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NASA TECHNICAL MEMORANDUM

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STRESS CORROSION CRACKING EVALUATION OF SEVERAL FERROUS AND NICKEL ALLOYS

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16. ABSTRACT

The stress corrosion cracking characteristics of H-11 steel, Hastelloy C, Inconel 718, Waspaloy, music wire, and stainless steels Arde (cryoformed) low silicon 301, AISI 303, AISI 304, Armco 21-6-9 are described. Three types of specimens (round tensile, flat tensile, and C-ring) were employed and the main test environment was alternate immersion in 3.5 percent salt solution. The results of the test indicated that music wire, Hastelloy C, Inconel 718, Waspaloy, and stainless steels Arde 301, AISI 303, AISI 304 and Armco 21-6-9 in most forms and heat treat conditions are resistant to stress corrosion cracking in environments containing moist chlorides. However, another investigator has reported both service and laboratory stress corrosion cracking of cryoformed 301 stainless steel under different conditions. H-11 steel is susceptible to stress corrosion cracking in both moist chloride environments and semi-industrial atmospheres.

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STRESS CORROSION CRACKING EVALUATION OF SEVERAL FERROUS AND NICKEL ALLOYS

SUMMARY

The rapid development of high strength alloys for space vehicle structure, hardware, fasteners, etc has resulted in an ever increasing requirement for technical knowledge of the stress corrosion characteristics of these alloys under the demanding service conditions of space application. This study is part of an overall program to evaluate the stress corrosion resistance of high strength steels, stainless steels, and so called superalloys for possible use in aerospace applications.

The results of this investigation indicated that music wire, Hastelloy C, Inconel 718, Waspaloy and stainless steel Arde (cryoformed) low silicon 301, AISI 303, AISI 304 and Armco 21-6-9 are resistant to stress corrosion cracking in 3.5 percent salt water in all forms and conditions tested. The only test material found to be susceptible to stress corrosion was H-11 steel.

INTRODUCTION

Superalloys according to T. D. Cooper(1) may be considered the backbone of current liquid-rocket engine technology since they are used extensively for turbine volutes and nozzles in the turbopumps. These alloys are particularly suited to meet the requirements of the new generation of high pressure engines. One of the superalloys which is being used extensively in rocket engines is Inconel 718. This was the first alloy in which a Cb addition (5 percent) was used to form the high columbium face-centered-cubic (fcc) gamma prime, Ni_3Cb, to increase the age hardening ability at low temperature. In addition, it possesses excellent fabricability and weldability.

The stainless steels of today offer many unique combinations of properties that provide the designer with improved design flexibility. Problems that a few years ago defied solution now can be solved with the newer stainless steels. One such stainless steel is Armco 21-6-9. This austenitic stainless steel combines good corrosion resistance, high yield strength, good elevated temperature properties, and high strength and toughness at sub-zero temperatures [2].

Data on mechanical properties, strength-to-weight ratios, fatigue strength, and cryogenic and high temperature properties are available for most metal alloys, but the stress corrosion cracking characteristics of many alloys are not available, or the published data are difficult to interpret because of the test method used to obtain the data. Investigators need to make available data that designers can use to readily ascertain the relative stress corrosion cracking resistance of metal alloys to natural environments such as inland and seacoast atmosphere.

EXPERIMENTAL PROCEDURE

The materials evaluated in this stress corrosion cracking investigation were H-11 steel, music wire, Hastelloy C, Inconel 718, Waspaloy, Arde (cryoformed) low silicon 301, AISI 303, AISI 304 and Armco 21-6-9 stainless steels in the forms of bar, tube, and sheet. Three types of specimens were required because of the material forms and the direction of applied stress. Flat tensile specimens, loaded by constant bending were used for testing sheet material. Round tensile specimens, stressed in uniaxial tension, were used for testing the longitudinal direction of all bar stock and the transverse direction of two inch or greater diameter bar. C-rings, utilizing the constant deflection method, were used for testing the transverse direction of tube and bar stock of less than two inch diameter. The types of specimens and methods of loading are illustrated in Figures 1 and 2.

The specimens were deflected or strained the calculated amount to give the desired stress levels, wiped with acetone, and placed in the alternate immersion tester until failure or until the test was terminated (approximately six months). A detailed description of the test specimens, formulas for calculating deflection and strain, and methods of loading and testing are given in Reference 3. Mechanical properties of alloys were measured in both longitudinal and transverse directions when feasible. The chosen stress levels were from 25 to 100 percent of the directional yield strength, except as noted for small diameter bar. Duplicate unstressed tensile specimens were exposed under identical conditions for comparison and control. The tests were conducted in a ferris wheel type alternate immersion tester (Figure 3) containing a 3.5 percent solution (deionized water) of sodium chloride, with an immersion cycle of 10 minutes in solution followed by 50 minutes of drying above the solution. In addition, music wire and H-11 steel were tested in 100 percent relative humidity at 100°F and to the outside environment at MSFC which is considered a mild industrial atmosphere.

RESULTS AND DISCUSSION

The compositions of the alloys evaluated in this program are listed in Table I. In some cases, the typical analysis is given because the composition of the specific material was not available. The mechanical properties and the heat treatments used to obtain the properties of the program materials are shown in Tables II and III, respectively. Listed in Table IV are the complete stress corrosion results obtained in this investigation.

The H-11 steel was found to be very susceptible to stress corrosion cracking in the accelerated test solution and in the MSFC atmosphere. In addition to the stress corrosion cracking, the H-11 specimens suffered severe rusting. This means that H-11 steel is not recommended for use in a moist or salt-laden atmosphere because of its low resistance to both rusting and stress corrosion cracking. However, Nickel-cadmium electroplate per AMS 2016 is effective in protecting H-11 steel against stress corrosion cracking (4). Music wire which is used extensively as spring material was found to be resistant to stress corrosion cracking in the accelerated test solution as well as in the MSFC atmosphere and in 100 percent relative humidity at 100°F. This material suffered moderate rusting and would require a protective coating, particularly in a moist salt environment.

All the stainless steels exhibited good resistance to stress corrosion cracking. Arde (cryoformed) low silicon 301 was resistant in the three conditions in which it was evaluated; unaged, aged, and welded and aged. Although another investigator (5) reported both service and laboratory stress corrosion cracking of cryoformed 301 stainless steel, the results are not necessarily conflicting since the reported failures occurred under different conditions such as oxygen screening and 100°F salt spray. Care should be taken in the use of this material until more information is available on the stress corrosion cracking resistance. Although one of the ten test specimens failed, 303 stainless steel is still considered to have exhibited a high resistance to stress corrosion cracking. This is so because the applied stress at which failure occurred was 100 percent of the yield strength. Several service failures, however, of relatively thin sections of 303 stainless steel components such as tube fitting sleeves have been attributed to stress corrosion cracking. The tensile stress at the point of failure in these sleeves is not known, but could easily have been at or above the yield point of the material. It is widely accepted that most metals are susceptible to stress corrosion cracking and vary mainly in degree of susceptibility. Any material whose stress corrosion threshold (stress level below which stress corrosion cracking is not encountered) is in the vicinity of its yield strength should be considered in the category of materials that possess high resistance to stress corrosion. Both seamless and welded 304 stainless steel tubes were resistant to stress corrosion cracking. Bar and sheet of Armco 21-6-9 stainless steel in the solution treated and sensitized conditions were resistant to stress corrosion cracking in both the transverse and longitudinal direction of grain orientation at tensile loads up to 100 percent of the respective yield strengths.

The three nickel alloys were found to be highly resistant to stress corrosion cracking in all forms and conditions tested. This high resistance was expected based on published test data and service experience. No failures were encountered with solution treated sheet and tube and as-welded sheet of Hastelloy C even at high stress loads. In addition, there were no failures of specimens made from aged bar of Inconel 718 and Waspaloy in either direction of grain orientation at stresses up to 100 percent of the yield strengths.

CONCLUSIONS AND RECOMMENDATIONS

The results obtained with this accelerated, six months, salt water, alternate immersion test indicate that:

1. H-11 steel heat treated to 245 ksi is susceptible to stress corrosion cracking and severe rusting in a moist chloride environment and a semi-industrial atmosphere.

2. Music wire is resistant to stress corrosion cracking but is susceptible to rusting in a moist environment especially in the presence of chlorides.

3. Stainless steels Arde (cryoformed) low silicon 301, AISI 303, AISI 304, Armco 21-6-9, and the nickel base superalloys Hastelloy C, Inconel 718, and Waspaloy are highly resistant to stress corrosion cracking in a moist environment containing chlorides at room temperatures.

Additional testing of AISI 303 and cryoformed 301 stainless steels is needed to ascertain more closely the stress corrosion cracking characteristics. Although much work is being done on various aspects of stress corrosion, there is a need for a more concerted effort to obtain basic data such as cracking susceptibility and threshold values on all structural alloys in natural environments including inland and seacoast atmospheres. The information will be of unlimited value in the preparation of the stress corrosion section of a design criteria for aerospace vehicles.

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4. Montano, J. W., "A Stress Corrosion Evaluation of AISI - H-11 Alloy Steel Plated with Nickel-Cadmium Coating," NASA TMX-64510, April 2, 1970
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TABLE I. CHEMICAL COMPOSITION OF ALLOYS

Alloy	Source & Heat No.	Form	C	Mn	P	Si	Cr	Ni	Mo	Al	N	Co	Fe	Ti	S	Cu	W	V	B	Zr
											Composition Wt. %									
H-11 Steel	Std. Pressed Steel Co.	Bar	.44	.29		.87	4.8		1.2				Bal.		.01	.047		.60		
Music Wire	Stock	Bar	.90	.31		.27							Bal.		.016					
Arde 301	Arde Inc. 9758	Sheet	.029	.02		.03	18.72	7.29	.27		.027		Bal.		P+S .011					
AISI 304**	Wall Tube Co. (welded) Pacific Tube Co. (seamless)	Tube	.08*	2.0*		1.0*	19	10					Bal.							
AISI 303**	Stock	Tube	.15*	2.0*		1.0*	18	9					Bal.		.15 Min.					
Armco 21-6-9**	Armco Steel Corp.	Sheet, Bar	.08*	9.0	.06*	1.0*	19.5	6.0			.28		Bal.		.03*					
Hastelloy C	Boeing 3-3414	Sheet	.06	.51	.008	.56	15.85	Bal.	15.90			1.82	5.06		.008		3.86	.18		
Inconel 718	Universal-Cyclops KH-3417K1	1" Bar	.073	.20	.002	0.15	17.87	Bal.	2.97	.70			19.5	.81	.007	.06	Cb+Ta 5.5		.0035	
Waspaloy	Universal-Cyclops KH-3480 K1	1" Bar	.053	.020	.002	.202	18.91	Bal.	3.97	1.42		12.80	.87	2.98	.005	.06			.0058	.047
Waspaloy	Universal-Cyclops KH-3884 K1	1.5" x 2" Bar	.058	.04	.002	.03	18.88	Bal.	3.85	1.41		12.89	.57	2.91		.06			.0065	.064

*Maximum Allowable

**Typical Analysis or Composition

TABLE II. MECHANICAL PROPERTIES

Alloy	Heat Treatment	Form	Grain Direction	Tensile Strength (ksi)	Yield Strength (ksi)	% Elongation
H-11 Steel	As Received	1" Bar	Long.	247	216	13
Music Wire	As Received	1/4" Bar	Long.	217	187	8
Arde 301	Unaged	.060" Sheet	Long.	245	245	4
Arde 301	Aged	.060" Sheet	Long.	261	261	5
Arde 301	Welded and Aged	.060" Sheet	Long.	254	253	2
AISI 303	Seamless, 1/4 H	1" Tube	Trans.	*	*	*
AISI 304	Seamless, 1/8 H	1" Tube	Long.	113	92	32
AISI 304	Welded, 1/8 H	1" Tube	Long.	108	90	38
Armco 21-6-9	As Received	1" Bar	Long.	107	58	36
Armco 21-6-9	Sensitized	1" Bar	Long.	107	57	37
Armco 21-6-9	As Received	.10" Sheet	Long.	124	73	46
Armco 21-6-9	As Received	.10" Sheet	Trans.	121	76	46
Amrco 21-6-9	Sensitized	.10" Sheet	Long.	126	80	47
Armco 21-6-9	Sensitized	.10" Sheet	Trans.	128	80	45
Hastelloy C	As Received	.063" Sheet	Long.	120	57	50
Hastelloy C	As Welded	.110" Sheet	Long.	119	57	48
Inconel 718	Aged 18 Hrs.	3/4" Bar	Long.	200	175	14
Inconel 718	Aged 19 Hrs.	1" Bar	Long.	186	138	30
Waspaloy	Aged	1" Bar	Long.	180	112	22
Waspaloy	Aged	1.5" X 2" Bar	Long.	195	136	22
Waspaloy	Aged	1/5" X 2" Bar	Trans.	197	138	25

*Not measured, hardness incidated material was 1/4 hard

TABLE III. HEAT TREATMENT

1. H-11 Steel

   As received: Heat treated to 245 ksi by Standard Pressed Steel Company per Specification No. 107.

2. Music Wire

   As Received

3. Arde 301 Stainless Steel

   a. Cryoformed at minus 320°F to a nominal 240 ksi, passivated
      Unaged
      Aged 790°F 20 hours in air.

   b. TIG welded per Arde AE5501 using argon. Cryoformed at minus 320°F to nominal 260 ksi. Aged 790°F 20 hours in air.

4. AISI 303 Stainless Steel

   As received, 1/4 hard condition

5. AISI 304 Stainless Steel

   a. Seamless: 1/8 hard

   b. Welded: Welded in annealed condition, cold worked 1/8 hard

6. Armco 21-6-9 Stainless Steel

   a. As received, solution treated

   b. Sensitized: 1250°F 1 hour (vacuum furnace), A.C.

7. Hastelloy C

   a. As received, solution treated (annealed)

   b. As welded: Butt welded using Hastelloy filler

8. Inconel 718

   a. 3/4" Bar: Solution annealed 1750°F 1 hour, A.C., aged 1325°F 8 hours, furnace cooled 1150°F and held for total aging of 18 hours.

   b. 1" Bar: Solution treated 1950°F 1 to 2 hours, A.C., aged 1325°F 8 hours, furnace cooled to 1150°F and held for total aging of 19 hours.

9. Waspaloy

   a. 1"Bar: Solution treated 1975°F 4 hours, A.C., stabilized 1550°F 4 hours, A.C., aged 1400°F 16 hours, A.C.

   b. 1.5" X 2" Bar: Solution treated 1850°F 1 hour, W.Q., stabilized 1550°F 4 hours, A.C., aged 1400°F 16 hours, A.C.

TABLE IV. STRESS CORROSION CRACKING TEST RESULTS (1) (Continued)

Material Form	Condition	Stress Direction	Applied Stress ksi	Applied Stress % YS	Failure Ratio	Days to Failure	% Loss in T.S.
			Waspaloy				
Bar (1" dia.)	Aged	Long.	84	75	0/3	-	N
		Trans. (C-ring) (5)	28	25	0/3	-	-
			56	50	0/3	-	-
			84	75	0/3	-	-
			112	100	0/3	-	-
Bar (1/5" X 2")	Aged	Long.	0	0	-	-	N
			136	100	0/3	-	N
		Trans.	0	0	-	-	N
			104	75	0/3	-	N
			138	100	0/3	-	N

N - Negligible change in tensile properties

Note (1) Test Data

a. Specimen: Round tensile (C-ring where noted) for bar stock and flat tensile for sheet.

b. Stress method: Constant strain - direct tension for round tensile and constant deflection for flat tensile and C-ring.

c. Medium: Alternate immersion in 3.5% NaCl solution

d. Exposure time: Until failure or six months.

(2) Data based on six months of exposure except as noted.

(3) 1 of 3 specimens stressed at 90% failed (167 days) from a duplicate set of specimens exposed for six months in MSFC atmosphere.

(4) No failures were encountered in duplicate sets of specimens after two years of exposure in 100% relative humidity at 100°F or in MSFC atmosphere.

(5) Load calculations were based on longitudinal rather than transverse yield strength.

(6) Load calculations were based on 50% of the weld tensile strength.

TABLE IV. STRESS CORROSION CRACKING TEST RESULTS (1)

Material Form	Condition	Stress Direction	Applied Stress ksi	Applied Stress % YS	Failure Ratio	Days to Failure	% Loss in T.S. (2)
			H-11 Steel (3)				
Bar (1" dia.)	H.T. to 245 ksi	Long	0	0	-	-	10 (1 mo)
			110	50	5/5	20 to 35	
			195	90	5/5	7 to 13	
		Trans. (C-ring) (5)	55	25	0/2	-	-
			110	50	2/2	27, 29	-
			195	90	3/3	2(3)	-
			Music Wire (4)				
Bar (1/4" dia)	As Received	Long.	131	70	0/3	-	11 (4.5 mo)
			Arde (Cryoformed) 301 Stainless Steel				
Sheet (.060" thick)	Unaged	Long.	185	75	0/3	-	N
	Aged	Long.	196	75	0/3	-	N
	Welded and Aged	Long.	0	0	-	-	N
		(Weld Face)	190	75	0/3	-	N
			227	90	0/3	-	N
			AISI 303 Stainless Steel				
Tube (1" dia)	1/4 H (seamless)	Trans. (C-ring) (5)	75	100	1/10	43	-
			AISI 304 Stainless Steel				
Tube (1" dia.)	1/8 H (seamless)	Trans. (C-ring) (5)	85	75	0/3	-	-
			107	95	0/3	-	-
Tube (1" dia.)	1/8 H (welded)	Trans. (C-ring) (5)	81	75	0/3	-	-
			103	95	0/3	-	-
			Armco 21-6-9 Stainless Steel				
Bar (1" dia.)	Soln. Treated	Long	0	0	-	-	N
			43	75	0/3	-	N
			58	100	0/3	-	N
	Soln. Treated	Trans. (C-ring) (5)	43	75	0/3	-	-
			58	100	0/3	-	-
	Sensitized	Long.	0	0	-	-	N
			43	75	0/3	-	N
			57	100	0/3	-	N

TABLE IV. STRESS CORROSION CRACKING
TEST RESULTS (1) (Continued)

Material Form	Condition	Stress Direction	Applied Stress ksi	% YS	Failure Ratio	Days to Failure	% Loss in T.S.
		Armco 21-6-9 Stainless Steel (Continued)					
	Sensitized	Trans.	43	75	0/3	-	-
		(C-ring) (5)	57	100	0/3	-	-
Sheet (.10" Thick)	Soln. Treated	Long.	0	0	-	-	N
			55	75	0/3	-	N
			73	100	0/3	-	N
	Soln Treated	Trans.	0	0	-	-	N
			57	75	0/3	-	N
			76	100	0/3	-	N
	Sensitized	Long.	0	0	-	-	N
			60	75	0/3	-	N
			80	100	0/3	-	N
	Sensitized	Trans.	0	0	-	-	N
			68	75	0/3	-	N
			80	100	0/3	-	N
		Hastelloy C					
Sheet (.063" thick)	Soln. Treated	Long.	43	75	0/3	-	-
	Soln. Treated	Trans.	43	75	0/3	-	-
Sheet (.110" thick)	As Welded	-	0	0	-	-	7
		Face	60	50 (6)	0/4	-	6
		Root	60	50 (6)	0/4	-	10
Tube (1 1/4" dia X .058" wall)	Soln. Treated	Trans.	30	50	0/3	-	-
		(C-ring) (5)	45	75	0/3	-	-
			60	100	0/3	-	-
		Inconel 718					
Bar (3/4" dia.)	Aged 18 hrs.	Trans.	44	25	0/3	-	-
		(C-ring) (5)	88	50	0/3	-	-
			132	75	0/3	-	-
			175	100	0/3	-	-
Bar (1" dia.)	Aged 19 hrs.	Long.	103	75	0/3	-	N
		Trans.	35	25	0/3	-	-
		(C-ring) (5)	69	50	0/3	-	-
			103	75	0/3	-	-
			138	100	0/3	-	-

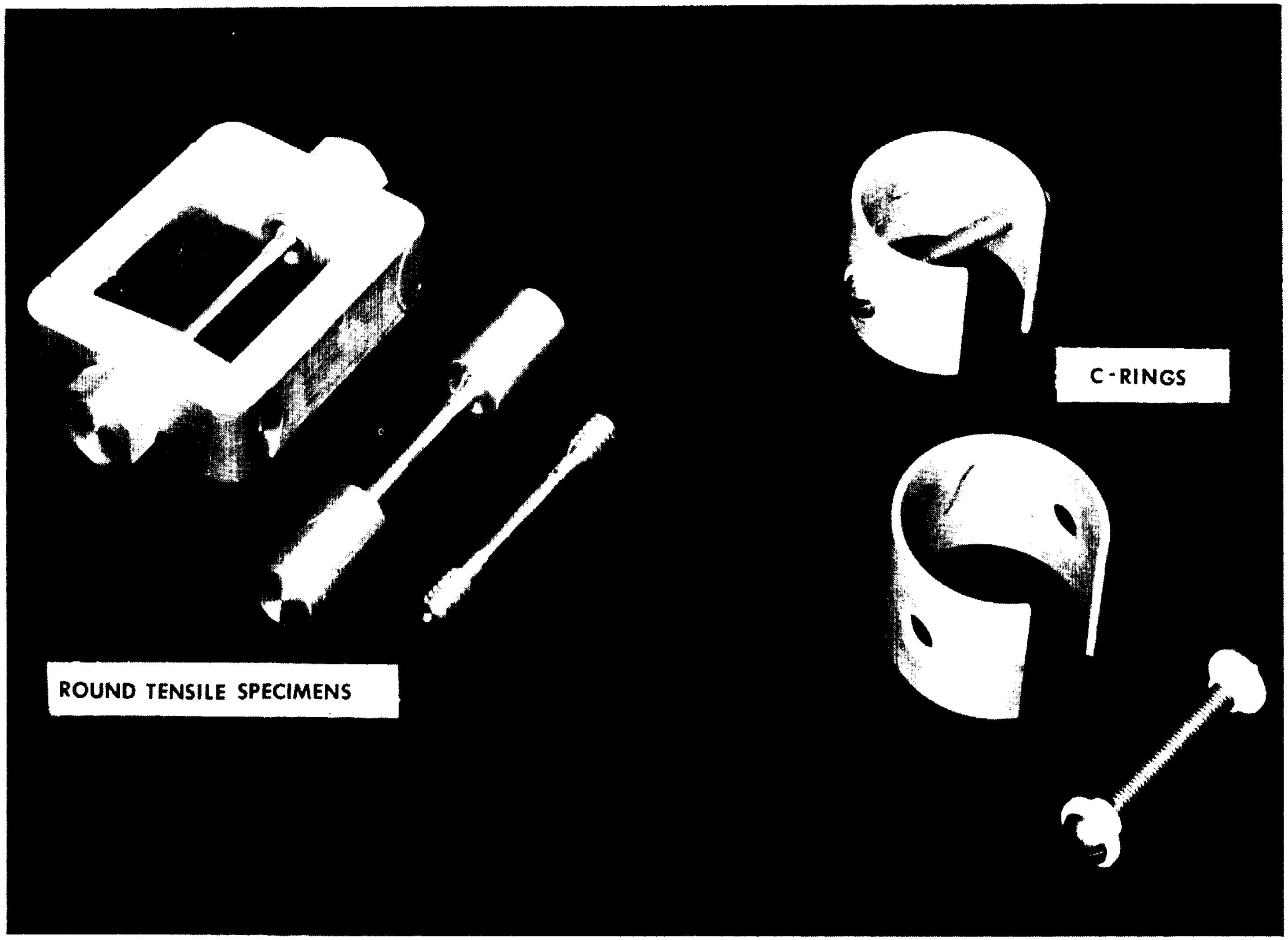

FIGURE 1 - ROUND TENSILE AND C-RING TYPE STRESS CORROSION TEST SPECIMENS

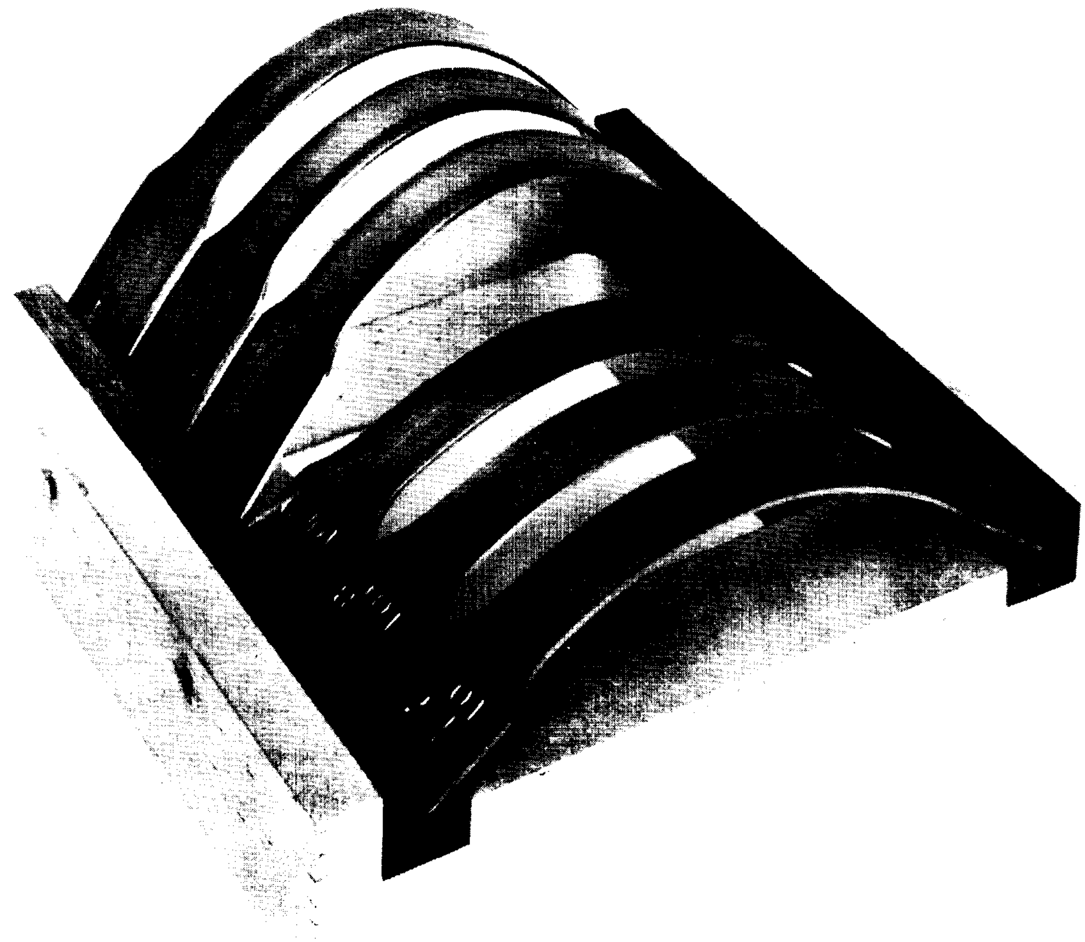

FIGURE 2 - FLAT TENSILE SPECIMENS LOADED IN A CONSTANT SPAN FIXTURE

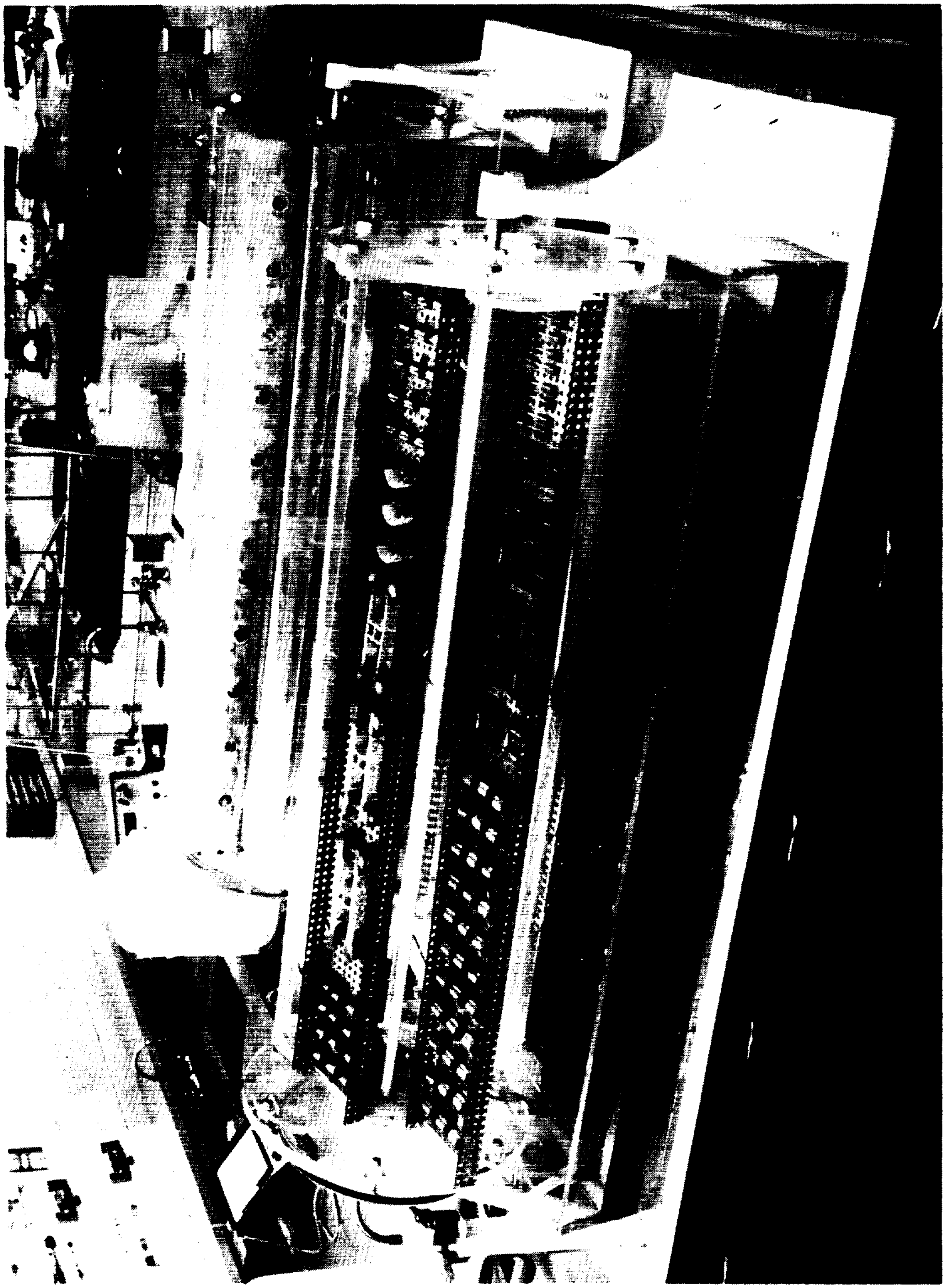

FIGURE 3 - ALTERNATE IMMERSION TESTER

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APPROVAL

STRESS CORROSION CRACKING EVALUATION OF SEVERAL FERROUS AND NICKEL ALLOYS

By

T. S. Humphries and E. E. Nelson

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