HIGH STRENGTH STAINLESS STEEL - ALTERNATIVE MATERIALS FOR TENSION MEMBERS IN CIVIL ENGINEERING

HOCHFESTE NICHTROSTENDE STÄHLE - ALTERNATIVWERKSTOFFE FÜR ZUGGLIEDER IM INGENIEURBAU

ACIER INOXIDABLE DE HAUTE RESISTANCE – MATERIAU ALTERNATIF POUR MEMBRES DE TENSION DU GENIE CIVIL

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ABSTRACT

Tests with high strength stainless steel strand justify the use of strength class S 1100 spiral strands made from the material 1.4436 under moderate chloride and sulfur dioxide load. The findings gained from tension members made of high strength stainless steel wires seem to indicate that strength class S 1100 strands made from the material 1.4401 should only be used in constructions of negligible chloride and sulfur dioxide contents. This assessment takes into account the behaviour compared with the most important types of corrosion such as pitting and crevice corrosion as well as stress corrosion cracking under the known marginal conditions for tension members in accordance with DIN 18800 part 1.

ZUSAMMENFASSUNG

Untersuchungen an hochfesten Litzen aus nichtrostendem Stahl rechtfertigen den Einsatz von Seilen der Festigkeitsklasse S 1100 aus dem Werkstoff 1.4436 bei mäßiger Chlorid- und Schwefeldioxidbelastung. Die speziell an Zuggliedern aus hochfesten nichtrostenden Stahldrähten im Versuch gewonnenen Erkenntnisse lassen es geboten erscheinen, Seile der Festigkeitsklasse S 1100 aus dem Material 1.4401 nur bei Konstruktionen ohne nennenswerte Gehalte an Chloriden und Schwefeldioxid einzusetzen. Diese Einschätzung berücksichtigt das Verhalten gegenüber den wichtigsten Korrosionsarten wie Loch- und Spaltkorrosion sowie Spannungsrisskorrosion unter den für Zugglieder nach DIN 18800 Teil 1 bekannten Randbedingungen.

RESUME

Des essais sur des torons en acier inox justifient l'utilisation de câbles de classe de résistance s 1100 en 1.4436 sous action modérée de chlorures et dioxyde de soufre. Les résultats obtenus pour les membres de tension acier inox de haute résistance indiquent que les câbles en 1.4401 de classe de résistance S 1100 ne doivent être utilisés uniquement dans des constructions sans teneur notable en chlorures et dioxyde de soufre. Cette estimation prend en compte le comportement face aux principaux types de corrosion tels que la corrosion par piqûres, la corrosion par fissuration et la corrosion fissurante sous tension sous les conditions définies dans la 1ère partie de la DIN 18800.

KEYWORDS: High strength steel, austenitic stainless steel, tension members, spiral strands, mechanical properties, corrosion behaviour, pitting corrosion, fretting corrosion, stress corrosion cracking, corrosion fatigue.

1. INTRODUCTION

In 1998, the German Institut für Bautechnik in Berlin, responsible for construction supervision, awarded the general certification for stainless steels [1] which regulates the use of these materials and their products under typical corrosion conditions when used in the building and construction industry. The certification relates to typical product items for steels with and without work hardening up to yield or tensile strengths of 690/850 N/mm^2. The listed types of steel meet the requirements for certain corrosion exposures and are broken down into resistance classes against corrosion.

High strength tension members in accordance with DIN 18800-1 (steel structures, dimensioning and construction) are not the subject matter of the general certification for stainless steels. Cold deformed steel wires with yield strengths of > 1000 N/mm^2 are not covered by the empirical range of the certification as laid down by the strength spectrum and with regard to known corrosion properties. Since in the meantime high strength steels on the one hand have become important alternative materials for load-bearing structural elements and on the other some innovation developments have taken place in this field some of the implications shall be mentioned here. The high strength tension member made of stainless steel will be highlighted as a good example of enhanced engineering. Meanwhile the German Institut für Bautechnik has awarded a certification for this construction product.

2. THE FREE TENSIONED TENSION MEMBER IN STRUCTURAL ENGINEERING [2, 3]

The tension elements consisting of steel wires for use in structural engineering are so-called "static ropes" which in contrast to "running ropes" in the hauling and hoisting will not be moved nor ridden upon. As opposed to other construction methods (steel structures, concrete constructions) ropes offer advantages. At relatively low cross-sectional dimensions they can transfer high tension forces and bridge large span lengths. Considerably higher strengths as opposed to construction steels can be utilized due to high tensile loads. Low wire dimensions and the type of rope construction have the effect that tension members can practically be considered as resilient (flexible).

Ropes consist of a great number of cold worked high strength steel wires which lie on top of each other in layers. Conventional ropes are manufactured from unalloyed carbon steel; the wire strength lies at 1700 N/mm^2. In tension members made of stainless steel wires the strength exceeds 1450 N/mm^2.

With regard to structural tension members a distinction is made between different types of construction (Fig. 1):

Spiral strands are of a design which are wrapped counterrotating in the individual layers of wire (single stranding) whereby the wires of one layer all form the same spiral shape. Open spiral strands (Fig. 1 a) are manufactured exclusively of round wires mainly of identical diameter. In the case of up to 3 layers applied to a core wire (1 + 6 + 12 + 18 = 37 wires) they are known as steel strand. Fully locked spiral strands (Fig. 1 b) receive further layers of preformed Z-profile wires over a core with several layers of round wires.

In general, open spiral strands made of round wires will rather be employed to bear minor loads at lower requirements to stiffness (as net ropes for wide-span structures or for guying in the event of pylons or in bridge construction). In contrast , the main operational range of fully locked spiral ropes is to be found with structures under higher stress such as main cables in bridges, edge ropes of wide-span structures. Whilst the application of profiled wires and their anchoring in sealing bodies (metal grouting or epoxy grouting plus steel balls) hampers the ingress of corrosion promoting aqueous media into the rope interior of locked spiral strands since the joints between the outer wires will close under load, crevices and capillar cavities can hardly be prevented in open spiral strands and also in their cable clip joints, so that humidity can penetrate in between the single wires. In a corrosive environment this can result in crevice corrosion.

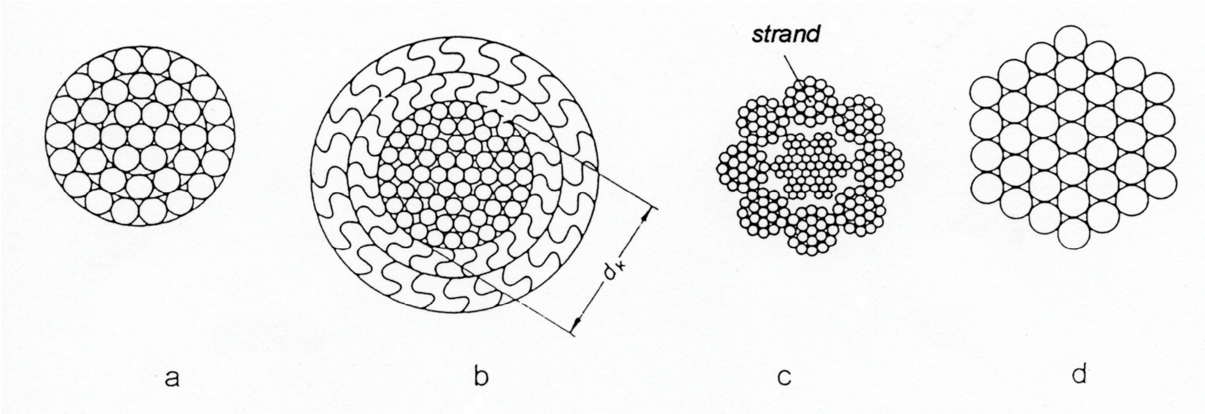

Fig. 1: Cross section for tension members

a: open spiral strand *b: Fully locked spiral rope*

c: stranded rope *d: bundle*

Apart from the ropes, **stranded ropes** (Fig. 1 c) are frequently used in constructional engineering consisting of one or several layers of steels strand, wound in spirals around a core. The multiple stranding applied in this case leads to a flexible tension member. However, the ensuing low metallic cross-sectional area factor of the rope, its low stiffness and its necessarily very small diameter increase the so-called spinning loss factor and impede corrosion protection.

Very big loads can be beared by **bundles** of parallel-arranged wires of steel strands (Fig. 1 d).

This paper deals with open spiral strands made of stainless steel wires representing 90 % of the application of tension members made of stainless steel wires and which are used almost exclusively under corrosion promoting conditions. In this case round wires sized 0.6 to 3.5 mm are processed to ropes of a diameter of 3 to 38 mm.

Up to now in the building and construction industry only austenitic stainless steel wires mad from the materials 1.4401 (X 5 Cr Ni Mo 17-12-2) and

1.4436 (X 4 Cr Ni Mo 17-13-3) with characteristic tensile strengths of ≥ 1450 N/mm^2 and 0.2 %-proof stress ≥ 1100 N/mm^2 (strength class S 1100) are in use. The elongation at break A_{10} of these ropes is of 6 % and the uniform elongation of ≥ 2 %. A maximum creep strain of $2.5 \cdot 10^{-2}$ % must be expected for load of 40 % of the tensile strength at ambient temperature after 1000 hrs.

The wires a the straight wire rope under tensile load are mainly strained by tensile stresses. Apart from that and as a result of the stranding, anchoring and deflection additional stresses occur which can have an influence on the bearing capacity, the working line, the creeping, the dynamic behaviour and also on the corrosion behaviour of the wires in the rope.

Under fatigue loading and under transverse stress a friction of the wires among themselves as well as at the anchorages, cable clips and deflections occurs. This has an adverse influence on the fatigue behaviour of the ropes.

3. ROPES MAD OF STAINLESS STEEL WIRES

3.1 Reasons for an application in structural engineering

Tensioned ropes made of high strength steel wires are subjected to static and dynamic stresses as well as various corrosive influences. With regard to a high durability they must therefore be sufficiently dimensioned and also protected against environmental impact when using corrosion susceptible wires made from unalloyed steels. So far such rope wires or ropes were protected by means of metal or polymer coatings. Presently the state of the art is a combination of both methods (metal plus paint-system). Such corrosion protection systems, however, may fail under extreme and mostly unforeseeable mechanical and/or corrosive stresses [4, 5-7] as a consequence of non-uniform corrosion, stress corrosion cracking, fretting and fatigue corrosion. Particularly in areas of load application at anchorages, cable clips diversions (saddle) it is possible that these protection measures are not sufficient even under "normal" environmental influences.

Hence it was apparent that by using high strength wires made of sufficiently high alloyed stainless steel one could dispense with additional corrosion protective measures and at the same time make allowances for esthetical aspects. Cold-drawn wires made from stainless steel have been manufactured for some

20 years with comparable mechanical properties and fatigue strength just like high strength wires made of unalloyed steels [8-10] and also further processing to ropes is not difficult. In practical use the ropes have stood the test also from a corrosion point of view (Section 2.3) and have given proof of their high resistance in laboratory and nature tests.

3.2 Manufacture of wires

Because of the required increased resistance to corrosion mainly austenitic steels of the chrome-nickel type are suitable for manufacturing the wires in the course of which with regard to a higher chloride resistance molybdenum is added in the alloy. The manufacture of high strength stainless steel wires for ropes takes into consideration the type of product "rolled wire quenched". Following that and in order to obtain the desired strength of at least R_m = 1450 N/ mm^2 depending on the strengthening effect the steels are cold drawn by approx. 50 to 70 %. Cold working leads to a considerable rise of the tensile strength and most of all of the 0.2 %-proof stress with rolled wire as a basis and whereby the deformation characteristics indeed decline, however, they remain sufficiently high (Fig. 2). Compared with unalloyed steel austenitic material show a relatively higher rise of the strength during the cold working due to strengthening (compare in Fig. 2 a and b the behaviour of the unalloyed steel C 70 with the high-alloy steel). This is based on:

- the distinct strengthening capabilities of the austenitic,
- the precipitation behaviour of the nitrogen in the case of nitrogen-alloy materials,
- the formation of deformation martensite (hard martensite needles in an austenitic texture) in materials which are unstable in their texture.

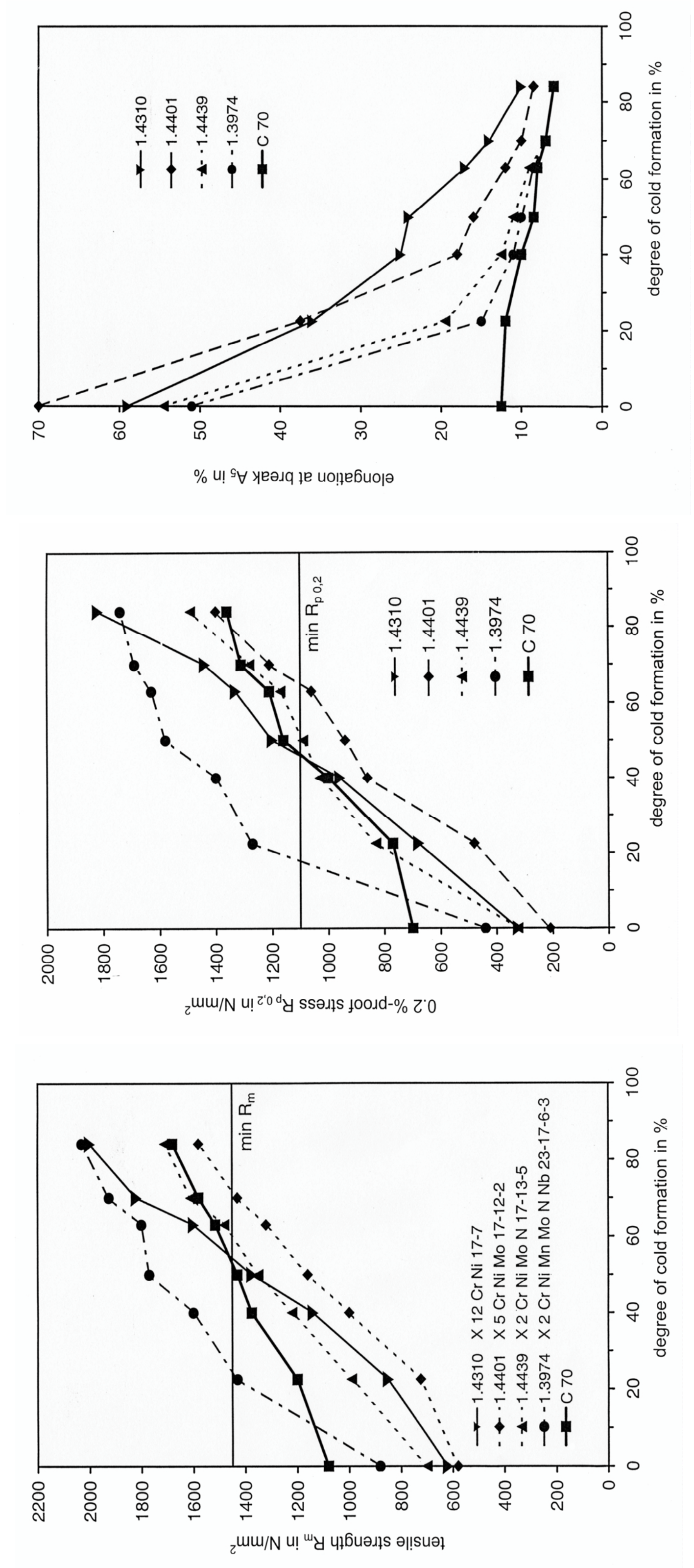

Fig. 2: Influence of cold deforming on mechanical properties [10]

The stability of the austenite against the formation of deformation martensite depends most of all on the contents of chromium, manganese, molybdenum and nitrogen in the steels [12,13]. Increasing contents of the elements hamper the formation of martensite. The publication [10] quotes an indicator for the austenitic stability:

$$M_{d30}{}^{+)} = 413 - 462\ (\%\ C + \%\ N) - 9{,}2\ \%\ Si - 8{,}1\ \%\ Mn - 13{,}7\ \%\ Cr - 9{,}5\ \%\ Ni - 18{,}5\ \%\ Mo$$

With a falling indicator M the stability of the austenite will rise. For the steel types shown in Fig. 2 as well as for a material 1.4436 used for open spiral strands the following series of an increasing austenitic stability will emerge (the values are based on real analyses):

1.4310	X 12 Cr Ni 17-7	M =	- 1 °C
1.4401	X 5 Cr Ni Mo 17-12-2	M =	- 11 °C
1.4436	X 4 Cr Ni Mo 17-13-3	M =	- 27 °C
1.4439	X 2 Cr Ni Mo N 17-13-5	M =	- 127 °C
1.3974	X 2 Cr Ni Mn Mo N Nb 23-17-6-3	M =	- 388 °C

Accordingly, the steel 1.4310 has a lower, 1.4401 a sufficient, 1.4436 a considerably improved and 1.4439 as well as 1.3974 a very high austenitic stability. Under [11] permeability measurements yielded that cold worked strand wires consisting of 1.4401 show portions of deformation martensite as opposed to those consting of 1.4439 and 1.3974.

In Fig. 2 the strength values of the steel 1.4310 rise particularly after cold working. Here, the effects of strain hardening and the formation of martensite overlie. The stable austenitic steel 1.3974 has a very strong strengthening effect; here, precipitations of the nitrogen (0.4 % N) in particular contribute to the increase in strength. The most negligable strengthening of the steel 1.4401 occurs during the deformation which hardly contains any martensite and is not nitrogen alloyed. During cold working the material 1.4436 would show a similar behaviour.

+) Temperature in degrees C at which an originally austenitic steel shows 50 % of martensite in the texture after a 30 % deformation.

Hence the formation of deformation martensite has a positive effect on the strengthening behaviour of the wires. Nevertheless nowadays no steels unstable in their texture are used in manufacturing these products since the martensite portions in the austenitic texture have an adverse effect on the corrosion behaviour (Section 2.3).

3.3 Corrosion behaviour of the ropes

In rope construction some particularities must be observed which also concern their durability and in particular their corrosion behaviour:

- Mostly open air conditions will prevail. As a consequence ropes are weathered where they are exposed to aggressive effects such as acid and/or chloride salt containing aqueous media.

- The high strength cold worked steel wire in the rope is particularly susceptible to mechanical and chemical effects and therefore an durable corrosion protection (or, as in this case) a selection of sufficiently corrosion-resisting stainless steels must be taken into consideration.

- The wires in the rope are constantly tensioned with up to 42 % of their tensile strength and, in addition to that, they are transversely pressed in the anchorage areas and the saddle.

- For ropes dynamic loads can occur as a consequence of oscillations under load or from outside forces, such as wind. This can lead to remarkable amplitudes and stress cycles in the event of a longitudinal tensile force. In the concurrence of environmental influences and corrosion wire fractures can occur due to fretting and corrosion fatigue cracking. In normally light and wide span supporting structures rhythmic vortex shedding on ropes in laminar wind can lead to lateral vibrations which results in bending load strains and additional fretting at the anchorages. Rhythmic stresses caused by gusts of wind or from a series of heavy vehicles on bridges can entail lateral rope vibration. For instance in cable-stayed bridges the traffic and vortex shedding due to aeolian vibration can cause amplitudes up to appr. 100 N/mm^2 [14].

- The constructive design of the tension member, their fittings and other details (e. g. crevices) have an influence on corrosion and demand particular care.

The existing knowledge on corrosion of austenitic stainless steels, paying particular attention to the aspects already mentioned, is compiled in [4,15]. The particular behaviour of ropes made from cold-worked austenitic steel wires is dealt with in [4,11]. Some partial aspects as well as the latest findings are summarized in the following parts. It is assumed that high strength ropes made of stainless steel are most likely to be subjected to the danger of pitting and crevice corrosion, stress corrosion cracking and crack corrosion under dynamic load.

3.3.1 Pitting and crevice corrosion

Electrolytic, material and design influences are responsible for pitting and crevice corrosion to happen.

The initiation of pitting corrosion requires the presence of chloride ions. The susceptibility to corrosion decreases with falling chloride content, falling temperature and rising pH-value. Chloride enriched acid media are particularly critical. In pitting corrosion inducing aggressive agents not sufficiently high alloyed stainless steels can be particularly endangered by crevice corrosion.

On the material side the alloying elements chromium, but most of all molybdenum, but also nitrogen have a favourable effect on the pitting corrosion behaviour. Hence the corrosion resistance of the material 1.4436 in pitting corrosion inducing media is higher than that of 1.4401.

The corrosion resistance in pitting corrosion inducing media also depends on the surface quality and can thus be impaired by a surface treatment and also by cold working. In principle, the resistance against pitting corrosion of stainless steels is the better, the smoother and more homogenous the surfaces are. From a corrosion point of view the quality of the surface will increase somewhat in the order of oxidized - rough grinding - blasted - finish grinding - pickled - polished [16]. The corrosion resistance also increases in this sequence. Cold drawn round wires for ropes, comparable with finish grinding materials, show relatively smooth surfaces which has a positive effect with regard to hampering local attack.

The results concerning the effects of a stronger working on the pitting and crevice corrosion behaviour are not uniform as can be seen in the literature on the subject [15]. In some tests rather an increase of the susceptibility at rising cold working was found. Other tests, however, showed no influence of the cold working up to forming degrees of appr. 60 %.

The deformation martensite which is formed during deformation process of structural unstable stainless steels can most likely have an unfavourable influence on corrosion behaviour but will, however, lead to a higher susceptibility only under pitting corrosion conditions. In chloride enriched aqueous media a preferred selective corrosion of the martensite takes place which intensifies the pitting corrosion [17] and as a consequence can also lead to cracking. In an inert damp environment, oxygen free and oxygen containing water, in an SO_2-containing atmosphere and even at (low) chloride contents of 50 mg/l of an aqueous phase the resistance of austenitic types will not be impaired by deformation martensite [18]. Therefore it is recommended that as is the case with the materials 1.4401 and 1.4436, to form such steels to become high strength wires which due to their alloying content show a sufficiently high structural stability in the cold deformation process.

Under [11] a series of specific tests was carried out on pitting and crevice corrosion of steel strand (the simplest type of open spiral strands) made from high strength austenitic steel wires, i. e. the materials 1.4401, 1.4439 and 1.3974:

A storage of specimens took place in artificial climates with particular emphasis on extreme seawater and deicing salt conditions and conditions in an industrial atmosphere. Strand wires we stored up to 3 years under 100 % relative humidity and a temperature of 45 °C. By means of an atomizer a 0.5 % NaCl solution and/or SO_2 water of pH 3 were sprayed daily on the strand wire. Within 3 years all materials sustained without any visible signs of rust and also in the crevices between the wires there was no corrosion attack.

Furthermore steel strand sections with attached bodies (crevices) were exposed to a 3 year outdoor weathering in the maritime splash zone and in sea atmosphere on the isle of Heligoland and in an industrial climate on the roof of a metallurgical plant in Duisburg. Apart from the crevices the same favourable corrosion behaviour was found as previously described in the artificial climates. In the area of crevices only wires made from the steel 1.4401 and only after exposure in the splash zone showed a weak pitting corrosion (pitting depths < 50 µm).

Crevice corrosion lab tests in a NaCl solution and SO_2 water of pH 3 were carried out at ambient over a period of 4 years. In the test steel strand sections were immersed vertically to about one half in a cylindrical sampler containing a 3.5 % NaCl solution or SO_2 water of pH 3 respectively. At the top the sampler was sealed with a chlorinated rubber plug pushed over the steel strand. During the test, due to capillarity, the test solution rose within the strand and evaporated above the top side plug. This way the steel strand in the case of the saline was always surrounded by a highly over saturated saline in the crevice of the plug. In the test in SO_2 water there was no proof of corrosion effects in all 3 strand materials. After the test in a NaCl solution, however, the strand wires showed preferably local corrosion attack only in the upper contact area with the top-side plug. These attacks as a result of crevice corrosion under a prevailing extreme corrosion load due to upgraded chloride salines are only distinct on the material 1.4401 (pitting depth of up to 100µm). They were negligible low (< 10 µm) in the case of 1.4439 and non-existing on the material 1.3974.

3.3.2 Anodic stress-corrosion cracking

In structures under tensile load transcrystalline stress-corrosion cracking must be taken into consideration mainly for relevant sensitive chrome-nickel steels in chloride containing media. Rising chloride contents and temperatures as well as falling pH-values of the attacking electrolytes reinforce the attack. The nickel content has a considerable influence on the stress-corrosion cracking of stainless steels. The austenitic steels 1.4401 and 1.4436 with nickel contents of 12 or 13 % respectively used for ropes are considered to be sensitive to stress-corrosion cracking. Additions of molybdenum to the steel have a positive effect since frequently the stress-corrosion cracking acts at the initial state of pitting corrosion (pitting induced stress-corrosion cracking) whereas increasing additions of molybdenum hamper pitting corrosion.

In [15] a critical examination of the bibliography on the influence of cold working on the stress-corrosion cracking behaviour of stainless steels was carried out. Altogether, weaker degrees of deformation do not seem to exert a relevant influence on the construction. However, as in higher deformations, residual tensile stresses can occur in areas close to the surface which will suffice to initiate stress-corrosion cracking in the event of critical material or electrolyte parameters.

In accordance with tests [19] the stress-corrosion cracking behaviour of austenitic steels will be improved after cold working whereby rather a positive effect is adjudged to the deformation martensite being generated at higher degrees of deformation. But then a stable austenitic steel showed rather a decreasing resistance at a higher degree of deformation [20]. Other tests [21], however proved that a selective corrosion at martensite accumulations also may lead to cracking. Several damages that occurred in an indoor swimming pool atmosphere on stainless steel as a result of stress-corrosion cracking portions of martensite were found in the texture [22].

A stronger cold working as is required for the manufacture of high strength wires may altogether improve the stress-corrosion cracking behaviour of stainless steels by raising the threshold stress for the stress-corrosion cracking resistance. If, however, an assessment is made at a tension which shows a constant relation to the yield strength an unfavourable impression may possible ensue concerning the influence of cold working [23, 24].

As a result of these connexions austenitic steels are considered to be susceptible to chloride induced stress-corrosion cracking whereby the environmental influences must be given particular attention:

- So far no grave damages on austenitic steels due to stress-corrosion cracking under atmospheric corrosion load have been made known. Also the data collected at the hanging spiral strands of older projects (see below) did not show any relevant indications.

- Tests [11] with concentrated chloride solutions on cold worked wire of steel strand made of the material 1.4401 pitting induced stress-corrosion cracking under crevice corrosion conditions was found (Fig. 3) which was not on the wires made from 1.4439 and 1.3974. High concentrations of chloride may also occur in the building trade if a local upgrading happens as a result of evaporation processes. Under atmospheric conditions extremely high chloride concentrations due to the deposits of hygroscopic salts can be obtained. Dry salts vapour from the air which is liberated as liquid water near the saturation humidity which is characteristic of any salt [4]. During a weathering exposure (rain test) in open air the above-mentioned salt upgradings cannot happen.

- Indoor swimming pools offer a particular hazard where apart from the aforementioned salt upgradings also acidizing of aqueous fluid films can occur e. g. as a result of water treatment using the chlorine gas method. The collected data under [25] also noted damages due to stress-corrosion cracking on high strength austenitic steels.

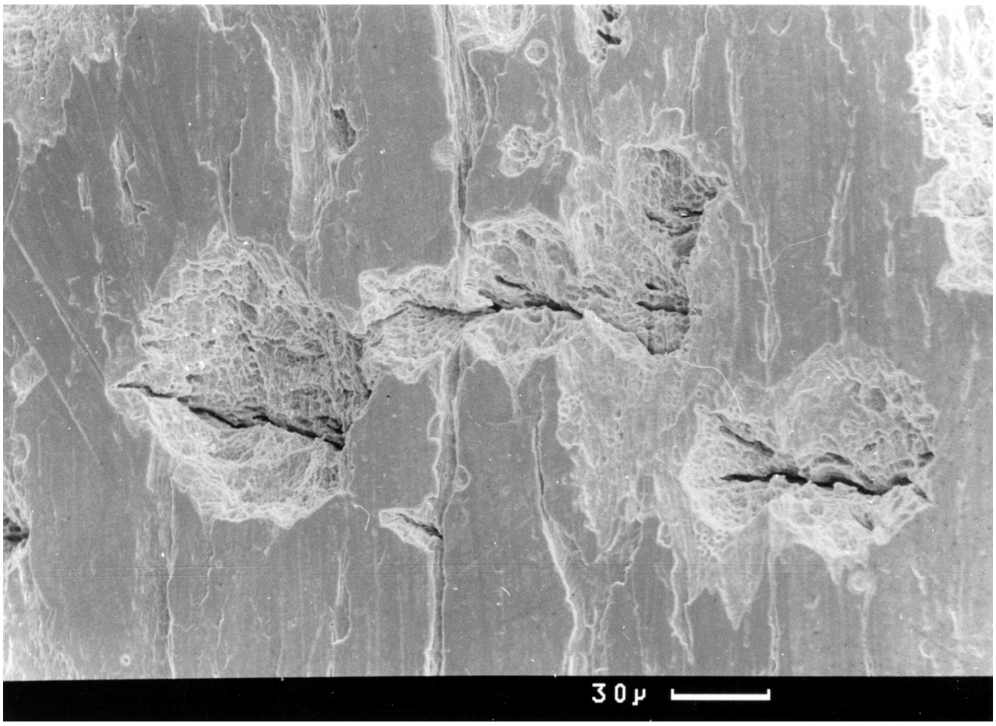

Fig. 3: Pitting induced stress corrosion cracking on a cold deformed steel wire made of stainless steel 1.4401 [11]

The fact that in the usual building practice, apart from special wear and tear as in indoor swimming pools and tunnels , no actual damages occur is due to normal weathering exposure not allowing any critical corrosion media (high concentrated acid chloride solutions) to build up.

The tests carried out and the data collected on crevice and stress-corrosion cracking thus were introduced into the new certification of ropes made from high strength stainless steel wires to the effect that ropes made of the material 1.4401 must be used only in structures without noticeable contents of chlorides and sulfur dioxide. The material 1.4436 is mainly reserved for ropes in environments with moderate chloride and sulfur dioxide contaminations.

3.3.3 Crack corrosion under dynamic load

Firstly, the dynamic behaviour of a rope is influenced by the properties of the wire (material, surface). Defects in the surface of a high strength wire severely degrade the fatigue strength. Fretting corrosion has a negative influence on the fatigue strength of the wires within the strand/rope. Fretting movements under pressure diminish the fatigue strength behaviour also at diversions, anchorages and cable clips.

In a natural environment fractures in the wires can occur under the effects of load changes and fatigue loads of the tension members as a result of

- fatigue (in dry air),
- fretting corrosion (in dry air and when attacked by aqueous media),
- corrosion fatigue (when attacked by aqueous media).

[4].

Fretting corrosion. Due to multiple influences the constantly high fatigue strength of the stainless steel individual wire [9] cannot be transferred to the final product "anchored strand/rope" [11]. Strands/ropes always have a much lower fatigue strength than the individual wires. This is attributable to additional loads on the wires after stranding and also to fretting movements among the wires under simultaneous transversal pressure and fatigue load. The surrounding air causes the fretting areas to oxidize and due to fretting corrosion and under fatigue load additional tensile loads will come up which constantly change their direction [26]. Furthermore at the fretting areas the metal texture will be locally disrupted by the interaction of mechanical and corrosive operations leading to initial cracking which, as sharp-edged notches, promote the generation of fatigue failures. There are a number of constructional influences such as anchorages and cable clips which permit to further reduce the bearable range of stress of tension members due to fretting corrosion. Since the force is gradually led into these components vibrations cause relative displacements with pressures between the strand/rope and the anchorage for instance (fitting on the open spiral strand). For this reason the inlet locations of the wires are in particular danger with regard to fretting corrosion and the initiation of fatigue failures.

Corrosion fatigue. The use of ropes in open air always requires an evaluation of corrosion fatigue under load [4]. The simultaneous interaction of a mechanical fatigue stress and an electrochemical corrosion stress reduces the number of cycles to failure found in air, i. e. without any influence of corrosion. An initiation of corrosion fatigue neither requires the specific sensivity of an alloy nor the specific properties of an electrolyte, and yet specifically effective ions in the aqueous attack medium such as Cl^- and/or H^+ will intensify the attack. The intensity of corrosion fatigue increases with a falling frequency of the vibration.

For the material it is true to say that with rising strength surface notches have an increasing negative effect. Alloying elements in the steel which intensify the passivity increase the corrosion fatigue strength under otherwise identical conditions. Therefore, as a rule, the fatigue strength in a corrosive medium is the higher the more corrosion resistant the material proves to be.

For an assessment of the corrosion fatigue behaviour of steel strand (single open spiral strands) made of high strength stainless steel wires under unfavourable atmospheric conditions in [11] and continuous evaluations under pulsating loads tests were carried out in chloride containing and/or acid atmospheric water (Fig. 4). As expected, the reaction was clearly better than that of steel strand in a comparative test made of high strength unalloyed steel wires. However, the strand did not react as favourably as can be expected of single wires. This has to do with the fact that under a dynamic load of the steel strand the corrosion fatigue is superimposed by a fretting fatigue due to fretting corrosion. With regard to fretting corrosion stainless steels react rather more sensitively than unalloyed steels so that the extremely positive behaviour of the single wire can only be carried over to the strand to a lesser extent. In high alloyed steels the initiation of active over regions on an otherwise passive surface is stimulated by fretting under transversal pressure.

The overall test results proved that even under most unfavourable environmental conditions and at a non-restive load the tolerable range of stress of a strand wire (i. e. an open spiral strand) made of high alloy steel can be set at a minimum of 100 N/mm^2.

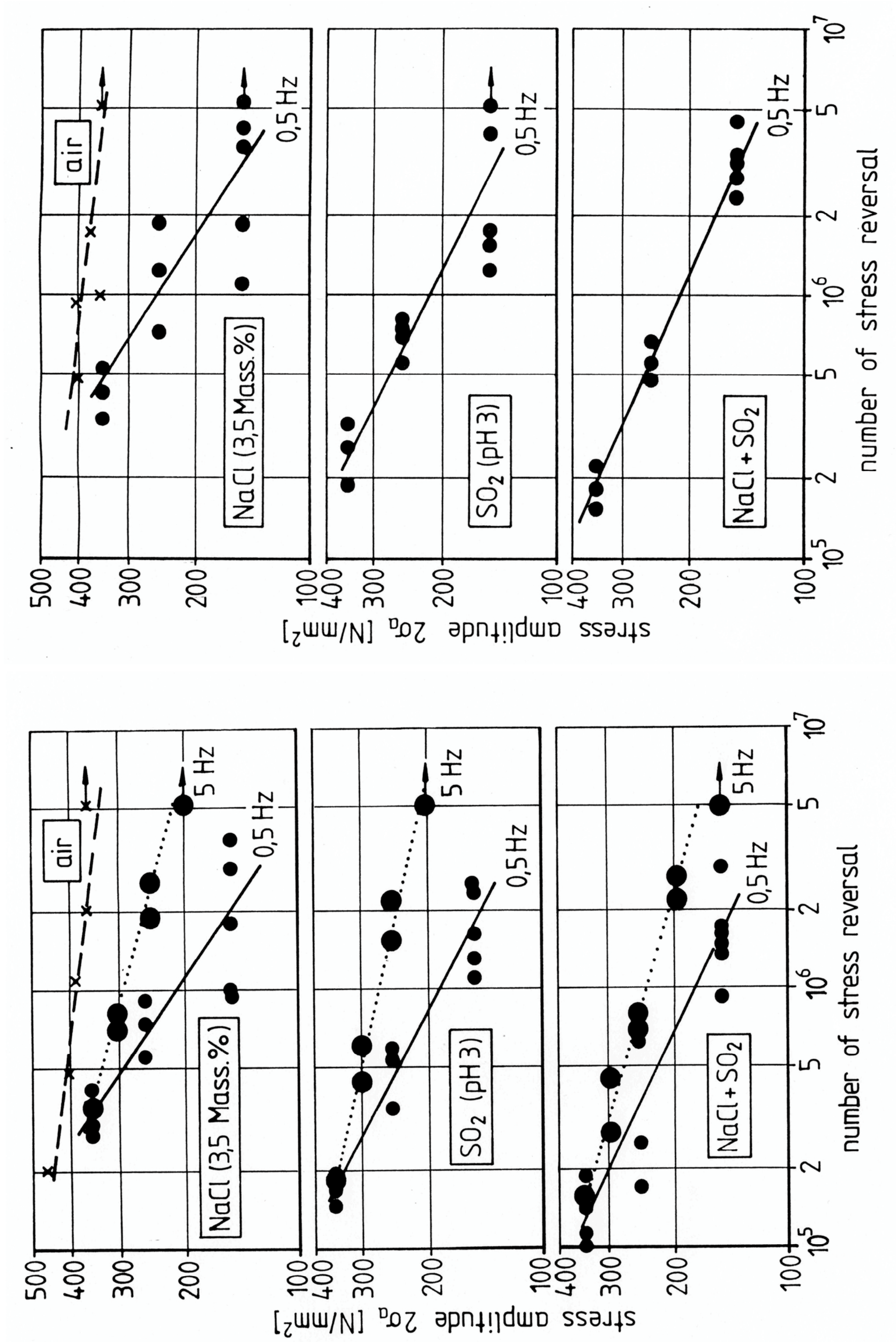

Fig. 4: Results of fatigue tests on high strength strands in air and corrosive media (frequency 0.5 and 5.0 s^{-1}) [11]

left: material 1.4401

right: material 1.4439

3.4. Pendant rope tests on older rope projects

Four up to 23 years old suspension bridges with suspended reinforced concrete footbridges were investigated in the Stuttgart urban area (Fig. 5 above). The main carrying ropes are fully locked-spiral ropes. The corrosion protection consists of a hot-dip galvanizing of the wires and a duplex coating of the rope. The attached pendant ropes for fixing the reinforced concrete slabs are spiral strands made from the materials 1.4401 or 1.4436. The anchorages and other fittings are cast steels made from the material 1.4462. Three of the footbridges span highly frequented federal highways undergoing deicing salt treatment in wintertime. One bridge crosses the Neckar river. The investigated strand segments and fittings are installed just as a few metres above the road surface and thus in the entrance region of deicing salt spray.

In all cases, apart from so-called "bleedings" on open pores of the cast fittings, no essential corrosion effects were found. The strands look virtually new (Fig. 5 below). This even applies to strands made from 1.4401 the 23 years-old "Rosensteigsteg" which spans the highly frequented federal highway B 14. Also in the entrance region of strands in fittings no signs of crevice corrosion were found.

4. EVALUATION

The tests conducted justify the use of strength class S 1100 spiral strands made from the material 1.4436 under moderate chloride and sulfur dioxide load. The findings gained from tension members made of high strength stainless steel wires seem to indicate that strength class S 1100 strands made from the material 1.4401 should only be used in constructions of negligible chloride and sulfur dioxide contents. This assessment takes into account the behaviour compared with the most important types of corrosion such as pitting and crevice corrosion as well as stress corrosion cracking under the known marginal conditions for tension members in accordance with DIN 18800 part 1. The more conservative rating of the material 1.4401 compared to the material 1.4436 is due to the fact that the material 1.4401 in the strength class S 1100 in the presence of chloride salts and their upgrading in cracks is not sufficiently safe against crevice corrosion and stress corrosion cracking.

Fig. 5: Open spiral strands of a suspension bridge with suspended reinforced concrete foot-bridge

The load on the strands is preferably static. In rare cases of a non-static stress amplitudes clearly under 100 N/mm^2 must be expected. Ropes made of the materials 1.4401 and 1.4436 will reach this stress value even under a high corrosion load due to chlorides and sulfur dioxide.

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