of layers in which diffusion took place in annealed and in rolled samples revealed mainly by applying the concentration lines for Cr nižjih temperaturah valjanja. Z določeno obliko zavarjenih paketov se krivljenju lahko v precejšnji meri izognemo.

Na klinastih vzorcih, zvaljanih v področju specifične redukcije od 0 do 40 %, smo želeli natančneje ugotoviti vpliv stopnje deformacije na izoblikovanje prehodne difuzijske plasti in trdnost spoja med jekloma.

Orodno in konstrukcijsko jeklo sta se v vseh primerih pri 15 % stopnji redukcije že dobro sprijeli. Pri manjših stopnjah redukcij pridejo do izraza različne napake, čeprav je lahko spoj že dober. Prehodna difuzijska plast je ožja, čim večja je stopnja redukcije. Temperatura pri zadostni stopnji redukcije ne vpliva na sprijetost jekel, pač pa le na debelino plasti, v kateri so potekali difuzijski procesi (**sl. 10**).

Iz meritev sile valjanja, stopnje deformacije in hitrosti deformacije smo izračunali preoblikovalno trdnost. Ta je glede na temperaturo in stopnjo redukcije od 80 do 190 N/mm^2. Te vrednosti ustrezajo poreoblikovalnim trdnostim orodnih jekel, kar kaže, da konstrukcijsko jeklo le malo vpliva na preoblikovalnost compound jekel. Vendar pa veljajo za valjanje teh jekel določene specifičnosti.

Valjanje z več redukcijami

Preizkusne vzorce smo zvaljali v največ šestih redukcijah z 12, 20 in 25 % stopnjami parcialnih deformacij. Na vzorcih smo merili temperaturo na začetku in na koncu valjanja.

Za difuzijo legirnih elementov veljajo iste ugotovitve, kot smo jih podali za žarjene vzorce. Odpiranje vzorcev smo opazili le pri prvi redukciji, vzroke za to pa smo lahko točno opredelili. Če sta se jekli v tej fazi sprijeli, med nadaljnjim valjanjem praktično ne more priti do razslojevanja. Zato menimo, da je ustreznejša višja stopnja prve redukcije (vsaj 15 %), da se tako izognemo razslojevanju. Rekristalizacija, ki poteka med valjanjem in v času med redukcijami, pospešuje vezavo med orodnim in konstrukcijskim jeklom.

Iz primerjave debelin plasti, v kateri so potekali difuzijski procesi v žarjenih in valjanih vzorcih, smo predvsem na osnovi koncentracijskih krivulj za Cr in V ugotovili, da se je prehodna plast med valjanjem zožila za specifično stopnjo deformacije. Kristalna zrna so zaradi rekristalizacije drobnejša, opazi pa se, da so zrna v konstrukcijskem jeklu v coni, kjer so potekali difuzijski procesi, večja kot sicer po preseku. Sicer pa je velikost zrn odvisna tudi od končne temperature valjanja.

Po literaturnih podatkih (1, 2) se difuzija med deformacijo močno poveča. Smer difuzije je paralelna s silo valjanja. Pri naših meritvah smo sicer skušali ločiti difuzijo, ki je potekala med ogrevanjem, od difuzije med valjanjem, vendar nam to ni uspelo. Verjetno je temu vzrok v premalo natančni pripravi vzorcev (popolno naleganje površin) in tudi v možnostih naše raziskovalne opreme. Upoštevati pa moramo tudi to, da so časi delovanja deformacijskih napetosti v primerjavi s časi žarjenja izredno kratki. Sicer pa tudi v literaturi nismo zasledili nobenih konkretnih podatkov.

Toplotno obdelani vzorci

Analize koncentracij Si, Mn, Cr, V, Mo in W, narejene v prehodni coni toplotno obdelanih valjanih vzorcev (mehko žarjenje, normalizacija, kaljenje, poboljšanje), niso pokazale, da bi ta bistveno vplivala na difuzijo teh elementov. Mikrostrukturne preiskave pa so pokazale, da normalizacija in deloma mehko žarjenje oz. počasno ohlajanje vplivata na difuzijo ogljika. To smo opazili tudi pri nekaterih valjanih vzorcih, ki so bili počasi ohlajeni.

and V that the transition layer was thinnened during the rolling for the specific degree of deformation. Crystal grains are finer due to recrystallization, but it was observed that the grains in the diffusion zone of structural steel were grater than those outside it. Further, the grain size depends also on the final temperature of rolling.

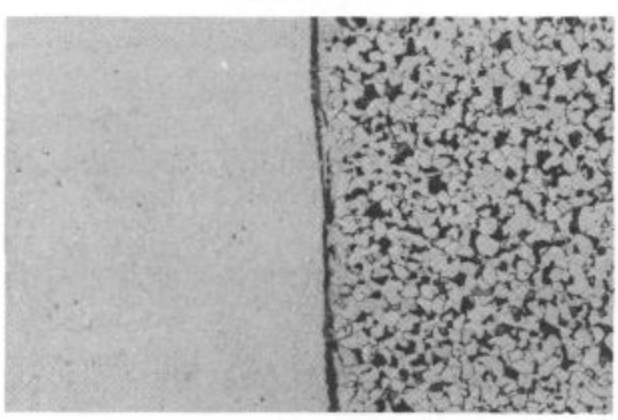
According to references (1, 2) diffusion is highly increased during the deformation. Direction of diffusion is paralel to the rolling force. Our trial to determine the difference between the diffusion during annealing and during rolling was not successful. The reason maybe in a not enough accurate preparation of samples (perfect fit of surfaces) or in the capacity of our research equipment. But it must be taken in account that the duration of deformation stressses is much shorter in comparison with the annealing times. Anyhow, also in references no concrete data could be found.

Heat treated samples

*Analyses of concentrations of Si, Mn, Cr, V, Mo, and W in the transition zone of heat treated rolled samples (soft annealing, normalizing, quench hardening, hardening and tempering) did not show any special influence of heat treatment on the diffusion of those elements. But microstructural investigations showed that normalising and partially soft annealing, or slow cooling have influence on the diffusion of carbon. This was observed also in some rolled samples which were slowly cooled. During heating, or annealing and rolling carbon diffuses into structural steel. Under certain conditions, especially in slow cooling between A_{r3} and A_{r1}, the activity of carbon is changed and the direction of diffusion is reversed. The activity of carbon is influenced also by other alloying elements. In structural steel a layer of pearlite is formed on the boundary with the tool steel, followed by a layer of ferrite. Such microstructure is shown in **Fig. 11.** In hardened and tempered samples such rearrangement of carbon does not occur (**Fig. 12**).*

Strength of bond

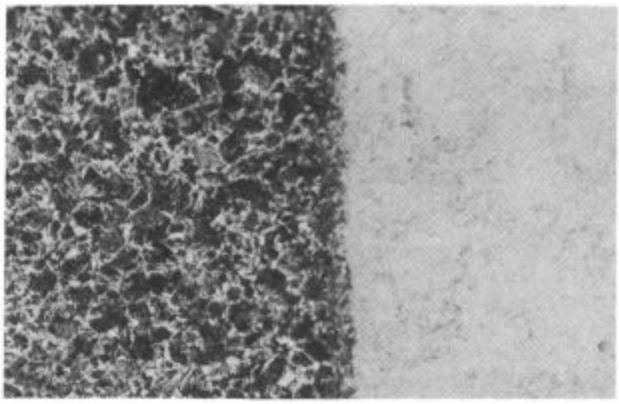
Mechanical properties, especially tensile strength of plated steel is given by the strength of structural steel, but to a great extent it depends also on the preparation of packs, and on the microstructural characteristics of the transition zone.



Slika 11
Mikrostruktura prehodne plasti vzorca OCR 12 VM/Ck 15 (1000 °C, 6 ur, 3 × 20 % redukcija) po normalizaciji (pov. 100 ×)

Fig. 11
Microstructure of the transition layer of the sample OCR 12 VM/Ck 15 (1000 °C, 6 hours, 3× 20 % reduction) after normalising (magn. 100×)

Med ogrevanjem, oz. žarjenjem in valjanjem difundira C v konstrukcijsko jeklo. V določenih pogojih, predvsem pri počasnem ohlajanju med A_{r3} in A_{r1}, se aktivnost C spremeni in difuzija poteka v obratni smeri. Aktivnost C je odvisna tudi od ostalih legirnih elementov. V konstrukcijskem jeklu nastane na meji z orodnim jeklom plast perlita, ki ji sledi plast ferita. Taka mikrostruktura je prikazana na **sliki 11**. Na poboljšanih vzorcih ne pride do take prerazporeditve C (**sl. 12**).



Slika 12

Mikrostruktura prehodne plasti poboljšanega vzorca Osikro sp./Ck 15—1200 °C, 1 ura, 4 × 20 % redukcija, 880 °C olje, popuščanje 200 °C, 60 HRc, raztržna trdnost spoja 640 N/mm² (pov. 200 ×)

Fig. 12

Microstructure of the transition zone of hardened and tempered sample Osikro sp./Ck 15—1200 °C, 1 hour, 4× 20 % reduction, 880 °C oil, tempering 200 °C, 60 HRc, tensile strength of bond 640 N/mm² (magn. 200×)

Trdnost spoja

Mehanske lastnosti, predvsem raztržna trdnost platiranih jekel je podana s trdnostjo konstrukcijskega jekla, precej pa je odvisna tudi od priprave paketov in mikrostrukturnih značilnosti prehodne plasti.

Oksidacijski film, ki lahko nastane med ogrevanjem za valjanje, je krhek in se med plastično predelavo trga in drobi, vendar kljub temu bistveno zmanjša trdnost spoja. Če je ta film debelejši, pa prepreči spojitev konstrukcijskega jekla z orodnim jeklom. Enak učinek ima tudi varilna žlindra, če med varjenjem paketov zalije režo med jekloma.

Na raztržno trdnost platiranih jekel vplivajo tudi pogoji ogrevanja (temperatura, čas) in valjanja (začetna in končna temperatura valjanja, redukcija). Mikropore v orodnem jeklu, intermetalne faze in karbidi, ki nastanejo v prehodni plasti pri neustreznih pogojih ogrevanja in valjanja, zmanjšajo trdnost spoja. Mikrostrukturne nehomogenosti so v prehodni plasti največje pri platiranih jeklih, kjer je v paru s konstrukcijskim jeklom ledeburitno orodno jeklo, vrste OCR 12. Že zelo tanek oksidni film, bogat s Cr, močno ovira spojitev jekel. Zato je pri platiranju teh jekel, bolj kot pri ostalih, pomembno, da poteka ogrevanje in valjanje pri optimalnih pogojih.

Dodatnim napetostim, nastalim med platiranjem in toplotno obdelavo, zaradi različnih fizikalno-metalurških lastnosti jekel, se ne moremo izogniti.

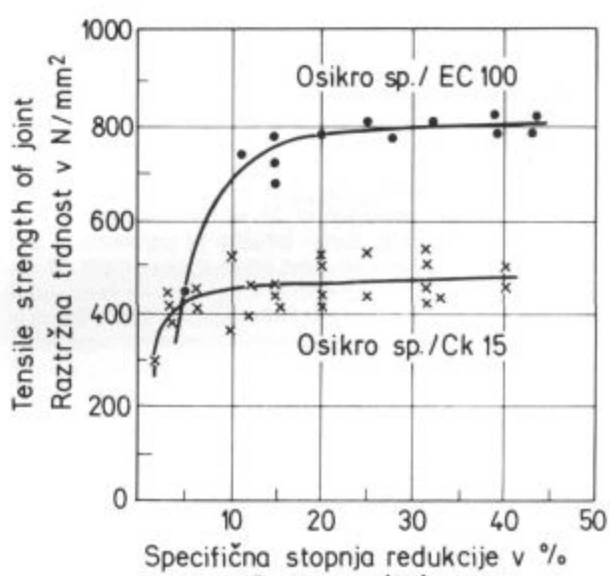
Na diagramih na **slikah 13 in 14** je prikazana odvisnost raztržne trdnosti, od specifične stopnje redukcije v poboljšanem stanju za vzorce, platirane iz orodnih jekel Osikro spec. in OCR 12 VM s konstrukcijskimi jekli Ck 15, EC 80 in EC 100. Raztržna trdnost je le malo odvi-

Oxidi film which can be formed in heating before rolling is brittle and it is broken during plastic working, but nevertheless it essentially reduces the strength of the bond. If this film is thicker, it can even prevent the adherence of tool and structural steel. The same effect has welding slag if it in welding the packs fills the gap between the two steels.

The tensile strength of plated steel is influenced also by the conditions of heating (temperature, time) and of rolling (initial and final temperature of rolling, reduction). Micropores in tool steel, intermetallic phases and carbides which are formed in the transition zone under unsuitable conditions of heating and rolling reduce the strength of bond too. Microstructural inhomogeneities in the transition zone are the highest in plated steel if a ledeburitic tool steel of OCR 12 type is in combination with a structural steel. Already a very thin oxide film rich with Cr hinders the adherence of steel to a great extent. Therefore it is especially in plating these steels important that heating and rolling is done under the optimal conditions.

Additional stresses which appear in plating and in heat treatment cannot be avoided due to different physico-metallurgical properties of steels.

*Plots in **Figs. 13 and 14** show the relation between the tensile strength and the specific degree of reduction in as hardened and tempered samples where tool steels Osikro spec. and OCR 12 VM were combined with Ck 15, EC 80, and EC 100 structural steels. Tensile strength varies with the reduction only to a small extent if it is higher than 15 %. Bond between the two steels is better and tensile strength is higher if samples were rolled in more passes. Due to recrystallization the microstructural inhomogeneities in the transition zone are smaller. Fracture of tensile test pieces occurs on the boundary of the two steels chiefly in the areas of any kind of structural inhomogeneities, and in structural steel, but only partially in tool steel.*

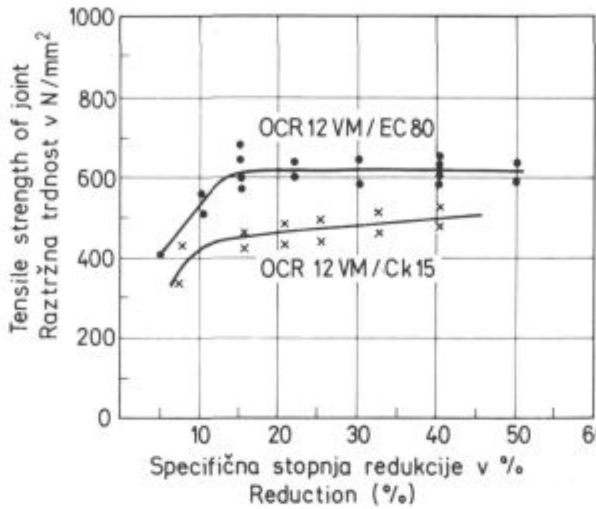


Slika 13

Raztržna trdnost spoja platiranih jekel Osikro sp./Ck 15 in Osikro sp./EC 100 v odvisnosti od stopnje redukcije

Fig. 13

Tensile strength of bond of plated Osikro sp./Ck 15 and Osikro sp./EC 100 steel related to the degree of reduction



Slika 14
Raztržna trdnost spoja platiranih jekel OCR 12 VM/Ck 15 in OCR 12 VM/EC 80 v odvisnosti od stopnje redukcije

Fig. 14
Tensile strength of bond of plated OCR 12 VM/Ck 15 and OCR 12 VM/EC 80 steels related to the degree of reduction

sna od redukcije, ko je ta večja od 15 %. Spoj med jekloma pa je boljši in je raztržna trdnost višja pri vzorcih, valjanih v več redukcijah. Zaradi procesov rekristalizacije so mikrostrukturne nehomogenosti v prehodni plasti manjše. Prelom nateznih preizkušancev poteka po meji med jekloma, predvsem tam, kjer so kakršnekoli mikrostrukturne nehomogenosti, in po konstrukcijskem jeklu, deloma pa lahko tudi po orodnem jeklu.

ZAKLJUČEK

Pri platiranju orodnih jekel na konstrukcijska jekla z vročim valjanjem nastane trden spoj med jekloma zaradi difuzijskih procesov. Difuzija legirnih elementov poteka med ogrevanjem za valjanje in med valjanjem. Difuzija začne potekati preko stičnih mest in se hitro nadaljuje kot površinska difuzija in nato kot volumska difuzija. Difuzija C, Cr in V je hitra in ti elementi imajo največji vpliv na izoblikovanje prehodne cone. Difuzija Mo in W je zelo počasna. Si in Mn sicer hitro difundirata, vendar zaradi majhnih koncentracijskih razlik med orodnim in konstrukcijskim jeklom ne vplivata bistveno na mikrostrukturo prehodne plasti.

Orodna in konstrukcijska jekla imajo različne fizikalno-metalurške lastnosti in pri platiranju nastanejo med njimi precejšnje napetosti. Z ustrezno pripravo paketov za valjanje moramo zagotoviti, da sta stični površini čisti in da preprečimo oksidacijo stičnih površin med ogrevanjem za valjanje.

Širina in mikrostrukturne značilnosti prehodne difuzijske plasti so odvisne od temperature in časa ogrevanja ter od termomehanskih parametrov vročega valjanja. Jekli se na stičnih mestih spojita že med ogrevanjem, trden spoj pa dobimo, če je redukcija med valjanjem večja od 15 %. Stopnja redukcije vpliva le v manjši meri na trdnost spoja, pač pa imajo višjo raztržno trdnost jekla, platirana v več redukcijah, kjer je prehodna plast zaradi procesov rekristalizacije homogenejša. Tudi s toplotno obdelavo (poboljšanje) se trdnost vezi izboljša. Pri mehkem žarjenju, normalizaciji, in predvsem pri počasnem ohlajanju v področju med A_{r3} in A_{r1} poteka difuzija ogljika v obratni smeri, to je iz konstrukcijskega jekla na mejo z orodnim jeklom. Difuzija ostalih legirnih elementov med

Conclusions

In plating tool steel on structural steel by hot rolling a firm bond is formed between the two steels due to diffusion processes. Diffusion of alloying elements occurs during heating before rolling and during rolling. Diffusion commences on contact spots and it is rapidly continued as a surface diffusion and later as a volume diffusion. Diffusion of C, Cr, and V is fast and these elements have the highest influence on the formation of the transition zone. Diffusion of Mo and W is very slow. Si and Mn diffuse namely fast but due to small concentration differencies between the tool and the structural steel they do not have any essential influence on the microstructure of the transition zone.

Tool and structural steel have different physico-metallurgical properties and in plating considerable stresses appear between them. By a suitable preparation of rolling packs it is necessary to ensure that contact surfaces are pure and that oxidation of these surfaces is prevented during heating before rolling.

Width and microstructural characteristics of the transition diffusion layer depend on the temperature and the time of annealing and on thermomechanical parameters of hot rolling. The steels adhere on contact points already in annealing, strong bond is obtained if the reduction in rolling is more than 15 %. Degree of reduction has a minor influence on the strength of bond, but higher tensile strength was obtained with plated steels being rolled in more passes since recrystallization enables the formation of more homogeneous transition layer. Also heat treatment (hardening and tempering) improves the strength of bond. In soft annealing, normalising, and chiefly in slow cooling in the interval between A_{r3} and A_{r1} the diffusion of carbon has reverse direction, i. e. from structural steel to the boundary with tool steel. Diffusion of the other alloying elements during heat treatment has no perceptible influence on the transition zone.

Under unsuitable conditions of anealing and rolling the transition diffusion zone is wide and unhomogeneous. Micropores, carbides, and intermetallic phases reduce the strength of bond. Oxide film is broken during working, but it nevertheless reduces the strength of bond. Microstructural inhomogeneities are the highest toplotno obdelavo nima zaznavnega vpliva na prehodno plast.

Pri neustreznih pogojih ogrevanja in valjanja je prehodna difuzijska plast široka in nehomogena. Mikropore, karbidi in intermetalne faze zmanjšajo trdnost spoja. Oksidni film se med preoblikovanjem sicer drobi, vendar zmanjša trdnost vezi. Mikrostrukturne nehomogenosti so največje pri platiranih jeklih, kjer je v paru s konstrukcijskim jeklom ledeburitno orodno jeklo, vrste OCR 12. Že zelo tanek oksidni film, bogat s Cr, močno ovira spojitev jekel. Sicer pa je raztržna trdnost spoja med orodnim in konstrukcijskim jeklom poleg od omenjenih lastnosti odvisna predvsem od trdnosti šibkejšega gradnika.

in plated steel where a ledeburitic tool steel of OCR 12 type is in combination with a structural steel. Already a very thin oxide film rich with Cr hinders the adherence of steels to a great extent. Further, the ultimate tensile strenght of bond between the tool and the structural steel depends mainly on the strength of weaker material beside the previously mentioned properties.

LITERATURA/*REFERENCES*

1. N. F. Kazakov: Diffusion Bonding of Materials, Mir Publishers, Moscov, 1985.
2. H. Dyja, M. Pietrzyk: On the Theory of the Process of Hot Rolling of Bimetal Plate and Sheet, Journal of Mechanical Working Technology, 8, 1983, 309—325.
3. F. Vizjak: Platiranje jekel, Železarski zbornik, št. 1, 1976, 13-23.
4. F. Grešovnik: Karakteristične temperature za jekla in jeklene litine, naloga ŽR-8102.
5. A. Knauschner, Plattierte Werkstoffe, VEB Deutscher Verlag für Grundstoffindustrie, Leipzig 1973.
6. D. Kmetič in sodelavci: Raziskave procesa valjanja compound jekel, naloga MI 84-037, Ljubljana 1985, naloga 85-025, Ljubljana 1986.
7. D. Kmetič in sodelavci: Termomehanski parametri in mikrostrukturna dogajanja pri platiranju visoko legiranih jekel na konstrukcijska jekla, naloga MI 86-038, Ljubljana 1987.