Study of Cladding of Steels by Laboratory Hot Rolling

Študij platiranja jekel z laboratorijskim toplim valjanjem

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Abstract: Cladding of commercial steels (tool steel OCR12VM - AISI D2 - DIN X155CrVMo12-1 and construction steel EC100 - DIN 20MnCr5) was studied by laboratory hot rolling experiments under the same thermo-mechanical conditions at which commercial rolling of compound strips is performed, i. e. at a temperature of 1150 °C with a high degree of deformation (0 - 0.5 for OCR12VM tool steel and 0 - 0.7 for EC100 constructional steel) and a slow cooling rate. Microstructure, hardness, tensile strength and diffusion of carbon were evaluated. The relations between the thermo-mechanical conditions during hot rolling and the mechanical properties of the compound strip are discussed in terms of the properties of the interfacial layer.

Povzetek: Platiranje orodnega jekla OCR12VM - AISI D2 - DIN X155CrVMo12-1 in konstrukcijskega jekla EC100 - DIN 20MnCr5) je bilo študirano z laboratorijski toplim valjanjem pri podobnih termomehanskih pogojih kot to poteka v industrijski praksi. Ovrednoten je bil mikrotdotni profil, natezna trdnost dobljenega spoja (vmesna plast), ter difuzija ogljika. Posebna pozornost je bila namenjena povezavi med trdnostnimi lastnostmi dobljenega spoja in pogoji valjanja.

Key words: Compounding, OCR12VM, EC 100, Hot rolling
Ključne beside: Platiranje, OCR12VM, EC 100, toplo valjanje OCR12VM, EC 100

Introduction

Various phenomena arise during the hot plastic deformation of compound steel which are interesting from both a fundamental and a commercial point of view. From the fundamental point of view the influence of plastic state and diffusion on the formation of the cladding zone are important, whereas the commercial point of view is concerned more with the preparation of the contact surfaces, the welding of the compound pack and the behaviour of the interfacial layer during the cooling process to room temperature. For the purpose of commercial rolling of strips it is important that laboratory rolling also takes place continuously in the plain strain state and with similar thermo-mechanical parameters. The cladding is considered to be successful if a good quality joint is already ensured at the first pass - thus avoiding oxidation of the contact surfaces at the following deformations - and if the joint strength at room temperature equals at least that of the basic metal [1-7].

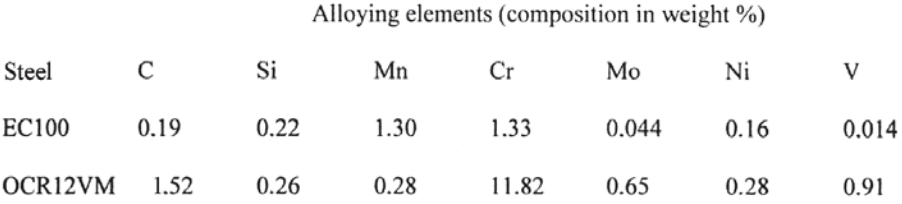
Scientific paper

Experiments

Both steels OCR12VM tool steel and EC100 constructional steel (compositions given in Table 1) were received as hot rolled plates with a thickness of 25 mm. Wedges were made out of these plates. Their basic surfaces were ground to the desired degree of roughness. The wedges of both steels were welded together (at the outside) just before heating (Figure 1). The conditions of heating, rolling, and cooling are shown in Figure 2. The microstructures of the as received steels are shown in Figures 3 a-b.

The plain strain state was achieved with an appropriate starting geometry. As the elongation of both steels is different, the local values of the average strain and strain rate were determined separately for each layer of

Table 1: The composition of the two steels used in this investigation (see text)



Alloying elements (composition in weight %)

Steel	C	Si	Mn	Cr	Mo	Ni	V
EC100	0.19	0.22	1.30	1.33	0.044	0.16	0.014
OCR12VM	1.52	0.26	0.28	11.82	0.65	0.28	0.91

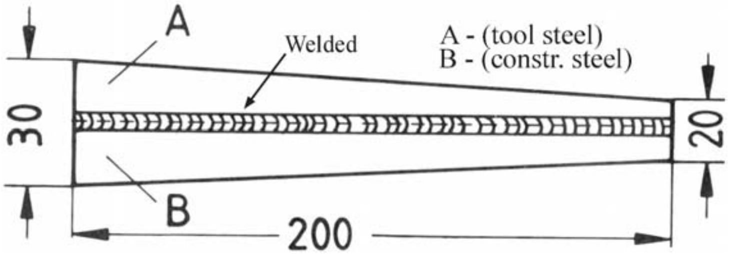


Figure 1: Geometry of the welded sample for the laboratory hot rolling experiment

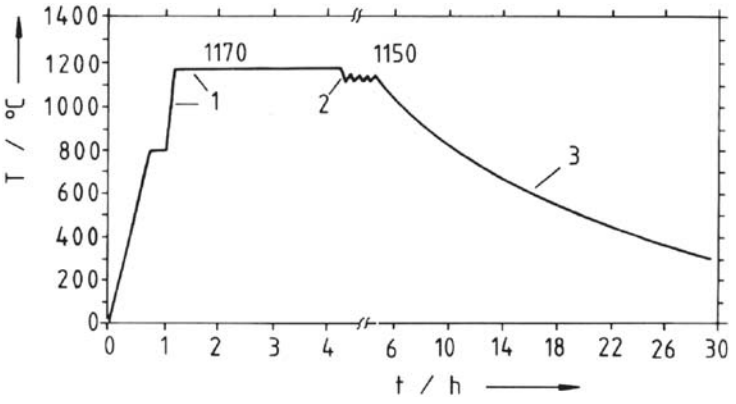


Figure 2: Temperature programme for cladding experiment: 1- heating, 2- rolling, 3- cooling

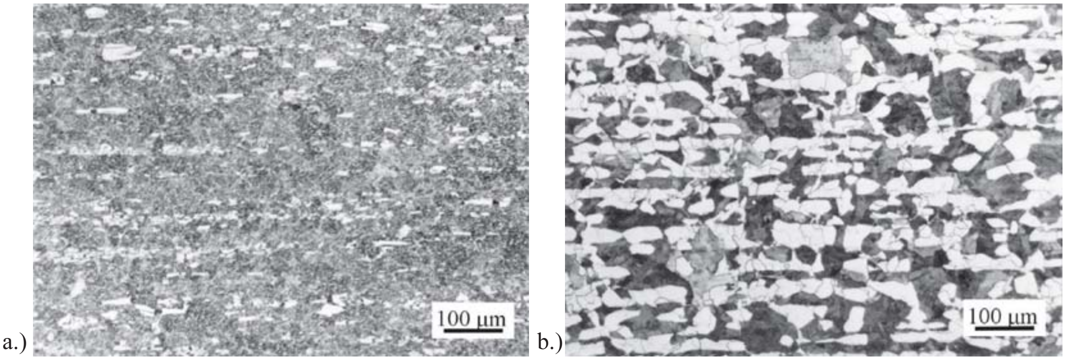


Figure 3: Initial microstructure: a.) OCR12VM, microhardness 250 HV_3, b.) EC 100, microhardness 160 HV_3

the deformed wedge. The rolled compound plates were controled cooled in the furnace. The clad layers of the wedge, dependant on the degree of reduction, were metallographically analysed with an optical microscope. The diffusion of the alloying elements was analysed using an electronic microanalyser and Auger electron spectroscopy (for carbon only). The clad strength of the compound plate was determined in a microtensile test, as shown in Figure 4.

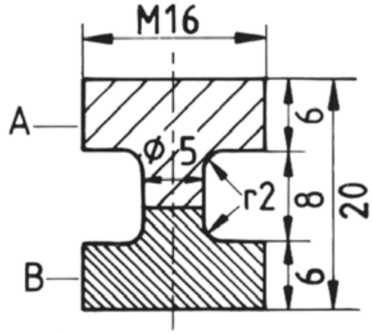


Figure 4: Geometry of the welded sample for the microtensile experiment

Results

Microstructure

The final microstructure is the result of all the three processes through which the compound passes during its production (see Figure 5).

Heating

During the heating phase diffusion of C, Cr, Mn, V and Mo occurs only in places where both steels are in direct contact and not via the gas phase. An adhesive clad of weak strength already appears in this phase. Weakness of the joint is due to the presence of surface contamination; incomplete metal contact because of the roughness of both surfaces, and growth of grains as a result of secondary recrystallisation.

Rolling

During the hot rolling process, direct contact between the surfaces is only possible in places which are free of oxides. Where the atoms of both surfaces reach an inter-atomic distance so that a metal bond appears among them, the so-called “anchor places” are formed. These are areas where the joining of both metals starts. As the deformation continues, the anchor places spread into cohesive bridges and the free surfaces on both sides gradually decrease. The process is completed when a common intermediate layer has been formed. The unjoined places are filled by atomic diffusion. The cohesive bridges between the grains have similar energy and mobility as the usual grain boundary. Voids, dislocations and other microstructural faults in anchor places and in cohesive bridges enable an intensive diffusion parallel to the surface which is more rapid than volume diffusion.

Cooling

The rolled compound samples were cooled (average cooling rate cca 42 °C/h) in a furnace to reduce thermal stresses. Diffusion also continues during the cooling process. Finally, the following microstructure is obtained at room temperature. Microstructure of EC100 steel consists from grains of lamellar perlit and grains of ferrite. Towards the OCR12VM/EC100 interface the amount of lamellar perlit increases (Figure 5, zone I). Very close to the mentioned OCR12VM/EC100 interface (still in EC100 constructional steel) the ferrite cone (Figure 5, zone III) of thickness of cca 80 - 100 μm with very finely precipitated carbides is visible. The microstructure of tool steel consists of spheroidal and dispersed perlit and carbides (Figure 5, zone II), further very close to OCR12VM/EC100 interface the tool steel microstructure (Figure 5, zone IV) is carburized and increased amount of carbides is visible. The thickness of the decarburized layer in the construction steel and the thickness of the carburized layer in the tool steel is independent of the degree of deformation. That is why both layers are considered to be formed during the cooling phase.

Microhardness

The microhardness of the cross section of the compound sample is in accordance with the structural changes in the intermediate layer Figure 6.

Concentration profile

The overall concentration profiles for Cr, Mo, V, Mn (Figure 7a), and C (Figure 7b) agree with the microstructure (Figure 5) and the microhardness (Figure 6), respectively.

Tensile strength

The tensile strength of the compound increases slightly during deformation from 620 N/mm^2 to 680 N/mm^2. Micro-tensile test samples broke down outside the contact surface namely in the ferrite layer, which was formed by the diffusion of carbon from construction steel to tool steel during the cooling process.

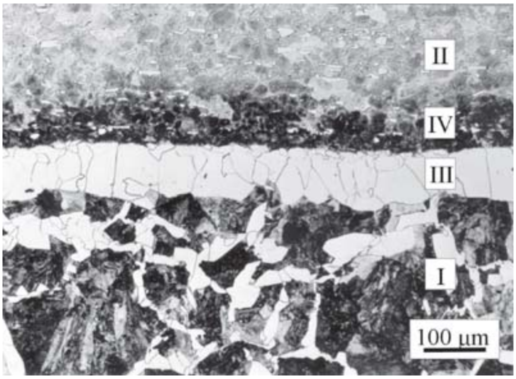


Figure 5: Microstructure of the interfacial layer of the compound OCR12VM/EC 100

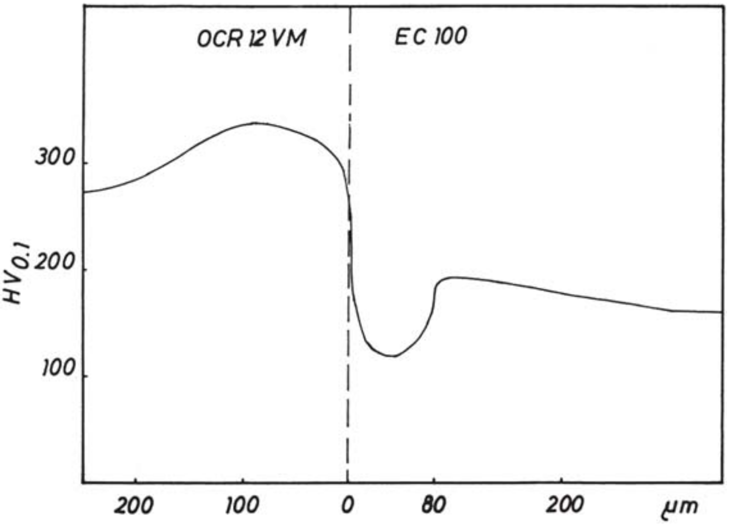


Figure 6: Microhardness profile in the contact zone

Diffusion of carbon

Microstructures in the intermediate layer are the result of the diffusion of carbon and alloying elements. Carbon diffuses at 1170 °C from tool steel to construction steel. During the cooling process the direction of the diffusion of carbon is changed at a certain temperature. Different degrees of carburisation of construction steel and different thicknesses of decarburized layers directly on the contact surface are obtained depending on the time of heating at 1170 °C and the cooling rate. In the literature [8] the expression “up hill” diffusion is found for this kind of diffusion. The activity of carbon changes because of alloying elements. The carbide-forming elements which reduce the activity of carbon in the range where the carbides precipitate, cause carbon to start diffusing in the opposite direction to the concentration gradient.

Decarburization of the construction steel and carburization of the tool steel probably occur in the temperature range between transformation points A_3 and A_1 of the construction steel (800 - 680 °C).

This possibility allows the following consideration: An eutectoid change (820 - 700 °C) occurs in tool steel in this temperature range. The average thickness of the diffusion layer of carbon (decarburized and carburized layer) is in our case 160 μm. The sample was in this temperature range for about two hours. From literature [8] values for the diffusiability of carbon it was estimated that diffusion occurred at 750 °C.

The boundaries of ferrite grains in the decarburized layer are perpendicular to the contact surface that is in the direction of diffusion. It is one of the pieces of evidence showing that decarburization occurs in the temperature range between transformation points A_{r3} and A_{r1} of the construction steel. The direction of the diffusion of carbon at a given temperature can be determined if the activity of carbon in both steels is known.

Diffusion of carbon at 1170 °C

The state before diffusion is shown in Figure 8a. Let us assume that a one-phase (gamma solid solution) binary (Fe - C) range is used for the construction steel EC100 and that a two-phase (gamma + one carbide phase) ternary (Fe - C - M) range is used for OCR12VM steel. This steel contains another carbide-forming element M. On the left of the figure a precisely determined concentration of carbon N_C corresponds to the activity of carbon a_C, on the right a concentration range appears which corresponds to the width of the two-phase range.

The activity of carbon can be approximately calculated in both steels. This activity is greater in OCR12VM than in EC100 steel.

According to the phase role there is another degree of freedom on the ternary side in addition to the temperature (p = const.). The activity of carbon can be changed.

The decrease in activity of the carbon causes the increase in activity of the element M. When the gamma and carbide phases are in a state of equilibrium, a change of activity in the gamma phase corresponds to an equal change of activity in the carbide phase. The mobility of the carbon in the carbide is much lower than in the gamma phase. This is the reason why carbon will only diffuse during the gamma phase. In EC100 steel there are, according to the phase rule, also two degrees of freedom, so the activity of carbon can be changed. The state after the completed diffusion is as follows - Figure 8b.

The diffusion of carbon in the cooling process in the temperature range between transformation points A_3 and A_1 of EC steel

In EC100 steel the transformation gamma to alpha occurs, the gamma and alpha phases being in equilibrium. In OCR12VM an eutectoid change occurs, the alpha, gamma and carbide phases being in equilibrium. In both steels the concentration of carbon moves in the ranges which correspond to the widths of the two-phase and three-phase ranges (Figure 9a). The activity of carbon in OCR12VM steel decreases because of the precipitation of the carbide phase. In the first approximation it is assumed that only one carbide phase is precipitated (Cr_7C_3). All three phases - alpha, gamma and carbide – are in equilibrium. A decrease in the activity of carbon in the carbide phase corresponds to an equal decrease in the activity in the other two phases. The activity of carbon in OCR12VM is because of the carbide precipitation much lower than in EC100 steel. Carbon diffuses in the opposite direction to the decrease in concentration. OCR12VM steel has only one degree of freedom (temperature) and therefore the activity can not be changed. The same applies to EC100 steel. Because of the diffusion of carbon, it accumulates in the intermediate layer on the side of OCR12VM so long, that when one of the two phases decomposed on the account of the other, a two-phase range would appear and as a result two degrees of freedom. On the side of EC100 steel close to the contact surface a one-phase range appears due to the outward diffusion of the carbon (Figures 9b and Figure 10).

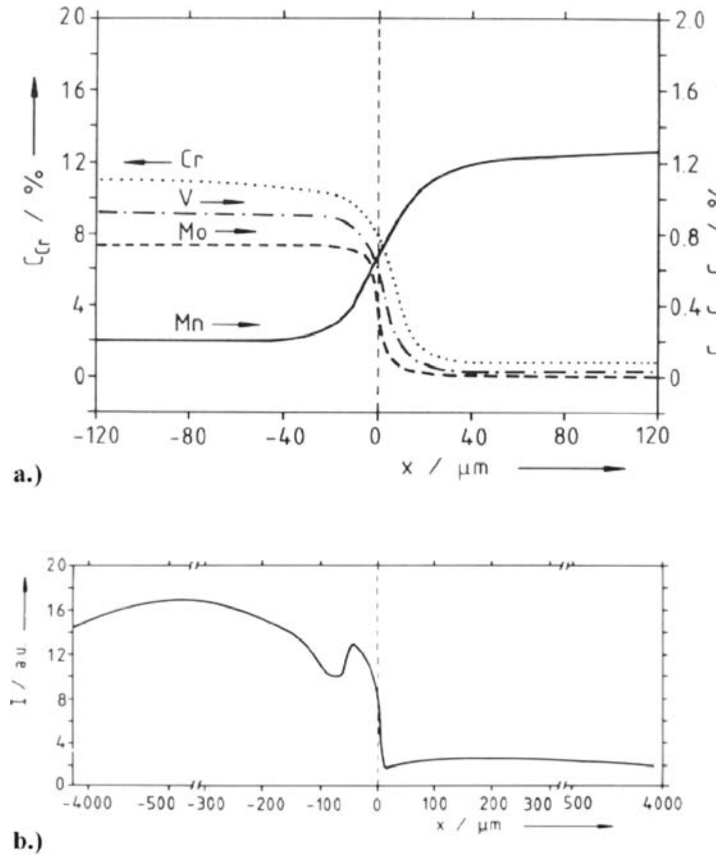
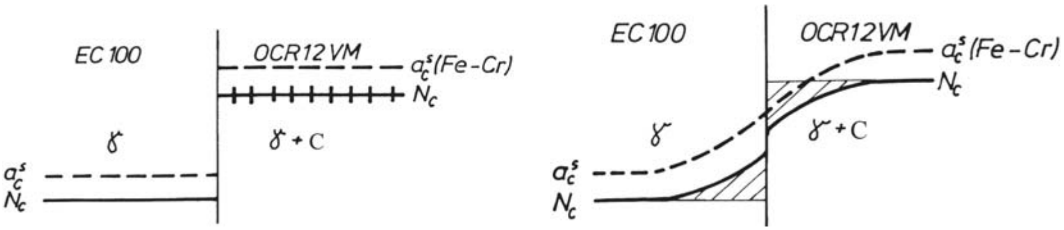
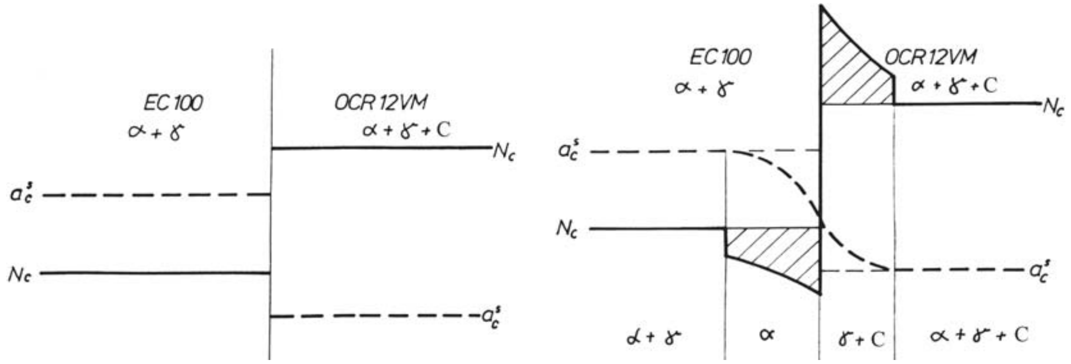


Figure 7: Concentration profiles after the cladding experiment: a.) Cr, Mn, Mo and V (WDS); b.) C (AUGER microscope)



a.) b.)

Figure 8: Diffusion of carbon on temperature 1170 °C (theoretical explanation): a.) state before diffusion process, b.) state after diffusion process, N_c=concentration of carbon, a5C= activity of carbon, C=carbides



a.) b.)

Figure 9: Diffusion of carbon in EC100 steel at cooling in temperature range between A_3 and A_1 transformation point (theoretical explanation): a.) state before diffusion process, b.) state after diffusion process, N_c=concentration of carbon, a5C= activity of carbon, C=carbides

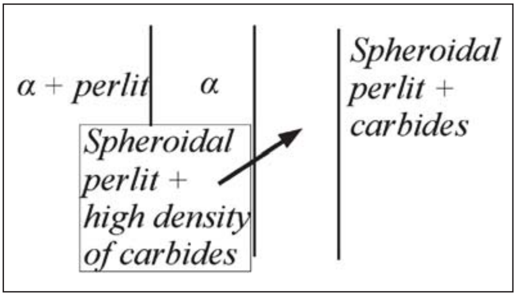


Figure 10: Microstructure of transition layer composed from clearly separated areas of particular phase after diffusion process

CONCLUSIONS

The experiments that simulate cladding of the two steels (OCR12VM/EC100) has been carried out. On the side of EC100 steel close to the contact surface a one-phase range appears due to the outward diffusion of the carbon that results in formation of pure ferrite layer. The thickness of the decarburized layer in the construction steel and the thickness of the carburized layer in the tool steel is independent of the degree of deformation. The moderate tensile strength of the compound material is due to mentioned pure ferrite layer in the contact zone. In further cooperative investigations we shall try to optimise the cooling conditions in order to avoid excessive uphill diffusion of carbon.

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