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DESIGN CRITERIA
(STRUCTURES)

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STRESS-CORROSION CRACKING IN METALS

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FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all published monographs in this series can be found at the end of this document.

These monographs are to be regarded as *guides* to the formulation of design requirements and specifications by NASA Centers and project offices.

This monograph was prepared under the cognizance of the Langley Research Center. The Task Manager was W. C. Thornton. The author was W. K. Boyd of Battelle Memorial Institute. A number of other individuals assisted in developing the material and reviewing the drafts. In particular, the significant contributions made by the following are hereby acknowledged: H. P. Adam, H. J. Siegel, and B. V. Whiteson of McDonnell Douglas Corporation; B.F. Brown of U. S. Naval Research Laboratory; F. X. Drumm and I. G. Hedrick of Grumman Aerospace Corporation; M. Dublin of General Dynamics Corporation; D. B. Franklin of NASA George C. Marshall Space Flight Center; R. E. Johnson of NASA Manned Spacecraft Center; C. F. Littlefield of The Boeing Company; E. E. Mathauser of NASA Langley Research Center; R. E. O'Brien of North American Rockwell Corporation; R. H. Raring of NASA Office of Advance Research & Technology; and R. W. Staehle of Ohio State University.

NASA plans to update this monograph periodically as appropriate. Comments and recommended changes in the technical content are invited and should be forwarded to the attention of the Design Criteria Office, Langley Research Center, Hampton, Virginia 23365.

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GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to provide a uniform basis for design of flightworthy structure. It summarizes for use in space vehicle development the significant experience and knowledge accumulated in research, development, and operational programs to date. It can be used to improve consistency in design, efficiency of the design effort, and confidence in the structure. All monographs in this series employ the same basic format – three major sections preceded by a brief INTRODUCTION, Section 1, and complemented by a list of REFERENCES.

The STATE OF THE ART, Section 2, reviews and assesses current design practices and identifies important aspects of the present state of technology. Selected references are cited to supply supporting information. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the CRITERIA and RECOMMENDED PRACTICES.

The CRITERIA, Section 3, state *what* rules, guides, or limitations must be imposed to ensure flightworthiness. The criteria can serve as a checklist for guiding a design or assessing its adequacy.

The RECOMMENDED PRACTICES, Section 4, state *how* to satisfy the criteria. Whenever possible, the best procedure is described; when this cannot be done, appropriate references are suggested. These practices, in conjunction with the criteria, provide guidance to the formulation of requirements for vehicle design and evaluation.

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STRESS-CORROSION CRACKING IN METALS

1. INTRODUCTION

Stress-corrosion cracking is a brittle fracture which occurs in both brittle and ductile metals under the combined action of corrosion and static tensile stress. Neither corrosion nor static tensile stress alone will initiate such cracks. Virtually all metal systems contain one or more alloys which are susceptible to stress-corrosion cracking in some environment, particularly such metal systems as aluminum, magnesium, nickel, high-strength low-alloy steels, stainless steels, and titanium, all of which are extensively used in aerospace vehicles.

Incidents of structural failure due to stress-corrosion cracking have been numerous in the aerospace industry, and some of them have been catastrophic. For example, the use of a high-purity grade of N_2O_4 resulted in an explosive failure of a titanium alloy tank. A similar catastrophic failure occurred when a titanium tank under test was pressurized with anhydrous methanol, which has a density similar to that of rocket fuel. Likewise, a number of booster cases of AMS 6434 steel shattered during proof testing because of stress-corrosion cracks generated by the tap water used as the pressurizing fluid.

Experience indicates that the assembly stresses caused by improper fit-up of mating parts or by inadequate design have been the greatest single cause of stress-corrosion failure. For example, serious accidents have resulted from the failure of aluminum and high-strength steel landing-gear housings and other structures which have assembly stresses caused by fasteners and interference bushings. In addition, the fasteners themselves have often suffered from stress-corrosion cracking, as in the frequent 1962 failures of AN 818 aluminum alloy hydraulic fittings ("B" nuts) made from 2014 and 2017, which are especially prone to stress-corrosion cracking. More recently, cadmium-plated titanium fasteners have failed from stress-corrosion cracking.

This monograph presents criteria and recommends practices to prevent stress-corrosion cracking from impairing the structural integrity and flightworthiness of space vehicles. Factors involved in the initiation, propagation, and identification of stress-corrosion cracks in metals only are discussed, though similar cracking occurs in nonmetallic materials. It does not discuss other forms of environmental cracking such as corrosion fatigue, caused by cyclic tensile stress and corrosion, nor hydrogen-stress cracking, which results from the introduction of hydrogen into the metal lattice. Although primary

emphasis throughout the monograph is on high-strength aerospace materials, namely aluminum, low-alloy steels, and titanium alloys, the information presented is also applicable to other alloy systems.

Stress-corrosion cracking is an insidious phenomenon, as is illustrated by the following characteristics:

- The cracks are difficult to detect because

  (a) They are so fine that there is generally no macroscopic indication that a flaw exists

  (b) There may be no visible indication of the corrosion itself

- Environments causing cracking are often quite innocuous, such as distilled water and the earth's atmosphere. The small amount of chloride ion in ordinary drinking water can cause cracking of a thick section of stainless steel in a few hours and a trace of oxygen in N_2O_4 has caused a catastrophic failure of a titanium alloy tank. Even seemingly undetectable amounts of ammonia in the air can cause cracking of copper-base alloys.

- An applied load is not necessary to initiate stress-corrosion cracks. Either residual stresses from forming, machining, heat-treatment, and welding operations or assembly stresses may be large enough for the initiation and propagation of a crack in the presence of a corrodent.

- A stress-corrosion crack can incubate a fatigue crack or a "brittle fracture" crack which otherwise might not occur.

The principal variables which significantly interact to influence stress-corrosion cracking are as follows:

- Alloy composition and related metallurgical factors

- Sustained surface tensile stress — either residual, assembly, or applied

- Environment, including temperature and time

Certain alloys and heat treatments in a given metal system are more resistant to stress-corrosion cracking than others. For example, cracking resistance usually improves in aluminum and titanium alloys with reduction in alloy content or with certain heat treatments. Depending on alloy composition and the nature of the corrosive environment,

the cracks may cross grains (transgranular cracking) or follow grain boundaries (intergranular cracking), although some alloys may exhibit both modes of cracking. Usually the fracture mode is similar for a group of related alloys.

Besides the corrosive environment, sustained tensile stress is necessary to cause cracking which initiates on the surface of the metal. This cracking has not been observed for metal surfaces in compression.

In general, the higher the stress, the shorter the time to failure. Stresses near the yield point of the material are most severe, but stress levels as low as 5 to 10 percent of the yield stress will sometimes initiate cracking. Typically, stress-corrosion cracking occurs when the tensile stresses from applied loads combine with residual and assembly tensile stresses to exceed the threshold level.

Cracking is most common in aqueous environments; however, certain moist gases and some liquid and solid metals (or their vapors) have caused stress-corrosion cracking. The number of offending environmental constituents is formidable and includes those found in the earth's atmosphere, cleaning and testing fluids, perspiration, salt air, caustics, and acids. Even distilled water will cause cracking of some alloys. Generally, the higher the temperature and the more concentrated the solution, the greater the likelihood of stress-corrosion cracking.

Stress-corrosion cracks have a great influence on the related subjects of fatigue, nondestructive testing, fracture mechanics, and acceptance testing. The fatigue life of a part can be significantly reduced by a stress-corrosion crack formed before the part has been placed in cyclic service. The detection of stress-corrosion cracks is difficult since they can be very small and there are usually no conspicuous surface indications which call attention to them. Therefore, nondestructive testing techniques are required to detect these cracks. The fracture mechanics aspects of mechanical crack growth and control are presented in the published monograph, Fracture Control of Metallic Pressure Vessels (ref. 1). Since stress-corrosion cracking is likely to occur as a result of residual stresses from manufacturing processes, assembly, and time in storage, acceptance tests often detect the cracks; these tests are discussed in the Acceptance Testing monograph (ref. 2).

2. STATE OF THE ART

Perhaps more than any other single corrosion phenomenon, stress-corrosion cracking restricts the use of high-strength structural metals and alloys. While some progress has been made in developing procedures and techniques for assessing the stress-corrosion cracking behavior of metals and alloys, the ability to predict the service life of any specific metal in any given environment has not been achieved. Thus there is no alternative but to test each alloy under the exact environmental conditions expected in service. The notion that testing in some aggressive laboratory environment will result in conservative data is dangerous and completely unacceptable.

The problem of premature failure of structural members as a result of stress-corrosion cracking is not new. However, the problem has become magnified by the trend toward the use of higher strength materials. For any given family of alloys, there ordinarily exists a direct relationship between the strength of the material and its susceptibility to stress-corrosion cracking. The higher the strength, the greater the susceptibility to stress-corrosion cracking. It is well known, for example, that plain carbon steels are immune to cracking in the atmosphere whereas the low-alloy, high-strength steels readily crack in the same environment at relatively low stress levels.

However, it is generally agreed that a single mechanism to explain stress-corrosion cracking is an unattainable goal. The evidence suggests that for any given situation of stress-corrosion cracking, a number of factors are operating; thus, it would appear that it is a critical combination of process interactions that comprise the mechanism of stress-corrosion cracking.

It is not the intent of this monograph to discuss the various hypotheses that have been put forth to explain the mechanism of stress-corrosion; the problems are too extensive and the mechanisms too complicated. However, it can be said that in general, an electrochemical process is implied as playing a part along with mechanical processes in the initiation and propagation of stress-corrosion cracks. The fact that propagating cracks can be stopped by applying cathodic protection or accelerated by anodic currents seems to preclude an entirely mechanical mechanism for most systems.

Those readers who wish to explore in greater depth the mechanistic aspects of stress-corrosion cracking are referred to the proceedings of the four major conferences on stress-corrosion cracking (refs. 3 through 6). Other papers and books have also treated a number of factors in stress-corrosion cracking (refs. 7 through 15).

The important variables affecting stress-corrosion cracking are:

- The environment, including time and temperature

- The metal composition and structure

- Sustained tensile stress

While there is no known universal environment which causes stress-corrosion cracking in all alloys, those containing chloride and/or other halide ions do promote cracking in a wide range of alloy compositions, including aluminum, high-strength low-alloy steels, stainless steels, titanium, and magnesium.

Considerable experience with stress-corrosion cracking of commonly used aerospace materials has been documented. For example, it is known that stress-corrosion cracking in the high-strength 2000 and 7000 series of aluminum alloys occurs most often in natural environments such as marine and industrial atmospheres. Similarly, high-strength low alloy steels and precipitation-hardened (PH) alloys will crack when stressed in industrial and marine environments.

Titanium alloys, on the other hand, are resistant to cracking under similar exposures. The most critical problems with titanium are flaw growth in sea water and other chloride-containing solutions, and cracking by hot, dry salt at elevated temperatures of from 532 to 810K (500 to 1000°F), although no service failures by hot-salt cracking have occurred. Austenitic stainless steels are also susceptible to stress-corrosion cracking in chloride environments but, with the exception of sensitized materials, not when the temperature is below about 322K (120°F).

Residual stresses introduced during manufacturing, such as heat treating and welding, or those stresses resulting from assembly, are difficult to control and account for the majority of stress-corrosion cracking failures. Applied loads in the absence of internal stresses rarely cause stress-corrosion cracking, and no cracking occurs in the absence of stress.

Other important aspects of stress-corrosion cracking which will be discussed in more detail below include crack morphology and time to failure.

2.1 Crack Morphology

Stress-corrosion cracks have the appearance of a brittle fracture. Depending on the composition of the alloy and the nature of the corrosive environment, the cracking may propagate either between or across grains; that is, it may be intergranular or transgranular. However, in general, the fracture mode of a group of related alloys will be similar. For example, the cracking in carbon steels, copper alloys, nickel alloys, and aluminum alloys predominately follows an intergranular path; in austenitic stainless steels and magnesium alloys, transgranular crack paths are characteristic.Titanium alloys can crack in either way.

Other typical characteristics of stress-corrosion cracks are their highly branching nature and the presence of significant secondary cracks. Figure 1 is a photomicrograph of transgranular cracking in austenitic stainless steel, which also illustrates the branching nature of this type of failure. Examples of intergranular stress-corrosion cracking are shown in the photomicrographs of figure 2. Both transgranular and intergranular cracking are revealed by scanning electron micrographs of aluminum and titanium alloys in figure 3. The high secondary-crack density typical of stress-corrosion cracking is clearly evident in the fracture of a titanium-alloy pressure vessel shown in figure 4.

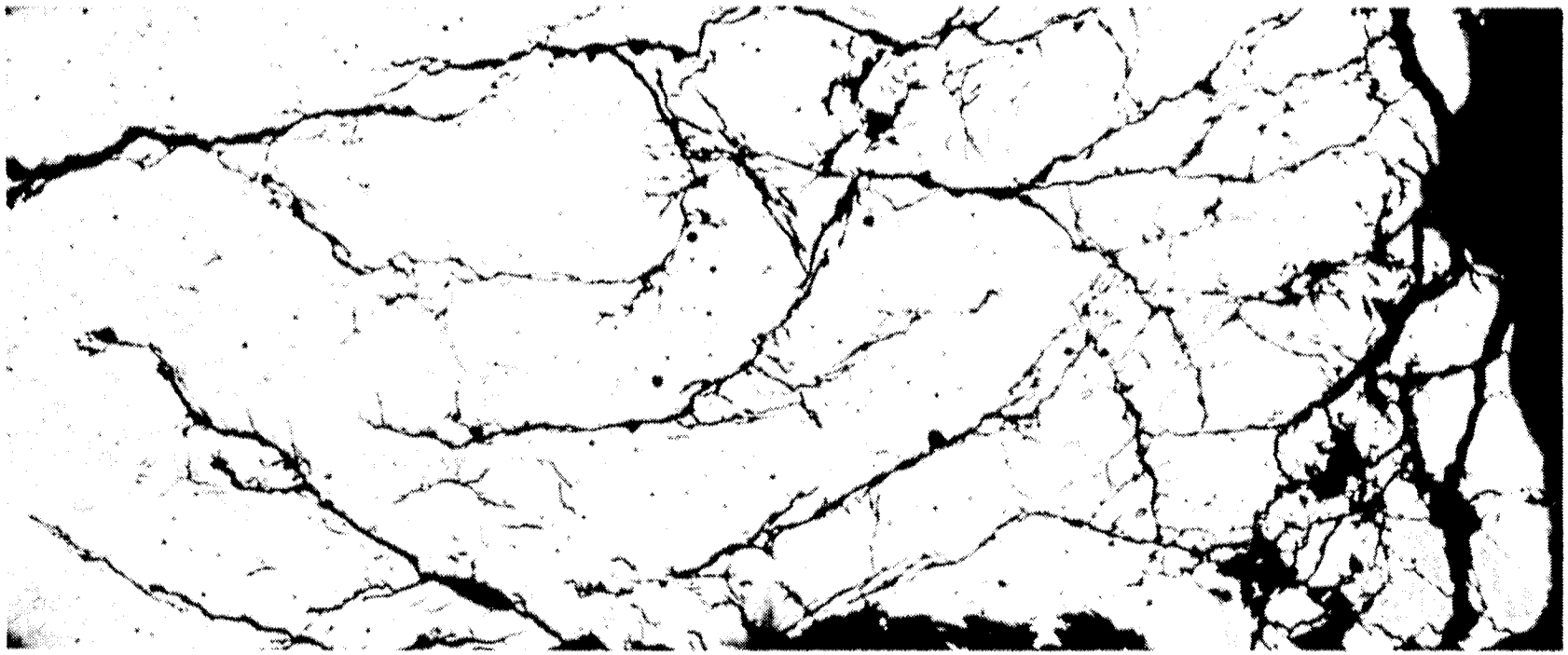
The presence of grain boundary precipitates and/or a thin region next to the grain boundary with enriched or impoverished alloy content has been suggested as the necessary prerequisite to intergranular cracking (ref. 16). In transgranular cracking, the metallographic evidence indicates that the cracks follow certain crystallographic planes.

2.2 Time to Cracking

In general, stress-corrosion cracking can be divided into two distinct phases: (1) initiation and (2) propagation. The time for the initiation of a stress-corrosion crack may vary from a few minutes to several years, depending on the alloy, the nature of the environment, and the magnitude of the stress. The initiation-time parameter used for design is essentially equivalent to the expected service life of the part, since the major structural damage occurs after a crack forms and propagates to a critical size, resulting in complete failure of component or structure. Service life is defined as the interval beginning with manufacture of a vehicle and ending with the completion of its specified mission.

Once the crack has initiated, the rate of propagation is quite similar for a number of alloys (ref. 6). The rate of propagation of stress-corrosion cracks is much slower than that in mechanical fast fracture at rupture (approximately one-fourth the speed of sound in the metal). For alloys such as plain carbon steels, aluminum alloys, stainless steels, and copper-base alloys, corrosion processes rather than stress are the dominant factor and rate of crack propagation is on the order of 0.277 μm/s (1 mm/hr). On the other hand, the rate of crack propagation is an order of magnitude higher, i.e., 2.77 μm/s (10 mm/hr), for titanium alloys and high-strength steels, where stress effects dominate those of corrosion.

Little or no correlation has been found between toughness of the material and its susceptibility to stress-corrosion cracking or between the rates of crack propagation for materials in a given alloy family. Fracture toughness properties, however, are important in the general application of alloys susceptible to stress-corrosion cracking, since it is desirable to know the size of the largest stress-corrosion crack that can be tolerated before catastrophic failure may occur at operating stress levels (ref. 1). The critical flaw size—that is, the depth of a long crack-like flaw which can be expected to initiate stress-corrosion cracking at yield-point stresses—is defined by the formula $0.2(K_{Iscc}/\sigma_y)^2$,

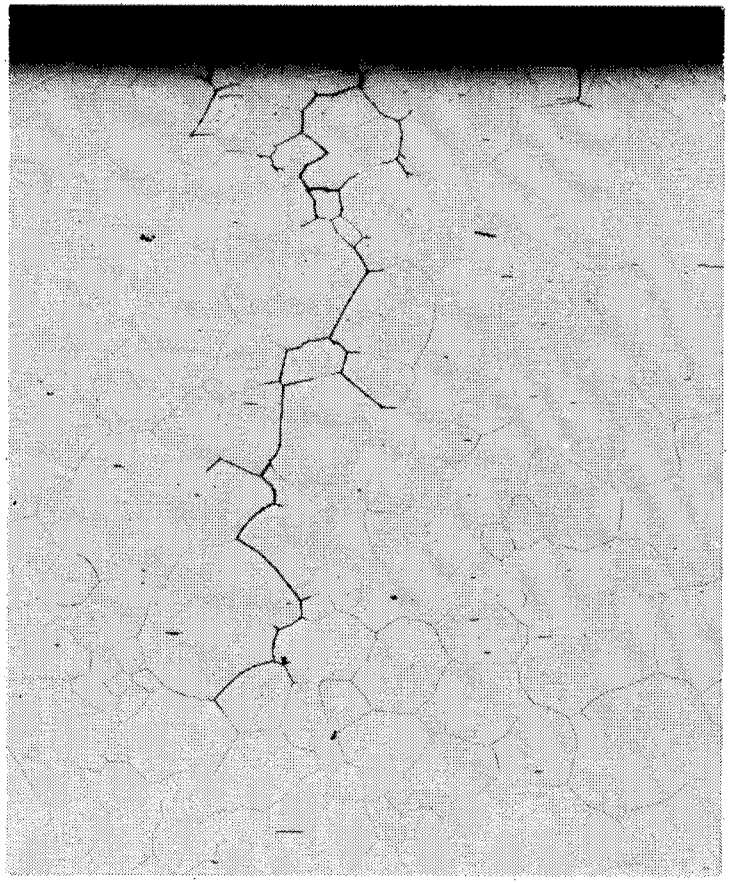


65X

Note branching nature of cracks.

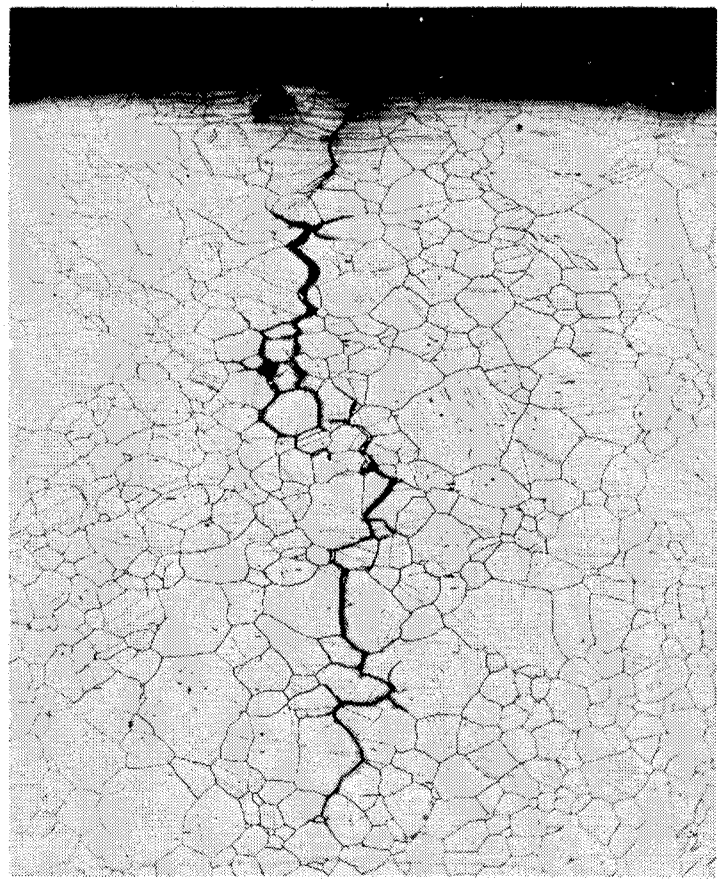
Etchant: Aqua regia.

Figure 1. – Photomicrograph showing typical transgranular stress-corrosion cracking of austenitic stainless steels.



150X

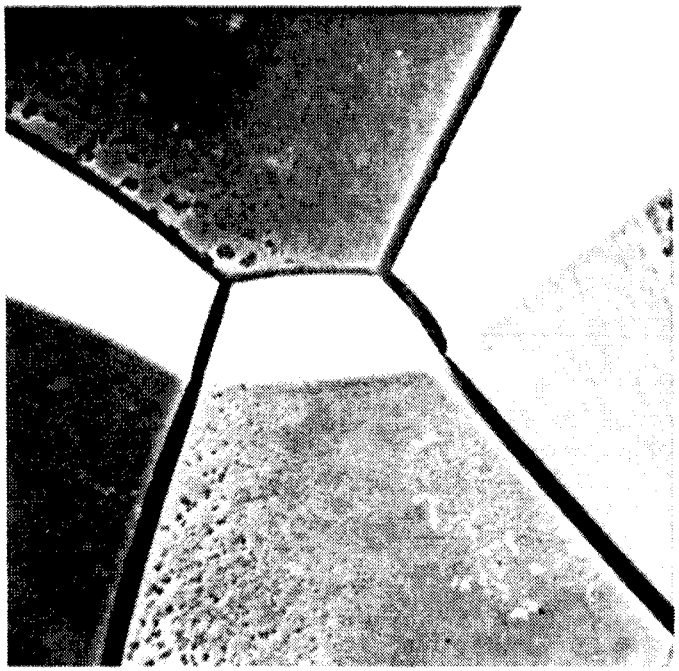
50-3A
2.9Al
(Annealed)



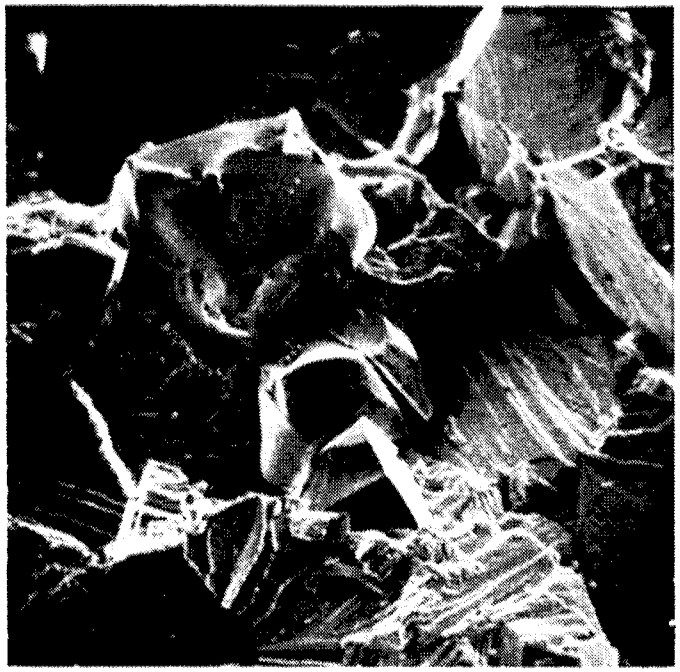
70X

47-2A
0.44Si
(Annealed)

Figure 2. – Intergranular stress-corrosion cracks in Inconel alloys.



1500X



1500X

Figure 3. – Scanning electron micrograph showing typical intergranular stress-corrosion cracking of 7075 aluminum alloy (left) and transgranular–intergranular cracking of Ti Alloy in N_2O_4 (right).

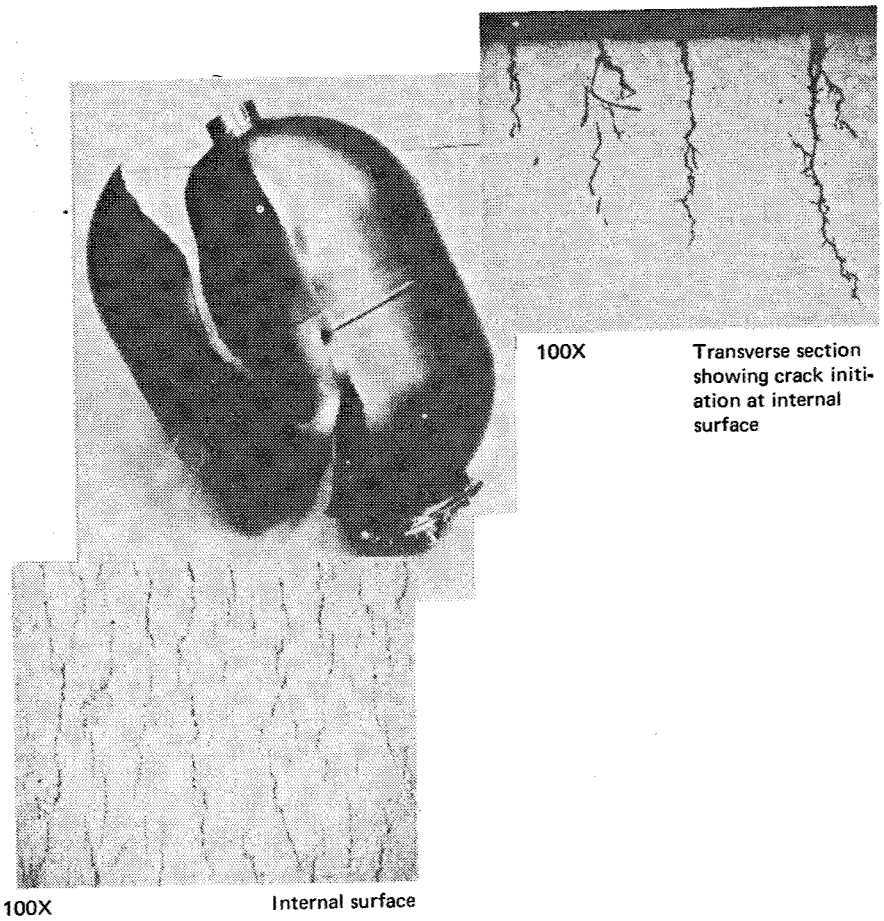


Figure 4. – Stress-corrosion cracking of a Ti-6Al-4V pressure vessel exposed to N_2O_4.

where K_{Iscc} is the maximum stress intensity that does not cause propagation of a flaw in a given environment, and σ_y is the yield strength of the alloy.

2.3 Environmental Factors

Of the factors in stress-corrosion cracking, perhaps the least understood are those relating to environmental effects. There does not appear to be any general pattern to the environments which promote stress-corrosion cracking. No occurrence of the phenomenon has been noted in a vacuum. Stress-corrosion cracking is usually associated with aqueous solutions, but may occur in liquid and solid metals, fused salts, gases, and nonaqueous organic and inorganic liquids. Examples of such failures are the cracking of brass, titanium, and aluminum alloys in mercury; carbon steel in molten lithium and zinc; stainless steels and nickel alloys in molten caustics; and titanium in hot, dry sodium chloride, in N_2O_4, in methanol, and in both liquid and solid cadmium. A list of offending environment-alloy combinations where stress-corrosion cracking has been encountered

is presented in table I. The table illustrates the broad range of crack-producing environments and the nearly universal presence of chloride in some form.

Additional environments which cause cracking of a given alloy are constantly being identified. Consequently, a reevaluation of the behavior of the alloy is required when the environmental conditions are changed. An example of the problems that can result from seemingly insignificant environmental changes is the cracking of titanium alloys in N_2O_4 containing traces of O_2, while the same alloys are immune to cracking if a trace of NO is present.

Crack-producing environments are usually those which cause negligible corrosion of the

TABLE I. - ENVIRONMENTS IN WHICH STRESS-CORROSION CRACKING HAS BEEN OBSERVED

Material	Environment
Plain carbon and low alloy steels	Caustic solutions; calcium, ammonium, and sodium-nitrate solutions; solutions containing H_2S or HCN; moist CO-CO_2; carbonate and bicarbonate solutions; sea water; marine and industrial atmospheres (high-strength, low-alloy steels); molten zinc, lithium, or Na-Pb alloys; anhydrous ammonia; $FeCl_3$ solutions (elevated temperatures); mixed acids (H_2SO_4-HNO_3)
Aluminum alloys	Moist air, marine and industrial atmospheres; sea water; NaCl, $CaCl_2$, and NH_4Cl solutions; mercury
Stainless steels	Acid and neutral chloride solutions; sea water; molten chlorides; industrial and marine atmosphere (sensitized materials); high-purity water + O_2 at 586K (599°F); high-temperature water + fluorides; polythionic acids
Nickel-base alloys	Fused caustics; hot concentrated caustic solutions; hydrofluoric acid; hydrofluorosilicic acid; steam and high-temperature water containing O_2 or traces of Pb; molten lead
Magnesium alloys	Sodium chloride-potassium chromate solutions; fluorides; tropical, industrial, and marine atmospheres; distilled water
Titanium alloys	Red fuming nitric acid; N_2O_4 + O_2; sea water; chlorinated hydrocarbons; hot dry sodium chloride and other chloride salts at temperatures above 563K (554°F); HCL; methanol; molten and solid cadmium; mercury; moisture

metal or alloy in the absence of stress. In fact, few instances of stress-corrosion cracking have occurred in environments where the corrosion rate of the material exceeded 4 to 8 pm/s (5 to 10 mils/yr).

As is the case with most chemical reactions, increasing temperatures promote the occurrence of stress-corrosion cracking. Some alloys may crack at room temperature while others require boiling temperatures of the environmental solutions. The most susceptible alloys, however, usually crack at temperatures below 363K (194°F).

The concentration of the environment is also important. As the solution concentration rises, the tendency for stress-corrosion cracking increases. For example, nickel-base alloys crack only in concentrated caustic systems and then only at high temperatures. Critical concentration levels have also been noted for other alloy systems.

Another important aspect of the environment is the type of exposure to which the alloy is subjected. Alloys exposed to alternate wetting and drying conditions are more susceptible to cracking than those exposed under immersed conditions only.

2.4 Metallurgical Factors (Composition and Heat Treatment)

Chemical composition significantly alters the susceptibility of a given alloy to stress-corrosion cracking. Almost all of the structural commercial alloy compositions currently used for aerospace applications exhibit some degree of susceptibility to stress-corrosion cracking. However, there are alloy compositions in each metal system that exhibit immunity. For example, Al-Mg alloys containing more than 4-percent magnesium are quite susceptible to stress-corrosion cracking whereas those containing less than 4-percent magnesium are for all practical purposes resistant to cracking in all tempers. Table II gives further evidence of the range of cracking susceptibility in the short transverse direction which can be obtained in aluminum alloys by compositional modifications.

In mild steels, carbon content influences cracking (ref. 14). As the carbon level is increased, susceptibility to cracking increases, reaching a maximum at about 0.12 percent. At higher carbon contents, the steels again become more resistant to stress-corrosion cracking.

Another good example of the effect of alloy composition is in the Fe-Cr-Ni alloy system. In this case, maximum susceptibility to cracking occurs at approximately 9-percent nickel. Alloys containing more than 40-percent nickel or less than 1-percent nickel are quite resistant to the well-known chloride-stress corrosion cracking (ref. 5).

TABLE II. – RELATIVE SUSCEPTIBILITY TO STRESS-CORROSION CRACKING OF VARIOUS ALUMINUM ALLOYS
[Adapted from ref. 10]

Alloy	Commercial designation	Temper	Susceptibility rating, (a)
Wrought, Strain-Hardened			
Unalloyed Al	1100	All	1
Al-Mn	3003	All	1
Al-Mg	5005, 5050, 5154	All	1
Al-Mg	5356	Controlled	2
Al-Mg-Mn	3004, 3005, 5454	All	1
Al-Mg-Mn	5086	All	2
Al-Mg-Mn	5083, 5456	Controlled	2
Al-clad	3003, 3004	All	1
Wrought, Heat-Treated			
Al-Mg-Si-Cu	6061, 6262	–0, –T6	1
Al-Mg-Si-Cu	6061	–T4	2
Al-Mg-Si	6063	All	1
Al-Si-Mg	6151, 6351	All	2
Al-Si-Mg-Cu	6066, 6070, 6071	–T6	2
Al-Cu	2219	–T3, –T4	4
Al-Cu	2219	–T6, –T8	2
Al-Cu-Mg	2024	–T3, –T4	4
Al-Cu-Mg	2024 (except forgings)	–T6, –T8	2
Al-Cu-Mg	2024 (forgings)	All	4
Al-Cu-Mn-Mg	2014	–T4, –T6	4
Al-Zn-Mg	7005, 7039	All	4
Al-Zn-Mg-Cu	7001, 7075, 7178, 7079	–T6	4
Al-Zn-Mg-Cu	7075	–T73	2
Al-Zn-Mg-Cu	7001	–T75	3
Al-Zn-Mg-Cu	7178	–T76	3
Alclad sheet	2014, 2024, 2219, 6061, 7075	All	1
Cast			
Al-Mg	214, 218, Almag 35	As cast	1
Al-Mg	220	–T4	4
Al-Si-Mg	356, A356, 357, 358, 359, Tens 50	All	1
Al-Si-Cu	319, 333, 380	As cast	2
Al-Si-Cu	355, C355, ×354	–T6, –T61	2
Al-Cu-Si	195, B195	–T6	4
Al-Zn-Mg	Ternalloy 7	–T6	4
Al-Zn-Mg	40E	As cast	4
Al-Zn-Mg-Cu	A612, 612	As cast	1

[a] 1 – Very resistant to stress-corrosion cracking. Only the effect of elevated temperature on stress-corrosion need be considered.
2 – Resistant to stress-corrosion cracking. Although failures have occurred under extreme laboratory conditions, these alloys can be used without many stress-corrosion-cracking design limitations.
3 – Susceptible to stress-corrosion cracking. These alloys can be used without expecting stress-corrosion cracking only if the phenomenon is considered as an important factor in design limitations.
4 – Very susceptible to stress-corrosion cracking. These alloys should not be used where high sustained tensile stresses are applied in the short transverse direction. When possible, stress-relieving tempers should be used to avoid quenched-in residual stresses.

In titanium alloys, the addition of molybdenum, vanadium, and to a lesser extent columbium, improves resistance to cracking, whereas elements such as aluminum and oxygen decrease resistance (ref. 6). Table III gives examples of the compositional factors affecting the susceptibility of precracked titanium alloys to stress-corrosion cracking in salt water, but their relative susceptibility cannot be ascertained in all cases from the available data. In the past, it was commonly accepted that pure metals were resistant to stress-corrosion cracking. However, the validity of such a generalization is questionable in light of the observed cracking of high-purity iron whiskers and of 99.999-percent copper. On the other hand, a marked improvement in cracking resistance has been observed in some alloy compositions prepared from extremely pure metals. Iron-chromium-nickel alloys of the 18Cr-8Ni type containing less than 20 ppm total impurities are highly resistant to stress-corrosion cracking.

TABLE III. – STRESS-CORROSION CRACKING BEHAVIOR OF PRECRACKED TITANIUM ALLOYS IN 3-PERCENT SODIUM CHLORIDE SOLUTIONS
[Adapted from ref. 17]

Alloys which have shown some degree of susceptibility but not listed in order of susceptibility.	Ti-unalloyed with 0.317-percent oxygen Ti-8Mn Ti-2.25Al-1Mo-11Sn-5Zr-0.2Si (IMI-679) Ti-3Al-11Cr-13V Ti-4Al-4Mn Ti-5Al-2.5Sn Ti-6Al-2.5Sn Ti-6Al-4V Ti-6Al-3Cb-2Sn Ti-6Al-4V-1Sn Ti-6Al-4V-2Co Ti-6Al-6V-2.5Sn Ti-7Al-2Cb-1Ta Ti-7Al-3Cb (as received and beta annealed) Ti-7Al-3Mo Ti-7Al-3Cb-2Sn Ti-8Al-1Mo-1V Ti-8Al-3Cb-2Sn
Alloys indicated by preliminary screening tests to be insensitive to salt-water crack propagation for the conditions used.	Ti-2Al-4Mo-4Zr Ti-4Al-3Mo-1V Ti-5Al-2Sn-2Mo-2V Ti-6Al-2Mo Ti-6Al-2Sn-1Mo-1V Ti-6Al-2Sn-1Mo-3V Ti-6Al-2Cb-1Ta-0.8Mo Ti-6.5Al-5Zr-1V Ti-7Al-2.5Mo [as received and beta annealed + WQ + 867K (1100°F), aged for 7.2 ks (2 hr)]

Susceptibility to stress-corrosion cracking is influenced by a number of other metallurgical variables in addition to alloy composition, such as grain size and shape, rolling direction, tempering temperature, composition and distribution of precipitates, and degree of phase transformation.

High-strength aluminum alloys exhibit the least resistance to cracking in the grain direction transverse to the rolling or forging directions (short transverse). In such cases, threshold stress levels for initiation of cracking may be less than 34.5 MN/m^2 (5000 psi) in the short transverse direction as compared with more than 137.9 MN/m^2 (20 000 psi) in the longitudinal direction. This effect is directly related to the distribution of second-phase precipitates during rolling. Heat treatments also influence cracking of aluminum alloys since they too can change the composition and morphology of grain boundary precipitates. Tempers have been developed which greatly improve resistance to stress-corrosion cracking of a given alloy composition. As shown in table II, 7075 aluminum in the T6 temper is very susceptible to cracking whereas the same alloy in the T73 temper exhibits a high degree of resistance.

Heat treatments are also effective in reducing susceptibility to stress-corrosion cracking of other alloy systems including mild steels, low-alloy steels, PH stainless steels, and titanium alloys. However, as in the case of aluminum alloys, those heat treatments which are most effective in developing immunity to cracking also lower the strength of the material.

2.5 Effect of Stress

Susceptibility to stress-corrosion cracking increases with increasing tensile stress and is most severe at or above the yield point of the material. Only sustained tensile stresses at the surface of the alloy cause initiation and propagation of stress-corrosion cracks. No cracking will occur if the metal surface is in compression. In fact, one preventive treatment is based on inducing surface compressive stresses (e.g., shot-peening and coining).

Surface tensile stresses may result from residual strains locked in the metal or they may result from an externally applied load. A number of sources are known to induce high residual stress. Such stresses resulting from welding or interference fits may approach the yield strength. Residual stress resulting from unequal cooling of a thick section from heat-treating or rolling and forging temperatures occurs in forgings and plate. Similarly, solid-state changes or rearrangements of crystalline structures may cause high levels of stress. Cold-forming, bending, and grinding also are known sources of significant residual stress levels.

It is generally accepted that each alloy-environment combination exhibits a threshold stress level below which no cracking will occur. However, at the present time, these

threshold levels are not well defined so that they are of little use to the designer. One of the problems in the development of meaningful data involves the selection of the test criteria for obtaining a true threshold stress level. For example, it may be defined as that stress level below which no initiation or propagation of stress-corrosion cracking will occur for any given alloy-environmental combination. More recently, it has been suggested that the stress level at which a flaw of subcritical size will begin to propagate in an environment is more useful to the designer (ref. 18).

Fracture mechanics data relating the fracture toughness K_{Ic} and the stress-corrosion threshold K_{Iscc} are being developed for high-strength alloy steels, aluminum alloys, and titanium. (K_{Iscc} is the highest stress intensity which does not cause propagation of a flaw in a given environment.) Materials resistant to stress-corrosion cracking exhibit K_{Iscc}/K_{Ic} values close to 1. Reference 1 provides more specific data on the aspects of flaw growth and control.

2.6 Prevention of Stress-Corrosion Cracking

Since the mechanism of stress-corrosion cracking is not universally understood, the techniques for preventing or controlling it are either quite general or empirical in nature. However, within the present state of the art, the possibility of stress-corrosion cracking can be reduced and essentially eliminated through the use of one or more of the following techniques.

Reduction of the stress. One method of controlling cracking is to reduce surface tensile stress below threshold values. In this respect, residual, assembly, and applied stresses have to be accounted for since their effects are additive. With the possible exception of pressure vessels, stress-corrosion failures seldom occur as a direct result of applied loads. More often they are caused by a combination of residual and assembly stresses. Such stresses can often be reduced to low levels by such techniques as avoiding misalignment of mating parts and eliminating cold-forming or bending operations and interference fits. However, many sources can induce residual tensile stresses during fabrication and assembly. Further, there is at present no practical (simple, rapid, economical, and precise) method for measuring residual stresses in an assembled part. Therefore, control of tensile stresses as a means of eliminating stress-corrosion cracking is rather difficult. Shot-peening can be used to change surface residual tensile stresses to compressive stresses; however, the possible influence of relaxation induced by dynamic loading of the part may lessen the effect. For some applications, it may be more practical to perform a stress-relief anneal.

Modification of the environment. It is often quite practical and effective simply to change the environment. The most common technique is to reduce or eliminate the specific

chemical ion species which promotes the cracking. For example, many problems with cracking of titanium during fabrication have been prevented by routinely eliminating the use of chlorinated solvents and limiting the amount of chlorides in cleaning and machining compounds (ref. 19). It is also feasible in some environments to add inhibitors. Phosphates, silicates, and other inorganic and organic inhibitors are quite effective in mildly aggressive environments. If the proper inhibitor level is not maintained, however, cracking may be accelerated.

Selection of the most resistant alloy or heat treatment for the expected environment. Selection of a resistant material is common practice; for example, Inconel is used in place of austenitic stainless steels where chloride stress-corrosion cracking is a possibility. Likewise, heat treatments have been developed which greatly reduce the chance for cracking in high-strength Al-Mg-Zn alloys (e.g., 7075 aluminum).

Other methods. Various other preventive methods have been used with varying degrees of success. However, none of them actually eliminates or controls the three basic factors (environment, alloy composition, and tensile stress) that cause stress-corrosion cracking. For instance, paint films are sometimes quite effective in preventing the environment from contacting the alloy, but only as long as the film remains undamaged. It is also possible to use cathodic protection to prevent stress-corrosion cracking of structures wet by an electrolyte, but this technique is not practical for most aerospace applications, and it may induce hydrogen-stress cracking in certain titanium alloys.

2.7 Methods for Detecting Stress-Corrosion Cracks

Several techniques have been succesfully used to detect the presence of stress-corrosion cracks in a structure. A common effective technique employed on readily accessible areas is a visual inspection of the surface with a low-power microscope. At 10×, many cracks are readily identified.

Commercially available nondestructive test (NDT) equipment/techniques have also been successfully used to detect surface cracks. These include magnetic-particle, dye-penetrant, and ultraviolet-light-fluorescent penetrants as well as ultrasonic and eddy-current methods. For a detailed description of these methods and their limitations, see references 20 to 22.

Although these methods have been successfully used to detect surface cracking in structures, they are not used without difficulties. For example, experience is needed in interpreting results because the NDT techniques may also disclose small flaws, scratches, and tool marks as well as cracks. In such instances, further examinations are required to definitely establish the presence of stress-corrosion cracks. At other times, the cracks may be sufficiently small or tight (from external compressive loads) to escape detection. In

this case, metallographic examinations are the only positive means of establishing the presence of the flaw or stress-corrosion crack.

2.8 Tests for Stress-Corrosion Cracking

There is no standard laboratory test available today which will accurately predict the stress-corrosion-cracking service life of a given metal-environment system. Consequently, there is no alternative to conducting tests in the anticipated environments for at least the duration of the expected service life. On the other hand, a number of laboratory tests have been developed which are useful in comparing the stress-corrosion-cracking behavior between compositions in one family of alloys. For example, the boiling 42-percent magnesium chloride solution test is extensively used to establish relative susceptibilities to stress-corrosion cracking of Fe-Cr-Ni alloys. Similarly, repetitive immersion in 3.5-percent sodium chloride solution is the standard test for evaluating aluminum alloys. Neither test, however, is satisfactory for titanium.

Laboratory stress-corrosion tests are valuable in the development of alloys having improved resistance to stress-corrosion cracking because they rapidly reveal which compositions and/or heat treatment conditions are the most resistant to cracking.

Laboratory tests are also useful in confirming the diagnosis of a stress-corrosion-cracking failure. In these and other studies, the optimum laboratory environment is one that contains the same chemical ion species present in service, but causes failure in much shorter periods. In addition, it should produce the same intergranular or transgranular cracking that occurs in service exposures. Finally, the test should rate the various compositions and heat treatments of one alloy family in the same order of merit as encountered in service.

Although laboratory stress-corrosion-cracking tests have been run for thousands of hours, experience shows that testing the samples for 2.59 Ms (720 hr) or until failure, whichever occurs first, will provide meaningful data in a reasonable period of time.

As with the environment, there is no one standard test-specimen configuration or means of stressing. Some specimens are simple, such as the U-bend, while others like the precracked and the tapered double-cantilever beam specimens are more complicated and require special fixtures and apparatus.

Notched specimens containing a fatigue crack extending into the metal and center-notched specimens have proved to be especially useful in evaluating the susceptibility of high-strength steels and titanium alloys (refs. 23 and 24). These precracked specimens are different from the bent-beam specimen because they eliminate the crack-initiation or

incubation period and consequently reduce the total time required to obtain useful test data.

In general, the stresses applied in laboratory stress-corrosion-cracking tests are high, ranging from 50 to 100 percent of the yield strength and higher. However, lower stresses may be required for establishing threshold limits.

It has been found that in stress-corrosion-cracking tests in the laboratory, care must be taken to avoid crevice corrosion, galvanic effects, and hydrogen embrittlement. Excellent discussions of testing methods for stress-corrosion cracking are presented in references 8 and 25.

3. CRITERIA

Space-vehicle structures shall be designed to be free of stress-corrosion cracking throughout the service life of the vehicle. This shall be accomplished by an effective combination of the following:

- Identification and control of the environments to which the structure will be exposed during construction, storage, transportation, and use
- Selection of alloy compositions and tempers which are resistant to stress-corrosion cracking in the identified environment
- Control of fabrication and other processes which may introduce residual tensile stresses or otherwise damage the material
- Limitation of the combined residual and applied tensile stresses to below the threshold stress level for the onset of cracking throughout the service life of the vehicle
- Establishment of a thorough inspection program

When data are not available for a particular metal-environment combination, appropriate tests shall be conducted as necessary to establish the probability of stress-corrosion cracking.

3.1 Identification and Control of the Environment

All anticipated natural or synthetic environments which may contact the vehicle structure during its service life shall be identified. The type and amount of chemical species known to promote stress-corrosion cracking (e.g., Cl^- NO_3^-, S^{--}) shall be identified for each environment. When the vehicle design has been established, adequate controls shall be initiated to prevent critical changes in the environment.

3.2 Selection of Alloy Compositions and Tempers

Only those alloy compositions and/or tempers with established immunity or low intrinsic susceptibility to stress-corrosion cracking under the projected service environment shall be selected unless it can be demonstrated that the design accounts for all stress-corrosion-cracking possibilities.

3.3 Fabrication and Processing

Procedures shall be established to evaluate stresses from fit-up and other fabrication variables. Those processes which introduce or increase residual tensile stress shall be avoided or treatments shall be employed to relieve any such stresses.

3.4 Stress Limitations

Analyses and tests shall be performed as necessary to establish confidence that the combined residual, assembly, and applied tensile stresses in the anticipated environments shall not allow the development of stress-corrosion cracks during the expected service life.

3.5 Protective Techniques

Coatings and other protective techniques normally used to minimize other forms of general corrosion shall not be relied upon to prevent stress-corrosion cracking.

3.6 Tests

If stress-corrosion-cracking data are not available for a given alloy-environment system, laboratory tests shall be conducted to establish the potential for the occurrence of stress-corrosion cracking. The testing techniques shall provide a realistic simulation of the combination of metallurgical and environmental conditions anticipated during the service life of the vehicle.

3.7 Inspection

Reliable nondestructive testing (NDT) inspection techniques shall be used for the detection of stress-corrosion cracks and related discontinuities on the surface of components before and during construction and at selected intervals during the service life of the vehicle.

4. RECOMMENDED PRACTICES

The basic procedure recommended for the effective control of stress-corrosion cracking is an appropriate combination of analysis and control of the environment; selection of alloy compositions and tempers not susceptible to cracking; control of fabrication processes to avoid formation of residual tensile surface stresses; reduction of tensile stress (residual plus assembly plus applied) to a level below which no stress-corrosion crack will be initiated and propagated for a given alloy-environment combination; and thorough inspections at all stages of service life [fabrication, assembly, storage, launch preparation, and mission(s)].

4.1 Identification and Control of the Environment

To prevent unexpected failure of metallic aerospace structures by stress-corrosion cracking, it is extremely important to identify both the natural and the man-made environments to which each structural component of the space vehicle will be exposed during its service life. Any recognized damaging environments should be avoided or controlled. When the nature of the environment is unknown, a chemical analysis should be conducted to determine the presence and the type and amount of chemical species known to promote cracking. Such ion species include but are not limited to Cl^-, OH^-, F^-, S^{--}, NO_3^-, etc. In addition, the environmental analysis should include any special conditions such as alternate wetting and drying, range of temperature excursions, the time of exposure to the environment, and whether the exposure is continuous or intermittent. The environments to be defined should include but not be limited to the following:

- Chemicals used in the cleaning, etching, and rinsing of compounds (process chemicals).
- Inspection fluids and marking inks and crayons.
- Lubricants and machining fluids.
- Pressure-testing fluids.
- Natural atmospheric conditions (includes humidity and temperature).
- Service chemicals (fluids used during operation).

When a potentially damaging environment is identified, steps should be taken to eliminate the environment or to control exposure to it. For example, specifications should limit the chloride ion level in inspection fluids; or if low-chloride materials are not available, then

steps should be taken to insure complete removal of the fluid from the surface of the component. Fingerprints on titanium alloys can result in hot-salt cracking; thus, critical parts subjected to temperatures above 560K (550°F) during fabrication or service should be handled with gloves or thoroughly cleaned before being heated.

When aqueous environments are employed for hydraulic testing of the system, they should contain a suitable inhibitor and/or pH control additive. Chromate additions are particularly effective inhibitors for a number of alloys, including steels and aluminum alloys. Other inhibitor types, including organic film formers and chelating agents, can be used (ref. 26).

To minimize the harmful environmental effects, structures should normally incorporate good general anti-corrosion design. Eliminating or sealing crevice areas and providing drainage for areas where moisture and other fluids can collect are examples of good design practices. Structures should also be designed for easy access so that critical areas can be inspected frequently to preclude the formation of critical-sized cracks.

For industrial and seacoast atmospheres where aggressive chemical ions are often present, environmentally controlled areas should be used, if necessary, for fabrication and storage of the structures. In many instances, reducing the relative humidity at ambient temperature to less than 50 percent will greatly minimize the occurrence of stress-corrosion cracking.

4.2 Selection of Alloy Compositions and Tempers

In the earliest stages of design, susceptibility to stress-corrosion cracking in the anticipated service environment should be given primary consideration in the selection of candidate materials. Company files which document previous experiences with specific alloy-environment combinations should be extensively used as an important source of information. Other current sources of data include corrosion abstracts, chemical abstracts, reports and books (refs. 6, 10, 12, 27, and 28), and the alloy manufacturers. If satisfactory data cannot be obtained, then tests should be conducted to develop the needed stress-corrosion-cracking susceptibility data for the anticipated service environment. From these data a listing of candidate materials should be compiled which includes those materials having a high degree of resistance to stress-corrosion cracking under the anticipated environments. This list should be used by the designer as a guide in the specification of materials.

Ideally, only those alloy compositions and heat treatments that have been demonstrated to possess the highest degree of resistance to stress-corrosion cracking in the anticipated environments should be selected for structural components. However, tradeoffs should be made to arrive at an optimum design from other considerations such as strength-weight

ratios, fracture toughness, and fatigue. When materials are selected which do not have a high degree of stress-corrosion resistance, a detailed analysis should be made for each specific part. This analysis should show how stress corrosion is being controlled for the part involved. *Because of the relationship between strength and susceptibility to stress-corrosion cracking, it should be a standard recommended practice to use the lowest-strength material compatible with the design.*

Specifications should limit selection of metals and alloys to those that are compatible with each other because galvanic couples and/or certain metallic ions in the environment can significantly alter the stress-corrosion cracking behavior of many alloy systems. In addition, improper material selection can lead to other types of environment-induced cracking such as corrosion fatigue, fretting corrosion, and hydrogen-stress cracking.

When the composition and configuration of the material have been selected, a quality control program should be inaugurated to insure that significant variations in composition, grain direction, phase relationships, and other metallurgical variables known to alter the stress-corrosion-cracking behavior of the selected alloy do not occur from one batch or heat of materials to another. For example, a forging should not get into the production line unless the chemistry, grain flow, and residual stress patterns have been checked against the specifications.

4.3 Fabrication and Processing

Components fabricated from alloys which exhibit directionality—that is, a higher degree of susceptibility in one direction of grain flow than in another—should be designed so that the critical direction will not be exposed to sustained tensile stresses. This is true particularly for most aluminum alloys (and to a lesser extent for high-strength steel alloys) which are highly susceptible to cracking in a plane normal to the short transverse direction. In forgings, it is imperative that the parting plane be controlled so that it will not be a highly stressed area.

The bending of high-strength aluminum alloys at room temperature in the fully heat-treated condition should be avoided because this procedure may introduce residual stresses approaching the yield strength of the material. If bending of fully heat-treated material cannot be avoided, then a complete survey of residual stresses should be made to establish that they are below threshold levels for all directions of grain flow. Bending at moderately elevated temperatures can also alleviate much of the problem [e.g., dimpling 7075-T6 aluminum alloy at 407K (275°F)].

Similarly, cold shearing of alloys in the fully heat-treated condition is an unsatisfactory procedure and should be avoided.

Distortion of components must be corrected with care to avoid the introduction of localized areas of high residual tensile stresses. Such components should be stress-relieved if the temperature required for stress relief does not exceed the temperature of the final heat treatment. If it does, the stresses should be relieved by other methods such as creep forming, shot-peening, compressing forgings, and stretching of plates and extrusions.

When an alloy susceptible to stress-corrosion cracking must be used, or when the applied tensile stresses approach the K_{Iscc} of the material or when assembly stresses are high, residual stress distributions should be determined to ensure freedom from stress-corrosion cracking. Forgings, particularly aluminum, are a case in point. The procedure is similar to the static and dynamic mechanical structural tests now required to demonstrate the integrity of the component with respect to its service life.

The methods used for measuring residual stresses need not be highly sophisticated to be of significant value. For example, fairly accurate estimates of the hoop stress in tubes, thick bars, and thick sections can be obtained by measuring the specimen, cutting it apart, then measuring the change in shape after cutting. The difference in shape is used to calculate residual stresses. Similarly, large pieces of metal can be step machined along one face, the released distortion measured, and the residual stresses estimated. Again, rosettes of strain gages, applied at suspect surface areas, measure relaxation (residual stresses) as metal is removed from the opposite surface of the part. Differences in the refraction of an X-ray beam caused by crystal lattice deformation provide a measure of the elastic surface strain at a point, which in turn can be converted into stress. Brittle lacquer or photoelastic coatings applied to the surface of components will provide data on residual stress levels. As with strain gauges, the coating is applied to the surface of the part and then metal material is removed by machining or drilling. The relaxation of stresses either gives rise to tension cracking of the lacquer film or photoelastic fringes in the plastic coating.

To supplement the residual stress measurements and to verify that the manufacturing procedures used will provide a serviceable component, a part from the first production lot should be subjected to an appropriate accelerated stress-corrosion-cracking test. The selected part should be dimensionally complete and conform to all design requirements. This test will indicate whether the part contains residual stresses of sufficient magnitude to induce rapid stress-corrosion-cracking of susceptible alloy compositions.

Manufacturing techniques should be modified until residual stresses are lowered to an acceptable level.

When thick, relatively simple components such as landing gear cylinders are quenched, compressive stresses are induced on the outer surface and tensile stresses on inner surfaces. For this reason, outer surfaces of machined components of heat-treatable alloys should be rough machined as closely to final dimensions as possible before final heat

treatment. Conversely, inner surfaces, on open or hollow shapes where residual stresses are tensile in nature, should receive some machining after heat treatment; because, apart from grinding, the operations of machining, milling, etc., produce residual surface compressive stresses unless negative rake tools are used (ref. 29). However, this technique may not be applicable to more complex shapes.

Because of the extreme sensitivity to stress-corrosion cracking of high-strength low-alloy steels, heat-treated to strength levels of 1.723 GN/m^2 (250 ksi) and above, machining operations of any kind after heat treatment should be avoided.

Production engineers and designers must insure that the materials are not damaged by seemingly harmless deviations from proven practice and that unfavorable residual stresses are not introduced in an otherwise acceptable design. An awareness of the importance of accurate processing should be developed at the shop level.

4.4 Stress Limitations

To use the full strength of alloys effectively, the design must account for all forms of tensile stress, including residual, assembly, and applied. Notches, sharp radii, scratches, and other surface defects which act as stress raisers should be minimized. The most effective treatments for minimizing the possibility of stress-corrosion cracking are those which introduce compressive stresses uniformly over the surface. Shot-peening or glass-bead peening for thin sections is one of the most common methods used today for establishing compressive surface stresses. Shot-peening for a given alloy should be in accordance with standard practices and specifications (refs. 30 and 31).

During the service life of the vehicle, the sum of residual, assembly, and applied stresses should not exceed the established threshold stress level for a given material (ref. 32). If the threshold stress level for the particular alloy-environment combination in question is unknown, then it should be determined by laboratory tests. This can be done, for example, by exposing a series of bent-beam specimens having applied stress levels ranging from 10 to 90 percent of the yield strength. The highest stress level at which no cracking occurs for the selected exposure period is the threshold stress level. An alternate method is to use a wedge-open-loaded (WOL) specimen to determine the stress at which a crack will not propagate in the service environment (ref. 27).

4.5 Protective Techniques

Organic and metallic coatings (with the exception of alclad aluminum alloy sheet) should not be relied upon to prevent stress-corrosion cracking. Although many surface treatments can prevent stress-corrosion cracking by excluding the environment from the

metal's surface, a scratch or a "holiday" in the coating can greatly minimize the protective value and sometimes can even cause more rapid failures.

4.6 Tests

When acceptable data on the behavior of a given alloy-environment are not available, laboratory stress-corrosion-cracking tests should be performed. Since no universal environment exists that can be used to evaluate the stress-corrosion-cracking behavior of all metal families, the ideal laboratory test environment is one that:

- Contains chemical ion species of the same type as those present in the environment to which the alloy will be exposed during its service life.
- Causes no appreciable general corrosion damage to unstressed materials.
- Produces the same type of cracking (intergranular or transgranular) as that encountered in actual service.
- Produces failures in a shorter period of time than is expected in service.

Where practical, however, tests should be conducted under the actual environmental conditions expected in service. It should not be assumed that testing in some aggressive laboratory environment will provide conservative design information regarding the service life of a given alloy-environment combination.

A major value of laboratory stress-corrosion-cracking tests is in alloy development work where it is desirable to determine the susceptibility of new alloys to stress-corrosion cracking as compared with existing compositions and tempers. For such studies, those environments listed in table IV should be employed, and the methods of references 8 and 25 should be used, as applicable. However, these tests should not be used to evaluate actual service life.

The exposure time in laboratory stress-corrosion tests is variable. For the environments listed in table IV, exposure periods of 2.59 Ms (720 hr) or until failure, whichever occurs first, should be sufficient to obtain reliable data. In other laboratory environments formulated to simulate anticipated service environments, the tests should be run for at least 7.20 Ms (2000 hr). Any unfailed specimens at this point should be subjected to metallographic examination to determine the extent and type of any cracking. For some alloy-environment systems, particularly natural environments, exposure times of 31.5 Ms (1 yr) or longer should be considered, especially if the expected service life is over 158 Ms (5 yr). These tests are not really indicative of a finite service life but they are useful for giving comparative data which can be used for material selection.

TABLE IV. – LABORATORY STRESS-CORROSION-CRACKING ENVIRONMENTS

Material	Environment	Continuous immersion	Alternate immersion
Aluminum alloys	57 g/1 NaCl + 10 ml/1 30-percent H_2O_2 at room temperature	X	
	3.5-percent NaCl solution at room temperature		X
Magnesium alloys	35 g/1 NaCl + 20 g/1 K_2CrO_4 at room temperature	X	
	0.01-percent NaCl solution at room temperature	X	
Ferritic and martensitic stainless steels	3.5-percent NaCl solution at room temperature	X	X
High strength low-alloy steels	3.5-percent NaCl solution at room temperature	X	
Plain carbon steels	20-percent boiling NH_4NO_3 solution. Boiling NH_4NO_3 + $Ca(NO_3)_2$	X	
Austenitic stainless steels	Boiling 42-percent $MgCl_2$ solution	X	
Titanium alloys	No universally accepted test environment but a precracked specimen in a room temperature 3.5-percent NaCl solution is recommended	X	

For most laboratory stress-corrosion studies, at least four replicate specimens should be tested at each stress level. The threshold stress level to initiate cracking and the K_{Iscc} (K_{TH}) value are the preferred criteria for assessing susceptibility to stress-corrosion cracking. Time to failure can be considered, but it is difficult to evaluate, because it may vary with stress level and because the scatter band for any given alloy is quite large.

There is a variety of acceptable specimen configurations (refs. 8, 25, 33, 34, and 35); therefore, the selection of the type of specimen (bent beam, tensile, U-bend, or precracked) should be determined by the form in which the alloy is available or will be used in service. At least one specimen in every evaluation should be precracked, and for titanium alloys and high-strength low-alloy steels, tests with precracked specimens should be used rather than smooth unflawed specimens, because of the long incubation times required for crack initiation in unflawed specimens.

4.7 Inspection

Space-vehicle components should be inspected by one or more of the following NDT techniques (Federal Test Method Standard No. 151):

- Magnetic particle (ASTM-275-61)
- Dye penetrant or ultraviolet-light fluorescent penetrants
- Ultrasonic, including pulse-echo, direct transmission, and resonance techniques (ASTM-E317)
- Eddy current
- Visual inspection at magnifications of 40× or greater

The dye and ultraviolet-light fluorescent penetrants used in the inspection should be chloride-free grades and should be thoroughly washed from the surface after each inspection.

The ultrasonic and eddy-current techniques are particularly useful and should be used as required for the inspection of internal surfaces of vessels and structures.

Although many cracks can be detected visually at low magnifications (10×), magnifications of 40× or higher should be used to detect the finer cracks.

Any confirmed indication of a stress-corrosion crack or deep crack-like flaw should be cause for the rejection and/or replacement of the component.

All occurrences of stress-corrosion cracking in service should be thoroughly analyzed and the results documented and given to the designer so that specific problems can be corrected and research for the future can be effectively directed.

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