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CONTROLLING STRESS CORROSION CRACKING IN MECHANISM COMPONENTS OF GROUND SUPPORT EQUIPMENT

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ABSTRACT

This paper deals with the selection of materials for mechanism components used in ground support equipment so that failures resulting from stress corrosion cracking will be prevented. It also provides a general criteria to be used in designing for resistance to stress corrosion cracking. Stress corrosion can be defined as combined action of sustained tensile stress and corrosion to cause premature failure of materials. Various aluminum, steels, nickel, titanium and copper alloys, and tempers and corrosive environment are evaluated for stress corrosion cracking.

INTRODUCTION

A failure of Hold Down Post of solid rocket booster occurred during the application of the pretension load on Mobile Launcher Platform (MLP). A portion of the tensioner containing the fractured surface was studied using scanning electron microscope. The study concluded the tensioner failed catastrophically in a brittle mode initiating a corrosion pit and propagating intergranularly as stress corrosion. The tensioner was fabricated from 18 Ni maraging steel of Rockwell Hardness (HRC) 55.

The National Transportation Safety Board has investigated four recent Boeing 727 mishaps involving structural failures in the landing gear due to corrosion. The first two incidents which occurred in Denver, Colorado on Sept. 29, 1985, and Norfolk, Virginia on January 16, 1986 concern stress corrosion failures discovered in the main landing gear (MLG) actuator support link assembly. Investigation found stress corrosion cracking (SCC) went undetected until the link failed. The third incident, which occurred in Memphis, Tennessee on January 9, 1986 involved failure of MLG shock strut outer cylinder. Examination showed that fracture of the strut stemmed from an area of stress corrosion cracking that initiated on outer diameter of the outer cylinder. Fretting and corrosion pitting were found on the surface of the cylinder in the area contacted by the clamp. The fourth incident which occurred in Miami, FL. on March 3, 1986 involved a nose landing gear (NLG) uplock actuator rod end. The examination disclosed that the rod end separation was the result of severe corrosion of threaded shank of the rod end. Heavy corrosion was found on the mating threads of the uplock actuator.

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As shown in Figures 1 and 2 stress corrosion cracking is a mechanical environmental failure process in which a sustained tensile stress and chemical attack combine to initiate and propagate fracture in a metal part. As shown in Figure 3, SCC failure is caused at a tensile stress well below the yield strength of the metal. There have been a number of stress corrosion failures for which design stresses were intermittent, short duration and surfaces of failed parts are not visibly corroded. Many SCC failures are caused by metal equipment to corrosive environment before the equipment is put into service. These environments include those associated with fabrication, testing, shipment, storage and installation. Marshall Space Flight Center (MSFC) had published guidelines for controlling SCC. However, it did not account for chloride and halide SCC in 300 alloy series. 300 series were listed as having high resistance to SCC.

Failed mechanism components analyzed at NASA Malfunction Analysis Lab., K.S.C., indicated that SCC was the major contribution to failures in Ground Support Equipment. Recently SCC has become a major concern in ground support equipment at KSC. Also there is no effective protection against SCC. Not only higher tensile strength play a role in SCC but also susceptibility of metal to SCC. Seventy five percent of all stress corrosion failure could have been prevented if the persons responsible for design, construction and maintenance of equipment had been sufficiently aware of the problem.

SOURCES OF STRESS IN METAL COMPONENTS

The principal sources of tensile stress in components include

a. Externally applied loads
b. Pretension loads such as in bolts and screws
c. Sources of stress in manufacturing
d. Sources of stress in services.

Externally Applied Loads: Externally applied loads are those loads that are directly applied on the mechanism to perform work. Tensile stresses are thus introduced in the components like links, actuators, fasteners, fittings, etc. of the mechanical equipment. Stresses also arise from reciprocating or rotary motion of mechanical devices either from normal operation or from abnormal effects such as vibration, resonance and fluid flow.

Pretension Loads: Most components are held together with fasteners and fittings. Fasteners such as bolts and screws require pretension loads. A majority of failures in ground support equipment occur in bolts. Tightening of fitting nuts in order to obtain liquid tight seal results in sustained tensile stress in the form of hoop stresses which initiate SCC. Fit-up and assembly operation are sources of tensile stress. Press fitting, shrink fitting and assembly welding are source of tensile stress that would lead to SCC. In a certain case stress produced by an interference fit of bushing in a hole in a fitting contributed to failure of the fitting which was exposed to a marine atmosphere. Forming operation used in assembly to retain component can produce residual tensile stresses that can induce SCC.

Sources of Stress in Manufacture: The principal sources of high local stresses in manufacture include thermal processing, stress raisers, surface finishing and fabrication. One of the frequently encountered source of thermal processing stress is welding. Shrinkage of weld metal during solidification impose restraints on the adjacent metal, can produce severe residual tensile stresses. Other thermal processing effects during manufacture include solidification of castings, improper heat treating practices, temperature nonuniformity in furnaces and quenching practices too severe. Residual stresses are introduced at notch in related mechanical component designs, notches created during accidental mechanical damage, electric arc strikes, deficiencies in post weld heat treatments, severe surface irregularities produced in grinding and rough machining, cladding, rolling, electroplating, spraying, brazing or soldering. Residual stresses are produced during electrical discharge machining. High residual tensile stresses result from bending, stamping, deep drawing and other cold forming operations.

Sources of Stress in Service: Stresses in addition to those that a component was designed to withstand are introduced in service by accidental mechanical impact, local electrical arching, local wear, fretting, erosion, cavitation such as pitting, selective leaching, intergranular attack and concentration-cell, cervice or galvanic corrosion. Exposure of metal part to high and low temperature is a major source of stress in service.

GRAIN ORIENTATION AND ENVIRONMENTAL EFFECTS ON SCC

In wrought mill products particularly aluminum such as shown in Figure 4, the grain orientation produced by rolling and extruding have directional effects. For susceptibility to stress corrosion cracking, the directional variation can be appreciable and must be considered in design of fabricated hardware of ground support equipment. Resistance of metals, particularly alloys of aluminum to stress corrosion cracking is always high when stressed in the direction of rolling or in the longitudinal direction, less in the direction perpendicular to the longitudinal or long transverse direction, and least in the direction through the thickness of the plate or short transverse direction. For forgings the direction perpendicular to parting plane or short transverse has the least resistance to stress corrosion.

Stress corrosion cracking often depends upon environmental impurities, alloy composition and structure. Impurities that are present in the environment often cause stress corrosion cracking. Sensitized austenitic stainless steel crack at room temperature in water containing 100 ppm of chloride or 2 ppm of fluoride. SCC in copper alloys are caused by environment that contains ammonia or ammonia like complexing agents. Marine and industrial environment contains halide ions are particularly aggressive in causing crack in high strength steels, corrosion resistant steels and aluminum alloys. Service environment, atmosphere containing SO_2, chlorides, ammonia, oxides of nitrogen, hydrogen sulfide, arsenic and antimony compounds cause by damaging substances such as chlorides or sulfur compounds can be leached from concrete, gasket materials, insulating materials and polyvinyl chlorides and similar plastic materials. Many SCC failures are caused by exposure of metal equipment to corrosive environments before the equipment put into service. Pre-service environments include those associated with fabrication, testing, shipment, storage and installation. Refer to Table 1 for various environments and their impurities have effect on commercial alloys.

STRESS CORROSION CRACKING IN COMMERCIAL STEEL ALLOYS

In several references it is stated that commercial steels containing 0.05% carbon concentration is very susceptible to stress corrosion cracking. However, pure iron is less susceptible to stress corrosion failure. Small amount amounts of carbon promotes stress corrosion cracking and it becomes less severe as carbon contents increased over 0.10%.

A large amount of information has been available on stress corrosion cracking with high yield strength. The term "high strength steel" as used in this paper to steel having yield strength of 900 MPa (130 ksi) or greater, whether the strength is developed by heat treatment of any sort or by cold working. A survey of the information has shown that the strength level of the steel is the most important single factor determining sensitivity to environment induced cracking. Most stress corrosion cracking service failures in high strength steel structure are due to a combination of design plus assembly loads, susceptible alloys and a number of environments including natural environments, salt solutions, organic solvents, various gases containing relatively small amounts of water vapor and hydrogen gas. For many small components such as bolts and springs made of high strength heat treated steels for stress causing service failures are the design stresses. For large forgings, the heat treating stresses are the most important cause of failures.

The initial step in the stress corrosion process is the formation of pits which are likely to form at inclusions. A threshold stress is observed below which cracking does not occur. However, there is no absolute threshold stress for stress corrosion cracking and it vary with specific service application and corrosive environment. The path of cracking in the higher strength steels may be intergranular or transgranular.

A primary measure to avoid SCC should be the selection of a steel with good stress corrosion properties in particular and selecting one with no higher strength than needed. This practice of specifying minimum strength on drawings will not only be of benefit with respect to stress corrosion cracking but also with respect to brittle fracture.

Table 2 at the end of the paper lists alloys that are least susceptible to SCC. Table 3 lists alloys that should be avoided in SCC environment.

STRESS CORROSION CRACKING IN ALUMINUM ALLOYS

The most prevalent form of stress corrosion cracking service failures in aluminum alloys is caused by a combination of water, aqueous solutions or atmospheric moisture, alloy of susceptible composition and structure, and sustained tensile stresses, most often caused by heat treatment or assembly. Both initiation and propagation of cracking are accelerated by moisture, temperature, chlorides and other industrial contaminants. Stress corrosion cracking in aluminum structure for atmospheric service is increased through accumulation of water in pockets and crevices. Not only is liquid water more aggressive than undrained pockets may collect salts which concentrate during evaporation and further accelerate stress corrosion.

The relative susceptibilities of various aluminum alloys vary widely. Members of 2000 series and 7000 series are particularly vulnerable in some tempers, and some of the more highly alloyed 5000 series in some strained hardened tempers. When these alloys are extruded, rolled, forged or drawn, the grains are elongated in the direction of maximum flow to produce a structure or texture which is of major importance to SCC behavior of these alloys. The longest grain axis is designated as the longitudinal direction, the shortest is designated as short transverse and the direction of intermediate grain dimension is designated as the long transverse direction. Shown in Figure 5, practically all service SCC failures of aluminum alloy components involve the short transverse properties.

The tensile stress which cause SCC in aluminum alloys may be provided by working stress, but large majority of service failures are caused by assembly stresses, or heat treating stresses, or both. To control SCC in aluminum alloys 1) select alloy with minimum susceptibility, 2) avoid tensile stresses in short transverse direction, 3) keep water and water vapor away from metal surface and 4) minimize chlorides to concentrate.

STRESS CORROSION CRACKING IN IRON-NICKEL-CHROMIUM ALLOYS

The four classes of stainless steels are

1. Martensite: Fe-Cr alloys which are hardenable by heat treatment and contains 11-18% chromium.

2. Ferritic: Fe - Cr alloys which are not hardenable by heat treatment and contains Cr in from 15 to 30%.

3. Austenitic: Fe-Cr-Ni alloys which are hardenable by cold working and contains 6-22% Ni and 16-26% Cr.

4. Precipitation Hardening Alloys: Fe-Ni-Cr which are hardenable additionally by precipitation.

The most serious stress corrosion cracking within stainless steel is caused by chlorides, extreme care is be taken to minimize chloride introduction. To avoid thermal insulation and gasketing materials high in chlorides, avoid sensitizing, minimize fabrication stress. Fluoride ion can cause SCC much the same way as chloride but with lesser concentration. SCC of Fe-Ni-Cr alloys occurs at high concentration of pH in the absence of chlorides.

STRESS CORROSION CRACKING IN COPPER ALLOYS

Copper and copper alloys have excellent SCC resistance in many industrial environment, in sea water and in marine atmosphere. Most service failures by stress corrosion cracking in copper alloys are caused by conjoint action of water, oxygen, tensile stress, alloy composition and structure, and ammonia or compounds of ammonia. SCC is also caused by moist SO_2 and mercury.

STRESS CORROSION CRACKING IN TITANIUM AND TITANIUM ALLOYS.

Titanium and its alloys have excellent SCC resistant properties. A number of environments that cause SCC are HCl, methyl and ethyl alcohol and fuming nitric acids. Alloys containing more than 6% aluminum are especially susceptible to stress corrosion cracking.

CONCLUSIONS

Stress corrosion cracking (SCC) is the major cause of failures in ground support equipment. There is no effective protection against SCC. In designing components of ground support mechanism a designer should take into account and evaluate:

1. Tensile properties of metals
2. Material Susceptibility to SCC
3. Fracture toughness
4. Type of corrosive environment

REFERENCES

1. B. F. Brown, "Stress Corrosion Cracking Control Measures," National Bureau of Standards Monograph 156, June 1977.

2. D. B. Franklin, "Design Criteria for Controlling Stress Corrosion Cracking," Marshall Space Flight Center, Document No. MSFC-SPEC-522A November 18, 1977.

3. R. W. Staehle, "Stress Corrosion Cracking," American Society of Metals Handbook, pp 205-227.

4. "Proceedings of Conference, Fundamental Aspects of Stress Corrosion Cracking," The Ohio State University, Sept. 11-15, 1967, Published by National Association of Corrosion Engineers, Houston, TX, 1969, pp. 214-307, 411-419.

5. "NTSB Safety Recommendations," Aviation Equipment Maintenance, Dec. 87. pp. 6-8,74.

TABLE 1. COMMON ENVIRONMENT EFFECTS FOR SCC

	ENVIRONMENT	DAMAGING SUBSTANCES	TYPE ALLOYS SUSCEPTIBLE
1.	Marine	Chlorides in aqueous or water solution	High Strength Aluminum alloys High Strength Steels Austenitic Stainless Steels Titanium Alloys
2.	Industrial	Sulfur dioxide *	Copper Alloys
		Ammonia	Copper Alloys
		Hydrogen Sulfide	High Strength Low Alloy Steel
3.	Atmospheric	Oxygen	Copper Alloys **
		Hydrogen Sulfide	Many Commercial Alloys
		CO - CO_2 & Moisture	Carbon Steels
		Ammonia	see above in industrial Envr.
		As & Sb Compounds +	High Strength Steels
		Sulfur dioxide	see above in industrial Envr.
		Chloride + Moisture	see marine environment

Notes: * The oxide produces H_2SO_3 & H_2SO_4
** Depends upon O_2 concentration
+ Contains in insecticides & other sprays

TABLE 2. ALLOYS LEAST SUSCEPTIBLE TO SCC

ALLOYS	CONDITION
STEEL	
Carbon Steel (1000 series for C>=0.10%)	UTS < 1240 MPa
Low Alloy Steel (4130, 4340, D6AC, etc.)	UTS < 1240 MPa
Music Wire (ASTM 228)	Cold drawn
HY-80, HY-130, HY-140, 1095 Spring Steel	Q and T *
21-6-9, Carpenter 20 Cb, Carpenter 20Cb-3 Stn. Stl.	All
AM350, AM355 Stn. Stl.	SCT 1000 & Above
Almar 362, Custom 455, 15-5 PH	H1000 & Above
PH 14-8 Mo Stainless steel	CH900, SRH950 & Above
PH 15-7 Mo, 17-7 PH	CH900
Nitronic 33, A 286 S.S.	All
NICKEL ALLOYS	
Hastelloy C, Hastelloy X, Incoloy 800, Incoloy 901,	All
Incoloy 903, Inconel 718, Inconel X-750	All
Monel K-500, Ni-Span-C 902, Unitemp, Waspaloy	All
Inconel 600, Inconel 625	Annealed
ALUMINUM ALLOYS	
Wrought **	
1000, 3000, 5000 (+) (++), 6000 series	All
2011, 2024 Rod & Bar, 2219	T8
2219	T6
7049, 7149, 7050, 7075, 7475	T73
Cast	
355.0, C355.0	T6
356.0, A356.0, 357.0, B358.0(Tens-50), 359.0	All
380.0, A380.0	As Cast
514.0 (214), 518.0 (218), 535.0 (Almag 35)	As Cast ++
A712.0, C712.0	As Cast

Notes: * Quenched and Tempered.
** Mechanically stress relieved (TX5X or TX5XX) were possible.
+ High Mg alloys should be used in controlled tempers (H111, H112, H116, H117, H323, H343) should be used.
++ Mg>3% not recommended for application temperature >66°C (150°F).

TABLE 2. ALLOYS LEAST SUSCEPTIBLE TO SCC (Continued)

ALLOYS	CONDITION
COPPER ALLOYS	
CDA NO. *	(Max % Cold Rlld.
110, 194, 422, 510, 521	37
170, 172	AT and HT **
195	90
230, 619 (9% B phase), 619 (95% B phase), 688	40
443	10
706	50
725	50, Annealed
MISCELLANEOUS ALLOYS (Wrought)	
Beryllium S-200C	Annealed
HS 25 (L605), HS 188, MP35N	All
Titanium: 3Al-2.5V, 6Al-4V, 13V-11Cr-3Al	All
Magnesium: M1A, LAZ933	All
Magnesium: LA141	Stablized

Notes: * Copper Development Association Alloy number
** AT - Annealed and precipitation hardened.
HT - Work hardened and precipitation hardened.
Source: Marshall Space Flight Center document No. MSFC-SPEC-250A

TABLE 3. ALLOYS LOW RESISTANCE TO SCC

ALLOYS	CONDITION
STEEL	
Carbon Steel (1000 series)	UTS > 1380 MPa
Low Alloy Steel (4130, 4340, D6AC, etc.), H-11	UTS > 1380 MPa
440C	All
18 Ni Maraging Steel - 200, 250, 300 & 350 grades	Aged at 482°C
AM350, AM355 Stn. Stl.	Below SCT 1000
Custom 455	Below H1000
PH 15-7 Mo, 17-7 PH Stainless steel	All Except CH900
ALUMINUM ALLOYS	
Wrought	
2011, 2024	T3, T4
2024	Forgings
2014, 2017, 7039	All
7075, 7175, 7079, 7178, 7475	T6
Cast	
295.0(195), B295.0(B195), 707.0(607, Ternalloy 7)	T6
520.0(220)	T4
D712.0(D612, 40E)	As Cast
COPPER ALLOYS	
CDA NO. *	(Max % Cold Rlld.
260, 353, 782	50
443	40
672	50, Annealed
687	10, 40
762	A, 25, 50
766	38
770	38, 50 Annealed
MAGNESIUM ALLOYS	
AZ61A, AZ80A	All

Notes: * Copper Development Association Alloy number
Source: Marshall Space Flight Center document No. MSFC-SPEC-250A

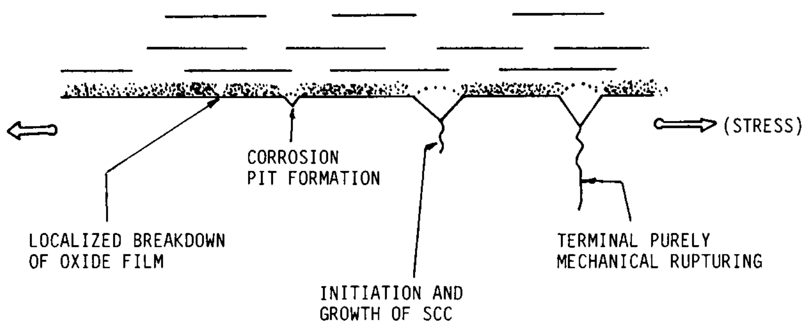

FIGURE 1. COMMON EVENTS IN SCC, LEFT TO RIGHT

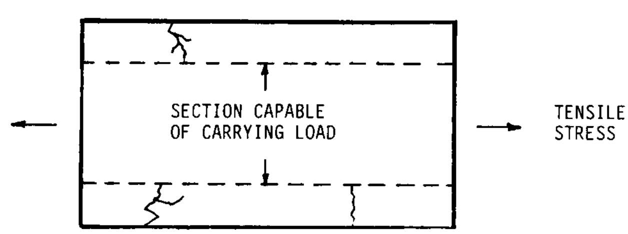

FIGURE 2. ENVIRONMENTALLY INDUCED CRACKS IN METAL SECTION

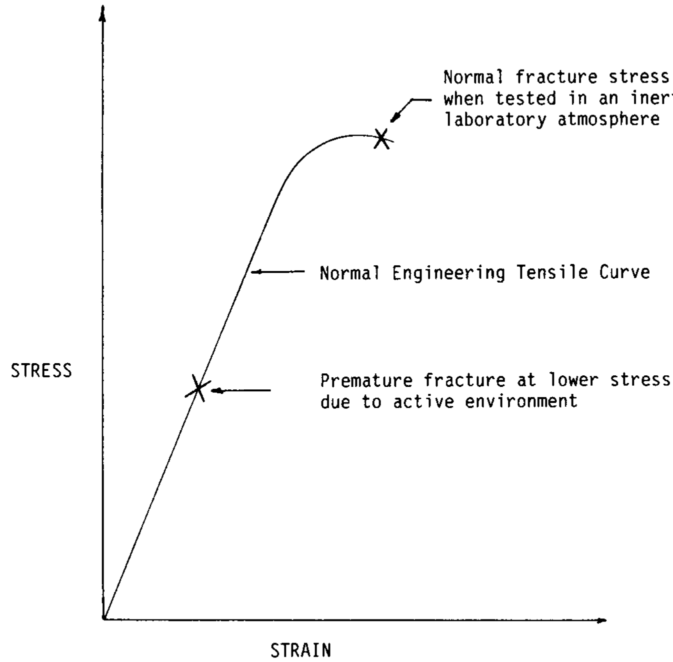

FIGURE 3. EFFECTS OF STRESS CORROSION CRACKING ON TENSILE CURVE

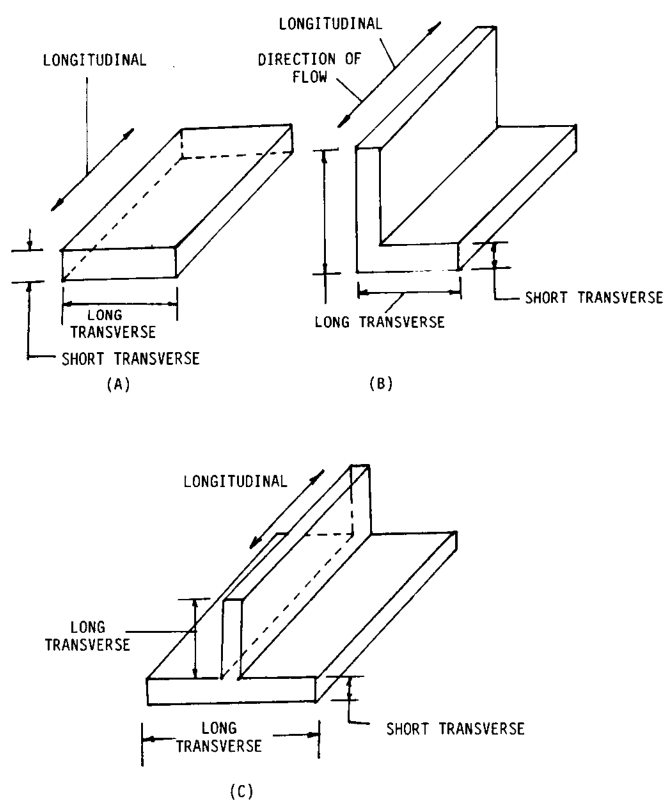

FIGURE 4. GRAIN FLOW PATTERN IN MILL PRODUCT

LOCKED IN ASSEMBLY STRESSES FROM MISMATCH

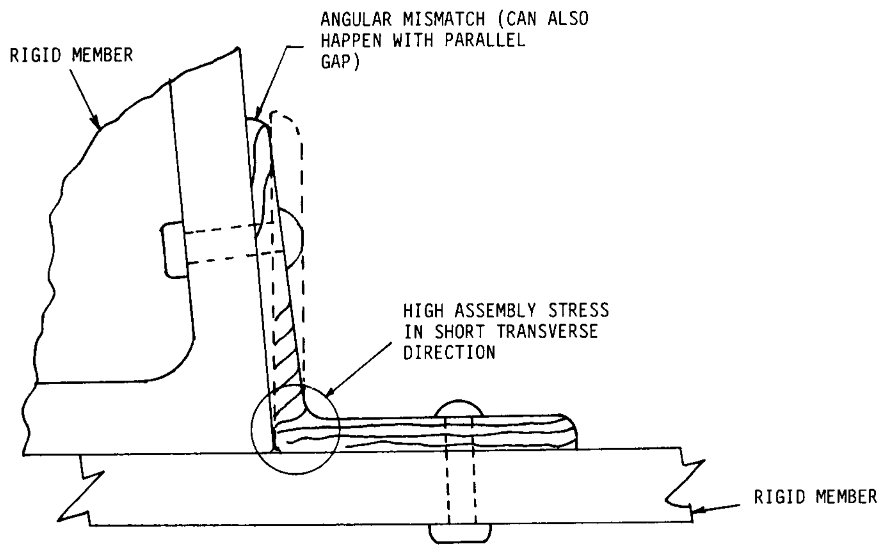

FIGURE 5. HIGH SUSTAINED STRESS GENERATED DUE TO ASSEMBLY MISMATCH