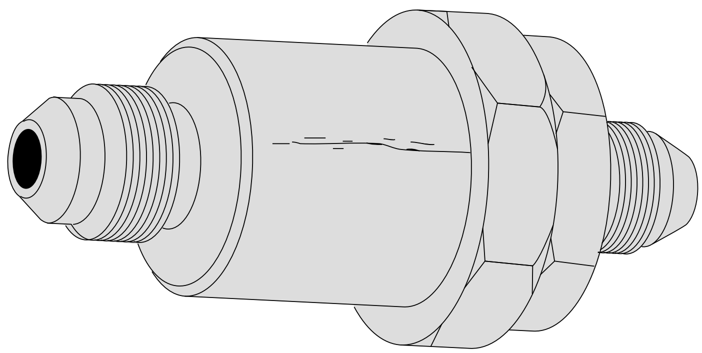
5.6.3.1.2 Failures Through Stress Corrosion Cracking (SCC).



SCC can cause engine parts to fail prematurely through **crack initiation and fracture**. It must be remembered, that SCC not only increases the subcritical **crack growth rate**, **minimizing the remaining life span in the crack growth phase**, but also decreases the critical **fracture toughness** considerably, shortening the critical crack length and further decreasing the crack growth phase.

Assuming that the requirements for stress corrosion cracking are sufficiently understood, and that construction, material specifications, and the allowable manufacturing processes reflect this, then SCC damage should only be **expected in case of unallowable deviations**. Experience seems to confirm this. In most cases, this type of damage occurs when the material of specific batches or lots is in a SCC-sensitive state due to certain deviating manufacturing steps or parameters (Ill. 5.6.3.1.2-1). These deviations can be due to, for example, steel heat-treatment processes. Especially sensitive materials are those with deviations towards **higher strengths/hardness** and simultaneously have **sensitive structural areas** (such as grain boundaries, Ill. 5.6.3.1.1-35). In hard **Al alloys**, such as are used in threads of fuel lines, deviations in the hardening process can cause unallowable sensitivity to **marine environments**. If the damage can be limited to specific lots or batches, the chance of achieving targeted and limited measures for replacement or risk assessment exists.

During **manufacture** and overhaul, changes to **auxiliary materials** such as **cutting, etching, and cleaning fluids** and/or **soiling** (wear products from tools, shot peening media, etc.), or **changes to the surface** (such as hardening, internal stress) can promote unexpected SCC damage.

However, it is also plausible for operating temperatures, acting over a long period of time, to cause damaging changes in the material (Ill. 5.6.3.1.2-2). This has been observed not only in superalloys (such as turbine stator vanes made from Co alloy) and steels, but also in Al alloys. SCC damage may then occur either during operation or during overhaul procedures, even though there was no unallowable deviation from regulations.

The SCC behavior of materials used in engine manufacture:

Cr steels:

Cr steels have very different sensitivity to SCC, depending on heat treatment processes (structure, hardness), carbon content, and alloy additions. For example, it has been observed that with Cr steels (13% Cr steel), of the type which are frequently used for threading on tension bands (Ill. 5.6.3.1.2-6), a **material-dependent minimum hardness** is required in order for SCC to occur under the influence of chlorides in a watery solution. In this way, in compressor stator vanes made from this type of material SCC occurred only above a hardness of about 40 HRC. The SCC-crack sensitivity is promoted through directional material impurities such as are typical for free-machine materials that contain sulfur. The use of this type of material in aviation should be avoided today.

Cr Ni steels:

These materials are sensitive to SCC if the austenite is in an unstable condition due to an **improper heat treatment**. Depending on the nickel content, sensitivity increases with higher carbon content. For example, the material type CrNi 18 9 is sensitive above a carbon content of about 0.045 %. Cold deformation increases the SCC sensitivity, as long as no deformation martensite has formed. Even very minor plastic cold deformation can make CrNi steels with over 10% Ni prone to cracking, even if they are SCC-resistant in the elastic range. Small amounts of martensite provide cathodic protection against SCC (base potential of the martensite). If, however, much more deformation martensite is created (on the gliding plane), the SCC-sensitivity is increased. If ferrite is present, it provides cathodic protection for the austenite, lowering the danger of SCC. Carbide precipitations (on the grain boundaries) decrease the danger of transcrystalline SCC. However, along with “normal intercrystalline corrosion“ on passive surfaces, intercrystalline SCC can occur on largely active surfaces. If the structure is so unstable, that (unusual?) operating temperatures cause undesired changes, then parts may only become sensitive to SCC during operation and suffer corresponding damages (Ill. 6.3.1.1-2).

If, in these steels, the adjacent tensile stresses are not sufficiently great to cause crack initiation, they often cause pitting corrosion (Ill. 5.6.3.1.1-9). The table on page 5.6.3.1.1-13 is an overview of the SCC-sensitivity of different steels, as well as Ni-based alloys.

SCC has been found on austenitic steels in engines in the following watery media, the corrosive components of which are primarily Cl and sulfite ions:

- Damp air,
- sea water,
- marine air,
- calcium chloride,
- sulfuric acid,
- zinc chloride,
- magnesium chloride,
- sodium chloride,
- damp hydrogen sulfide.

Cl-ion contents of greater than 60 mg/l at temperatures above 70°C have been shown to be generally damaging.

Al alloys:

Intercrystalline SCC can affect Al materials in watery electrolytes containing halogen, in organic solutions, and in damp air. The high-strength and temperable, but corrosion-sensitive Al alloys of type AlZnMg and AlZnMgCu have been shown to be susceptible to SCC. Even normally corrosion-resistant AlMg alloys have been affected by SCC in cases where the structure was in a critical state. AlCuMg and AlMgSi alloys have proven to be largely immune to SCC, but they tend to intercrystalline brittle (force) fractures in their fully hardened states. However, alloying additional “stabilizers“ (such as Mn, Cr, or V) and suitable heat treatment (delayed quenching after solution annealing, gradual quenching) permits sufficiently safe use of high-strength Al alloys. The primary cause of SCC-sensitivity in Al materials is believed to be grain boundary precipitations, which cause the typical intercrystalline crack progress that occurs when a potential difference is created between the precipitations and the alloy components of depleted grain boundaries. The crack progress runs along the grain boundaries that are perpendicular to the direction of the loads. Therefore, the crack growth rate is largely dependent on the specific grain shape and the manufacture of the semi-finished product (as far as this affects the structural orientation), and also on the intensity of the stress. However, the damage symptoms indicate that, aside from the precipitations, a further SCC-promoting mechanism is involved. This mechanism may be cold-hardening zones, which are caused by single-phase segregation at low temperatures.

“**Pre-corrosion**“ in an unloaded state can drastically reduce the time to fracture due to SCC under loading. The critical tension, above which SCC occurs, may only be 10% (!) of the tensile strength of the material, depending on the “direction of fiber“ of the material. The critical tension can lead to crack initiation, but it will not usually be sufficient to cause crack growth.

Ti alloys:

Titanium alloys without cracks or sufficiently sharp nicks are not SCC-sensitive in watery media that contain chloride. This is evidently also true with regard to crack-initiating **hot salt corrosion** (Ill. 5.6.3.1.1-7). Crack growth only occurs above a stress concentration threshold. Sensitivity to SCC is especially pronounced in tests with constant strain rates (see page 5.6.3.1.1-4), which indicates strain-induced SCC (Ill. 5.6.2-1 and Ill. 5.6.3.1.1-1). Critical crack growth rates (at which the influence of SCC becomes noticeable) have been observed between 0.02 mm/h und 1.5 mm/h. No SCC damage is to be expected outside of this range, unless the loads reach the local tensile stress, such as in a nick. However, this is not true for all SCC-inducing media. SCC fractures were observed on flat samples in halogenide-containing alcohols with low water content (10^{-1} to 10^{-2} %).

Although no operating damages to high-strength Ti alloys due to hot salt stress corrosion (above 300°C, see Lit. 5.6.3.1.2-4) have been reported, there is a potential crack problem in case of **hot salt contact** (Ill. 5.6.3.1.1-7). This reduces the bearable loads, increases the creep strain, and the contraction at fracture at room temperature is reduced after the attack. However, the increased creep strain is less due to any ductile material behavior than to an accordion effect following the large crack initiation. In tests with the alloy Ti6A14V, the hot salt SCC-sensitivity considerably increased with increasing grain size (from 0.025 to 0.1mm).

It can be assumed that, under hot salt SCC action, the strength perpendicular to the deformation direction are considerably worse than those that are parallel. In case of perpendicular loading, fractures are usually crystalline. As the temperature increases, the time to an SCC fracture decreases considerably more than could be explained by creep effects alone. Cold hardening worsens the performance against hot salt SCC, contrary to normal SCC in watery solutions.

This brings up the question as to what extent hot salt SCC on titanium alloys can be seen as SCC in the strictest sense of the word.

***Ill. 5.6.3.1.2-1** (page 5.6.3.1.2-6): Experience has shown that parts/elements of **auxiliary units** are especially prone to SCC damage. So-called "**catalog parts**" evidently exhibit the following characteristics/weaknesses most often:*

- The parts are relatively inexpensive.

- The parts do not always meet the high quality demands of aviation technology.

- The designer accepts the technical data some what uncritically.

- These vendor parts are evidently not as closely monitored as "own parts" by the aviation companies.

Further reasons for SCC damage might lie in the use of materials such as strong Al alloys and heat treatable steels, which have a certain potential susceptibility to SCC, and are more likely to be used in operation in temperature ranges that cause structural changes that sensitize them to SCC. These materials cannot simply be replaced by less sensitive ones, since they have certain necessary properties (such as high strength in screws and ball joints).

***Pipe and hose screws** (middle left diagrams):*

These elements are often made from bar stock with a pronounced lengthwise structure (see page 5.6.3.1.2-2). This promotes crack growth in case of SCC, because the threading and internal pressure makes operating loads act perpendicular to the structural direction (see page 5.6.3.1.2-2 and Ill. . 5.6.3.1.2-1)

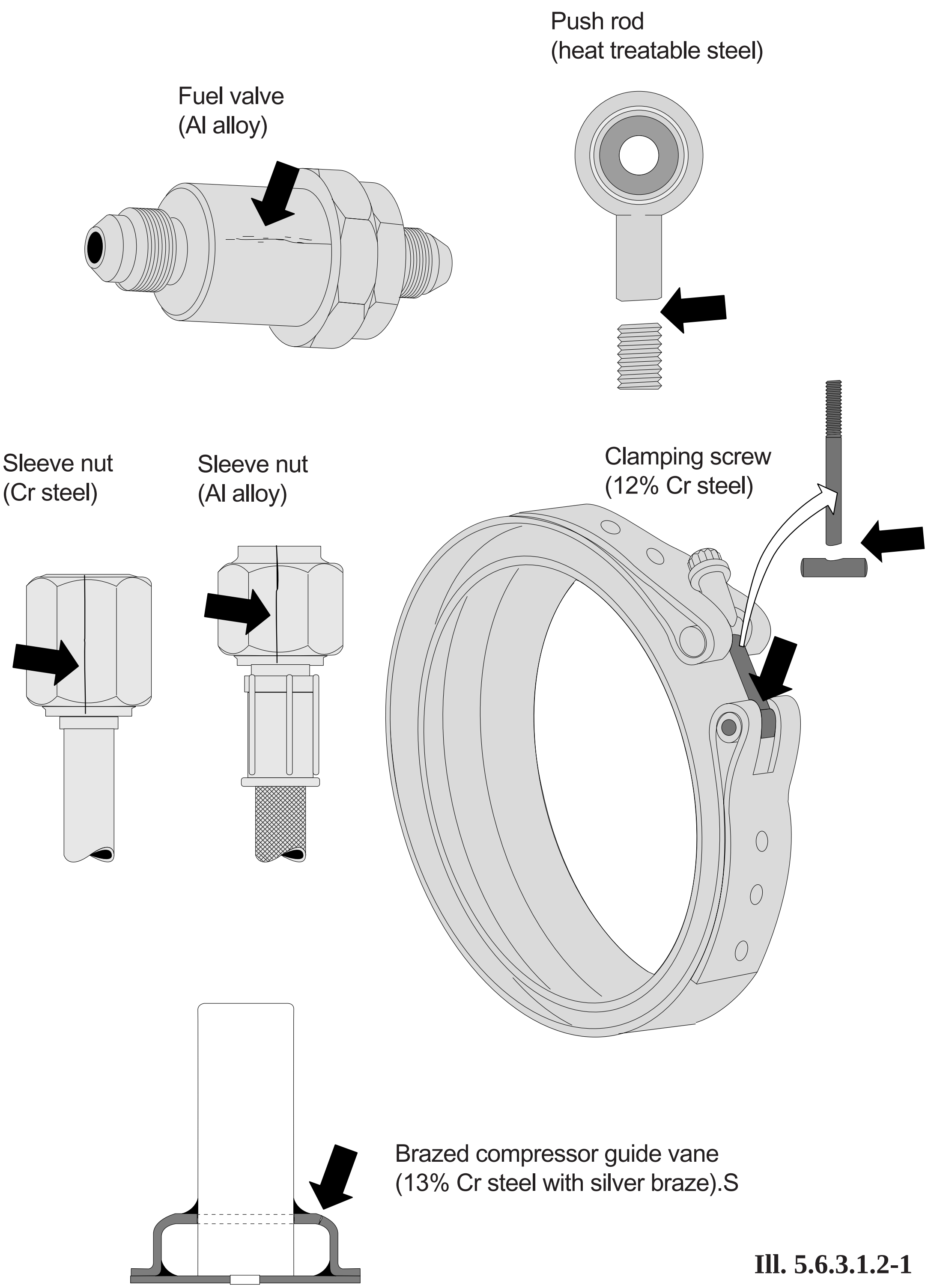
Clamping and fastening screws (right top and middle diagrams):

Clamping screws of the type frequently used on tension bands to fasten auxiliary components, are traditionally made from 13% Cr steels. Heat treatable steels are also used for ball joint sockets, which play an important role in mechanical force transmission. These materials become SCC-prone when they exceed the intended strength, which is usually due to improper heat treatment during manufacture.
Experience has shown that the risk zones are usually in the first carrying threads (plane which lays on the nut, Ill. 5.6.3.1.1-6) or in formed notches, such as the forged-on head of the T-screws of tension bands.

Compressor blading (older engine types):

Deviations during manufacture resulted in root boxes that were brazed to 13% Cr steel compressor stator vanes (bottom diagram) having a hardness above 40 HRC, which is dangerous for SCC. During operation, large lengthwise cracks formed in the bending radius. It is not entirely certain how great the influence of the high strength and resulting high internal stresses was on the crack initiation.

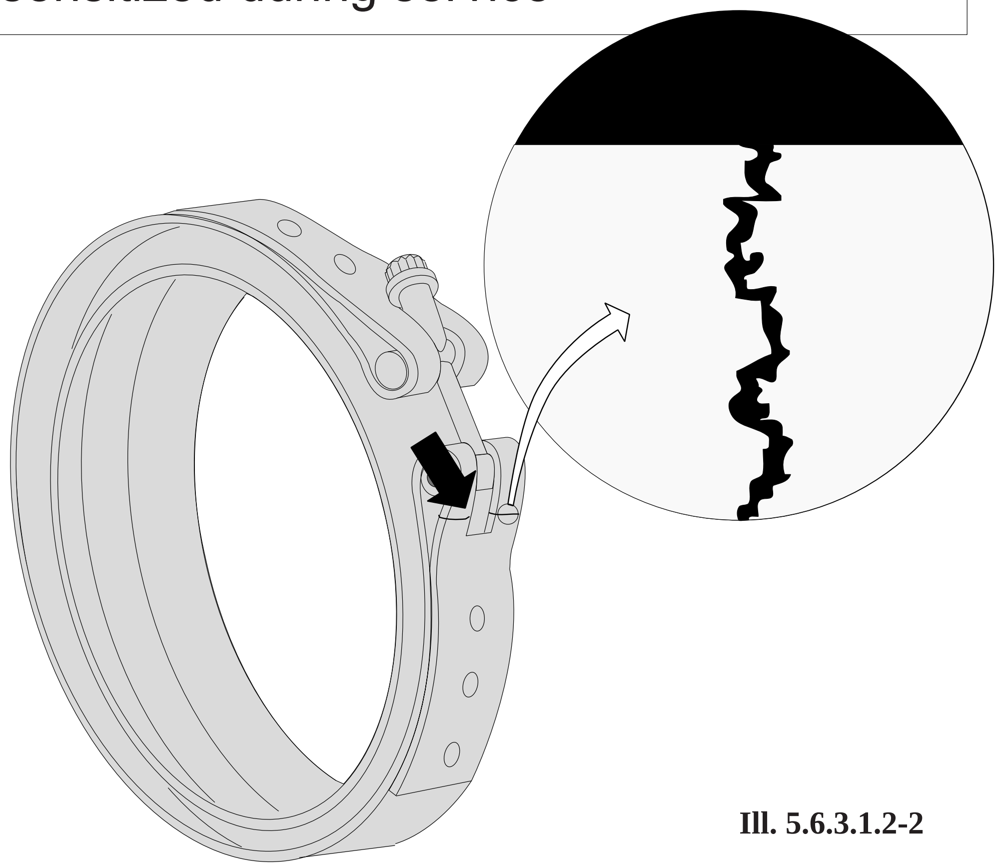
Stress corrosion cracking can occur during operation on very different engine parts.



Ill. 5.6.3.1.2-1

Ill. description see previous page.

Intergranular stress corrosion on a part, sensitized during service



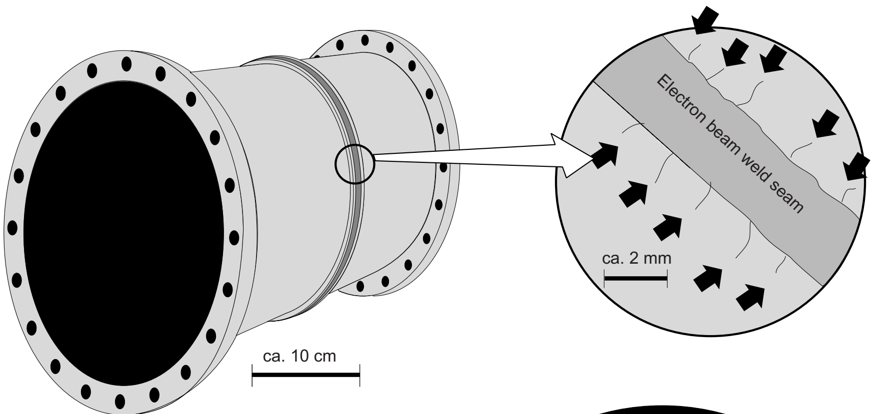
Ill. 5.6.3.1.2-2

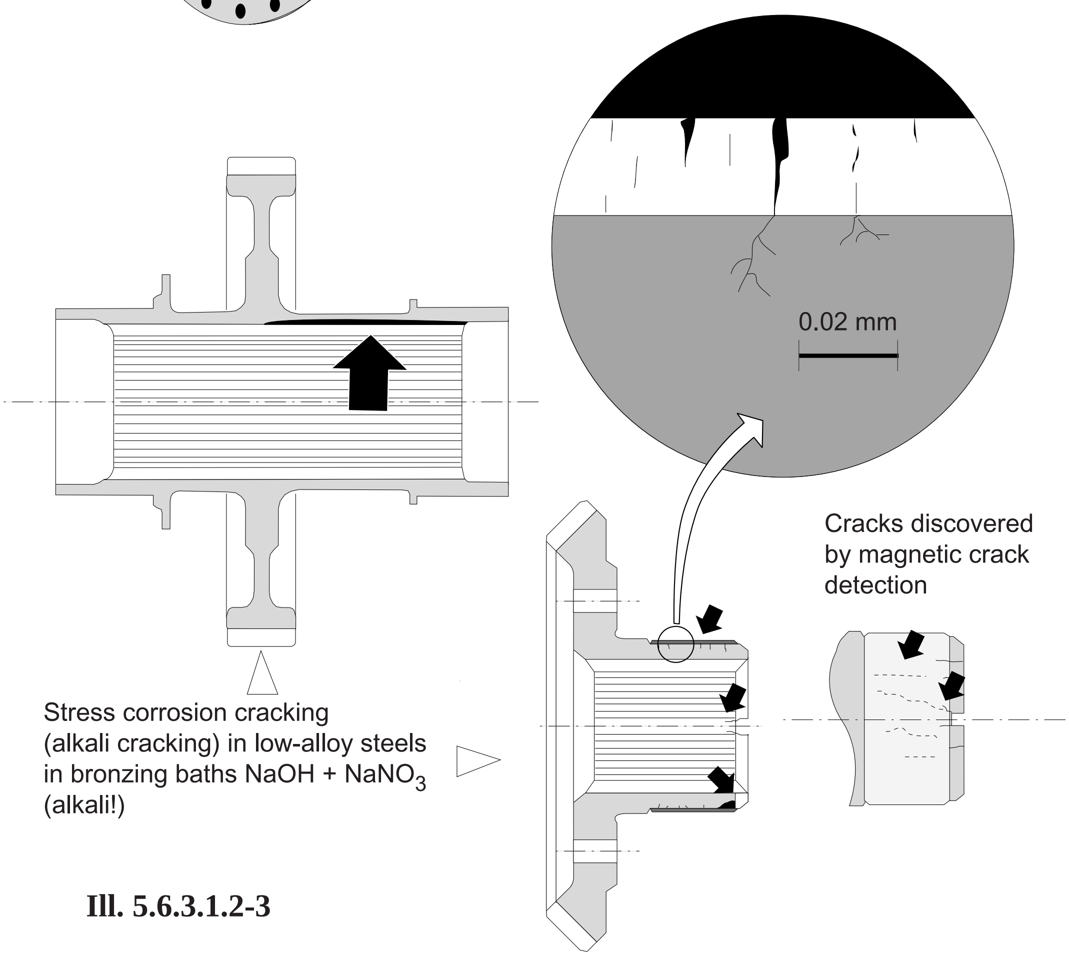
***Ill. 5.6.3.1.2-2** (Lit. 5.6.3.1.2-1): This **tension belt** comes from a fighter aircraft engine and is used to fasten the hot air outtake pipe to the compressor. The sheet metal that was used for manufacture was made from a material of type CrNi 19 9 with 0.3%* carbon content. The **operating temperature** was between 425 and 540°C. After an operating time of between 2 and 3 years, the fastening flange for the tension bolt failed due to an intercrystalline fracture, even though there was no prescribed life span for the tension clamp (area indicated by arrow). The results of a metallographic inspection revealed that the damaged area contained coarse grain, which was probably due to a **straightening process** during manufacture. There were many carbides on the grain boundaries in this area. Under operating conditions, the **sensitization** caused by the cold-deformed structural instability resulted in characteristic crack progress under influence of an intercrystalline SCC attack in **marine atmosphere** (see detail, page 5.6.3.1.1-6).*

** the 0.3% carbon content of the affected material given in the literature seems much too high, and suggests that the wrong material was used: This would make the damage unavoidable.*

Stress corrosion cracking due to the influence of baths during production and overhaul.

Stress corrosion cracking around a weld seam on a shaft made from a high-strength Ti alloy: After degreasing in a bath containing Cl with no inhibitor followed by a heat treatment.





Ill. 5.6.3.1.2-3

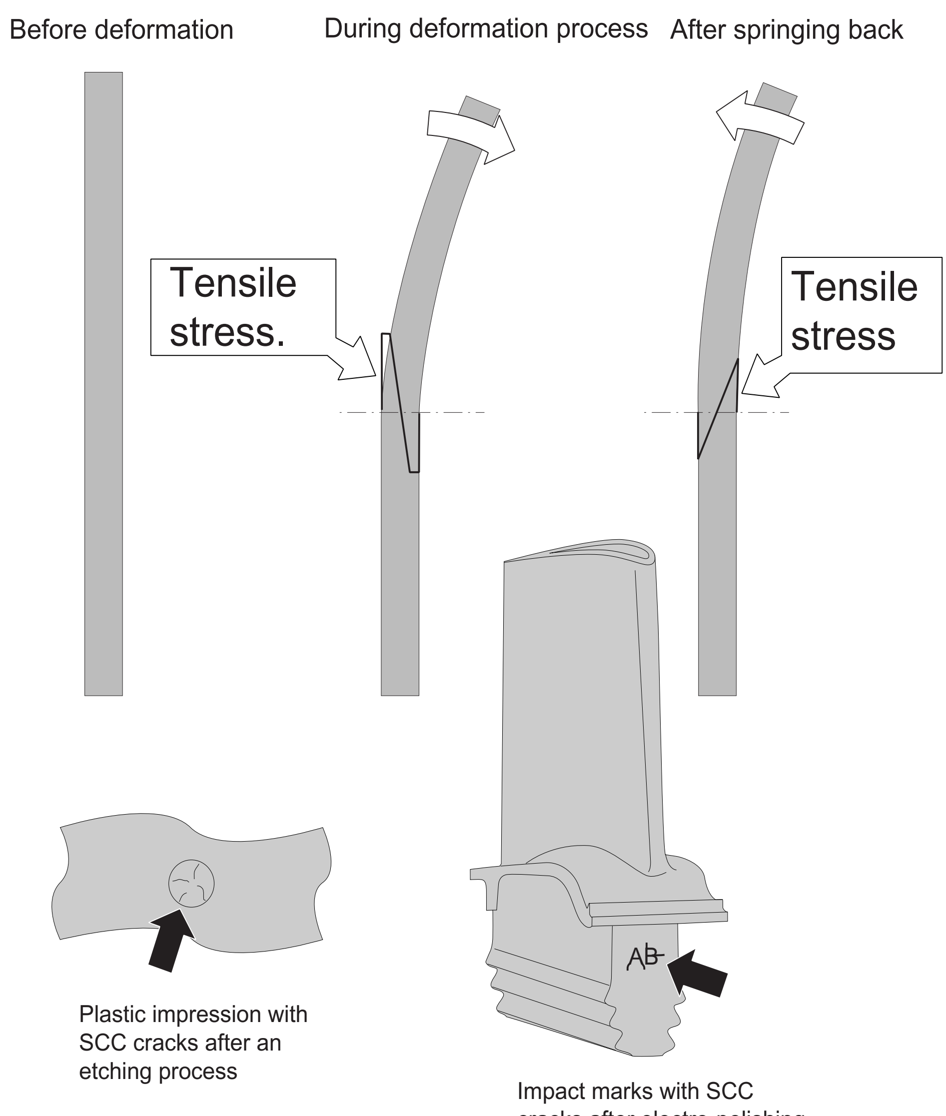
***Ill. 5.6.3.1.2-3** (Lit. 5.6.3.1.2-3): Stress corrosion cracking damage to **titanium alloy** parts is extremely rare, and has only been known to happen in connection with **manufacturing processes**. For example, cleaning in hot degreasing liquids containing Cl, such as perchlorethylene or trichlorethylene, can cause SCC in areas with notches or high tensile stress, such as around a weld seam head (top diagram). Even if no spontaneous crack initiation occurs in the bath, it must be assumed that reaction layers on the **surface containing Cl were created in the bath together with water/humidity from the air** before chromium plating and burnishing. So they can lead to crack initiation during later heat treatment or even at normal operating conditions. Therefore the concerning cleaning baths must be checked for chlorine and changed in time. It is also possible, that parts that have been degreased in the listed baths, and that have reaction coatings containing Cl, will tend to crack initiation during welding.*

*With low-alloy steels of the type that are used as a standard material for **transmission gears** and **multiple-splined shafts** for powering auxiliary units, pronounced crack initiation due to SCC can occur (bottom diagrams). These damages have been observed not only **during new part production**, but also occur increasingly during **repair** and **recoating** of toothed gears. In these parts, worn bearing seats and seal ring tracks were ground down and chromed. The **Cr coating** is then ground and polished to the right size. If intercrystalline cracks are found in this coating during magnetic crack detection after bronzing, then it is possible that the cracks which are normally a part of the Cr coating are acting upon the base material, which is subject to grinding tensile stresses. Evidently, grinding stresses that were created during the grinding of the Cr coating also play a role. The **bronzing/ burnishing bath** is a hot alkali (NaOH + $NaNO_3$ + $NaNo_2$). For this reason, this state is referred to as **alkali cracking** or **alkali brittleness.***

*If magnetic crack detection shows cracks in the Cr coatings, then these cracks are not the allowable and typical cracks associated with Cr coatings, as is often mistakenly assumed (the typical allowable cracks are not to verify magnetic and will not be detected). In this case, it must be assumed that the **detected cracks are in the magnetic base material below the Cr coating.***

***Shot peening of the entire part surface has proven to be effective**, especially the ground surface before it is chromed and bronzed.*

Stress corrosion cracking in plastically deformed surfaces.



Ill. 5.6.3.1.2-4

Ill. 5.6.3.1.2-4: *SCC cracks can occur in **unexpected part zones**, such as in areas where compressive stresses would seem more likely. During the **deformation process**, localized exceeding of the yield point plastically compresses the material under compressive stress, i.e. it is shortened and then permanently stretched in the tensile stress zone. When the external loads stop acting and the material/part **springs back**, the stresses are reversed. Compressive stresses develop in the plastically stretched areas, while tensile stresses develop in the compressed zones. These tensile stresses can be a prerequisite for SCC. This type of damage has been discovered during **repair work** involving **galvanic or chemical treatment** of engine parts.*