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INNOVATION

CORROSION BEHAVIOUR OF DISC SPRINGS

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INTRODUCTION

When advice is offered on the use of disc springs, questions about environmental conditions with corrosive attack come up regularly, but in many cases, they can only be addressed very speculatively. Therefore, especially when durability must be guaranteed over a long period of time, it makes sense to proceed with a field test.

When specifying a disc spring under corrosive conditions, the load spectrum must be analysed precisely: corrosion medium, temperature, static or dynamic stress, friction and wear on contact sites, and the way they change over time. When selecting a material, in addition to the ideal material properties, the actual existing properties of the starting material play a large role, and then become the decisive selection criteria. Other material concepts, such as the coating of materials that are not resistant to corrosion, may then be of interest. In the transition to such alternative solutions, the differences that emerge in a direct comparison are then of interest.

This article describes the results from a research proposal conducted as AVIF Project Number A 210, ‘Investigations of the corrosion behaviour of disc springs and disc spring stacks’, advised by the Spring Association (VDFI), Subcommittee on Disc Springs, via the Technical University of Darmstadt, Institute for Materials.

Systematic results on the behaviour and durability of disc springs under application-related corrosive conditions were to be determined.

DISC SPRING VARIANTS, CORROSION MEDIA AND TEST METHODS

Table 1 lists the disc spring variants that were studied. In addition to the conventional grades of stainless spring steel in various production variants, 51CrV4 steel was also studied with various coatings.

Table 1: Disc spring variants studied

No.	Material	Dimensions	Production
01	1.4310	63 x 31 x 1,9 x 4,15 **(C)**	Punched **(S)** + turned **(D)**
02	1.4310	63 x 31 x 1,9 x 4,15 **(C)**	Punched **(S)** + turned **(D)** + shot-peened **(K)**
03	1.4310	80 x 41 x 3 x 5,3 **(B)**	Punched **(S)** + turned **(D)**
04	1.4568	63 x 31 x 1,8 x 4,15 **(C)**	Punched **(S)** + turned **(D)**
05	1.4568	63 x 31 x 1,8 x 4,15 **(C)**	Punched **(S)** + turned **(D)** + shot-peened **(K)**
06	1.4568	63 x 31 x 1,8 x 4,15 **(C)**	Punched **(S)** + turned **(D)** + Kolsterised
07	1.8159	63 x 31 x 1,8 x 4,15 **(C)**	Mechanically zinc-plated + yellow chromatised + sealed
08	1.8159	63 x 31 x 1,8 x 4,15 **(C)**	Mechanically zinc-plated + transp. chromatised + sealed
09	1.8159	63 x 31 x 1,8 x 4,15 **(C)**	Coated with Dacromet 500
10	1.8159	63 x 31 x 1,8 x 4,15 **(C)**	Coated with Geomet
11	1.8159	63 x 31 x 1,8 x 4,15 **(C)**	Delta Tone (2x) + Delta Seal (2x)-coated
12	1.8159	63 x 31 x 1,8 x 4,15 **(C)**	Chemically nickel-plated
13	1.8159	63 x 31 x 1,8 x 4,15 **(C)**	Lacquered with water-thinnable paint
14	1.8159	63 x 31 x 1,8 x 4,15 **(C)**	Oiled

MATERIALS

51CrV4 (1.8159) is a ferritic steel suitable for the production of spring components of every kind and acceptable for the use of all DIN springs. The alloy supplements allow, in the case of greater material thicknesses, and after tempering, the formation of a uniform structure over the entire cross-section. In addition, the alloy components had a positive effect on the relaxation behaviour.

X10CrNi18-8 (1.4310) and **X7CrNiAl17-7** (1.4568) are, according to DIN EN 10 151, rust-resistant spring steels that are distinguished by their special resistance against chemically corrosive substances. They acquire their spring abilities through work hardening and/or heat treatment. **X10CrNi18-8** (1.4310) achieves its strength only via cold forming and is therefore generally used only up to a thickness of 2 to 2.5 mm. Depending on cold forming grade, the cold forming begins to decrease significantly at about 100°C. These materials should therefore not be used at higher temperatures.

The material **X7CrNiAl17-7** (1.4568), up to a thickness of 2.5 mm (at larger quantities up to 3.0 mm), is subjected to a simple hardening (annealing at 480°C) in addition to coldforming, which enables high thermal stability up to 350°C. The increase in stability achieved via annealing has the advantage that for the same final strength, less cold sforming is required than for X10CrNi18-8 (1.4310). This has a positive effect on the corrosion behaviour. This material state was used in the present study.

The material X7CrNiAl17-7 (1.4568) is processed in thicknesses > 2.5 mm (3 mm) in the soft solution-annealed state. The necessary strength is then achieved through a double annealing procedure (structure tempering). Since the first annealing must occur at a temperature of 760°C, chrome carbide is precipitated selectively at the grain boundaries. The corrosion resistance of this material state is thus substantially minimised. Springs in the structure-annealed state should only be used when hot strenght is required.

COATINGS

The coatings for the disc spring variants from 1.8159 are listed in the following table. The selected types are oriented toward actual usage and have properties proven by experience. The coatings were applied without phosphating.

Coating	Layer thickness
Mechanically zinc-plated + yellow chromatised + sealed	≧ 8 µm
Mechanically zinc-plated + transp. chromatised + sealed	≧ 8 µm
Coated with Dacromet 500	≧ 5 µm
Coated with Geomet	≧ 8 µm
Delta Tone (2x) + Delta Seal (2x)-coated	≧ 14+4 µm
Chemically nickel-plated	≧ 25 µm
Lacquered with water-thinnable paint	≧ 15 µm

Table 2: Coatings for the disc springs from 1.8159 and layer thicknesses

MECHANICAL ZINC PLATING

The most frequently used zinc plating process for disc springs is pellet plating. In this type of zinc plating, the parts are provided with a thin copper layer after careful cleaning in a dipping process (currentless), then the parts are stirred in a drum together with zinc powder and glass pellets of different sizes while a promoter is added. The treatment is terminated after a specified time, by which 95–98 % of the added zinc is plated onto the disc springs. Finally, the parts are chromatised in a chromate solution. The effectiveness of chromate coating decreases again at temperatures over 60 °C. When the process is applied skilfully, hydrogen-induced embrittlement of the piece being worked is negligible.

DACROMET COATING

Dacromet is an inorganic, metallic, silvery-grey coating of zinc and aluminium layers in a chromate compound (which contains CrVI). The lamellar structure can reduce the advance of corrosion perpendicular to the surface through horizontal deflection (diagram below).

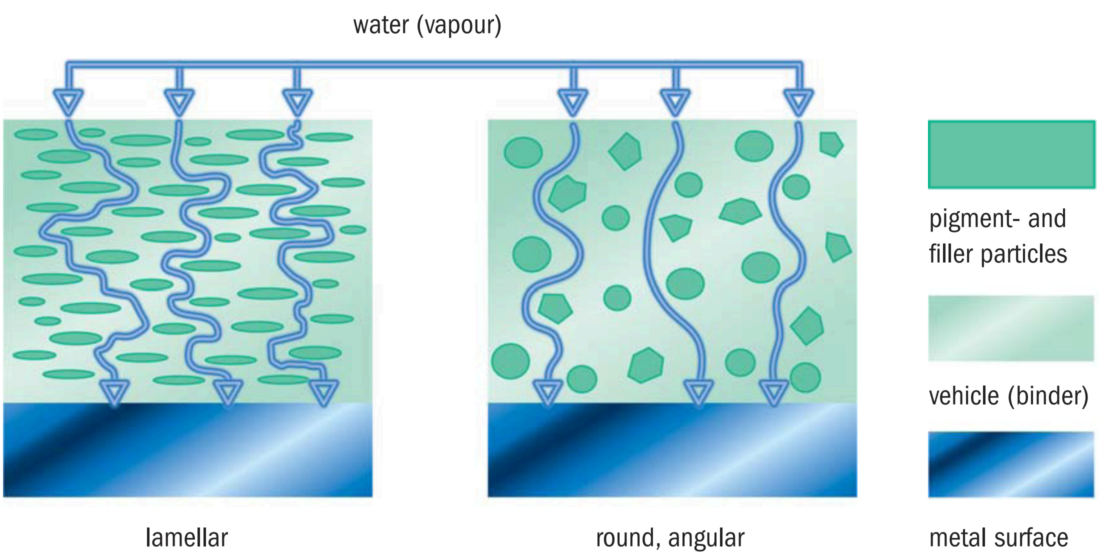


Figure 1: Diagram of diffusion of water in pigmented lacquer [1]

The components are treated as single of bulk goods and the coating is then burned in at temperatures < 280°C. Dacromet-coated springs display very good resistance in the salt spray fog test. In the conventional process, i.e., without pretreatment with an etchant, hydrogen embrittlement is completely precluded.

The springs are dipped in a metallically pure state into an aqueous dispersion of zinc flakes, chromic acid, and various organic components. The layer is burned in at high temperatures. This process can be repeated multiple times, which can create layer thicknesses of about 6, 8, or 12 µm for single, double, or triple applications, respectively. After a double application, the corrosion resistance in the salt spray test according to DIN 50 021 SS amounts to more than 240 h.

GEOMET COATING

As an alternative to the Dacromet product line, which contains chrome (VI), the Geomet coating has been developed. The goal was to achieve the same corrosion-resistant properties as for the Dacromet coating, which contains chrome (VI). Analogous to the Dacromet and Delta Tone coating, this is a coating that is not electrolytically applied, consisting of zinc and aluminium layers and a mineral seal that can also be provided with an organic coating. There is no danger of hydrogen embrittlement.

DELTA TONE + DELTA SEAL COATING

Similar to the Dacromet coating, this is an inorganic metallic pigmented coating material that, thanks to feasible cathode protection of steel, has been developed as an alternative to galvanic or mechanical zinc coating. After burning in the solvent-containing coating, applied like paint (the metallic particles are cross-linked with an inorganic binding agent at 200°C for 15 min), silvery-metallic coatings are produced.

For a large number of applications, Delta Tone with or without organic sealing achieves extremely good corrosion protection. There is no danger of hydrogen embrittlement.

- Resistance in salt spray test according to DIN 50 021: 1000 h
- Resistance in Kesternich test according to DIN 50 018: 15 cycles
- Resistance in condensation water test according to DIN 50 017: 1000 h

The so-called »base coat« of Delta Tone, which contains Zn and Al, can be applied like paint in layer thicknesses between 5 und 12 µm. In the hardened state, organic components are no longer present in the coating, capable of isolating the metallic pigments.

The organic »top coat« of Delta Seal works to isolate and protect against contact corrosion, and is resistant to acids and alkalis. The frictional resistance can be reduced by application of solid lubricants.

CHEMICAL NICKEL PLATING

Nickel layers are generally used for precisely defined applications to protect against corrosion or wear, or for cosmetic reasons. In this context, chemical nickel plating is used for disc springs. In this process, the coating material is created as nickel-phosphorus alloys. The level of phosphorus content affects the behaviour of the coating. The best corrosion resistance and best ductility are achieved at 10–13 % phosphorus. With decreasing phosphorus content, the resistance to wear increases and the resistance to corrosion decreases. Since hydrogen is produced as a side reaction during the deposition process, hydrogen embrittlement cannot be completely precluded.

The following table gives an overview of the conventional coating process and its resistance in the salt spray fog test according to DIN 50 021.

Process	Layer composition	Layer thickness [µm]	Resistance in salt spray fog test according to DIN 50 021 [h] 200 400 600 800 1000
Burnishing	Metal oxide + oil	0,5 – 1,5	
Phosphatising	Zinc phosphate + oil	10 – 15	
Phosphatising	Zinc phosphate + wax	ca. 10 – ca. 40	
Galvanic zinc-plating	Zinc	≧ 8	
Galvanic zinc-plating	Zinc	≧ 12	
Galv. zinc-plating + yellow chromat.	Zinc + chromium	≧ 8	
Galv. zinc-plating + yellow chromat.	Zinc + chromium	≧ 12	
Mech. zinc-plating	Zinc	≧ 12	
Mech. zinc-plating + yellow chromat.	Zinc	≧ 12	
Delta Seal	Zinc ph. + org. layer + oil	10 – 15	
Delta Tone	Zinc ph. + zinc powder coat.	10 – 15	
Chemical nickel-plating	Nickel	ca. 25	
Dacromet 500-A	Chromat. zinc lamellae	≧ 5	
Dacromet 500-B	Chromat. zinc lamellae	≧ 8	

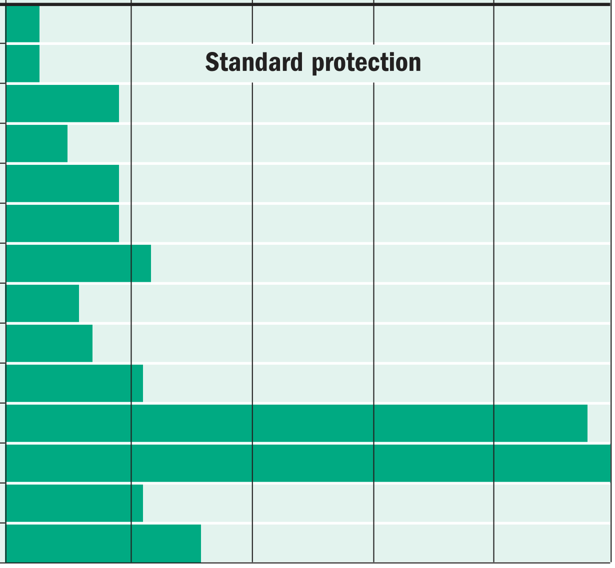


Table 3: Relative estimate of corrosion protection and its resistance in the salt spray fog test [2] achievable for various processes

CORROSION MEDIA

The environmental media shown in Table 4 were used in the study. Six media with different character were selected to form conditions close to those encountered in practice, found frequently in experiments.

Saturated artificial seawater atmosphere simulates environmental conditions in a marine environment. Disc springs often serve for pretensioning bridges or sluice gates in the vicinity of the sea. For the studies, artificial seawater according to DIN 50905, which has a standard salt content of 3.5 % and a pH value in the range from 7.8 to 8.2, was thus used.

The 3% NaCl solution represents, for instance, work conditions in car industry. In that context, disc springs come into contact with chloride-containing solution through the use of road salt in winter. In order, in addition, to study the effect of chloride concentration on the corrosion behaviour on disc springs, the 40 % $MgCl_2$ solution was also included in the study programme, since $MgCl_2$ salt is easier to dissolve at room temperature.

Further applications for disc springs can also be found in the food industry. For machines and plants in the food industry, corrosion attacks come not only from possible aggressiveness of the material being processed, but often also through intensive cleaning of the devices with acidic or

Media	pH	Conductivity [mS/cm]
Saturated **sea water atmosphere**	7,80	52,70
40%ige $MgCl_2$ solution (magnesium chloride)	5,02	140,60
3%ige NaCl solution (sodium chloride)	5,29	42,40
0,1 N NaOH (sodium hydroxide)	12,90	19,77
0,1 M citric acid ($C_6H_8O_7$	2,09	2,90
Deionised water	7,40	0,002

Table 4: Environmental media for the studies

alkaline solutions. The 0.1 normal NaOH and 0.1 molar citric acid are to be considered as representative of alkaline and acidic media.

Deionised water is desalinated water with low conductivity and was used as a neutral reference medium.

CORROSION TESTING PROCEDURES

In the research proposal, the following study procedures were used and several results are shown here:

- Immersion experiments without stress
- VDA alternating test
- Electrochemical experiments *
- Stress corrosion crack experiments with constant stress
- Strain-induced stress corrosion crack experiments
- Fatigue crack corrosion experiments
- VDA alternating tests with mechanical stress
- Accompanying experiments (metallographic experiment, raster electron microscopic experiment, residual stress measurement)*

The experiments indicated with * are not cited in this report.

Since the immersion experiments are not normalised, the standardised VDA alternation test [3] was incorporated as an addition to the experimental programme.

IMMERSION EXPERIMENTS

The immersion experiments show the corrosion behaviour of the disc spring variants under simple corrosive attack. The visual manifestations of corrosion on the disc spring are observed over the course of the experiment (4 weeks) and a first qualitative impression of the corrosion resistance of the disc springs in the various media is obtained.

The experiments were carried out at room temperature and without introduction of air into the medium. The test specimens were hung such that they extended halfway into the medium and were not stressed mechanically or electrically. Only the visual manifestations of corrosion were observed, since in practice, the disc springs mostly break due to stress corrosion cracking or corrosion fatigue, and local corrosion is more important. Thus, no evaluation was made of the loss of weight.

Table 5: Summary of results of immersion experiments

Tellerfedervarianten	40 % $MgCl_2$	3 % NaCl	0,1 n NaOH	0,1 m acid
1.4310/C/S + D	★	☆	☆	☆
1.4310/C/S + D + K	★	☆	☆	☆
1.4310/B/S + D	★	☆	☆	☆
1.4568/C/S + D	★	☆	☆	☆
1.4568/C/S + D + K	✪	★	☆	☆
1.4568/C/S + D + kolsterised	●	✪	☆	☆
Mechanically zinc-plated + yellow chromatised	☆	✪	☆	●
Mechanically zinc-plated + transparently chromatised	☆	★	☆	●
Dacromet-coated	☆	☆	☆	●
Geomet-coated	☆	☆	☆	●
Delta Tone + Delta Seal	☆	★	☆	✪
Chemically nickel-plated	✪	✪	☆	✪
With water-dilutable paint	☆	☆	★	✪
Oiled	●	●	☆	●

☆ – good
★ – moderate
✪ – poor
● – very poor

Figure 2:
Experimental setup for immersion experiments

RESULTS OF THE IMMERSION EXPERIMENTS

To provide an overview of the results, they have been evaluated according to the following scheme and listed in Table 5:

Good: no recognisable visual manifestation of corrosion
Moderate: low manifestation of corrosion (as dots)
Poor: covered with thin layer of corrosion product (as blotches).
Very poor: covered with thick layer of corrosion product (overall an area).

Since within the immersion experiment the disc springs are only attacked corrosively (without mechanical or electrical stress), the results of the immersion experiments form a basis for evaluating the corrosion behaviour of the disc springs under complex stress.

Stainless steels 1.4310 and 1.4568 corrode in the 40 % $MgCl_2$ solution. Shot-peening improves the behaviour somewhat for 1.4310, but for 1.4568, it degrades it. Kolsterising also has a negative impact for 1.4568.

The coated disc springs have better corrosion resistance in 40 % $MgCl_2$ solution than do springs from stainless steels, with the exception of chemically nickel-plated variants. The chemically nickel-plated variant is prone to blemishes in the layer in the form of pores.

The steel springs that have merely been oiled only exhibit short-term corrosion protection and do poorly.

In 3 % NaCl solution, the springs of stainless steel behave better than those in 40 % $MgCl_2$ solution, but the coated springs perform worse, in part. The springs coated with Zn behave better in the solution with high Cl content due to the formation of a layer of Simonkolleite ($Zn_5[(OH)_8Cl_0]\cdot H_2O$).

None of the studied disc spring variants corroded in 0.1 N NaOH, since a thick protective layer formed. The water-dilutable paint dissolved in 0.1 N NaOH.

For disc spring applications in acids, stainless steels should be used, since they showed good resistance here. The Zn coatings react with the acid and dissolve at different speeds. Due to the pores in the layer, the chemical nickel-plating also shows poor effectiveness.

VDA ALTERNATING CORROSION TEST

The VDA alternating corrosion test is a recognised and frequently used process for studying corrosion, especially in the automobile industry. Since the immersion experiments are not normalised, the standardised VDA alternation test [3] was also incorporated into the experimental programme as a recognised and frequently used process for studying corrosion, especially in the automobile industry.

One cycle of the VDA alternation test according to VDA test sheet 612-415 consists of [4]

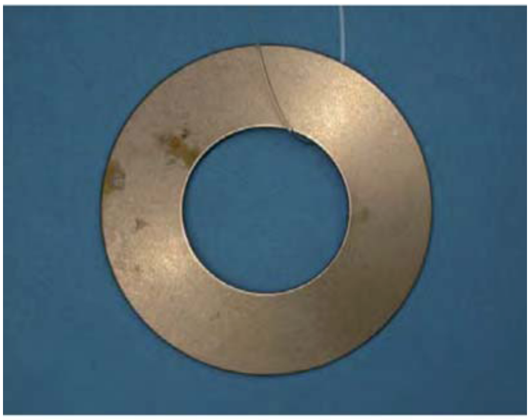
- 24 hour salt spray fog test according to DIN 50021 at 35°C
- 96 h condensed water test according to DIN 50017 KFW at 40°C
- 48 h standard atmosphere according to DIN 50014

In the salt spray chamber, the individual disc springs were simply hung from rods. The test lasted for 4 VDA cycles (four weeks). The important evaluation criterion here is the intensity of visual manifestation of corrosion.

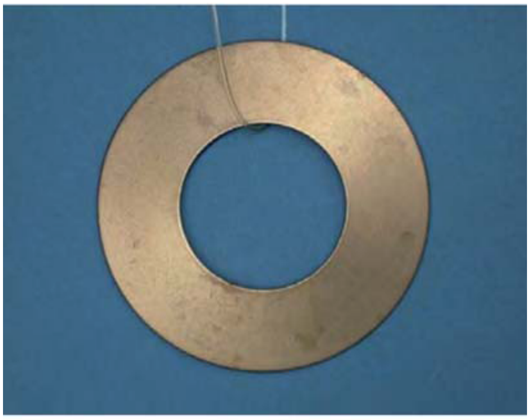
RESULTS OF THE VDA ALTERNATION TEST AND DISCUSSION

Fig. 3 shows all 14 tested disc spring variants after 4 VDA alternation test cycles. No corrosion can be seen in the shot-peened disc spring composed of 1.4310; on the other two variants, a low number of brownish spots can be found, similar to the non-shot-peened disc spring variant composed of 1.4568. The shot-peened variant composed of 1.4568 behaves somewhat worse, but the difference is very low. Thus, after the four-week regular experimental time span, these five variants were left for a further 9 weeks in the salt spray chamber. The Kolsterised variant composed of 1.4568 displays the worst resistance to corrosion among the disc spring variants composed of the various stainless steels. The spring is almost fully covered with a large number of deep rust-brown spots.

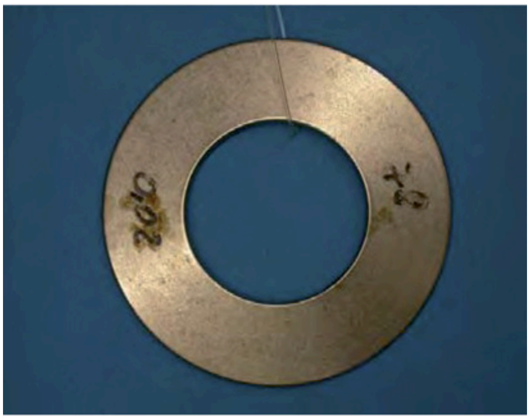
Figure 3: Visual manifestation of corrosion on the disc springs after 4 cycles of the VDA test



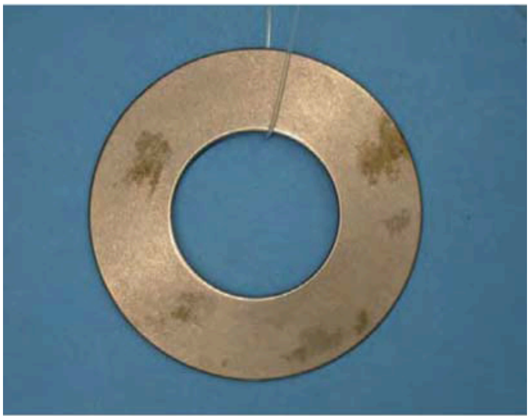
1.4310 / C / S + D



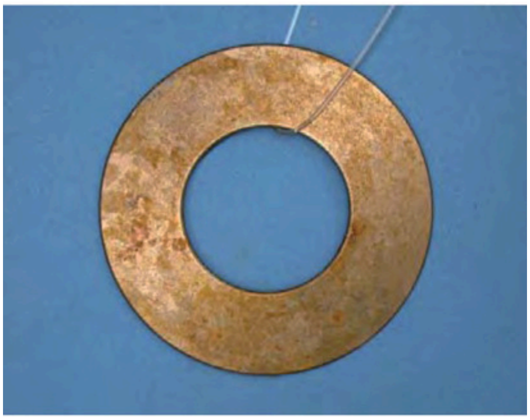
1.4310 / C / S + D + K



1.4310 / B / S + D



1.4568 / C / S + D



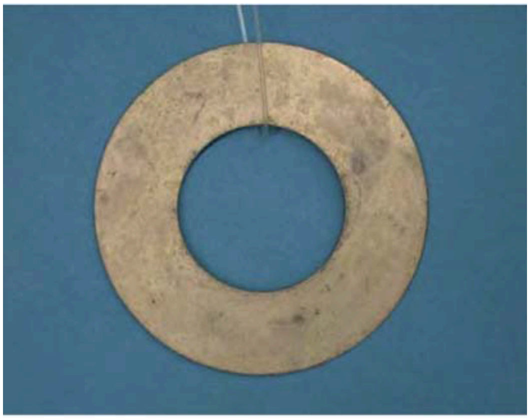
1.4568 / C / S + D + K

1.4568 / C / S + D + Kolsterised

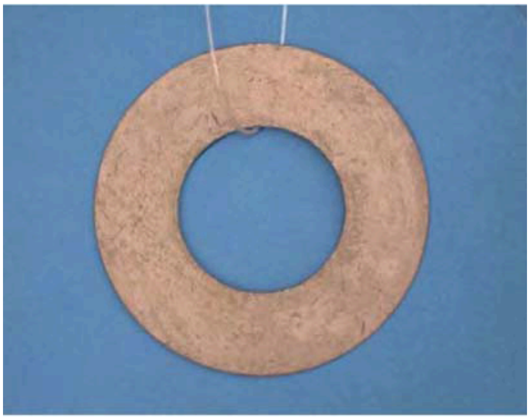
Figure 3: Continuance

Mechan. zinc-plated + yellow chrom.

Mechan. zinc-plated + transp. chrom.

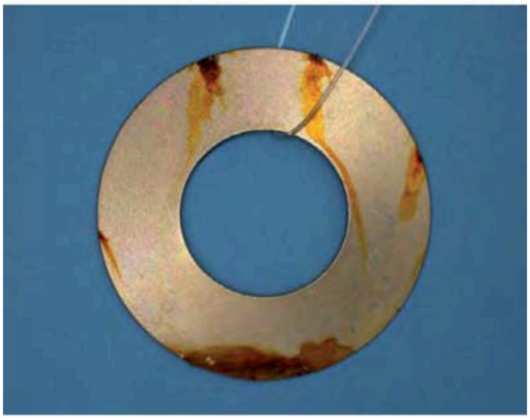


Dacromet-coated

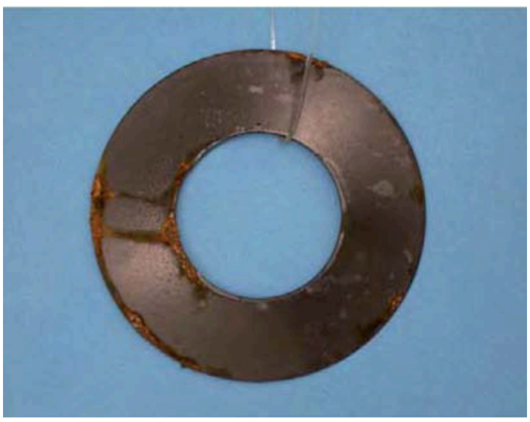


Geomet-coated

Delta Tone + Delta Seal

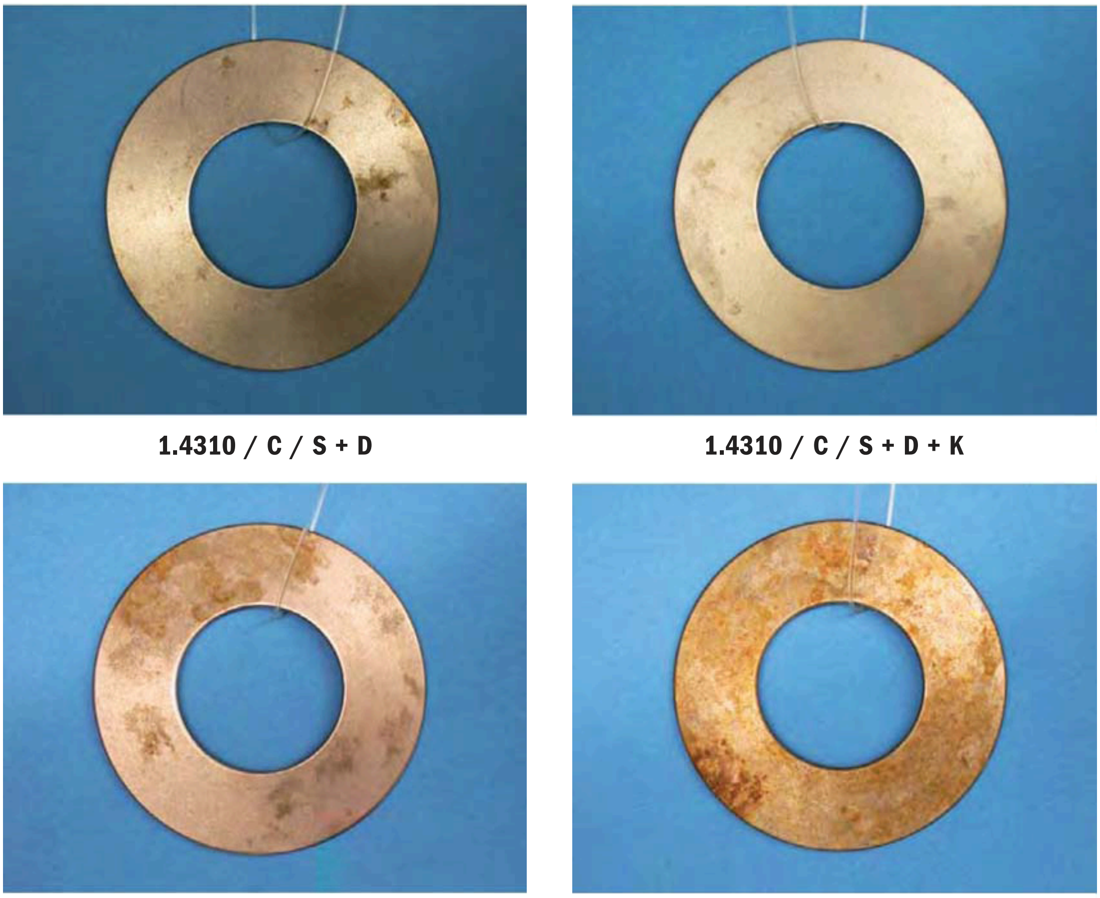


Chemically nickel-plated



Water-dilutable painted

Oiled



1.4310 / C / S + D

1.4310 / C / S + D + K

1.4568 / C / S + D

1.4568 / C / S + D + K

Figure 4:
Visual manifestation of corrosion on the disc springs after 13 cycles of the VDA test

Table 6:
Comparison of results from the immersion experiments and VDA alternation tests [6]

☆ – good
★ – moderate
✪ – poor
● – very poor

+2: 2 levels better
–2: 2 levels worse, etc.

Disc spring variants	VDA alternation test	3 % NaCl	40 % $MgCl_2$
1.4310/C/S + D	☆	0	+1
1.4310/C/S + D + K	☆	0	+1
1.4310/B/S + D	☆	0	+1
1.4568/C/S + D	★	-1	0
1.4568/C/S + D + K	✪	-1	0
1.4568/C/S + D + Kolsterised	●	-1	0
Mechanically zinc-plated + yellow chromatised	●	-1	-3
Mechanically zinc-plated + transparently chromatised	✪	-1	-2
Dacromet-coated	☆	0	0
Geomet-coated	☆	0	0
Delta Tone + Delta Seal	★	0	-1
Chemically nickel-plated	✪	0	0
With water-dilutable paint	✪	-2	-2
Oiled	●	0	0

The Dacromet- and Geomet-coated steel disc springs do not corrode like the shot-peened disc spring composed of 1.4310. The Delta Tone + Delta Seal coated disc spring was attacked by the corrosion medium, forming a large number of white spots, meaning that the base material of 1.8158 did not corrode. The mechanically zinc-plated disc spring variants behave even worse. The yellow chromatised variant was covered with a large number of deep rust-brown spots, and the transparent chromatised variant by a small number of rust-brown spots and a large number of white spots. The problem with blemishes in the coating on the edges appears in the chemically nickel-plated and the spring with water-thinnable paint. A moderate number of rust-brown spots indicate that the base material has corroded. The disc spring variant that has only been oiled behaves the worst and displays heavy surface corrosion.

In Table 6, the results from the VDA alternation test and from the immersion experiments in 40 % $MgCl_2$ solution and in 3 % NaCl solution are compared with each other. The three experiments are similar in that they involve a chloride-containing solution and the presence of oxygen. They differ in concentration and experimental temperature. The high concentration of chloride can foster corrosion by destroying the protective layer formed in air, such as for the disc spring variants composed of stainless steels, or inhibit corrosion by forming the Simonkolleite layer, as for the disc spring variants coated with zinc.

A high oxygen concentration has the same effect: for the disc spring variants composed of stainless steels, it prevents progressive corrosion by forming an oxide layer, while at the same time, it accelerates the rate of corrosion via participation in reaction [5]. Thus it is recommended that each metal/medium/stress combination be regarded as its own system and treated separately. During the VDA alternation test, the hung disc springs receive significantly more oxygen than during the immersion experiment, but less chloride, since according to VDA test sheet 612-415, they have direct contact with the salt spray fog for only 24 hours per cycle (7 days).

Figure 4 displays photographs of stainless steel disc springs after 13 cycles of the VDA alternation test. The disc spring composed of 1.4568, turned and especially shot-peened, is somewhat worse than the variants composed of 1.4310.

SUMMARY OF VDA ALTERNATION TEST

Despite the large supply of oxygen, the disc springs composed of 1.4310 and the Dacromet and Geomet-coated disc springs display very good resistance to corrosion. The disc springs composed of 1.4568 are somewhat worse than those composed of 1.4310. The Kolsterised, the mechanically zinc-plated, and the oiled-only disc springs behave significantly worse in the VDA alternation test.

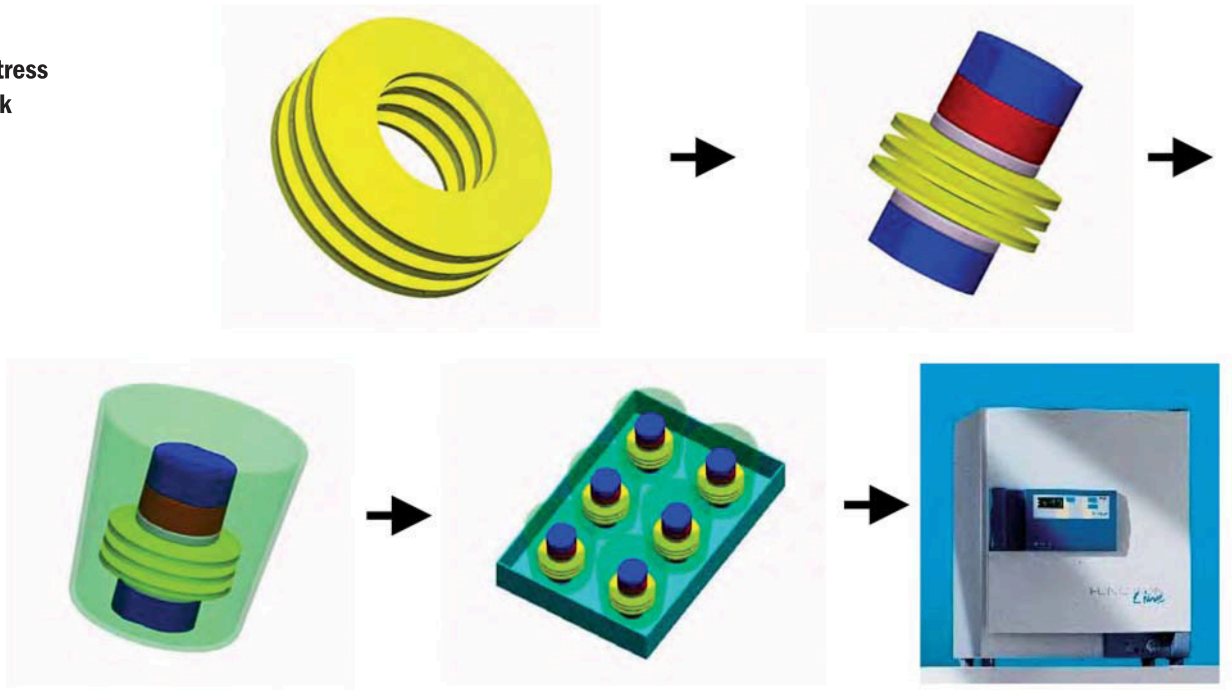
STRESS CORROSION CRACK EXPERIMENTS

In the stress corrosion crack experiments, the corrosion effects are studied in combination with static mechanical stress. The disc springs are first placed under tension as 6 x 1 or 4 x 2 disc spring stacks and then immersed in the corrosion medium. Newly designed test equipment for tension ensures that the disc springs do not undergo contact corrosion. Like the immersion experiments, the stress corrosion crack experiments are not standardised, so the VDA alternation test is also performed with mechanical stress. In addition, strain-induced stress corrosion crack experiments are carried out. In these experiments, the experimental temperature of the disc spring stacks under tension is changed slowly from 40 °C to 80 °C and back in order to test the behaviour induced by temperature oscillations.

EXECUTION OF THE STRESS CORROSION CRACK EXPERIMENTS

The preparation of the stress crack corrosion experiments runs according to the following steps (Figure 5): Cleaning, applying tension as 6 x 1 or 4 x 2 stacks on a special device for $0.2h_0$, $0.4h_0$, $0.6h_0$ or $0.8h_0$, placing the stacks in a sealed glass container (Figure 6) with the corrosion medium, and storing in a heated container at 40 or 80 °C. The test specimens were examined daily, and the corrosion solution was refreshed every 2 weeks. If a fracture developed in a spring, the experiment was terminated.

Figure 5: Steps in the stress corrosion crack experiments



RESULTS OF STRESS CORROSION CRACK EXPERIMENTS AND DISCUSSION

When stress corrosion cracking occurs, disc springs principally fail due to crack formation. Thus, the lifespan of the disc spring column until it fractures is considered the most important characteristic for evaluation here. To analyse the effect of the coating, the experiments were performed on a 6 x 1 coated disc spring column as well as on a 4 x 2 coated disc spring column.

CORROSION BEHAVIOUR OF 6 X 1 STACKED DISC SPRING COLUMN

In the experiments it was determined that temperature and stress are the decisive factors for the lifespan of the spring. Higher temperature means a higher corrosion rate; the bending tension in the disc spring is decisively responsible for crack formation.

The extent of (local) bending tension depends not only on the pretension, but also on the notch effect from the corrosion-induced notch. In addition to these, there are other factors, such as the condition of the surface, possible flaws in the material, and the production state of the disc springs, which can determine the mechanism of crack formation. The experiment results thus displayed a relatively large spread, so the experiments were repeated as often as possible. In each case, the shortest lifespan was selected for evaluation. After 2500 h, the experiments in which no fracture had occurred were terminated and treated as the limit of resistance.

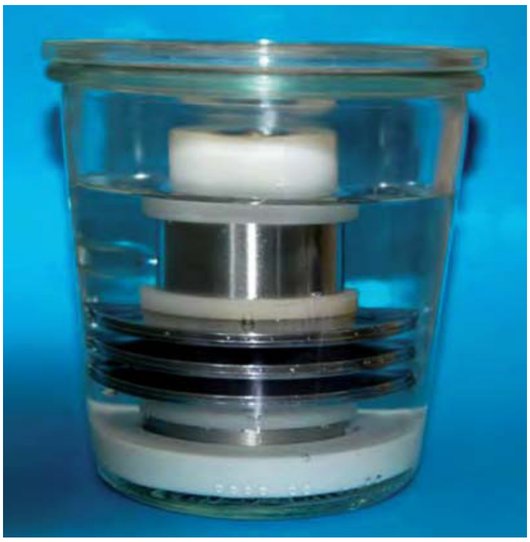


Figure 6: disc spring stack under tension in glass container

Disc spring variants	Seawater	$MgCl_2$	NaCl	NaOH	Säure
1.4310 / C / S + D	>2500h	356h	>2500h	>2500h	>2500h
1.4310 / C / S + D + K	>2500h	429h	>2500h	>2500h	>2500h
1.4310 / B / S + D	>2500h	1968h	>2500h	>2500h	>2500h
1.4568 / C/ S + D	>2500h	140h	>2500h	>2500h	>2500h
1.4568 / C / S + D + K	>2500h	140h	>2500h	>2500h	>2500h
1.4568 / C / S + D + kolsterisiert	284h	2177h	>2500h	>2500h	>2500h
Mechanically zinc-plated + yellow chromatised	912h	>2500h	>2500h	>2500h	68h
Mechanically zinc-plated + transparently chromatised	1129h	>2500h	>2500h	>2500h	68h
Dacromet-coated	>2500h	>2500h	>2500h	>2500h	891
Geomet-coated	>2500h	>2500h	>2500h	>2500h	891
Delta Tone + Delta Seal	620h	>2500h	738h	>2500h	526h
With water-dilutable paint	1057h	837h	455h	>2500h	380h
Oiled	837h	>2500h	360h	>2500h	262h
Geölt	1323h	1752h	1534h	>2500h	839h

Table 7: Lifespan of 6 x 1 disc spring stacks in the stress crack corrosion experiment at 0.8 h_0 and 80°C

Table 7 shows the shortest lifespan values for the disc springs reached at static compression 0.8h_0 (80 % compression) and experimental temperature of 80 °C.

All disc springs studied show very good stress corrosion crack behaviour in 0.1 N sodium hydroxide in contrast to other media. No disc spring variant failed in sodium hydroxide, which can be traced to a good tolerance and rate of repassivation. Even the disc spring variant with water-dilutable paint, whose paint dissolved entirely after 2 days at 80 °C, as had already been seen in the immersion experiment, is stable due to protective oxide or hydroxide protective layers that form at pH > 10.

The disc springs composed of stainless steels only fractured in 40 % $MgCl_2$ solution, with the exception of Kolsterised disc spring variants, which only failed in seawater atmosphere.

The Dacromet- and Geomet-coated disc spring variants did not fracture in any corrosion media in the stress corrosion crack experiment, where the coatings dissolved after some time, since in acid solutions of organic materials, zinc is not resistant (Dacromet coating after about 20 hours of the experiment, Geomet coating after about 50 hours).

At the end of the experiment, these two disc spring variants show extensive corrosion of the dissolved coating like that of the oiled-only spring in citric acid.

The chemically nickel-plated disc springs failed in all media except for sodium hydroxide similarly to the failure for the disc springs with water-dilutable paint. The oiled-only disc spring variant behaved the worst during the immersion experiment but in the stress corrosion crack experiment, it only broke in the seawater atmosphere. In keeping with the result for the immersion experiment, the Delta Tone + Delta Seal coated disc spring in the 40 % $MgCl_2$ solution had a longer lifespan than in the 3 % NaCl solution. Most coated disc spring variants failed in the seawater atmosphere, though not in the chloride-containing solutions. In the deionised water, only the stainless steel disc springs were studied, with all springs withstanding 2500 hours of the experiment without event.

The experiments carried out at 80°C with failure of at least one disc spring were performed again at 40°C. The results are summarised in Table 8. The number of broken disc springs at 40°C is sharply reduced, since with the decrease in temperature, the corrosion rate falls and there is less

Disc spring variants	Seawater	$MgCl_2$	NaCl	NaOH	Acid
1.4310 / C / S + D		>2500h			
1.4310 / C / S + D + K		>2500h			
1.4310 / B / S + D		>2500h			
1.4568 / C / S + D		>2500h			
1.4568 / C / S + D + K		>2500h			
1.4568 / C / S + D + Kolsterised	>2500h	>2500h			
Mechanically zinc-plated + yellow chromatised	>2500h				45h
Mechanically zinc-plated + transparently chromatised	>2500h				284h
Dacromet-coated					>2500h
Geomet-coated					>2500h
Delta Tone + Delta Seal	>2500h		>2500h		>2500h
Chemically nickel-plated	834h	694h	116h		1917h
With water-dilutable paint	>2500h		>2500h		356h
Oiled					

Tab. 8:
Table 8: Lifespan of disc spring stack (6 x 1 stacking) in the stress corrosion crack experiment at $0.8h_0$ and 40 °C

corrosive stress. However, the chemically nickel-plated disc spring variant failed in 40 % $MgCl_2$ solution and in 3 % NaCl solution, as did the mechanically zinc-plated and painted variants in 0.1 M citric acid. For the chemically nickel-plated disc spring variant, it appears that the acceleration in local corrosion of the base material at weak points in the inert coating is more effective than reduction of corrosion due to the low temperature. The coatings for the mechanically zinc-plated and painted disc springs also react very strongly with the citric acid.

After comparing the disc spring variants regarding the lifespan until fracture in different corrosion media (Tables 7 and 8), the following extracts represent the stress corrosion crack behaviour in the different media. The visual manifestations of corrosion of the springs after termination of the experiment are considered in addition to the lifespan until fracture, since visual manifestations of dissolution of the disc springs (without immediate crack formation) are to be evaluated after a certain period of time as failure (compare Figure 7).

Figure 7:
Condition of the mechanically zinc-plated and transparently chromatised disc springs after over 2500 h under $0.2h_0$ stress in citric acid

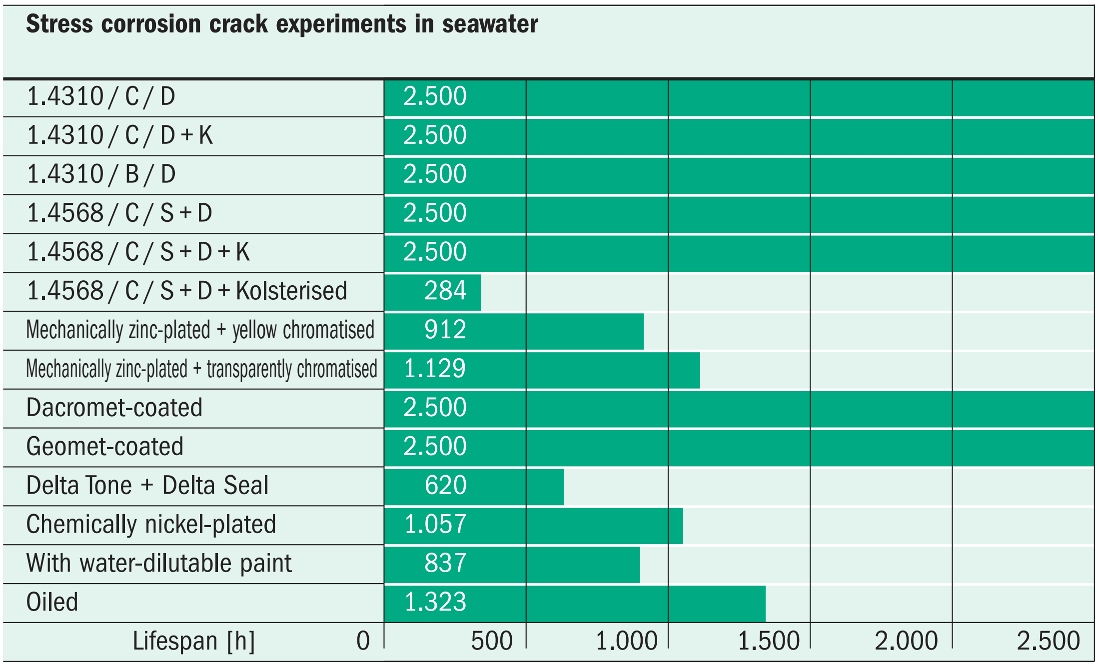


Figure 8: Comparison of lifetime of all disc spring variants in the stress corrosion crack experiment in seawater atmosphere (0.8 h_0 and 80°C)

STRESS CORROSION CRACK BEHAVIOUR IN SEAWATER ATMOSPHERE

Figure 8 shows the lifespan of all disc spring variants in saturated seawater atmosphere at 0.8h_0 and 80 °C. All stainless steel disc springs with the exception of the Kolsterised ones and the Dacromet- and Geomet-coated disc springs did not break in the seawater atmosphere. The Kolsterised disc springs, by contrast, showed the shortest lifespan (284 hours).

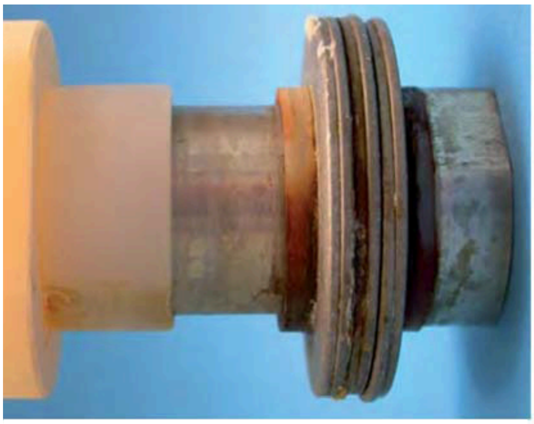
The salts dissolved in the seawater consist of about 77.8 % sodium chloride (table salt) and about 10.9 % magnesium chloride, where chloride ions are a main component. Chloride ions have an especially deleterious corrosive effect, since they make the oxide layers on stainless metals porous [3].

The disc springs composed of stainless steel showed a significantly better corrosion behaviour than the Kolsterised variant (Figure 9). After the experiment had run 2500 h, only small rust-brown spots appeared on the outer edge (shot-peened 1.4310). No traces of corrosion could be seen on the upper or lower faces of the disc springs. Disc springs often corrode in the edge region to a greater extent than on the upper and lower faces. For coated springs, the thin or permeable coating is not optimal protection from corrosion. For stainless steel disc spring variants, punching and turning creates deformation-induced martensite, which is less resistant to corrosion than austenite, in the edge region.

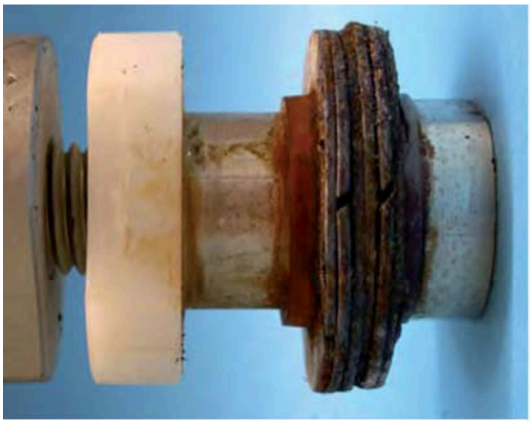
The disc spring variants composed of stainless steels show good stress corrosion crack behaviour, since the concentration of the chloride ions contained in the seawater atmosphere is not high enough to completely destroy the protective layer. At the same time, the protective layer is continuously repaired by the oxygen in the air. (The springs are not immersed in the medium.) The Kolsterised springs were the sole exception, being covered by a thick rust-brown corrosion product layer by the end of the experiment. The cause is the high carbon content in the edge zone.

The Dacromet- and Geomet-coated springs looked as new after 2500 h. These two coatings bestow optimal protection on the slightly alloyed basic material in the seawater atmosphere. The mechanically zinc-plated disc spring is covered with a foamy rust-brown corrosion product layer. Due to the low chloride concentration in the atmosphere, no Simonkolleite ($Zn_5(OH)_8Cl_2 \cdot H_2O$) layer forms; rather, loose and voluminous coatings are generated on the surface. These have no defined composition; rather, they consist of a variety of products. In addition, the effectiveness of chromate layers decreases at temperatures over 60°C.

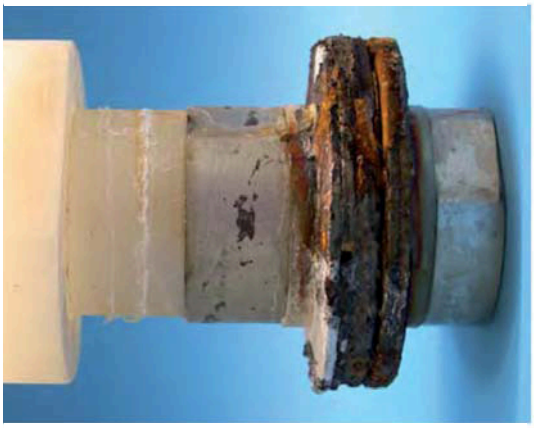
The Delta Tone/Delta Seal-coated spring is in a significantly worse condition than the Geomet-coated spring, but better than the mechanically zinc-plated spring. Only in the problem zone, the edge region, are there some rust-brown dots. The variant with the water-dilutable lacquer and the chemically nickel-plated variant display the same problem of a locally permeable coating. The oiled-only disc spring corroded heavily. The protective oil bestows only short-term protection, and the high oxygen content in the atmosphere accelerates the corrosion.



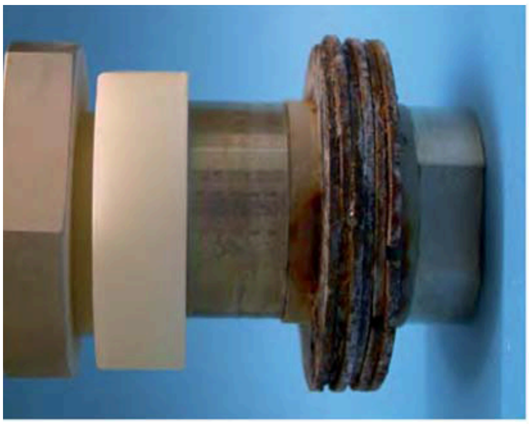
1.4568 / C / S + D + K



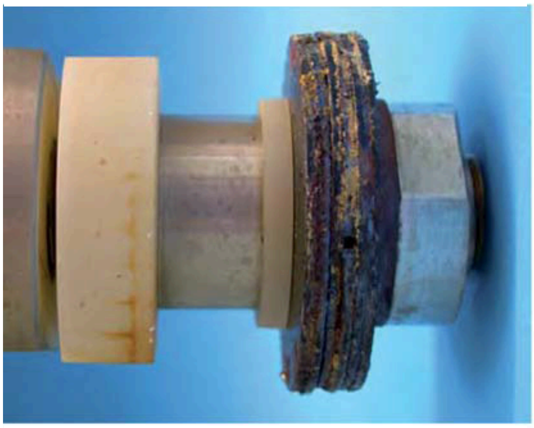
1.4568 / C / S + D + kolsterisiert



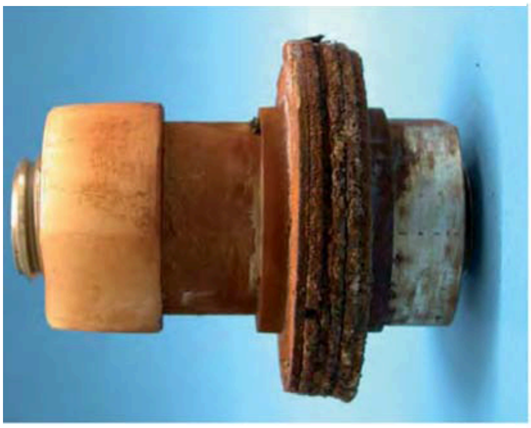
Mechan. verzinkt + gelb chrom.



Delta Tone + Delta Seal



Wasserverd. lackiert



Geölt

Figure 9: Visual manifestation of corrosion on the disc springs in the stress corrosion crack experiment in seawater atmosphere ($0.8h_0$ and 80 °C)

STRESS CORROSION CRACK BEHAVIOUR OF THE DISC SPRING STACK IN A 40 % MGCL$_2$ SOLUTION

Figure 10 compares the lifespan of all variants in 40 % $MgCl_2$ solution at $0.8h_0$ und 80 °C. Of the coated disc springs, only the chemically nickel-plated variant fractured, due to local corrosion at the blemishes in the coating and the associated notch effect. The low oxygen content and the high chloride concentration in the 40 % $MgCl_2$ solution reduce and inhibit corrosion of the basic material 1.8159. These two features of 40 % $MgCl_2$ solution are also the main reasons for the bad stress corrosion crack behaviour of the disc springs composed of stainless steels, whose course of deterioration is determined by pitting corrosion.

For springs composed of the material 1.4310, series B and C (different thickness), the spring with size B shows a longer lifespan than spring C in the stress corrosion crack experiment, as opposed to the electrochemical test, where spring B corrodes more heavily. This is due to a longer phase of crack progression, caused by the greater thickness of the material; thus, there is a significant size-related effect.

As with the electrochemical experiment (not reported here), shot-peening is shown to have a positive effect on disc springs composed of 1.4310 and no clear effect on disc springs composed of 1.4568 with regard to stress corrosion crack behaviour. In general, shot-peening brings residual compressive stress into the surface layer of the springs [7]; as a result of the superposition with external stresses, the resulting bending tension is reduced. This only works when the surface is not heavily corroded. The surface corrosion leads on the one hand to an operation-induced notch effect and on the other hand to the erosion of the layer under residual compressive stress. From the immersion experiment, it was known that the shot-peened disc spring composed of 1.4568 corroded relatively heavily in 40 % $MgCl_2$ solution.

The springs composed of 1.4310 generally have a longer lifespan than the springs composed of 1.4568. This also applies to the non-shot-peened spring composed of 1.4310 and the shot-peened spring composed of 1.4568. This means that the material itself is of greater significance than its method of preparation for determining the corrosion behaviour of the disc springs.

Almost disc spring variants made from stainless steels are covered with a thin layer of rust-brown corrosion product, with the exception of the Kolsterised variant. This matches the results from the immersion experiment. For the rust- and acid-resistant heavily alloyed chrome steels and chrome-nickel steels, there is danger of pitting corrosion in aqueous solutions containing halides (especially chlorides and bromides). Halide ions are in a position to 'break through' the passive layers formed

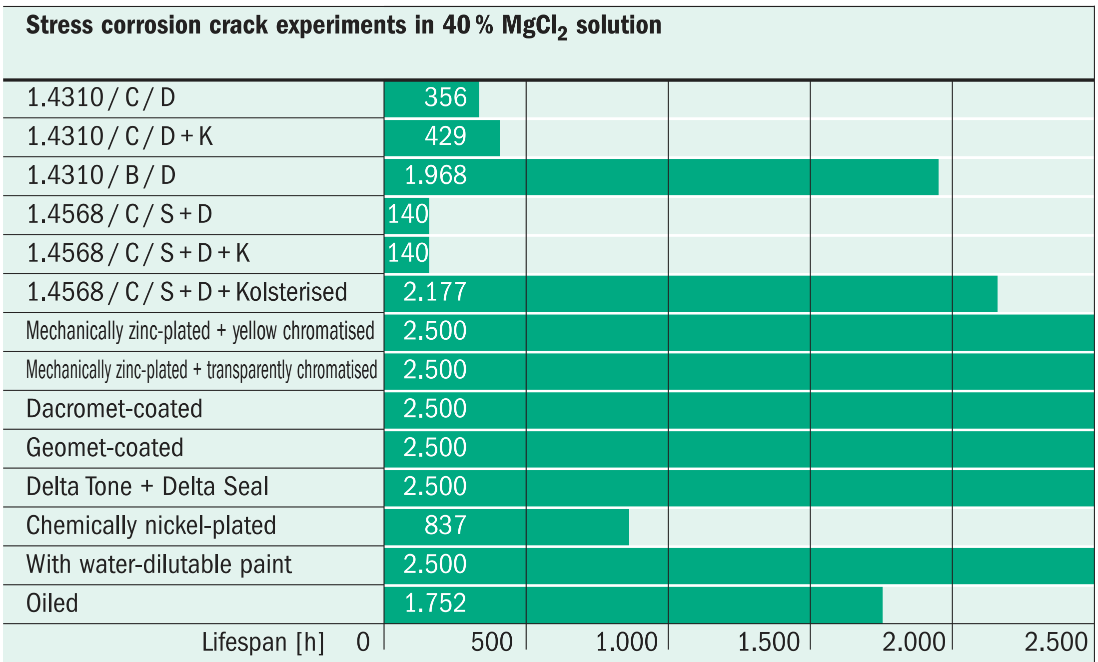
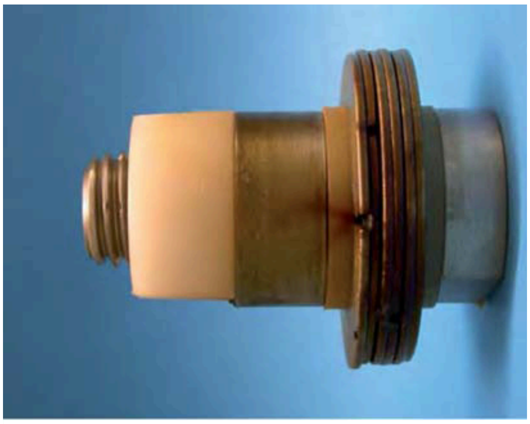
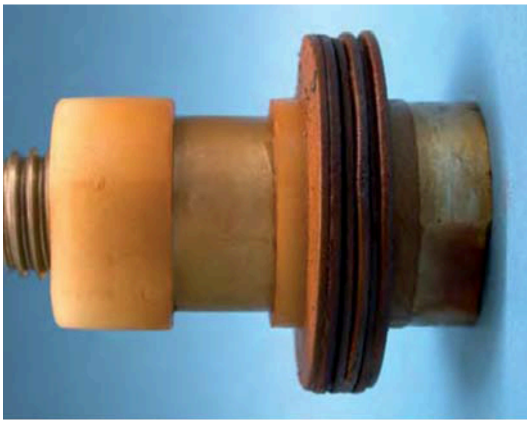


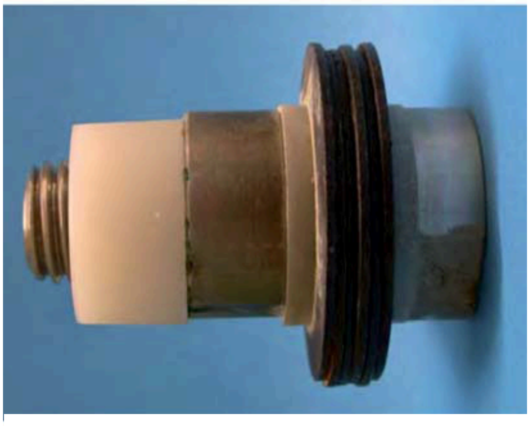
Figure 10: Comparison of lifetime of all disc spring variants in the stress corrosion crack experiment in 40 % $MgCl_2$ solution ($0.8h_0$ and 80 °C)



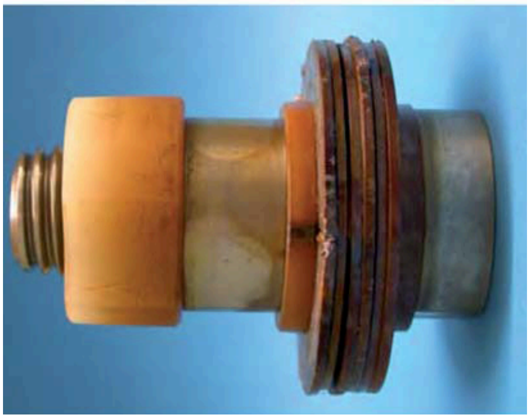
1.4310 / C / S + D



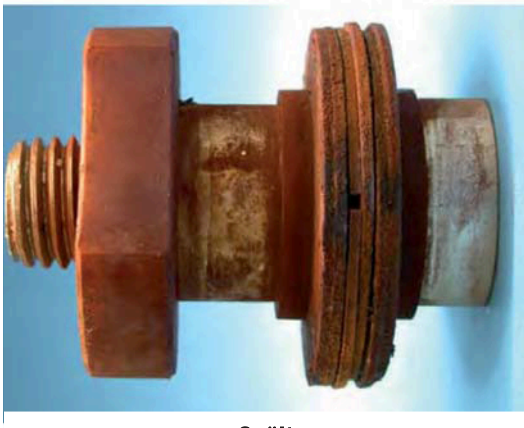
1.4568 / C / S + D + kolsterisiert



Delta Tone + Delta Seal



Chemisch vernickelt



Geölt

Figure 11: Visual manifestation of corrosion on the disc springs in the stress corrosion crack experiment in 40 % $MgCl_2$ solution ($0.8h_0$ and 80 °C)

in the air in such steels and thus to form local, actively corrosive anodic centres. Since the passive layers conduct electrons, the undisturbed environment acts as a cathode. Rapid penetration of the corrosion into the material is the result. The danger of pitting in such steels rises with increasing contamination.

The notches created by pitting lead, however, to a local elevation of tensile stress. If no intermediate repassivation is possible, the attack will continue to grow deeper, and the crack will propagate at an increasing rate. In media containing chloride, the mechanism of crack formation is accompanied by pitting which then can grow sharply even if the crack only progresses slowly. The variants depicted in Figure 12 are thus produced according to the rate of crack propagation.

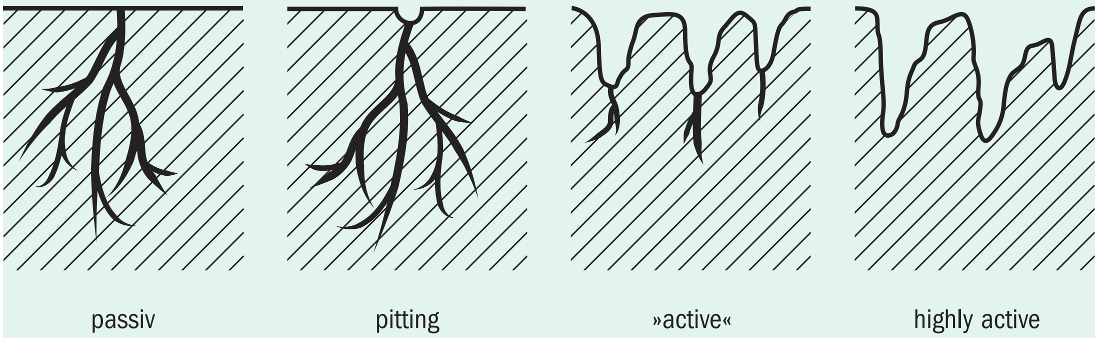


Figure 12: Appearance of Tran crystalline stress corrosion crack in rust- and acid-resistant Cr-Ni steels in metallographic cross-section (schematic) [8]

Since the edge area corrodes most heavily and receives the most stress, the crack often appears on the external edge of the spring. It then spreads toward the inner edge of the spring. This process is slower in springs composed of 1.4310, since 1.4310 steel is more ductile. Susceptibility to cracking generally increases with higher bending tension and rising temperature.

The Kolsterised variant did not fail by fracturing, although the spring was covered by a thick covering layer. Initially, it corrodes very heavily, but after some time it stops, and the solution remains clear. This thermodynamically stable covering layer (Fe3O4, Fe(OH)2) acts as a protective layer and prevents the further progress of the corrosion. The other reason that the Kolsterised spring did not fracture is that here only surface corrosion occurs, thanks to the impermeable and evenly distributed carbon. The same is true for the oiled-only spring; it behaves worst in the immersion experiment in 40 % $MgCl_2$ solution.

The chemically nickel-plated disc spring broke, due to the notch effect caused by local corrosion. On the mechanically zinc-plated, Dacromet-coated, and Geomet-coated springs, almost no traces of corrosion can be seen. The Simonkolleite

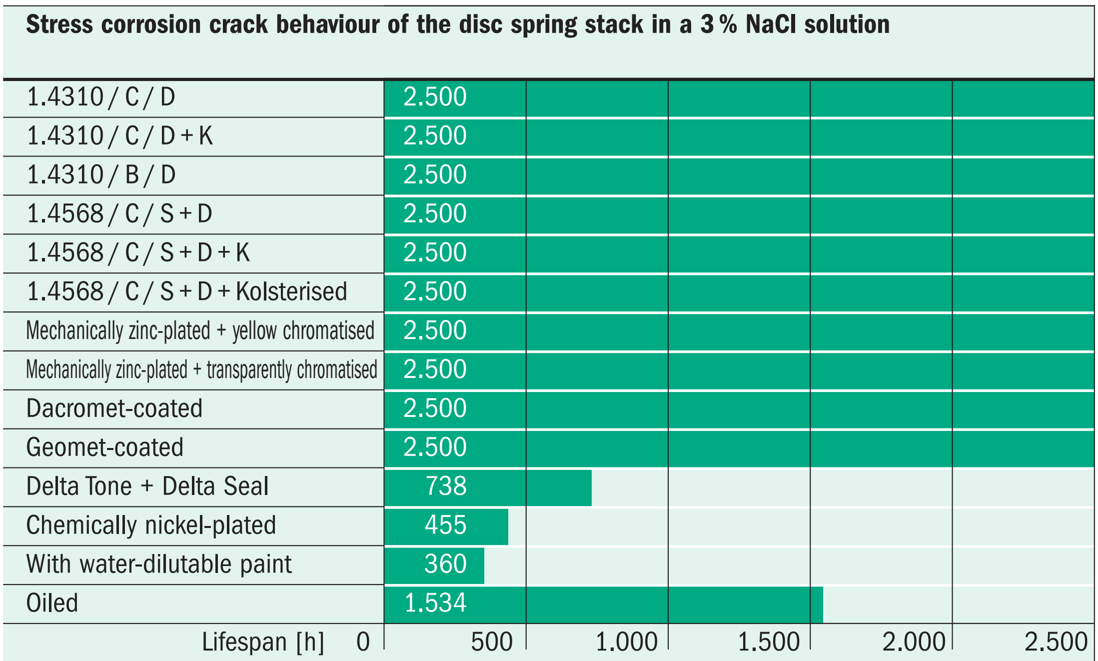
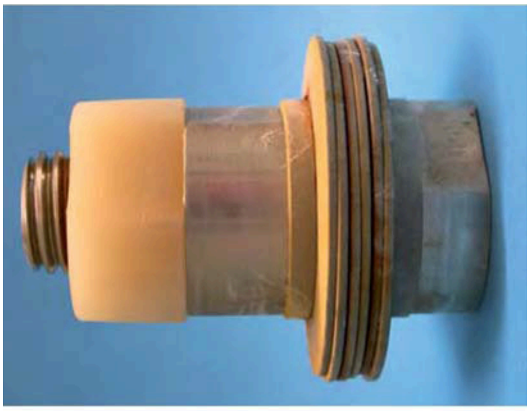
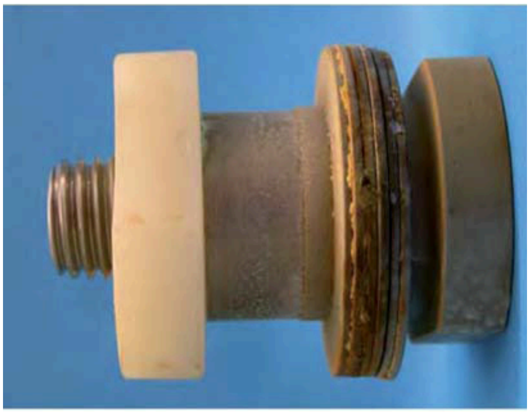


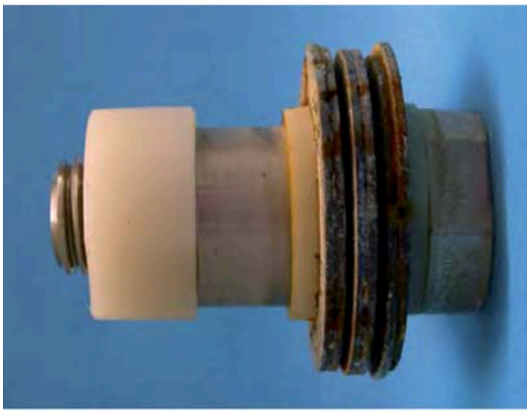
Figure 13: Comparison of lifetime of all disc spring variants in the stress corrosion crack experiment in 3 % NaCl solution (0.8h_0 and 80 °C)



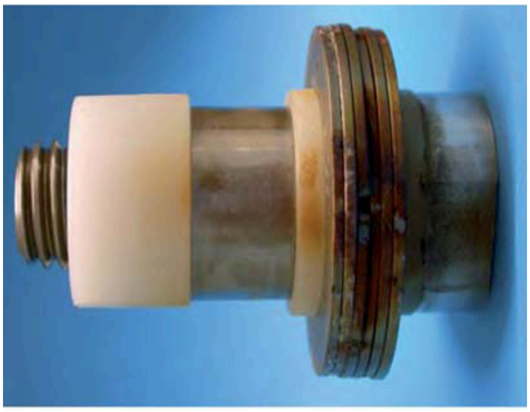
1.4568 / C / S + D + K



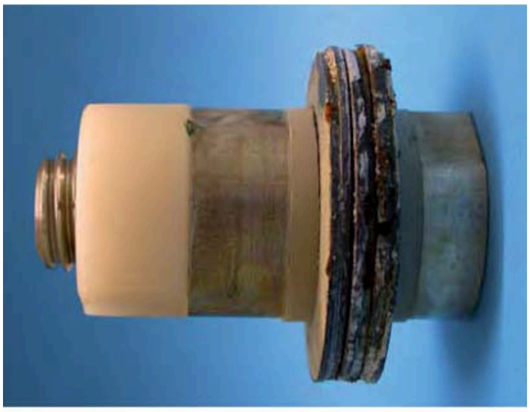
1.4568 / C / S + D + Kolsterised



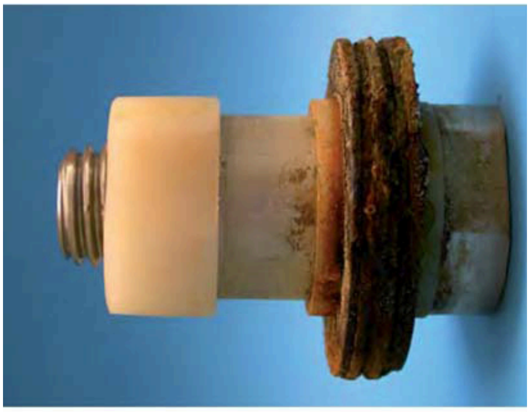
Delta Tone + Delta Seal



Chemically nickel-plated



With water-dilutable paint



Oiled

Figure 14: Visual manifestation of corrosion on the disc springs in the stress corrosion crack experiment in 3 % $MgCl_2$ solution ($0.8h_0$ and 80 °C)

layer that is produced protects the springs against corrosion; the other coating component, aluminium, is highly resistant to corrosion in neutral corrosion electrolytes (pH 5 to 9). The spring coated with Delta Tone/Delta Seal is somewhat worse in comparison; it displays some rust-brown corrosion dots on the edges of the spring.

STRESS CORROSION CRACK BEHAVIOUR OF THE DISC SPRING STACK IN A 3 % NACL SOLUTION

Figure 13 compares the lifespan of all variants in 3 % NaCl solution at $0.8h_0$ und 80 °C. The stress corrosion crack behaviour of most disc springs in 3 % NaCl solution is better than in 40 % $MgCl_2$ solution, since the electric conductivity of 3 % NaCl solution is lower than that of 40 % $MgCl_2$ solution and fewer ions that would favour corrosion on the metal surface go into solution. Here there was no stainless steel variant that failed. In contrast, the variant with water-dilutable paint and the variant coated with Delta Tone and Delta Seal broke.

Figure 14 shows several disc springs after the experiment in 3 % NaCl solution. All in all, the condition of the springs is better than after the experiment in seawater atmosphere and in 40 % $MgCl_2$ solution. Here there is a lower oxygen supply than in seawater atmosphere, since the disc spring stack is immersed in the solution. The lower chloride concentration has the advantage that the air-passivated layer is not heavily damaged, which is the reason that the disc springs composed of stainless steels are covered only by a thin brownish layer. On the other hand, there is also the disadvantage that the Simonkolleite layer on the Delta Tone and Delta Seal-coated disc spring was not fully formed via the low Cl-concentration. White spots and rust-brown corrosion dots are the evidence for corrosion of the coating and base material.

For the disc spring variant with water-dilutable paint and the Delta Tone/Delta Seal-coated variant, the NaCl solution reached the base material through the channels in the coating. This led the springs to break. The permeable coating is not a sure factor for the corrosion behaviour of the disc spring. A similar situation applies for the chemically nickel-plated disc springs due to the existing pores in the coating, where the contact corrosion between coating and base material leads to acceleration. The chemical nickel-plating provides no protection here and the final failure was the breakage of the disc spring.

The oiled-only disc springs likewise failed at the end through breakage, since the oil can only offer short-term corrosion protection.

STRESS CORROSION CRACK BEHAVIOUR OF DISC SPRING STACK IN 0.1 M CITRIC ACID

Figure 15 presents the lifespan of all variants in 0.1 M citric acid at $0.8h_0$ and 80 °C. The disc spring variants composed of stainless steels withstand 2500 hours of the experiment without breaking. The same is true for the Dacromet- and Geomet-coated springs and for the oiled-only spring, though with substantial surface corrosion attack. The mechanically zinc-plated springs display the shortest lifespan in citric acid of the six media studied. As in 3 % NaCl solution, the springs coated with Delta Tone and Delta Seal, the ones with water-dilutable paint, and the chemically nickel-plated ones broke.

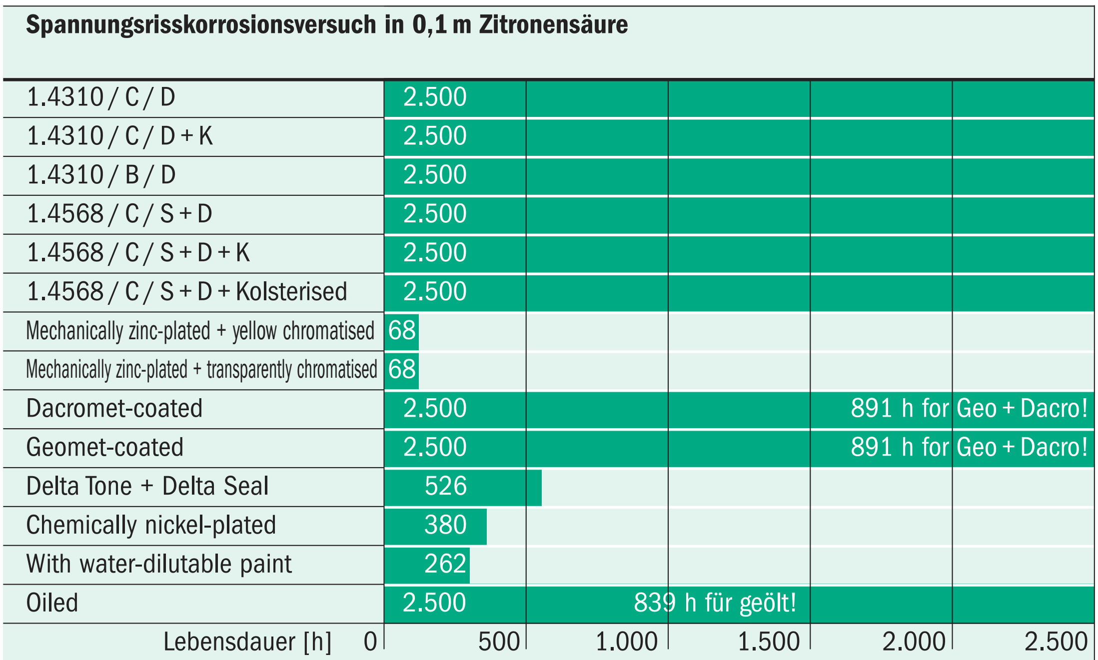
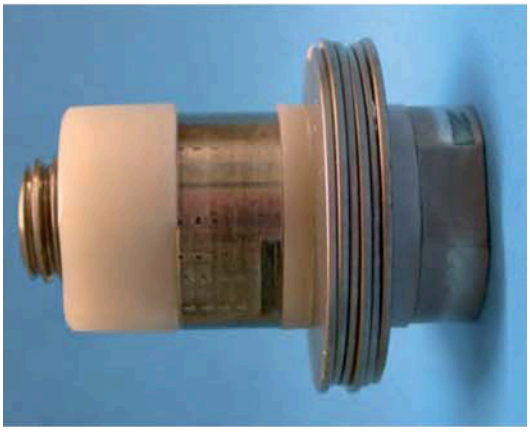
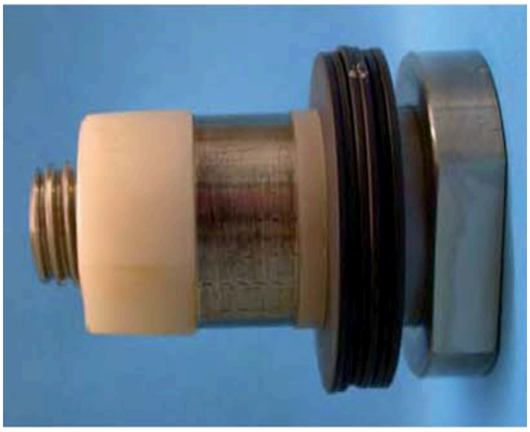


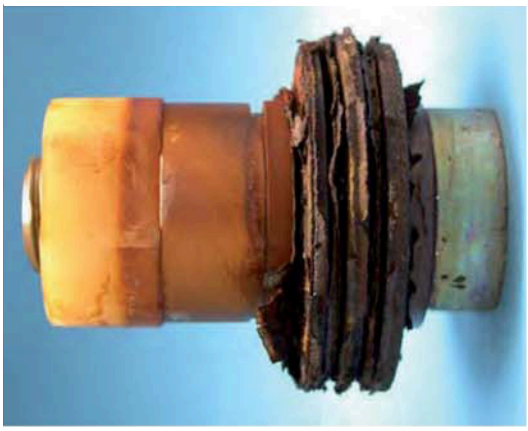
Figure 15: Comparison of lifetime of all disc spring variants in the stress corrosion crack experiment in 0.1 M citric acid ($0.8h_0$ and 80 °C)



1.4568 / C / S + D + K

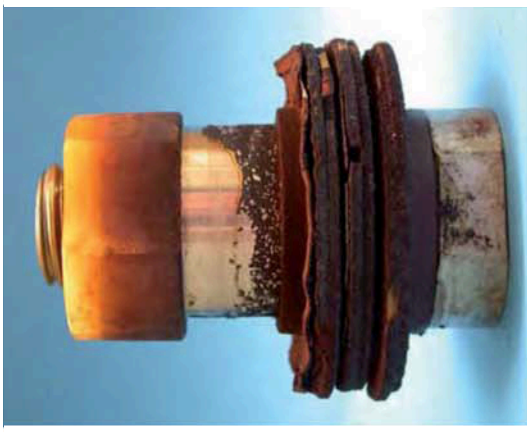


1.4568 / C / S + D + Kolsterised

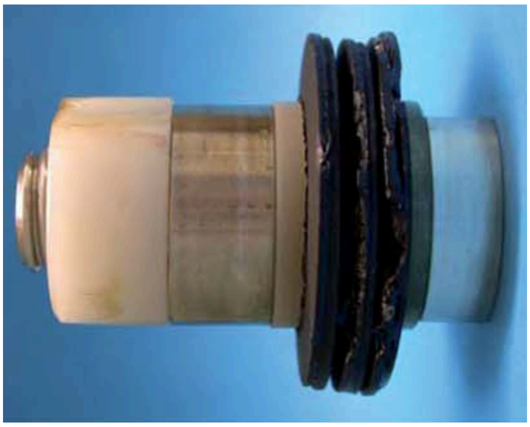


Mechanically zinc-plated + yellow chromatised

Delta Tone + Delta Seal



Chemically nickel-plated



With water-dilutable lacquer

Oiled

Figure 16: Visual manifestation of corrosion on the disc springs in the stress corrosion crack experiment in 0.1 M citric acid (0.8h_0 and 80 °C)

Figure 16 shows the different disc spring variants after the experiment with 0.1 M citric acid. There are no visual manifestations of corrosion to be seen on the disc springs composed of stainless steels, with the exception of the Kolsterised disc spring. Citric acid belongs to the media that generate a passive layer. It can be assumed from the results of the electrochemical study (not reported here) that the damaged passive layer on stainless steels in citric acid is even repaired. The disc springs composed of stainless steels are protected against corrosion by the passive layer formed in air and in acid by their high chrome content. On the Kolsterised spring, a black layer consisting of carbon is formed.

The coated springs behaved much worse than the stainless steels in 0.1 M citric acid. None of the variants had a lifespan over 1000 h. It is known from the electrochemical study (not reported here) and the immersion experiment that the Zn portion of the coating reacts chemically with the citric acid. This caused cracks in the surface of the mechanically zinc-plated springs, which, due to the excellent adhesion of the coating, extended all the way into the base material. Moreover, the effectiveness of chromate layers only persisted up to temperatures of 60°C. Both factors led to a drop in lifespan of the mechanically zinc-plated disc springs and thus to the shortest endurance time (68 h).

In acid solutions of organic materials, zinc is not resistant. The Dacromet and Geomet coatings dissolved in the citric acid. After some time, the springs were completely free of coating (Dacromet coating after about 20 h, Geomet coating after about 50 h). Thus, at the end of the experiment, these two disc spring variants displayed surface corrosion like that of the oiled-only spring in citric acid.

The disc spring coated with Delta Tone and Delta Seal behaves better in citric acid than the other coating variants. The coating was only destroyed at the edges; the organic covering Delta Seal layer acted as insulation and resisted acids and alkalis. But due to the poor distribution of the covering layer on the edges, only a short lifespan was achieved.

The permeable areas in the paint layer and nickel layer of the water-dilutable painteded and chemically nickel-plated disc springs, respectively, which have already been mentioned for the immersion experiment, caused gap corrosion under the coating. This causes a rapid penetration of the corrosion into the depths of the base material with the result of a premature wall collapse.

Susceptibility to cracking generally increases with higher bending tension and rising temperature. If the bending tension in the disc spring is too low, the disc spring stack breaks not due to the crack formation, but rather through dissolving (see Figure 7). Disc springs that come into contact with citric acid should optimally be produced from stainless steels.

The stress crack corrosion experiments were declared to have ended if a spring in the stack broke or the experiment had lasted over 2500 hours. When breakage occurred as cause of failure, it was determined that the position of the broken disc spring in the stack was relatively evenly distributed.

At the end of the experiments, it was determined that the lifespan until failure could not be fully represented by the stress corrosion crack behaviour of the disc spring. Thus, for example, the disc springs shown in Figure 7 are evaluated as »no failure« and thus as »good«; likewise with the oiled disc springs shown in Figure 16 with a thick corrosion layer. In practice, this corrosion layer is presumably completely destroyed, which allows the corrosion to proceed rapidly until the disc spring completely dissolves. A further evaluation option is to add the loss of mass as a second evaluation criterion. Table 9 gives the loss of mass for disc springs whose experiments are listed in Table 7. The mechanically zinc-plated and yellow chromatised spring failed after 68 hours with a loss of mass of 1.347 g, the oiled spring lost a mass of 18.992 g without breaking, since the oiled spring corroded on the surface over 2500 hours in 0.1 M citric acid. This shows that the loss of mass does not readily reflect the corrosion behaviour either. Nevertheless, Table 9 shows that the Dacromet-coated and Geomet-coated springs had a »no coating« behaviour similar to the oiled spring after their coatings had been dissolved in the citric acid.

Disc spring variants	Seawater	$MgCl_2$	NaCl	NaOH	Acid
Mechanically zinc-plated + yellow chromatised	1,9394 g	0,5482 g	-0,2192 g	1,3707 g	1,3470 g
Mechanically zinc-plated + transparently chromatised	2,6715 g	-0,2885 g	-0,2210 g	1,6221 g	1,6088 g
Dacromet-coated	0,6649 g	0,7984 g	1,0361 g	0,9095 g	19,0022 g
Geomet-coated	0,0059 g	0,1439 g	0,0835 g	1,6671 g	19,0970 g
Delta Tone + Delta Seal	0,6709 g	-0,2747 g	0,1009 g	0,0049 g	4,0592 g
Chemically nickel-plated	-0,1139 g	0,5140 g	0,1984 g	0,1427 g	4,2412 g
With water-dilutable paint	0,5094 g	0,1108 g	0,5552 g	2,2457 g	3,8797 g
Oiled	1,3517 g	1,8057 g	0,8286 g	1,9917 g	18,9917 g

Table 9: Loss of mass for disc spring stack (6 x 1 coating) in the stress corrosion crack experiment at $0.8h_0$ and 80 °C

In conclusion, a combination of the visual manifestation of corrosion with the lifespan until failure is used to evaluate the corrosion behaviour. The stress corrosion crack behaviour of the disc springs was evaluated and classified according to the following criteria:

- **Good:**
  - Over 2500 h without failure at $0.8h_0$ load and
  - Low manifestation of corrosion (as dots)
- **Moderate:**
  - Lifespan between 1200 h and 2500 h at $0.8h_0$ load or
  - Clear visual manifestation of corrosion (as blotches)
- **Poor:**
  - Lifespan between 300 h and 1200 h at $0.8h_0$ load or
  - The springs are covered by thin corrosion products (surface)
- **Very poor:**
  - Lifespan less than 300 h at $0.8h_0$ load or
  - The springs are covered by thick corrosion products (surface)

The disc springs evaluated as »good« are usable in appropriate circumstances without reservation; the disc springs evaluated as »very poor«, by contrast, should never be used. The use of disc springs with the evaluation »moderate« or »poor« must be weighed carefully case by case.

Table 10: Behaviour of disc spring in stress corrosion crack experiment (80 °C)

☆ – good
★ – moderate
✪ – poor
● – very poor

Disc spring variants	Seawater	$MgCl_2$	NaCl	NaOH	Acid
1.4310/C/S + D	☆	✪	☆	☆	☆
1.4310/C/S + D + K	☆	✪	☆	☆	☆
1.4310/B/S + D	☆	★	☆	☆	☆
1.4568/C/S + D	☆	●	☆	☆	☆
1.4568/C/S + D + K	☆	●	☆	☆	☆
1.4568/C/S + D + Kolsterised	●	●	★	☆	✪
Mechanically zinc-plated + yellow chromatised	✪	★	★	★	●
Mechanically zinc-plated + transparently chromatised	✪	★	★	☆	●
Dacromet-coated	☆	☆	☆	☆	●
Geomet-coated	☆	☆	☆	☆	●
Delta Tone + Delta Seal	✪	★	✪	✪	✪
Chemically nickel-plated	✪	✪	✪	☆	✪
With water-dilutable paint	✪	✪	✪	★	●
Oiled	✪	●	●	★	●

Disc spring variants	Seawater	$MgCl_2$	NaCl	NaOH	Acid
1.4310/C/S + D	☆	☆	☆	☆	☆
1.4310/C/S + D + K	☆	☆	☆	☆	☆
1.4310/B/S + D	☆	☆	☆	☆	☆
1.4568/C/S + D	☆	★	☆	☆	☆
1.4568/C/S + D + K	☆	★	☆	☆	☆
1.4568/C/S + D + Kolsterised	✪	★	★	☆	★
Mechanically zinc-plated + yellow chromatised	★	☆	☆	☆	●
Mechanically zinc-plated + transparently chromatised	★	☆	☆	☆	●
Dacromet-coated	☆	☆	☆	☆	✪
Geomet-coated	☆	☆	☆	☆	✪
Delta Tone + Delta Seal	★	☆	☆	✪	✪
Chemically nickel-plated	✪	✪	●	☆	✪
With water-dilutable paint	✪	✪	✪	★	✪
Geölt	✪	✪	✪	★	✪

Table 11: Behaviour of disc spring in stress corrosion crack experiment (40 °C)

☆ – good
★ – moderate
✪ – poor
● – very poor

Tables 10 and 11 summarise the evaluation of the stress corrosion crack behaviour of the disc springs in the five media at 40 °C and 80 °C. Most disc springs behave better at 40 °C than at 80 °C due to the reduction of the corrosion rate.

CORROSION BEHAVIOUR OF 4 X 2 STACKED DISC SPRING COLUMNS

Some selected disc spring variants were also studied in the form of a 4 x 2 disc spring stack and some results are shown in Tables 12 and 13. The lifespan of the 4 x 2 disc spring stack was substantially longer than for the 6 x 1 layering.

Temperature	Stress	1.4310 / C / S + D		1.4310 / C / S + D + K	
		6 x 1-layering	4 x 2-layering	6 x 1-layering	4 x 2-layering
40 °C	0,6 h_0	>2500 h	>2500 h	>2500 h	>2500 h
	0,8 h_0	>2500 h	>2500 h	>2500 h	>2500 h
80 °C	0,6 h_0	596 h	766 h	476 h	>2500 h
	0,8 h_0	356 h	766 h	429 h	1033 h

Table 12: Comparison of the lifespan of disc springs composed of 1.4310 for different layering arrangements in 40 % $MgCl_2$ solution

Temperature	Stress	Yellow chromatised		Transparently chromatised	
		6 x 1-layering	4 x 2-layering	6 x 1-layering	4 x 2-layering
80 °C	0,4 h_0	220 h	2056 h	95 h	2032 h
	0,6 h_0	45 h	284 h	69 h	142 h
	0,8 h_0	68 h	142 h	68 h	116 h

Table 13: Comparison of lifespan of mechanically zinc-plated disc springs for different layering arrangements in 0.1 M citric acid

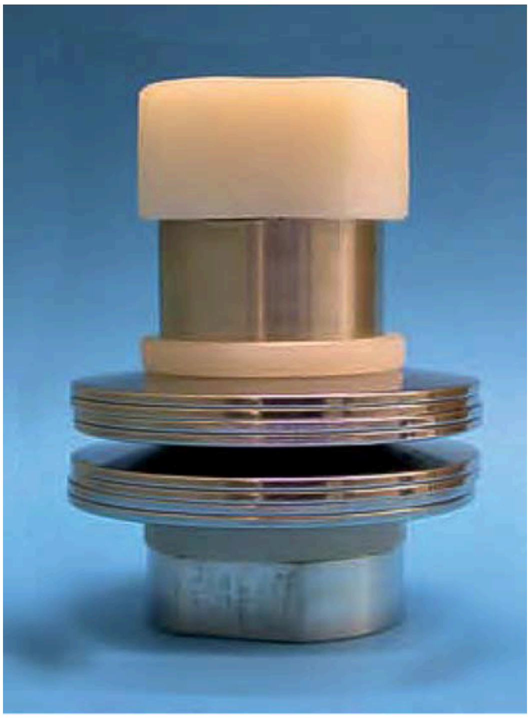


Figure 17: 4 x 2 disc spring stack placed under tension at $0.2h_0$ (20 % deflection)

Figure 18: Visual manifestation of corrosion on the mechanically zinc-plated disc springs in citric acid

Through the parallel layering of disc springs in the 4 x 2 disc spring stack, additional friction is generated between the conical surfaces, which delays the propagation of the cracks. Moreover, for the 4 x 2 disc spring stack, unlike for the 6 x 1 layering, some surfaces are not in contact with the corrosion medium (see Figures 17 and 18).

The positions of the broken disc springs in the 4 x 2 layering are distributed relatively evenly, similarly to the 6 x 1 layering.

SUMMARY OF THE STRESS CRACK CORROSION EXPERIMENTS

The Dacromet-coated and Geomet-coated springs have the best stress corrosion crack behaviour in four of the studied media, but not in citric acid. The coated disc springs are not suitable for use in citric acid due to the lack of chemical resistance. The mechanically zinc-plated disc springs behaved somewhat worse due to the lack of a barrier effect. Disc springs that come into contact with acid should optimally be produced from stainless steels. Almost all spring variants behaved well in sodium hydroxide and deionised water. In the media that contain chloride, the disc springs composed of stainless steels failed due to the high chloride concentration (40 % $MgCl_2$ solution) and some coated variants due to the chloride concentration in combination with a high oxygen supply (seawater atmosphere). The chemically nickel-plated and painted disc spring variants failed in almost all media.

Table 14 shows the results from the immersion experiment compared to those from the stress corrosion crack experiment. The results from the stress corrosion crack experiment are significantly worse than from the immersion experiment, i.e., despite different experimental conditions, initial hints of stress crack corrosion behaviour can already be drawn from the immersion experiment.

Tellerfedervarianten	40 % $MgCl_2$		3 % NaCl		0,1n NaOH		0,1m Säure	
	Tauch-versuch	SpRK	Tauch-versuch	SpRK	Tauch-versuch	SpRK	Tauch-versuch	SpRK
1.4310/C/S + D	★	✪	☆	☆	☆	☆	☆	☆
1.4310/C/S + D + K	★	✪	☆	☆	☆	☆	☆	☆
1.4310/B/S + D	★	★	☆	☆	☆	☆	☆	☆
1.4568/C/S + D	★	●	☆	☆	☆	☆	☆	☆
1.4568/C/S + D + K	✪	●	★	☆	☆	☆	☆	☆
1.4568/C/S + D + Kolsterised	●	●	✪	★	☆	☆	☆	✪
Mechanically zinc-plated + yellow chromatised	☆	★	✪	★	☆	★	●	●
Mechanically zinc-plated + transparently chromatised	☆	★	★	★	☆	☆	●	●
Dacromet-coated	☆	☆	☆	☆	☆	☆	●	●
Geomet-coated	☆	☆	☆	☆	☆	☆	●	●
Delta Tone + Delta Seal	☆	★	★	✪	☆	✪	✪	✪
Chemically nickel-plated	✪	✪	✪	✪	☆	☆	✪	✪
With water-dilutable paint	☆	✪	☆	✪	★	★	✪	●
Oiled	●	●	●	●	☆	★	●	●

Table 14: Comparison of the results from the immersion experiment and the stress corrosion crack experiment

☆ – good
★ – moderate
✪ – poor
● – very poor

VDA ALTERNATION TEST WITH MECHANICAL LOAD

EXECUTION

VDA alternation tests with mechanical stress represent a combination of stress corrosion crack experiments and the VDA alternation test (VDA test sheet 612-415). A disc spring stack under tension is exposed to the standardised VDA alternation test conditions [4].

RESULTS OF THE VDA ALTERNATION TEST WITH MECHANICAL STRESS AND DISCUSSION

The experimental conditions for the VDA alternation test with mechanical stress are similar to those for the stress crack corrosion experiments in seawater atmosphere. The samples are placed in an atmosphere that intermittently contains chloride. The samples are exposed to a great deal of oxygen.

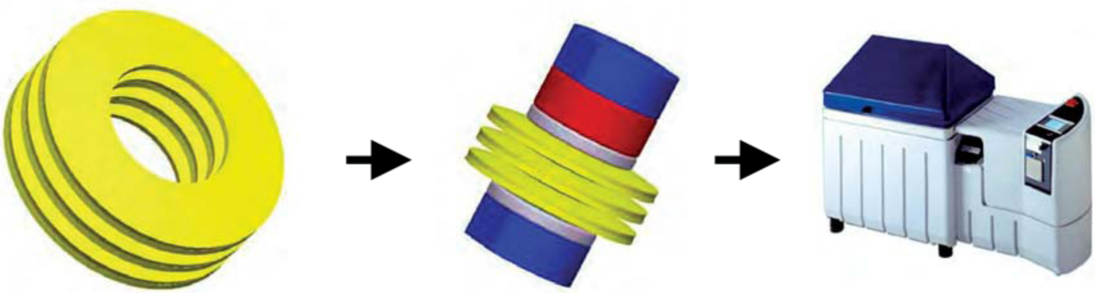


Figure 19: Steps for the VDA alternation test with mechanical stress

Since the experimental temperature for the VDA alternation test is significantly lower than 80 °C, the lifespan in the VDA alternation test is longer than for the stress corrosion crack experiments in seawater atmosphere at 80 °C, but shorter than at 40 °C. All results are shown in Table 15. For stainless steels, only the Kolsterised variant failed. As in the VDA alternation test, the yellow chromatised springs behave worse than the transparent chromatised springs. Even the oiled and chemically nickel-plated variants failed here, but with decreasing preload the lifespan increases significantly. Permeable sites in the coating lead to point corrosion at the edges of the chemically nickel-plated and painted disc springs.

Figure 20 shows the visual manifestation of corrosion on the disc springs after the VDA alternation test. The oiled, the Delta Tone/Delta Seal-coated, the mechanically zinc-plated, and the Kolsterised disc springs are covered by a thick corrosion product layer. No clear corrosion was visible on the Dacromet-coated or Geomet-coated disc springs. Most disc spring variants were covered by a thin rust-brown layer. Permeable sites in the coating lead to point corrosion at the edges of the water-dilutable painted and chemically nickel-plated disc springs.

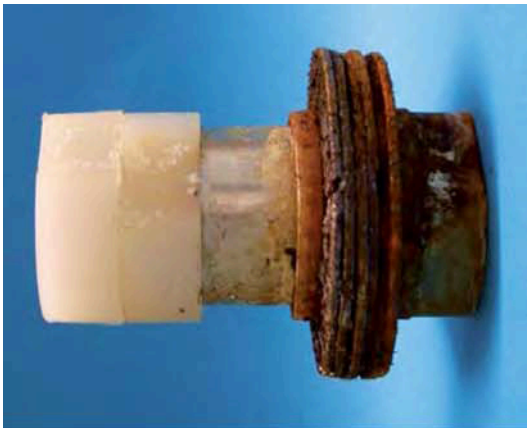
SUMMARY OF VDA ALTERNATION TEST WITH MECHANICAL LOAD

In the VDA alternation test, the disc spring variants composed of 1.4310 showed a very high resistance to corrosion due to the high proportions of Cr and Ni in the material. The corrosion resistance of the disc spring variants composed of 1.4568 is somewhat worse, especially the Kolsterised variant, due to the high carbon content on the surface introduced by Kolsterising. In the VDA alternation test, a full Simonkolleite layer was not formed on the zinc coating. After the zinc coating was worn away, the base material corroded heavily. The Dacromet coating and the Geomet coating offered sufficient protection to the low alloyed springs. The chemical nickel plating and the water-dilutable paint are evaluated as poor due to the permeable sites in the coatings. The oiled variant behaves the worst, since the base material is only low alloyed and the oil only offers short-term protection.

Disc spring variants	$0{,}2\ h_0$	$0{,}4\ h_0$	$0{,}6\ h_0$	$0{,}8\ h_0$
1.4310/C/S + D	>2500 h			>2500 h
1.4310/C/S + D + K	>2500 h			>2500 h
1.4310/B/S + D				>2500 h
1.4568/C/S + D				>2500 h
1.4568/C/S + D + K				>2500 h
1.4568/C/S + D + Kolsterised				1228 h
Mechanically zinc-plated + yellow chromatised				2043 h
Mechanically zinc-plated + transparently chromatised				>2500 h
Dacromet-coated				>2500 h
Geomet-coated				>2500 h
Delta Tone + Delta Seal				>2500 h
Chemically nickel-plated			1636 h	841 h
With water-dilutable paint				>2500 h
Oiled				1924 h

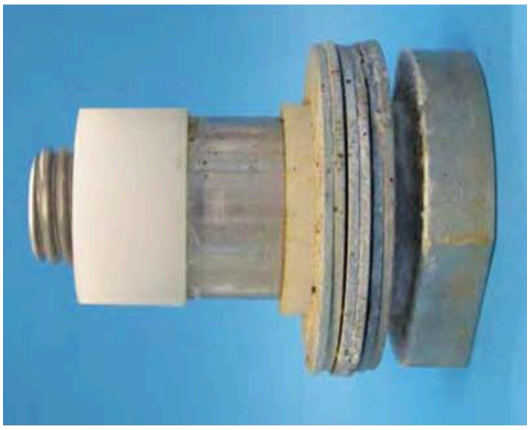
Table 15: Results of all VDA alternation tests with mechanical load

1.4310 / C / S + D

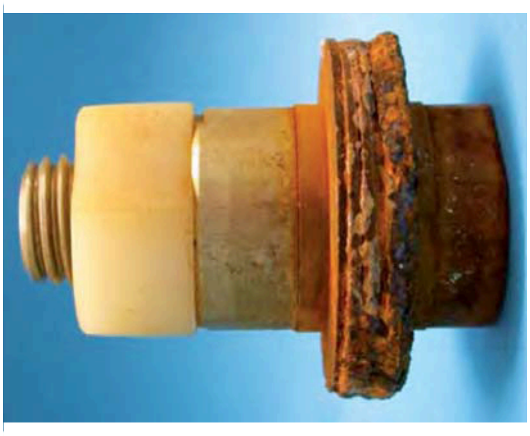


1.4568 / C / S + D + Kolsterised

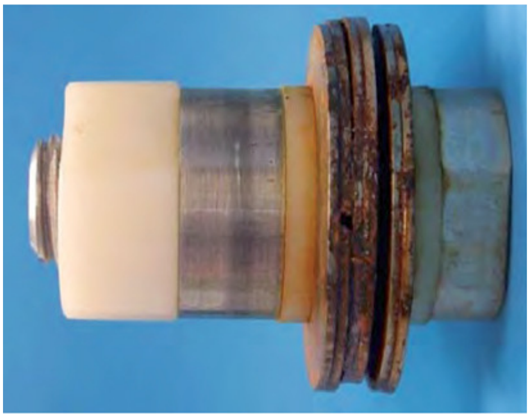
Mechanically zinc-plated + yellow chromatised



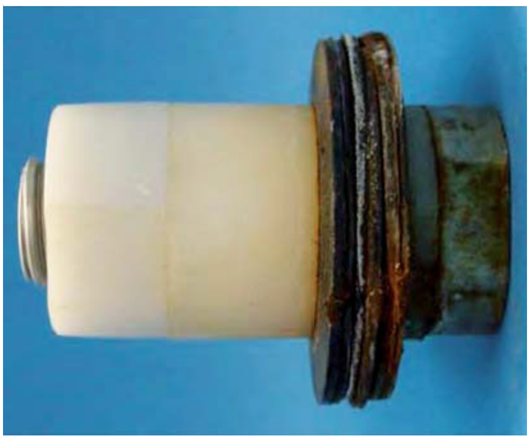
Dacromet-coated



Delta Tone + Delta Seal



Chemically nickel-plated



With water-dilutable paint

Oiled

Figure 20:
Visual manifestation of corrosion on the disc springs after the VDA alternation test with mechanical load

FATIGUE CRACK CORROSION EXPERIMENTS

Similar to the stress corrosion crack experiment, the disc springs are subjected to a complex stress (mechanical and corrosive), but in contrast to the stress corrosion crack experiment, an alternating mechanical load (cyclic) is applied here.

EXECUTION OF THE FATIGUE CRACK CORROSION EXPERIMENTS

For these experiments, special requirements were placed on the execution. The 6 x 1 disc spring stacks had to be used with an internal guide without grease and thus continuous irrigation with the corrosion medium took place. No complete immersion of the stack in the corrosion medium occurred during the experiment in order to avoid creating a build-up of hydrostatic pressure in the inner region of the stack, which could cause additional forces on the disc springs.

The tools for test arrangement for using the columns were produced from a ceramic material of sufficient hardness, corrosion, and wear resistance which is also electrically insulating. Initial failures of the test equipment were able to be fixed using a suitably constructive structure.

The test setup for the fatigue crack corrosion experiments (Figures 21 and 22) consists of three modules: servohydraulic test machine (maximum force 63 kN, maximum stroke 100 mm), corrosion chamber, and storage vessel with pump.

RESULTS OF THE FATIGUE CRACK CORROSION EXPERIMENTS

Table 16 summarises the cycles until failure for the disc springs in the fatigue crack corrosion experiment (cycle width $0.2h_0 - 0.8h_0$) in the different media. Experiments in seawater atmosphere (hard to achieve) and in 40 % $MgCl_2$ solution (highly aggressive) were not performed. A 3 % NaCl solution represented the chloride solutions.

The disc spring variants composed of stainless steels had the longest lifespan in 0.1 N sodium hydroxide, the shortest in deionised water. The lifespan decreased from 0.1 N sodium hydroxide through 0.1 M citric acid and 3 % NaCl solution to deionised water. The deionised water as a medium

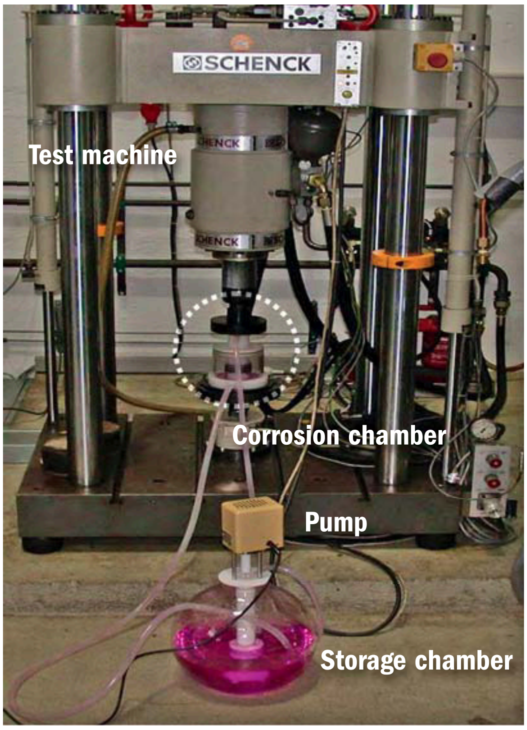


Figure 21 Test setup for fatigue crack corrosion experiment

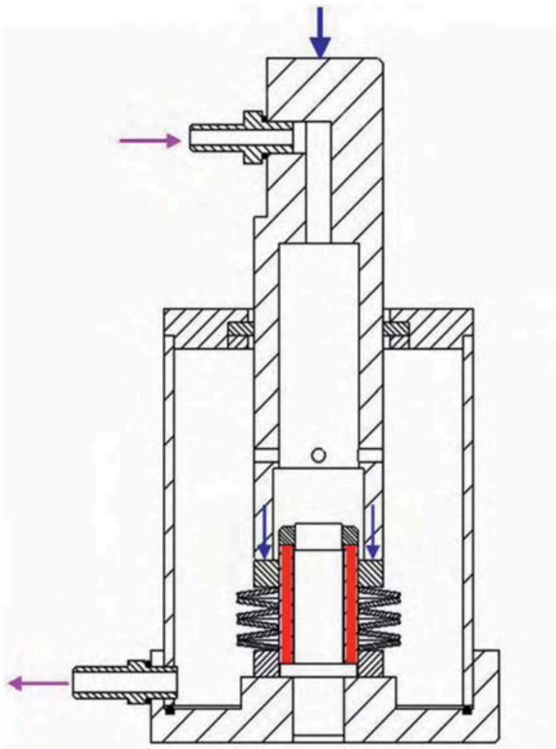


Figure 22: Corrosion chamber with load device

could not electrochemically or chemically destroy the passive layer formed in the air, meaning that the stainless steels are resistant to corrosion in deionised water. Under fatigue condition , however, local formation of slip bands was able to destroy the passive layer. The regions thereby exposed could not be repassivated and became electrochemically active sites (local anodes) on the surface. A local anode created in this way could achieve stability due to the unfavourable surface relation of anode to cathode surface, the resulting local high material conversion, and the decrease in pH at the bottom of the hole, and lead to the formation of a notch.

In 3 % NaCl solution, the results from the immersion experiment showed that the chloride ions broke through the air-passivated layer. Multiple active centres were created on the disc spring surfaces, which made the surface ratio of anode surface to cathode surface more favourable, hence the material conversion lower and the lifespan longer.

In 0.1 N sodium hydroxide and 0.1 M citric acid, the active centres were covered again due to repassivation of the passive layer; the capacity and rate of repassivation in sodium hydroxide is better than in citric acid. This is confirmed in electrochemical studies and in the literature.

The coated disc spring variants had the longest lifespan in 0.1 N sodium hydroxide, the shortest in 0.1 M citric acid. As with the disc spring variants of stainless steels, the longest lifespan could be traced to the hydroxide layer formation in 0.1 N sodium hydroxide, which protects the disc springs against corrosion. Zinc layers react with citric acid, which had already been seen in the immersion experiment and the stress corrosion crack experiment. This chemical reaction led to crack formation in the layer that then continued into the base material. In addition, the low alloyed material 1.8159 was very susceptible to corrosion in 0.1 M citric acid due to the low pH value (2.09). The higher conductivity of the 3 % NaCl solution (about 42.4 mS/cm) induced a shorter lifespan for some coated disc spring variants than in deionised water (about 0.4 mS/cm). For others, the opposite was the case. The Simonkolleite layer formed in the chloride-containing solution continuously repaired the damaged sites and failure was delayed.

Disc spring variants	Deionised water	NaCl	NaOH	Zitronensäure
1.4310/C/S + D	14.171	17.952	37.767	22.280
1.4310/C/S + D + K	18.255	20.300	38.033	25.389
1.4568/C/S + D	12.924	17.207	32.747	19.520
1.4568/C/S + D + K	20.480	24.823	34.555	20.090
1.4568/C/S + D + Kolsterised	11.339	22.199	32.533	30.883
Mechanically zinc-plated + yellow chromatised	26.839	25.510	26.477	14.058
Mechanically zinc-plated + transparently chromatised	7.841	11.323	14.509	4.318
Dacromet-coated	5.676	4.944	6.033	4.849
Geomet-coated	5.428	6.159	4.517	4.031
Delta Tone + Delta Seal	24.975	10.355	10.127	5.563
Chemically nickel-plated	7.083	6.461	12.058	6.414
With water-dilutable paint	22.138	13.469	9.902	4.195
Oiled	13.956	5.493	19.606	5.178

Table 16: Lifespan (fatigue cycles until failure, N) of the disc springs in 6 x 1 stack for the fatigue crack corrosion experiments (cycle width $0.2h_0$ to $0.8h_0$)

Table 17: Lifespan (fatigue cycles until failure, N) of the disc springs in 6 x 1 stack for the fatigue crack corrosion experiments (cycle width 0,2h_0 to 0,6h_0).

Disc spring variants	Deionised water	NaCl	NaOH	Zitronensäure
1.4310/C/S + D	19.552	21.858		30.037
1.4310/C/S + D + K	33.236	40.005	51.965	47.338
1.4568/C/S + D	12.357	17.383		34.692
1.4568/C/S + D + K	21.845	27.974		41.433
1.4568/C/S + D + Kolsterised	32.933	34.000		40.250
Mechanically zinc-plated + yellow chromatised	103.618	292.537		73.386
Mechanically zinc-plated + transparently chromatised	153.506	295.742	1.702.463	49.507
Dacromet-coated	129.507	46.388		28.192
Geomet-coated	141.642	59.555		24.128
Delta Tone + Delta Seal	167.443	240.707		22.578
Chemically nickel-plated	47.429	27.854		19.208
With water-dilutable paint	94.033	91.741		15.703
Oiled	106.702	32.806	1.443.281	28.078

In Table 17, the results of the fatigue crack corrosion experiments are listed with a cycle width 0.2h_0 ↔ 0.6h_0. By reducing the amplitude of the travel, the lifespan of the coated disc spring variants was significantly lengthened, but those of the stainless steel variants only to a small extent.

Figure 23 summarises the lifespan values of all disc spring variants for the fatigue crack corrosion experiment (cycle amplitude 0.2h_0 ↔ 0.6h_0) in deionised water.

The coated disc springs had a significantly longer lifespan than the stainless steel disc spring variants. The passive layer (oxide film) on the stainless steels during fatigue was broken through in a highly localised manner by a slip band penetrating outwards. This region now formed a small, highly active local anode. The corrosion attack followed the slip band into the material. In deionised water, the materials 1.4310 and 1.4568 were not in a position to regenerate the original passive layer at the sites of corrosion. The notches created by the material conversion that had already occurred

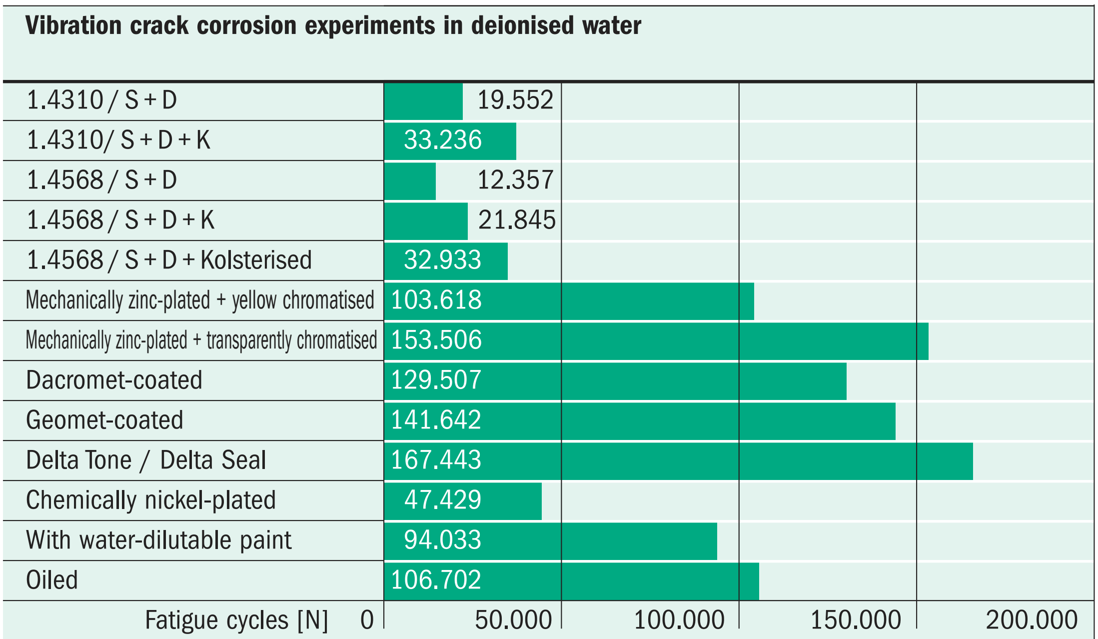


Figure 23: Comparison of lifetime of all disc spring variants in the stress corrosion crack experiment in deionised water (cycle amplitude 0,2h_0 to 0,6h_0).

then led to a local increase in stress; the crack progressed at an increasing rate until breakage occurred [8]. No passive layer was formed on the coatings in air. Thus, the coated disc springs did not experience this problem in deionised water. In addition, numerous places in the literature show that the material 51CrV4 displays a better resistance to fatigue than the materials 1.4310 and 1.4568 [9]. Shot-peening and Kolsterising had a positive effect during the fatigue crack corrosion experiment. The residual compressive stress generated near the edge reduced the mean stress of the fatigue load. The oiled spring endured 106,702 cycles. Significantly longer or shorter lifespans always indicated the involvement of the coating. Thus, for example, the chemically nickel-plated spring failed after 47,429 cycles due to the permeable site in the coating, through which the base material corroded at an accelerated rate.

In 3 % NaCl solution, the coated disc spring variants showed, on average, better fatigue crack corrosion behaviour than the stainless steel disc spring variants (Figure 24). The disc springs composed of 1.4310 had a longer lifespan due to the better corrosion resistance than the disc springs composed of 1.4568; in 3 % NaCl solution, cracks in the disc springs composed of 1.4310 and 1.4568 were initiated by chloride-induced pitting corrosion, which can be viewed as an operation-induced notch effect. Many crack nuclei were created, which eventually expressed themselves as transcrystalline running cracks. As a result, in this case, the break profile can be clearly distinguished from a fatigue failure in air.

No impermeable protective layer could form on the oiled disc spring in air or in 3 % NaCl solution, so fatigue crack corrosion occurred in the active state. Corrosion grooves were created, which acted as notches from which cracks formed due to the component of mechanical stress. Due to the worse corrosion resistance in 3 % NaCl solution than in deionised water, the oiled spring had a shorter lifespan. This applied in a similar way for the chemically nickel-plated, the Dacromet-coated, and the Geomet-coated springs. The painted spring had almost the same lifespan as in the deionised water, that is, the fatigue resistance of the paint layer is the deciding factor for the fatigue crack corrosion behaviour in deionised water and in 3 % NaCl solution. The Dacromet and Geomet coatings are brittle and only adhere to the base material to a limited extent. After only a few cycles, the layers peeled away in flakes. Thus, the Dacromet- and Geomet-coated disc springs behaved in all media like the oiled spring. The mechanically zinc-plated disc spring and the disc spring coated with Delta Tone and Delta Seal endured a higher number of cycles than in deionised water through the formation of the Simonkolleite layer on top of the zinc layer.

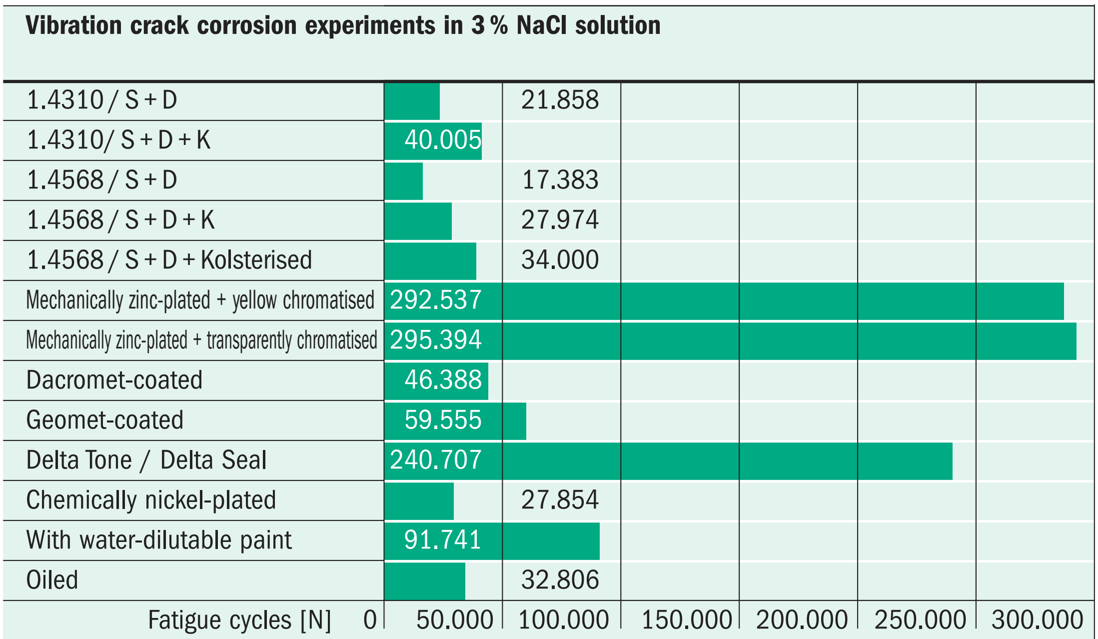


Figure 24: Comparison of lifespans of all disc spring variants in the fatigue crack corrosion experiment in 3 % NaCl solution (cycle amplitude $0{,}2h_0$ to $0{,}6h_0$).

Fatigue crack corrosion experiments in 0.1 M citric acid

Variant	Fatigue cycles [N]
1.4310 / S + D	30.037
1.4310/ S + D + K	47.338
1.4568 / S + D	34.692
1.4568 / S + D + K	41.433
1.4568 / S + D + Kolsterised	40.250
Mechanically zinc-plated + yellow chromatised	73.386
Mechanically zinc-plated + transparently chromatised	49.507
Dacromet-coated	28.192
Geomet-coated	24.128
Delta Tone / Delta Seal	22.578
Chemically nickel-plated	19.208
With water-dilutable paint	15.703
Oiled	28.078

Fatigue cycles [N] 0 20.000 40.000 60.000 80.000

Figure 25: Comparison of lifespan values of all disc spring variants in the fatigue crack corrosion experiment in 0.1 M citric acid (cycle amplitude $0,2h_0$ to $0,6h_0$).

In 0.1 M citric acid (Figure 25), the disc spring variants in stainless steel have on average a longer lifespan than the coated disc spring variants. The chemical reaction between citric acid and zinc, present in most coatings, dissolved the coatings. The water-dilutable paint layer was not chemically resistant in 0.1 M citric acid, either. These factors led to earlier failure of the coated disc springs in 0.1 M citric acid than in deionised water or 3 % NaCl solution. From the results of the electrochemical studies (not reported here), it was known that citric acid is a medium that produces a passive layer for the passivatable chrome-nickel steels. Thus, the stainless steel disc spring variants here experience fatigue crack corrosion in the passive state.Cyclic loading creates surface regions free of a passive layer via slip bands that penetrate outwards. These regions now formed small, highly active local anodes. The corrosion attack followed the slip band into the material. In citric acid, the chrome-nickel steels were in a position to regenerate the original passive layer at the sites of corrosion. The crack then predominantly came to a halt. However, the notch created by the material conversion that had already occurred led after some time, with increase in notch formation, to a locally elevated tensile stress, which cracked the just-formed passive layer again. The attack then always continued into the depths of the material. The crack propagated at an increasing rate [8]. The chrome-nickel steels had a better repassivation ability in 0.1 N NaOH than in 0.1 M citric acid, as shown by a correspondingly longer lifespan.

In contrast to the even distribution of breaks over the disc spring stacks in the stress corrosion crack

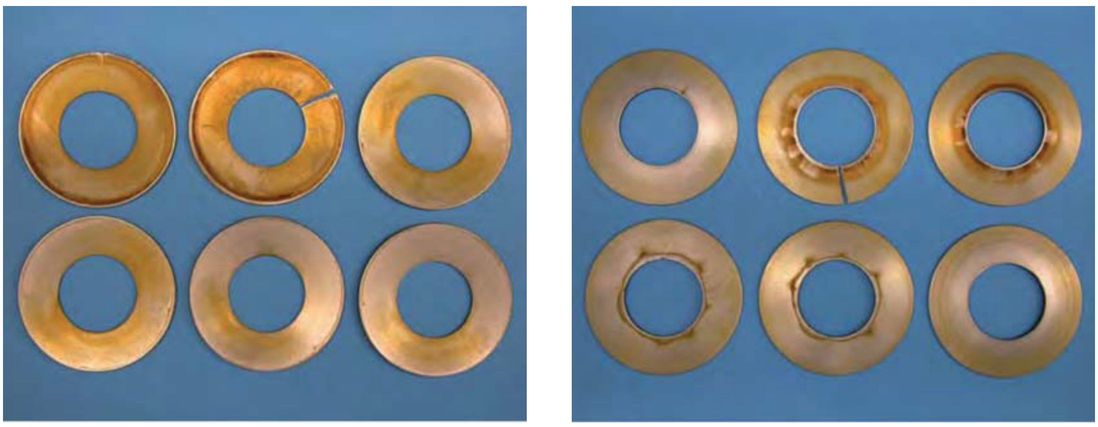


Figure 26: Visual manifestations of corrosion on non-shot-peened disc springs composed of 1.4310 after the fatigue crack corrosion experiment in 3 % NaCl solution

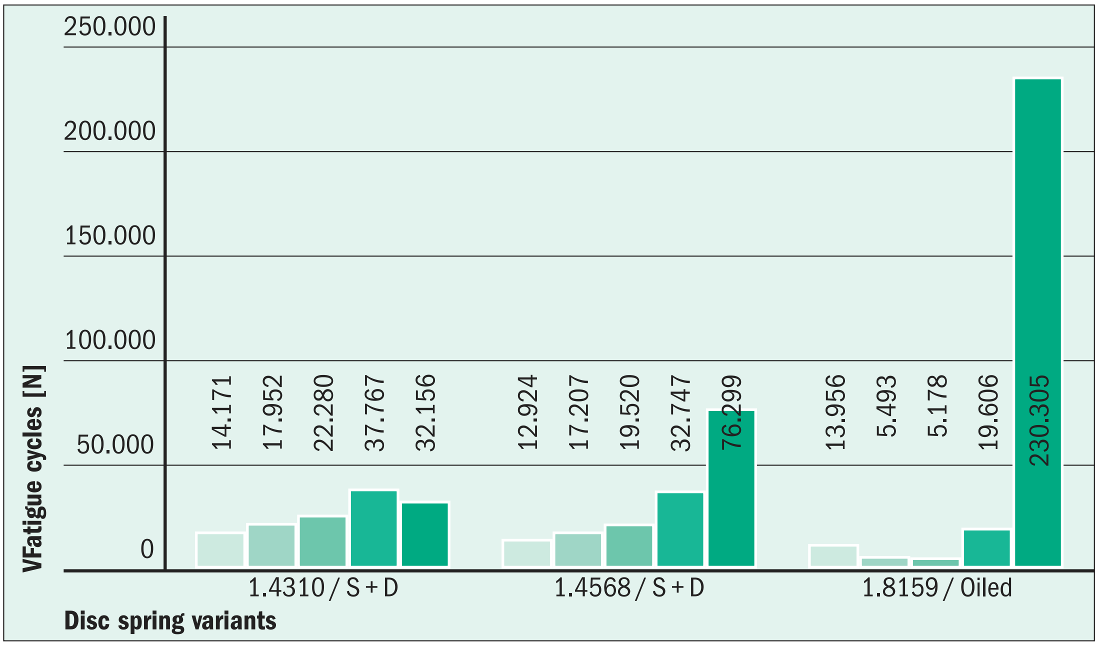


Figure 27: Comparison of lifespan values of all disc spring variants in corrosion media and in air (cycle amplitude $0{,}2h_0$ to $0{,}8h_0$).

experiment, in the fatigue crack corrosion experiment it was predominantly the second spring in the 6 x 1 stack that failed, since due to the experimental arrangement, the second spring corroded most heavily on the upper and lower sides (Figure 26).

In the context of the research project AVIF A115 »Fatigue resistance studies of individual disc springs and disc spring stacks of freely variable layering arrangements« and the continuation project AVIF A155 »Supplementary studies of disc springs«, the fatigue resistance properties of disc springs in air were studied. In Figure 27, the results from both research projects are compared with the results from this research project.

The negative influences and effects of corrosion on component resistance to cyclic operational load have been shown by experience to be more severe as the strength of the construction material increases. Conventional, low alloyed spring steels offer no protection of their own against corrosion. Thus, for springs which must in principle be comprised of high-strength materials that are relatively sensitive to notching in order to fulfill their function, sufficient protection against these influences is necessary. Damage to the surface of the spring through chemical or electrochemical attack is to be avoided to the greatest extent possible, since even the smallest corrosive pits can lead to breakage.

SUMMARY OF THE FATIGUE CRACK CORROSION EXPERIMENTS

In deionised water, the disc springs composed of stainless steels had the shortest lifespan (fatigue cycles endured). With relation to medium, their lifespan was in the following order: sodium hydroxide > citric acid > NaCl > deionised water. The shot-peening had a positive effect, independent of material, on the lifespan of the spring, especially at small amplitudes of cycle. The coated disc springs composed of 51CrV4 generally had better fatigue resistance properties than the disc springs of stainless steels, except in citric acid. Of the coated disc springs, the mechanically zinc-plated disc springs behaved the best; the Dacromet and Geomet coatings are brittle and not suitable for cyclically stressed disc springs.

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