CORROSION BEHAVIOUR OF WELDED STAINLESS REINFORCED STEEL IN CONCRETE

KORROSIONSVERHALTEN GESCHWEISSTER NICHTROSTENDER BEWEHRUNGSSTÄHLE IN BETON

COMPREMENT A LA CORROSION D'ARMATURES SOUDEES INOXYDABLES DANS LE BETON

Ulf Nürnberger, Willibald Beul, Gerhard Onuseit

SUMMARY

The electrochemical investigations and field tests on reinforced concrete elements demonstrated that stainless steel reinforcement is superior concerning corrosion conditions to common reinforcing steel.

In welded applications, deformed reinforcing bars of type 1.4003 are permanent corrosion resistant under moderate corrosion attack, this means in carbonized normal and lightweight concrete. The application of these materials, which have a favorite cost-efficiency-relation, seems to be reasonable if the attack of chloride containing watery solutions can be excluded.

The applications of the types 1.4571 or 1.4462 is recommended, if chlorides with a higher concentration can penetrate into the concrete (normal and lightweight aggregate concrete). These types are also in a welded application permanent corrosion resistant in carbonized concrete containing chloride.

The use of stainless steel reinforcing bars according to the above mentioned recommendation can permanently exclude steel corrosion in concrete structures.

ZUSAMMENFASSUNG

Aufgrund der durchgeführten elektrochemischen Untersuchungen und von Auslagerungsversuchen sind Bewehrungen aus nichtrostendem Stahl den herkömmlichen Bewehrungsstählen korrosionstechnisch weit überlegen.

In geschweißter Ausführung sind Betonrippenstähle der Sorte 1.4003 unter mäßiger Korrosionsbeanspruchung, nämlich in karbonatisiertem Normal- und Leichtbeton, dauerhaft korrosionsbeständig. Der Einsatz dieser Stähle mit einem günstigen Kosten-Leistungsverhältnis ist daher dann sinnvol, wenn die Einwirkung chloridangereicherter, wässriger Medien ausgeschlossen werden kann.

Der Einsatz der Sorten 1.4571 oder 1.4462 ist dann zu empfehlen, wenn Chloride höherer Konzentration in den Beton (Normalbeton oder Leichtbeton) gelangen können. Im chloridhaltigen alkalischen oder karbonatisierten Beton sind diese Stähle auch in geschweißter Ausführung dauerhaft korrosionsbeständig.

Mit dem Einsatz nichtrostender Betonstähle entsprechend der vorgenannten Empfehlung kann Bewehrungsstahlkorrosion im Betonbau dauerhaft ausgeschlossen werden.

RÉSUMÉ

Les études electro-chimiques et les essais de vieillissement ont montré que du point de vue résistance à la corrosion les armatures en acier inoxydable sont supérieures aux armatures traditionelles.

En état soudé les armatures de la qualité 1.4003 sous attaque de corrosion modérée, c'est-à-dire dans un béton normal et béton léger carbonatisé, résistent durablement à la corrosion. C'est pourquoi l'application de ces armatures avec une relation favorable frais-effectivité est donc recommendée si l'influence d'un millieu aqueux enrichi de chlorures peut être exclue.

L'application des qualités 1.4571 ou 1.4462 est à recommender si les chlorures de concentration plus élevée peuvent pénétrer dans le béton (béton normal, béton léger). Dans un béton alcalin où carbonatisé ces armatures résistent, mème en état soudé, à la corrosion.

Par l'utilisation d'armatures inoxydables selon les recommendations ci-dessus mentionnées, la corrosion des armatures dans ces construction en béton peut être exclue durablement.

KEYWORDS: Corrosion, stainless steel, welding, normal-weight concrete, lightweight, carbonization, chloride.

1. INTRODUCTION

In reinforced concrete structures the concrete guarantees a chemical and a physical corrosion protection of the unalloyed reinforcement: the alkaline electrolyte of the pores blocks by passivity the anodic reaction of the corrosion and the concrete, as a more or less dense (fine porous) material, keeps away from the reinforcements the corrosion-inducing substances, if a sufficient concrete cover is provided. In general, steel in concrete is sufficiently protected against corrosion. Problems only arise if

- the concrete cover and the concrete quality is - aware or unaware - reduced related to the necessary values for the given surrounding environment conditions (e.g. extrem filigree elements);
- special structures have to be erected e.g. connections between precast and cast in place elements or at insulated joints between the structures and external structural elements (balkonies);
- non-dense or dense lightweight concrete is performed to reach a required thermal insulation as well as low ownweight;
- higher corrosion conditions occur e.g. in park decks with an attack of deicing salts.

An extreme critical application from present point of view represents non-dense reinforced lightweight concrete particularly with chloride environments. But even under "normal" conditions for element with external concrete protection (weather protection of concrete surface), corrosion of the reinforcement can not excluded. Because of the production conditions or due to a quick propagation of carbonatization, the active corrosion protection disappears and the passive protection is relatively low compared to normal dense concrete [1]. In consequence

- lightweight concrete with open or porous structure is only limited used as reinforced concrete under corrosive conditions (e.g in open air),
- or that there is a tendency to apply an additional corrosion protection of the reinforcement.

The performance of the previoulsy applied protection methods is generally insfficient and undurable. Therefore, the aim of the present work is to study recent developements of corrosion protection and their application for lightweight concrete. This work presents test results concerning the behaviour of stainless steel bars in concrete. In reinforced concrete structures with stainless steel bars - compared to unalloyed reinforcing bars - improved possibilities for corrosion protection in carbonized and chloride containing concrete are of particular interest. In addition to the danger of reducing the area of the cross section and the loss of bearing capacity, the volumious corrosion products and the danger of spalling concrete parts should be prevented. This type of corrosion occurs for unalloyed steel bars after depassivation of the reinforcement by carbonization and/or chloride attack [2]. At present in Germany cold deformed, weldable stainless steel bars of the austenitic type 1.4571 were offered. Thin bars were also used for welded wire meshs. The application of these types of in stainless reinforcing steel is up to now very seldom.

For an application in concrete structures and from the corrosion aspect in principle all ferritic, austenitic and ferritic-austenitic steels are possible [3] as far as these can be produced as ribbed bars within the common range for strength and deformability [4] and are unrestricted weldable. It was therefore necessary within the range of existing materials to find an optimal and economic reasonable choice concerning the following aspects:

- Behaviour in alkaline concrete with chlorides, carbonized concrete and carbonized concrete with chlorides.
- Behaviour of the reinforcing bars in their typical surface condition (deformed welded bars).
- Type specific behaviour with respect to the reduction of cross section (due to pitting corrosion) and the formation of large corrosion products compared to unalloyed steel bars.

The investigations are based on further tests on stainless steel bars in concrete [5-7]. According to these results pitting corrosion is possible on stainless steel bars depending on the type of steel, the state of the surface, the concrete properties (ph-value, content of chlorides) and the anodic polarization. The susceptibility to pitting corrosion increases with the decreasing so called "effective sum" (% Cr + 3.3 % Mo) following Cr-Ni-Mo-steel, Cr-Ni-steel, Cr-steel. Welded bars show a distinctive worse behaviour than unwelded and the negativ action of chlorides is more pronounced in carbonized than in alkaline concrete. These relations coincide with the behaviour of stainless steel in other field of applications.

In order to characterize the corrosion behaviour of the steel bars, electrochemical tests to determine the pitting corrosion potential were carried out together with comparative field tests on reinforced elements under typical corrosion conditions.

2. DETERMINATION OF THE PITTING CORROSION POTENTIAL

2.1 Materials

Table 1 shows the stainless steels used (material 1 to 7) together with the comparative unalloyed steel. The high alloyed materials were subdivided in the former used austenitic steel 1.4571, the higher alloyed steels 1.4439 (austenitic) and 1.4462 (ferritic-austenitic) an a serie of ferritic steels with different chromium content between 7 and 17 mass-%. The sensitivity against pitting corrosion is characterized by the "effectiv sum" (% Cr + 3.3 % Mo). If also the nitrogen content were considered to the effective sum, the materials 1.4439 and 1.4463 would represent an even higher value.

The different materials were tested welded and unwelded. Usual covered electrodes were used for welding. In general, the welding line was not treated; this means that the tests were preformed with fixed weld seam and a thin oxid-layer on the surface of the steel bar within the area of the weld. In special cases the weld seam was removed by a corrosive paste.

The electrochemical potentiostatic investigations were performed in a first step on welded specimens with plain surface. The values for the surface roughness, which mainly influence the corrosion behaviour, were $R_{max} < 20\ \mu m$ which is less compared to the average value for the surface of usual cold deformed reinforcing bars. Because of technical reasons the specimens could neither be produced with the same dimensions nor in all cases with cold deformed surface. On four typical steel combinations tests were carried out on the final product of unwelded and welded reinforcing bar. During production these steel bars were hot rolled to plain round bars; the stainless steel bars were annealed and then cold deformed with a reduction in cross section of 20 to 30 %. Table 2 contains the different diameters and mechanical properties. In countrary to the ferritic steels 1.4003 and 1.4006 respc. (alloyed and unalloyed respc.), the ferritic-austenitic steel 1.4462 shows a significant higher 0.2 % - yield and tensile strength at similar fracture elongation. The austenitic steel 1.4571 has a relativ reduced yield strength and an extreme high fracture elongation compared to usual deformed reinforcing bars.

The specially produced reinforcing bars 1.4462 and 1.4003 were cold deformed by a non-driven stamp roler; as a consequence some mechanical damages (scratches) occured particularly on the inclined ribs. This inhomogenity of the surface initiated pitting corrosion during the tests. Although this was not significant for the pitting corrosion potential (see chapt. 2.3) it governed for the field tests the amount and intensity of the pitting corrosion for material 1.4003. In order to guarantee a perfect shape in future, these ribbed bars, as also the types 1.4571 and 1.4066, should be deformed by a driven casette roler.

2.2. Testing procedure

By means of mortarelectrodes presented schematically in Fig. 1 first anodic potentiodynamic current density, potential curves were determined starting from the restpotential. The linear potential rate in time was 36 mV/h. The potential belonging to a current density of about 0,02 mA/cm^2 was regarded as the pitting corrosion potential. For the mortar electrodes a concrete quality B 25 was used. Different concentrations of 1,3 and 5 % chloride (related to the cement-content) were added. One half of the alkaline mortar electrodes (without and with chloride) were artificially carbonized in 3 Vol-% content air. For practical conditions this value of 3 % mass-% represents the upper limit for the chloride concentration near the reinforcing bar. The mortar electrodes were dipped in an electrolyte during the tests. This was an saturated $Ca(OH)_2$-solution for the alkaline and tap water for the carbonized specimens. For comparison a saturated calomel electrode was used.

The following combinations were tested. The corrosion conditions between brackets indicate practical experience of corrosion on unalloyed reinforcing bars:

- carbonized concrete, chloride content $<<$ 1 mass-% (moderate corrosion attack),
- alkaline concrete, chloride content $\geq$ 1 mass-% (heavy corrosion attack),
- carbonized concrete, chloride content $\geq$ 1 mass-% (very high corrosion attack).

The state "carbonized" is possible for normal weight concrete of unadequate quality and also for structural lightweight concrete during the period of using. Non-dense lightweight concrete is either not high-alkaline or tends to carbonize quickliy.

The state "alkaline plus chloride content" can be expected most realisticly for chloride attacked normal weight and structural lightweight concrete. In this case a simultaneous occurence of carbonization and increased chloride contents is e.g. not possible: chlorides penetrate most likely together with water into the concrete; a carbonization is reserved to not humid concrete.

The state "carbonized plus chloride content" is most likely expected for special cases at non dense lightweight concrete.

Orientated at the potentiodynamic preliminary tests, in a second step the pitting corrosion potential was determined quasistationary. For this preliminary tests the potential was increased stepwise by 50 mV/24 h. At a current density of ≥ 0,02 mA/cm^2 the test was terminated and the specimen examined concerning appearance of corrosion. For an exact determination of the pitting corrosion potential in a third step poteniostatic tests were performed. The test results, presented in the diagrams, are e.g. average values of three tests. In this paper only the convincing results of the potentiostatic tests are presented.

2.3 Results of the potentiostatic tests

2.3.1 Round specimens with plain surface

Besides the pitting corrosion potential also the location of the first corrosion appearance could be used for the judgement of the potentiostatic tests. This corrosion appearance varied very much for the different steel types and should be therefore included in the suitability of the steel for a reinforcement. Fig. 2 shows a survey of possible types of corrosion and Fig. 3 shows typical examples for welded round specimens with plain surface. Type A represents corrosion of the weld metal and type B indicated corrosion of the heat treated zone: B1 indicates the transition zone between weld metal and heat treated zone; B2 more or less the transition between heat treated zone and the basic material. Type C also shows corrosion within the area of the welding line outside the above mentioned zones; this is the region of the surface covered with an oxid film which is commonly called as temper color. Other investigations [8] showed that thin oxidfilms, originated by welding, reduce significantly the pitting corrosion potential of stainless steel.

The results of the potentiostatic tests on the welded plain bars are presented in Fig. 4 and Fig. 5. The following essential conclusions can be drawn:

- The pitting corrosion potential decreases with decreasing effective sum of the steel types.

  Partically three groups appear:

  - the austenitic and ferritic-austenitic types 1.4439 (mat. 1), 1.4462 (mat. 2) and 1.4571 (mat. 3);
  - the ferritic types 1.4016, 1.4021 and 1.4003 (mat. 4 to 6) with chromium content > 10 mass-%;
  - the ferritic types 1.4713 and 1.4066 (mat. 7 and 8) with chromium content ≥ 7 mass-%.

The resistance against pitting corrosion decreases gradually these three steel types.

- For the austenitic steel 1.4439 (mat. 1) and the ferritic-austenitic steel 1.4462 (mat. 2) the critical area for corrosion were the transition zone between filler material and heat treated zone (corrosion type B1) and for the austenitic steel 1.4571 (mat. 3) the area between heat treated zone and the basic material (corrosion type B2)
- For the ferritic steel 1.4016 (mat. 4) with 17 mass-% chromium first corrosion was observed in the area A and B (B1 and B2).
- The ferritic materials 1.4021 and 1.4003 (mat. 5 and 6) with 13 and 11 mass-% chromium rsp. showed a general corrosion within the whole welding line; this relates to corrosion type A - C.

For the materials with ≤ 7 mass-% chromium no difference was observed between the corrosion within or outside the welding zone; this corresponds to corrosion type A - D.

The materials 1 to 6 showed always pitting corrosion, while the materials 7 and 8 indicated a wide pitting till even general corrosion attack.

- In the carbonized concrete, free of chlorides, besides the austenitic and ferritic-austenitic steel types also the welded ferritic steel with > 11 mass-% chromium behaves passive and shows therefore a distinctly better corrosion behaviour than the active materials with ≤ 7 mass-% chromium.

- The pitting corrosion potential decreases with increasing chloride content of the concrete. This reduction is more pronounced between 0 and 1 mass-% chloride than between 0 and 1 mass-% chloride than between 1 and 5 mass-%.

- The pitting corrosion potential in carbonized concrete with chlorides is always shifted to negative values. This is distingtly pronounced for the ferritic materials with ≥ 11 mass-% chromium; here the reduction was determined to appr. 200 to 300 mV.

According to these results on welded, round specimens with plain surface the types 1.4462 (ferritic-austenitic), 1.4571 (austenitic), 1.4003 (ferritic) and 1.0466 (ferritic, unalloyed) were chosen for the further investigations on welded, deformed reinforcing bars.

2.3.2 Deformed reinforcing bars

Fig. 6 shows the typical type of corrosion for reinforcing bars based on attack in concrete with chlorides. In case of anodic effected corrosion during the potentiostatic test of at the rest potential (only the types 1.4003, see later) only corrosion type C occurs for the ribbed surfaces (fig. 6 above and middle). These are always single pittings which usually start at scores due to production mear the inclined ribbs. For comparison unalloyed materials show, under comparative corrosion intensity, an attack with many, partly small hollows and scores with larger areas of the surface affected by the corrosion attack (fig. 6 below).

Fig. 7 collects the results from ribbed steel types 1.4571 (austenitit) and 1.4003 (ferritic). In order to judge the influence of the welding, unwelded deformed reinforcing bars were also tested.

Parameters selected were the ph-value of the concrete (alkaline and carbonized) and the chloride content. Based on test results the following conclusions can be drawn, in addition to those from welded specimens with plain surface (see above):

- In the welded state (deformed) reinforcing bars show a more unfavorite behaviour than plain bars. This is more pronounced for the ferritic steel 1.4003 than for the austenitic steel 1.4571 and more distinct in alkaline than in carbonized concrete. For the welded material 1.4003 the reduction of the pitting potential E_L was measured to about 200 mV.

- Unwelded deformed stainless reinforcing bars in concrete with chlorides show a more positive pitting corrosion potential E_L of approx. 100 mV than welded bars. For unalloyed material no difference between welded and unwelded bars was observed. In total the ribbs of the bars and the application of welding have a negative influence of the pitting corrosion behaviour of stainless steel. The ribbs and the scratches produced during cold forming have a disadvantageous influence only together with the welding; in the unwelded state the influence of surface quality can be neglected, because there is only a small readiness for corrosion. Scratches are only unfavorite, if the steelsurface contains additional oxidlayers due to welding.

For a practical judgement of the results presented in fig. 7 the following arguments are helpful: from potential measurements on concrete elements with chloride attack, reinforced with stainless steel ribbed bars and exposed to open air, it can be seen that the corrosion potential E_{Korr} is always more negative than -100 mV_{kal}. This is valid for all possible climatic conditions, which, among others, are influencing the aeration of concrete and therefore the corrosion potential. This means, that corrosion of reinforced structures in open air can only be expected, if the pitting corrosion potential is more negative than -100 mV_{kal}; in this case the necessary condition $E_L < E_{Korr}$ is fullfilled. According to this definition and the results presented in fig. 7, for the following materials and corrosion conditions, corrosion can not be excluded or is extreme probably:

- unalloyed steel (unwelded and welded) in carbonized and/or chloride contaminated concrete;

- ferritic, welded steel 1.4003 in chloride contaminated, alkaline and chloride contaminated carbonized concrete;
- ferritic, unwelded steel 1.4003 in chloride contaminated, carbonized concrete

On contrary no corrosion may occur:

- for austenitic steel 1.4571 (unwelded and welded) under all possible corrosive conditions (carbonized, chloride contaminated alkaline, chloride contaminated carbonized);
- for ferritic unwelded steel in chloride contaminated alkaline concrete.

In fig. 8 results of potentiostatic tests were presented including a steel material 1.4462. For an alkaline concrete with a chloride content of 3 mass-% the following parameters were studied: the appearance of the surface (plain, ribbed), the existance of welding (yes, no) and a treatment of the welding line. In order to remove the welding seam and oxid layers, the welded specimens were either brushed (mat. 1.4462) or treated with pickle paste (mat. 1.4462 and 1.4003). for the chemical treatment, a usual pickle paste, developed for welding line for stainless steel, was applied with a paintbrush for about 45 minutes and then thoroughfull flushed with water.

From fig. 8 it can be recognized, that material 1.4462 shows for plain and deformed bar better behaviour than steel 1.4571; this is even more pronounced for the welded and unwelded state.

Brushing of the welded area and removing of the welding cinder only slightly increases the pitting corrosion potential. The treatment of welded specimens with a pickle paste resulted in an unusual improvement: the pitting corrosion potential increased to the level of oxygen production by +600 mV_{kal}. For the example of material 1.4003 it became clear, that a welded and pickled deformed reinforcing bar has a lower tendency for pitting corrosion than an unwelded, unpickled reinforcing bar. Obviously the pickling reduces the pitting initiating effect of scatches at the steel surface.

3. FIELD TESTS WITH REINFORCED CONCRETE ELEMENTS

3.1 Materials and testing procedure

Concrete elements reinforced with deformed bars of about 1 m length were exposed in open air up to 2 years. The steel material, already listed in table 2, consisted of unalloyed and stainless steel. In longitudinal direction the bars had 5 welding lines of about 4 cm length at a distance of 10 cm. This usual welding was performed with normal covered electrodes. There was no treatment of the welding line (see chapt. 2.1). The concrete quality for the normal weight concrete was B 25[1)] (cracked and uncracked); for the lightweight concrete two types were chosen: autoclave gas (GB 3.3)[1)1] and open structural concrete (LB)[19]. The main important properties of these concrete mixtures are given in tab. 3. More details, concerning the corrosions protection from the physical (density) and chemical (passivation) point of view is given in [1].

In case of cracked normal weight concrete the test arrangement allowed to have permanently open cracks with crack width of 0,1 to 0,8 mm during the complete period of the exposure. This cracks were located both, within and outside the

---

[1] Classification of nominal strength according to German standards

welding. The reinforcing steel bars had a concrete cover of 1,5 and 2,5 mm and the welding line was orientated to the concrete surface.

Some of the test specimens with normal weight concrete B 25 were artificially carbonized until the upper steel layer (1,5 cm) with air of 3 vol-% CO_2. The none-dense lightweight concrete mixtures have either by production only a ph-value of about 10 (gas concrete) or they are partly carbonized due to channel-type pores deep into the inner part (open structural concrete). From corrosion point of view both concrete mixes have to be regarded as carbonized.

Partly chlorides (as NaCl) were mixed under the normalweight concrete mixes. Thus the following states were investigated:

- alkaline without chlorides;
- alkaline, 1 mass-% chlorides, related to cement (0,12 mass-%, related to concrete)
- alkaline, 2,5 mass-% chlorides, related to cement (0,30 mass-%, related to concrete);
- carbonized, free of chlorides

One part of the lightweight concrete specimens were treated similar to the conditions of structures in the splash zone of highway where deicing salts are used. This simulation was performed by spraying a water solution with 1,5 mass-% chloride on the concrete surface. With regard to a typical composition of a deicing salt the used chloride consisted of about 87 % NaCl and 13 % $CaCl_2$. Two types of treatings were applied:

a: - 50 sprayings with 5 g salt/m^2, distributed over 25 days during summer and

25 days during winter time (type chloride 1).
b: - 150 sprayings per year with 5 g salt/m^2 in regular periods (type chloride 2).

The treatment chloride 1 was developed from actual chloride attacks on structures by deicing salts (spraywater). The treatment chloride 2 does not represent practical conditions for lightweight concrete. It was only chosen to make clear the limits of corrosion protection in lightweight concrete.

By spraying the specimen of lightweight concrete it was kept in mind, that the added chlorides during casting are washed out from macropore by weather influences. Table 4 lists chloride contents from specimens removed after 2 years. The chloride contents were related, both to the weight: of concrete and cement. For the structural concrete it was assumed for calculating the relation to cement, that the aggregates don't contain any chlorides; in fact, there is a certain, unknown amount of chlorides proportionally also within the aggregates.

During the field tests at typical climatic conditions and moisture content of concrete the corrosion potentials were determined by applying Kalomel electrodes on the concrete surface.
The test samples were removed after 0,5 and 2 years. For the corroded steel bars, the corrosion products were pickled with inhibited hydrochloric acid; finally the state of corrosion was investigated concerning type and amount of steel corrosion, separated for unwelded areas and welding line.

3.2 Results of the field tests

The results of the steel-corrosion after 2 years can be seen from table 4. The depth of pits, measured with the roughness device as an average value of the three deepest pits within 5 cm length of bar, and the average corrosion, determined from the loss of weight, were assigned to corrosion classes between 0 (no corrosion) and 6 (very heavy corrosion). Distinction was made between unwelded zone and the region along the welding. No significant difference in the corrosion behaviour (pitting, corrosion potential) was found concerning concrete cover (1,5 and 2,5 cm) and crack state (cracked and uncracked), so these parameters were not separated.

In addition in table 4 also the corrosion potentials for the normal weight concrete elements are reported. The scattering refers also to the influences of weather and concrete cover (the negative values were determined mostly after rainfall or a heavy moisture content above steel bars with the higher concrete cover). The results of the corrosion tests showed the following relations:

- As expected unalloyed steel corrodes in carbonized and/or in chloride contaminated concrete. In the carbonized concrete predominates general corrosion; with increasing chloride content more pitting and wide pitting corrosion appears (see fig. 6 below). The highest attack is possible in carbonized plus chloride contaminated concrete.
- The ferritic chromium steel 1.4003 shows a distinct better behaviour than unalloyed steel. In carbonized concrete (normal and lightweight concrete) no corrosion attack was found for this material. Also in chloride contaminated, alkaline normal weight concrete not attack was found for unwelded steel. Within welding line chlorides produce locally distinct pitting corrosion; this pits appear around the complete circumference (see fig. 6 above and center). The depth of pittings within the welding line

depth of pits, measured with the roughness device as an average value of the three deepest pits within 5 cm length of bar, and the average corrosion, determined from the loss of weight, were assigned to corrosion classes between 0 (no corrosion) and 6 (very heavy corrosion). Distinction was made between unwelded zone and the region along the welding. No significant difference in the corrosion behaviour (pitting, corrosion potential) was found concerning concrete cover (1,5 and 2,5 cm) and crack state (cracked and uncracked), so these parameters were not separated.

In addition in table 4 also the corrosion potentials for the normal weight concrete elements are reported. The scattering refers also to the influences of weather and concrete cover (the negative values were determined mostly after rainfall or a heavy moisture content above steel bars with the higher concrete cover). The results of the corrosion tests showed the following relations:

- As expected unalloyed steel corrodes in carbonized and/or in chloride contaminated concrete. In the carbonized concrete predominates general corrosion; with increasing chloride content more pitting and wide pitting corrosion appears (see fig. 6 below). The highest attack is possible in carbonized plus chloride contaminated concrete.
- The ferritic chromium steel 1.4003 shows a distinct better behaviour than unalloyed steel. In carbonized concrete (normal and lightweight concrete) no corrosion attack was found for this material. Also in chloride contaminated, alkaline normal weight concrete not attack was found for unwelded steel. Within welding line chlorides produce locally distinct pitting corrosion; this pits appear around the complete circumference (see fig. 6 above and center). The depth of pittings within the welding line

increases with increasing chloride content. The so-called critical chloride content, from which in alkaline concrete at untreated weldings on deformed ferritic reinforcing bars (type 1.4003) pitting corrosion occurs, lies in the same range as for unalloyed steel. For the ferritic chromium steel the pitting corrosion at welded line is however more pronounced than for unalloyed steel; but the overall general corrosion (loss of weight), which leads to huge corrosion products and to spalling of the concrete cover, is significantly smaller. For simultaneous carbonatization and existance of chlorides (e.g. in chloride contaminated porous lightweight concrete), which is similar to the situation for unalloyed steel, the corrosion is more pronounced than in chloride contaminated, alkaline concrete. In chloride contaminated, carbonized concrete also for the unwelded steel 1.4003 a pitting corrosion appears, which however is significantly reduced compared to welded materials. It can be assumed that this rate attacks under extreme corrosion conditions can be practically neglected. Eventually they appear not at all, if the quality of cold deformation will be improved, which is possible from the technical point of view.

- At the <u>austenitic Cr-Ni-Mo-steel</u> no corrosion appeared, both for the unwelded and welded state. This is valid for all conditions within the concrete: carbonized and chloride infiltrated.

- A comparison of the test results concerning the corrosion behaviour after 0,5 and 2,0 years show a time dependent increase of the corrosion as follows:

Corrosion 0,5 years: Corrosion 2,0 years ~ 1,0 : 1,4

The results form the potential measurements at reinforced concrete elements with and without addition of chlorides are listed in table 4. The given values always represent the scatter for the concrete covers of 1,5 and 2,5 cm and the actual differences in moisture content. I.g. the negative values relate to the higher cover and after an intensive weathering of the specimen. On contrary, the positive values belong to a low concrete cover and a dry concrete due to drying out. In case of corrosion, the corrosion potentials are always more negative than in a case without corrosion; they decrease with increasing chloride content. With corrosion, under comparable conditions the chromium-alloyed steel 1.4003 shows always slightly more positive values than the unalloyed steel. For practical conditions, corrosion of stainless steels can be expected if the corrosion potentials fall below -150 mV_{kal}.

4. CONCLUSION

As a consequence of the performed investigations, stainless steel is recommended for special applications of reinforced concrete structures. Depending on the actual corrosion attack, ferritic steel (mat. 1.4003) or austenitic steel (mat. 1.4571) as well as ferritic-austenitic steel (mat. 1.4462) can be used. The corrosion resistance increases in the sequence: uanlloyed - 1.4003 - 1.4571 - 1.4462. For the ferritic-austenitic steel 1.4462 the much better mechanical properties have to be emphasised against the austenitic steel 1.4571. The unalloyed steel leads always to largerly extended corrosion with spalling of the concrete cover whilst for stainless steel only locally concentrated attacks occur; different from unalloyed steel, only near the welding seam significant corrosion was observed.

Table 5 shows a general view of reasonable possibilities for the technical applicability of stainless steel. For three conditions of corrosion

- carbonized concrete, chloride content < 1 mass-% (moderate corrosion attack, possible for normal and lightweight concrete),
- alkaline concrete, chloride content ≥ 1 mass-% (heavy corrosion attack, possible for normal and dense lightweight concrete),
- carbonized concrete, chloride content ≥ 1 mass-% (very heavy corrosion attack, possible for non-dense lightweight concrete)

it is subdivided between the application of a ferritic steel 1.4571 with and without welding as well as with and without treating of the welding and the ferritic-austenitic steel 1.4462, both in welded performance. The types 1.4571 and 1.4462 are in the welded performance applicable for normal and lightweight concrete.

Unwelded or with treated welding the type 1.4003 may protect in carbonized or chloride contaminated normal weight concrete against heavy corrosion. Welded and without additional treating of the welding, steel of this types protect reliable (in carbonized concrete) against moderate corrosion attack.

5. REFERENCES

[1] **Mansour, T.** Korrosion und Korrosionsschutz von Stahl in Leichtbeton. Diplomarbeit Universität Stuttgart, Juli 1991

[2] **Autorenkollektiv** Korrosionsschutz im Massivbau. Band 297 Kontakt & Studium. Expert-Verlag, Ehningen 1991

[3] **Edelstahlvereinigung e.V. und Verein Deutscher Eisenhüttenleute** Nichtrostende Stähle, Eigenschaften, Verarbeitung, Anwendung, Normen. Verlag Stahleisen mbH, Düsseldorf 1989

[4] DIN 488 (1984 und 1986) Betonstahl

[5] **Flint, G.N., Cox, R.N.** The resistance of stainless steel partly embedded in concrete to corrosion by seewater. Magazine of concrete research 40 (1988) 142, 13-27

[6] **Sorensen, B.** The corrosion of stainless steel reinforcement, S. 601-610; in "C.L. Page, K.W.J. Treadaway, P.B. Bamforth: Corrosion of Reinforcement in Concrete". Elsevier Applied Science, London-New York 1990

[7] **Menzel, K.** Einfluß von ph-Wert, Chloridgehalt und Stahlsorte auf das Korrosionsverhalten nichtrostender Stähle, S. 116, in [2]

[8] **Ruge, J.** Einfluß von durch Schweißen erzeugten Oxidfilmen auf die Lochkorrosionsbeständigkeit nichtrostender austenitischer Chrom-Nickel-Stähle in annähernd neutralen Chloridlösungen. Ergebnisse des Forschungs- und Entwicklungsprogrammes "Korrosion und Korrosionsschutz", Dechema Frankfurt, Band 5: 1987-1989, S. 101-104

Table 1 Listing of the applied materials

Nr.	material		structure	effective sum 1)	
	DIN-standard	material Nr.		RS	WM
1	x2CrNiMoN 17 13 5	1.4439	A	33.5	28 2)
2	x2CrNiMoN 22 5 3	1.4462	F-A	31.9	
3	x6CrNiMoTi 17 12 2	1.4571	A	23.6	
4	x6Cr 17	1.4016	F	17	12 2)
5	x20Cr 13	1.4021	F	13	
6	x2Cr 11	1.4003	F	11	
7	x10CrAl 7	1.4713	F	7	
8	(unalloyed)	1.0466	F	0	0

1) effective sum: % Cr + 3,3 % Mo
2) for specimens with plain surface
RS reinforcing steel

WM welding materials
F ferritic
A austenitic

Table 2 Mechanical properties of the deformed bars

mat. Nr.	structure	material nr.	D	$R_{p0,2}$	R_m	A_{10}
			mm	N/mm²	N/mm²	%
2	ferritic-austenitic	1.4462	7,0	870	934	13,1
3	austenitic	1.4571	10.0	456	599	39,3
6	ferritic	1.4003	8,0	518	608	15,6
8	ferritic (unalloyed)	1.0466	8,0	533	596	11,6

Table 3 Composition and main properties of the used concrete mixtures

type of concrete	nominal strength	cement		w/c	aggregates		hardened concrete		
		type	content		degradation/ type	content kg/m³	density t/m³	compr. str. N/mm²	porosity Vol-%
normal weight concrete	B 25	FAZ 35 F	270	0.78	0-2 0-8 0-16	655 578 1927 694	2.30	37.0	15
open structural concrete	LB 8	-	230	0.52	Liapor 4 Liapor sand 0-4 sand 0-2	410 52 712 250	1.10	9.0	52
gas concrete	GB 3.3	PZ 35 F or 45 F	130 cem. + 65 line	0.50 to 0.70	fine silic. sand 70% <90 um	400	0.65	3.4	74

Table 4a Average corrosion (loss of weight)

steel	concrete	normalweight concrete B 25			GB 3.3 - LB 8			
		alkaline			carbonized			
	Chloride in mass-%	0	0.12[1]	0.30[1]	0	0	0.3 0.7[1]	0.5 1.2[1]
			1.00[2]	2.50[2]			1 - 3[2]	-2-5[2]
un-alloyed	unwelded	x	0.7	3.6	2.7	3.1	4.4	5.2
	welded	x						
1.4003	unwelded	x	x	x	x	x	0.8	1.2
	welded	x	1.5	2.5	x	x	2.8	3.2
1.4571	unwelded	x	x	x	x	x	x	x
	welded	x	x	x	x	x	x	

[1] related to concrete weight [2] related to cement weight

x no corrosion

Table 4b Depth of pits (pitting and wide pitting corrosion)

un-alloyed	unwelded	x	2.7	3.8	0.5	2.1	3.9	4.7
	welded	x						
1.4003	unwelded	x	x	x	x	x	2.5	3.1
	welded	x	3.5	4.7	x	x	2.0	5.2
1.4571	unwelded	x	x	x	x	x	x	x
	welded	x	x	x	x	x	x	x

Table 4c Corrosion potential (mV_{kal})

unalloyed	unwelded	110 / -180	-220 / -260	-340 / -450	-320 / 410
	welded				
1.4003	unwelded	+10 / -90			
	welded		-160 / -250	-290 / -414	
1.4571	unwelded	+50 / -105			
	welded				

Table 4d Degree of corrosion

KG	depth of pits in μm	average corrosion in μm
0	0	0
1	1 - 100	1 - 25
2	100 - 300	25 - 50
3	300 - 500	50 - 100
4	500 - 800	100 - 150
5	800 - 2000	150 - 300
6	2000 - 4000	300 - 500

Table 5 Permissible technical application of stainless steel reinforcing bars

type	welding W	treatment of welding line T	corrosion attack CA				allowable application		
			moderate		heavy	very heavy			
			carb.	alkal. $\mathrm{Cl} \ll 1\%$	alkal. $\mathrm{Cl} \leq 1\%$	carb. +Cl			
1.4003	no		-	-	-	+	heavy CA	without W	NC: A LC: B
	yes	no	-	+/-	+	+	moderate CA	with W	NC: B LC: B
	yes	yes	-	-	-	+	heavy CA	with T	NC: A LC: B
1.4571 1.4462	yes	no	-	-	-	-	very heavy CY	with W	NC: C LC: C

\- no corrosion +/- low corrosion + heavy corrosion

NC normalweight concrete
LC lightweight concrete
A: carbonized or chloride contaminated concrete
B: carbonized concrete
C: carbonized and chloride contaminated concrete

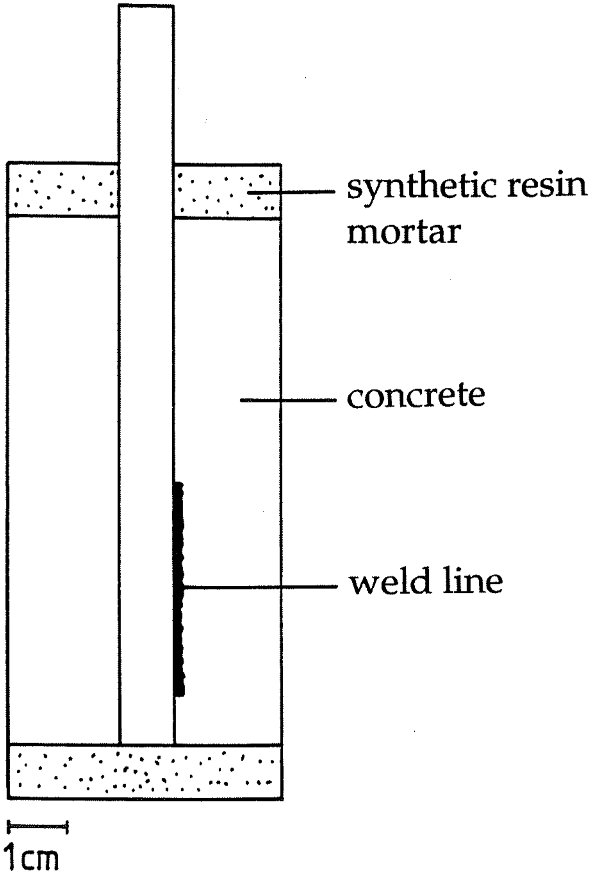


Fig.1: View of the applied mortar-electrode

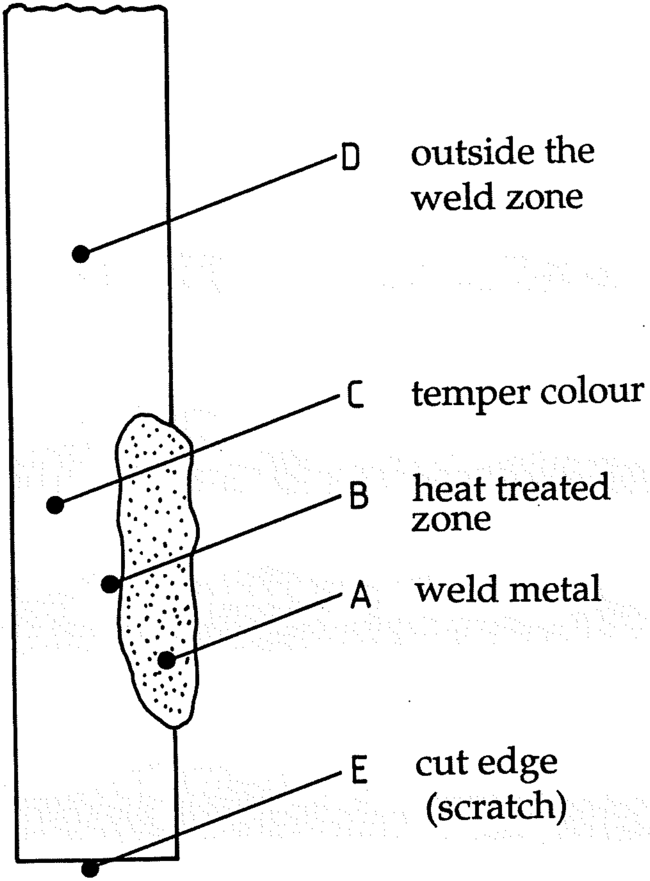


Fig.2: Types of Corrosion

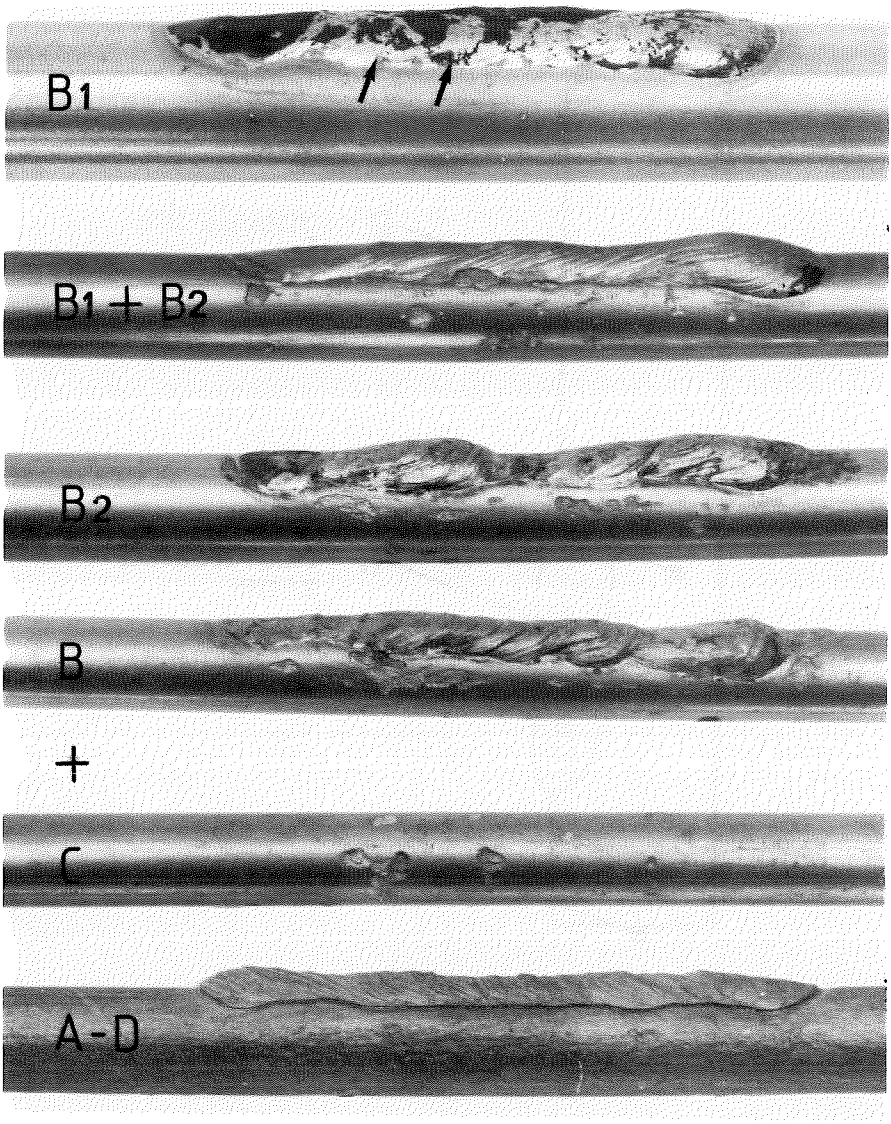


Fig.3: Types of corrosion for the potentiostatic tests

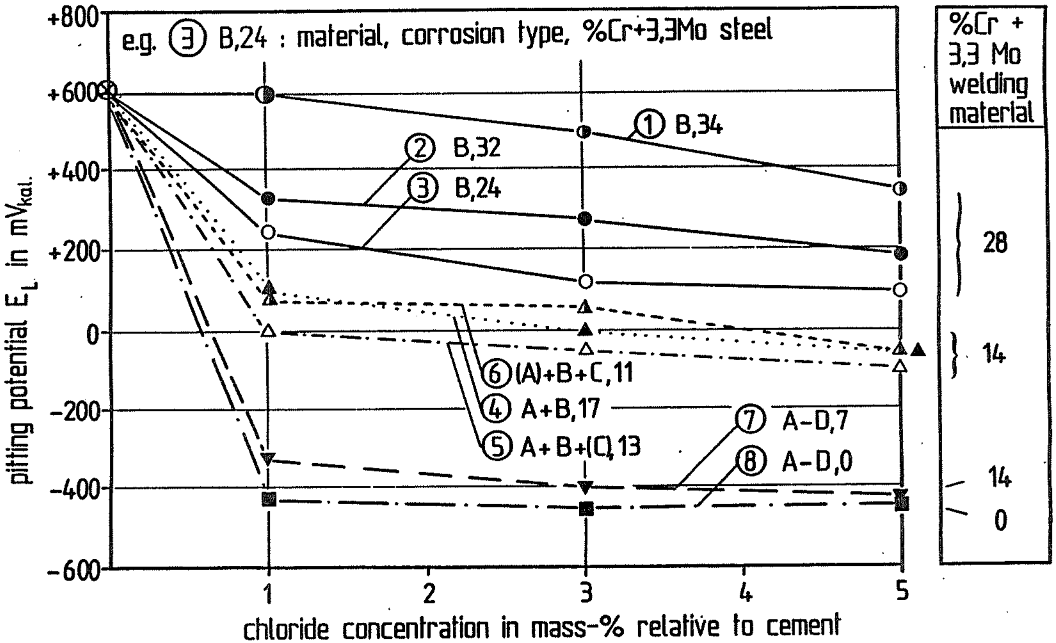


Fig.4: Pitting potential of plain welded steel specimens in PC-mortar-electrodes depending on the steel-type and chloride content; potentiostatic test (t = 24 h), oxygen evaluation $E = +600\ mV_{Kal.}$

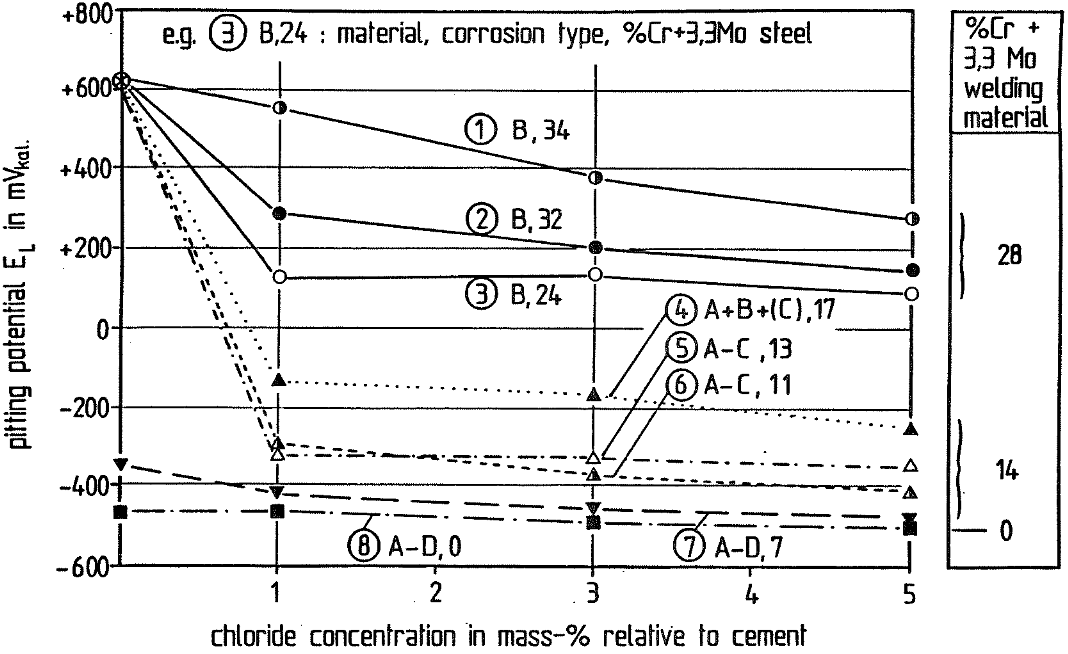


Fig.5: Pitting potential of plain welded steel specimens in carbonized PC-mortar-electrodes depending on the steel-type and chloride content; potentiostatic test (t = 24h), oxygen evaluation E = +600 $mV_{Kal.}$

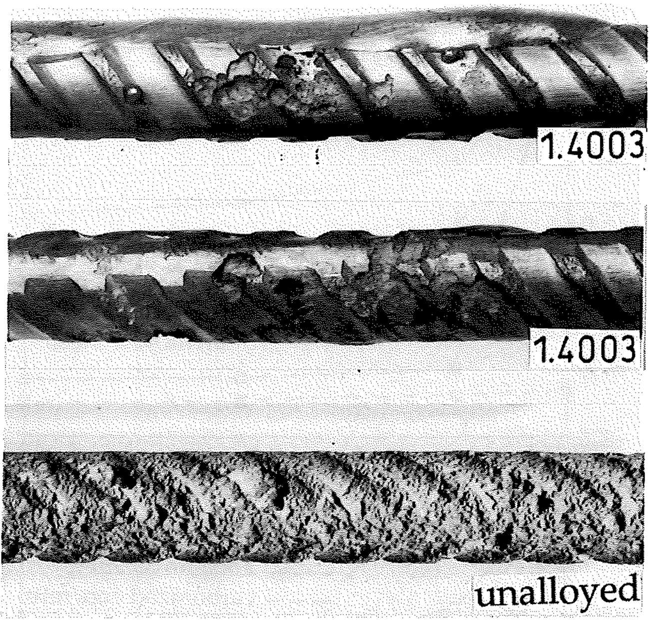


Fig. 6: corrosion of deformed reinforcing bars in concrete (2 years; 2,5% Cl^-)

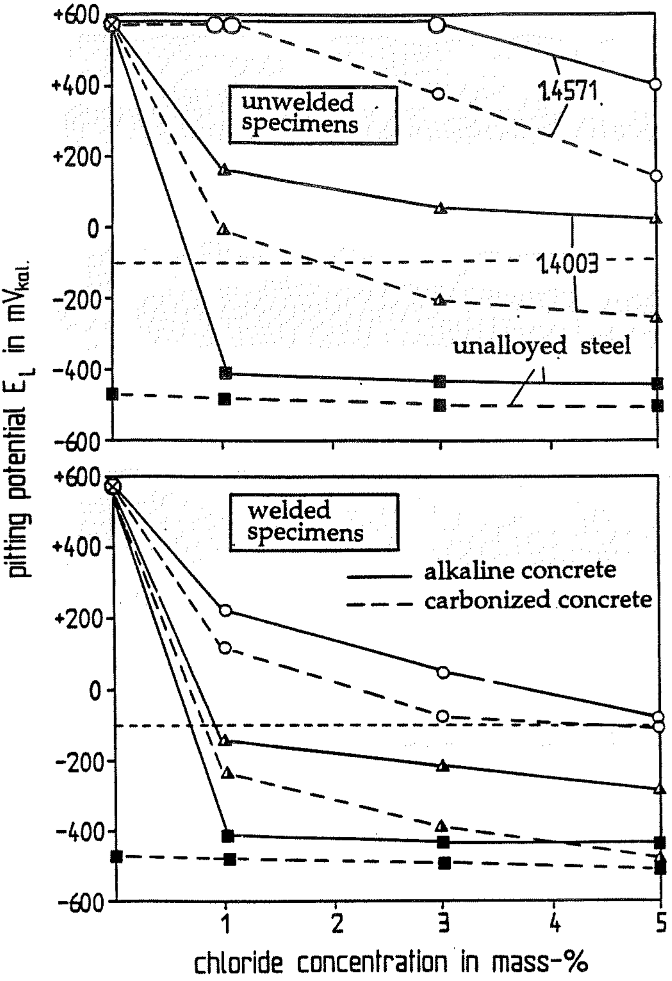
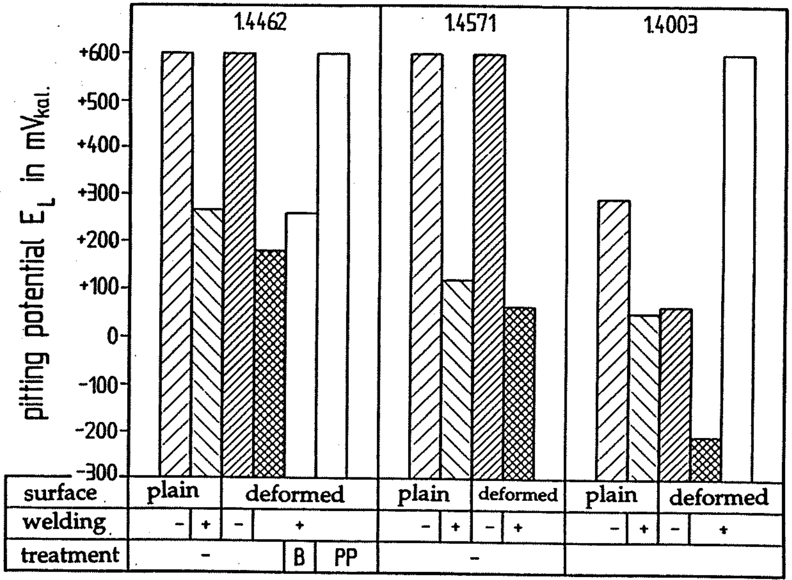


Fig. 7: Pitting potential of deformed steel specimens in mortar-electrodes depending on the steel-type, the presence of welding, carbonation and chloride content;
potentiostatic test (t = 24 h),
oxygen evaluation E = +600 $mV_{kal.}$



B = brushing PP = pickling paste - no + yes

Fig.8: Pitting potential of steel specimens in alkaline concrete containing 3 mass-% chlorides (related to cement) depending on the steel-type, the surface conditions, the presence of welding and the type of treatment (brushing, pickling paste);
potentiostatic test (t = 24 h)