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EFFECT OF CORROSION RESISTANT COATINGS ON THE FATIGUE STRENGTH OF CAST MAGNESIUM ALLOYS

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- Shot Peening

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A study was made for the Army Aviation Materiel Readiness Command to evaluate the effects of various surface treatments and corrosion resistant coating systems on the fatigue properties of three sand cast magnesium alloys (AZ91-T6, ZE41-T5, and EZ33-T5) of current or potential use in helicopter component housings. This was part of a larger program undertaken by the Frankford Arsenal to provide significant reduction of costs and downtime associated with the corrosion degradation of these housings. (Cont'd)

407 207

20. (Continued)

Coatings evaluated were DOW 1 and DOW 7 chromate conversion coatings and the HAE and DOW 17 anodic coatings, both light and heavy applications. Pretreatments such as acid pickling, shot peening, and polystyrene impregnation were also evaluated as well as several different organic topcoats.

R. R. Moore rotating beam (R = -1) and sheet flexure (R = .1) fatigue tests were run with machined and as-cast surfaces, respectively. The test results showed that:

1. The chromate conversion and anodic coatings are not necessarily detrimental to the fatigue properties of the three magnesium alloys when applied to unpickled surfaces. In fact, for two alloys, AZ91 and ZE41, an increase in fatigue strength was observed. Thus, acid pickling is seen to be a major detriment.

2. Shot peening eliminates the deleterious effects of pickling and coatings for all three alloys.

3. The HAE heavy anodic coating performed somewhat better than the others in regard to its effect on substrate fatigue strength, although no coating performed significantly best. The HAE heavy coating did outperform the DOW 17 heavy anodic and DOW 7 chromate conversion coatings with respect to minimizing the effects of corrosive environment (both salt fog and high humidity) on subsequent fatigue properties.

4. The ZE41 alloy casting material appeared best in that it showed the most favorable interaction with the various coatings and treatments with respect to subsequent fatigue performance.

SUMMARY

INTRODUCTION

A study was made, for the Army Aviation Materiel Readiness Command, St. Louis, to evaluate the effects of various surface treatments and corrosion resistant coating systems on fatigue properties of three and cast magnesium alloys - AZ91C-T6, ZE41A-T5, and EZ33A-T5 - of current or potention use in helicopter component housings. This was part of a larger program undertaken by ARRADCOM (Frankford Arsenal) to provide significant reduction in costs and downtime associated with the corrosion degradation of these housings.

Currently, the housings are AZ91C-T6 alloy castings, protected with DOW 7 chromate conversion coating and an acrylic lacquer organic topcoat. Castings of ZE41A-T5 and EZ33A-T5 alloys, although of somewhat lower strength, are of interest because of improved resistance to corrosion and good weld repairability, respectively, compared to AZ91C-T6 castings. Coatings evaluated were DOW 1 and DOW 7 chromate conversion coatings and the HAE and DOW 17 anodic coatings - both light and heavy applications. Pretreatments such as acid pickling, shot peening, and polystyrene impregnation were also evaluated as well as several different organic topcoats.

R. R. Moore rotating beam (R = -1) and sheet flexure (R = .1) fatigue tests were run with machined and as-cast surfaces, respectively; and fatigue life and strength were measured. Also, some tests were run after specimens were exposed to salt fog or humid environment.

SUMMARY OF RESULTS

1. R. R. Moore Screening Tests

a. Acid pickling and shot peening were of major influence on the fatigue strength of all three magnesium alloy cast materials: pickling reducing the fatigue strength by 15 to 20%; peening increasing the fatigue strength by 25 to 35%. The negative effect of pickling was eliminated by prior shot peening: with peened and pickled fatigue strengths 10 to 35% greater than those for the controls, depending upon the alloy.

b. Chromate conversion and anodic coatings provided a minor or second order influence on the magnesium substrate fatigue properties. None of the coatings proved significantly best - although the HAE heavy anodic coating performed consistently well. Anodic coatings on bare surfaces (no pickling or peening) actually showed improved fatigue strength for the AZ91 and ZE41 alloys.

c. Coated ZE41 material showed a 5 to 15% increase in fatigue strengths compared to the pickled only and peened and pickled surfaces; coated AZ91 material showed a 10% increase to 40% decrease; and coated EZ33 showed a 0 to 30% decrease.

2. Sheet Flexure Tests Of As-Cast Surfaces

a. Alkaline cleaned and coated specimens provided up to 25% greater fatigue strength than the untreated specimens. Also, the alkaline cleaning alone appeared to provide some beneficial effect.

b. Compared to the DOW 7 and DOW 17 heavy coatings, the HAE heavy coated specimens provided up to 20% greater fatigue strength in the unexposed tests and also after salt fog and high humidity exposure.

c. ZE41 alloy showed slightly better basic fatigue strength than the AZ91 alloy and better response to the alkaline cleaning and coatings.

CONCLUSIONS

1. Acid pickling has a significant detrimental effect on the fatigue strength of cast AZ91, ZE41, and EZ33 magnesium alloys.

2. Shot peening has a significant beneficial effect on magnesium fatigue strength and eliminates or reduces any degradation due to acid pickling or coatings.

3. Chromate conversion and anodic coatings applied without prior acid pickling, are not necessarily detrimental to the fatigue properties of the three magnesium alloy cast materials - and can be beneficial.

4. The HAE heavy coating appears best with respect to influence on substrate fatigue and in minimizing the effects of corrosion damage on subsequent fatigue performance.

5. The cast ZE41 alloy provided the most favorable interaction with the various coatings and treatments with respect to subsequent fatigue performance.

6. In all three alloys, the anodic coated magnesium fatigue strength was comparable to, or better than, that for the DOW 7 system currently used.

RECOMMENDATIONS

1. Where fatigue strength is a performance criteria, acid pickling should not be utilized as a pretreatment for chromate conversion or anodic coating application. Anodic coating processes should be controlled to minimize substrate surface effects. Shot peening should be utilized, especially when acid pickling or very heavy anodic coatings are required.

2. The ZE41 alloy with HAE coating applied to unpickled surfaces should be used for optimum fatigue characteristics, with and without corrosive environment. For even greater fatigue strength, shot peening should also be utilized.

3. To optimize the fatigue performance of the anodic coated magnesium housings in-service, it is further recommended:

a. to evaluate shot peening of the magnesium cast material to determine the practical range of peening parameters (shot size/material and intensity), depth of compressive stresses obtained, and extent of surface damage;

b. to evaluate the effects of specific coating process parameters on coating porosity, integrity, and thickness and on the substrate magnesium surface roughness.

c. to evaluate full scale components and component material especially with respect to determination of the effects of casting weld repairs.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

INTRODUCTION

This study was initiated for the purpose of determining the effects of various surface treatments and corrosion resistant coating systems on the fatigue properties of three cast magnesium alloys, AZ91C-T6, ZE41C-T5, and EZ33A-T5, of current or potential use in military helicopter component housings. It was part of a larger program coordinated by the Materials and Manufacturing Technology Division for the Army Material Readiness Command to improve the service life and maintenance requirements of the magnesium housings by updating and optimizing the housing material/environmental protective coating system used.

Recent helicopter designs have relied heavily on the use of magnesium castings for such components as transmission, rotor, and combiner housings. This is true for aircraft currently in use such as the CH-47 and CH-54 as well as new designs such as the Heavy Lift Helicopter (HLH) and the Utility Tactical Transport Aviation System (UTTAS). A major problem associated with the use of cast magnesium alloy housings has been their general poor resistance to environmental degradation with the protective coating system now used.

Currently, housings are sand cast from AZ91 alloy, solution heat treated, and thermally aged. The protective coating system employed is a DOW 7 chromate conversion coating over which is applied a chromate primer acrylic lacquer topcoat system. Providing corrosion resistance through the use of improved alloys and surface protection systems would mean significant savings due to decreased maintenance, repair, and replacement of the housings and decreased aircraft downtime.

Although, to date, no housings have failed due to fatigue or have required replacement due to fatigue cracking, neither has design analysis been made to determine housing dynamic loadings in service. Concurrently, there is little data in the literature on the fatigue properties of coated magnesium and what there is indicates that magnesium fatigue strength is significantly reduced by anodic coatings, references (1) and (2). Thus, it became necessary to ascertain the effects of surface treatments and coatings on the fatigue properties of the three candidate magnesium alloys to provide assurance that housing reliability with respect to dynamic loading would not be jeopardized with any of the new alloy/coating systems under consideration. Also, information was needed on the basic fatigue properties of the new magnesium casting alloy materials ZE41 and EZ33. The ZE41 alloy was developed to provide improved strength and corrosion resistance and the EZ33 alloy was developed for better casting weld repairability.

Two types of fatigue test were performed in this evaluation. Initially, high frequency R.R. Moore rotating beam fatigue tests were performed on machined specimens to provide a comprehensive screening of the effects of the various coating systems and conditioning treatments on the fatigue strength of the three magnesium alloys. These included chromate conversion and anodic coatings and various organic topcoats as well as pre-treatments such as shot peening and acid pickling. The two or three best coating systems (with required pre-treatments), as determined from these screening tests, as well as from the corrosion tests of the Frankford Arsenal, were then further evaluated by sheet flexure fatigue tests of as-cast surfaces. In addition, the effects of exposure to 5% salt fog or high humidity prior to fatigue testing was evaluated. For all tests stress-cyclic life curves and fatigue strength were determined.

MATERIALS

Materials used for the fatigue program were from the same lots of castings ordered from Hitchcock Industries, Inc. by Frankford Arsenal and used in the corrosion studies. Plates of sand-cast magnesium alloys AZ91C-T6, ZE41A-T5, and EZ33A-T5, measuring 1/4-in. and 5/8-in. (6.4 and 16 mm) thick, were provided. The chemical compositions are given in table I. The heat treatment and mechanical properties are given in table II.

Table I

Chemical Composition of the Magnesium Castings*

Alloy/Element	Al	Zn	Ce	Zr	Mg
AZ91	8.75	0.81	-	-	Bal.
ZE41	-	3.71	1.44	0.89	Bal.
EZ33	-	2.57	2.94	0.68	Bal.

* Data from Frankford Arsenal

Table II

Tensile Properties of the Magnesium Castings*

Alloy	Heat Treatment	UTS, ksi (MPa)	.2% Offset Yield, ksi (MPa)	% Elongation in 2-in. (50.8 mm)	% RA
AZ91	T6 - Solution heat-treated & artificially aged	39.4 (272)	23.2 (160)	4.0	5.1
ZE41	T5 - artificially aged	32.6 (225)	21.6 (149)	5.1	5.5
EZ33	T5 - artificially aged	21.3 (146)	14.9 (103)	2.5	2.2

* Data from Frankford Arsenal

EXPERIMENTAL PROCEDURE

Screening Tests

1. Test Conditions

In the screening test phase of the program the intent was to study the effect of the many candidate corrosion resistant coating systems and preconditioning treatments on the fatigue strength of the three magnesium alloys. The coatings were chosen by the Army Materiel Readiness Command on the basis of improving corrosion protection over the currently used DOW 7 chromate conversion coating. The standard acid pickling pretreatment was also evaluated as well as practices not currently employed such as polystyrene impregnation and shot peening. Impregnation was included since the castings were to be receptacles for lubricants and possible through pores would require sealing.

Shot peening is a standard practice used to protect structural metals from the deleterious fatigue effects of electrodeposited metals or plasma sprayed coatings, references (3) and (4). The residual compressive surface stresses resulting from shot peening are generally sufficient to reduce or eliminate the detrimental effects of the coatings. However, the specific shot peening technique to be used for these tests was not immediately obvious because peening of magnesium is not usually a required procedure. Little information was available. Previous work reported in the literature, reference (5), and some experience by Metal Improvement Co. indicated large sized, hard balls impinged at low velocity yielded the optimum results with respect to providing maximum residual compressive surface stresses with least microstructural damage. Thus, large sized, .125 in. (3.2mm) diameter stainless steel balls (stainless steel to preclude highly corrosive surface contamination) were selected. With respect to peening intensity, a minimum of 5 to 10 mils (0.127 - 0.254 mm) depth of compressive stress was considered necessary to provide adequate protection even after such inherently metal consuming treatments as pickling, chromating, or anodizing had been performed. To assure that this requirement could be met, the Frankford Arsenal made a preliminary study in which Almen No. 2 gage intensities of .005A and .010A were evaluated by metallographic, SEM, and x-ray diffraction techniques to determine depth of peening effect. While metallography and SEM failed to provide meaningful information, x-ray diffraction showed there to be little difference between the two peening intensities and a depth of compressive stress of .007 - .017 inches (0.177 - 0.431 mm) was achieved depending upon alloy. Thus the 5A Almen intensity was chosen for use in this study.

Several organic topcoat systems were also evaluated, selected on the basis of providing greater corrosion resistance and/or coating flexibility.

Polishing of the machined test specimen surfaces was performed at NADC while any required shot peening was performed by Metal Improvement Co. at their Carlstadt, N.J. facility. All other treatments and coatings were provided by the Frankford Arsenal. Table III summarizes the various conditions tested in this phase of the program. Table IV describes the processes used in applying the various surface treatments and coatings.

Table III

R.R. Moore Rotating Beam Fatigue Screening Test Conditions

Test Condition(M)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Polished	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Peened		✓		✓								✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Alkaline Cleaned			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pickled			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Impregnated					✓							✓													
DOW 1 (EZ33 & ZE41)						✓							✓												
DOW 20 (AZ91)						✓							✓												
DOW 7							✓							✓											
HAE Light									✓							✓									✓
HAE Heavy								✓							✓				✓	✓	✓	✓	✓	✓	
DOW 17 Light											✓							✓							
DOW 17 Heavy										✓							✓								
Epoxy Primer & Lacquer																			✓						
Epoxy Primer & Topcoat																				✓					
Epoxy Seal & Topcoat																					✓				
Epoxy Primer & Polyurethane																						✓			
Chloro-Rubber & Polyurethane																							✓		

Table IV

Description of Surface Treatments and Coatings

Condition	Description
Polished	#400 wet or dry polishing paper of machined surfaces in longitudinal direction only
Shot Peened	0.125 in. (3.2 mm) dia. alloy steel burnishing balls to 5A Almen intensity and 200% coverage
Alkaline cleaned	Immersed in sodium orthosilicate solution (60 g/1 + 3 g Nacconal 40F at 30° C)
Pickled	Nitric acid (concentration = 8%) + sulfuric acid (concentration = 2%) at 28° C for 10 sec. Approx. 1 mil (.025 mm) surface magnesium material removed.
Impregnated	Polystyrene monomer - under vacuum 10 mins.; followed by application of 90 psi (6.35 kg/cm²) for 30 mins., Oakite 61B cleaning, cold water rinse, alkaline cleaning in Oakite 94, rinse, and 300° F (149° C) 3 hour cure.
Chromate Conversion Coatings (Conform to MIL-M-3171)	Type I (DOW 1):0.01 - 0.1 mil (0.00025 - 0.0025 mm) thickness
	Type I (DOW 20):0.01 - 0.1 mil (0.00025 - 0.0025 mm) thickness
	Type III (DOW 7): 0.01 - 0.1 mil (0.00025 - 0.0025 mm) thickness
Anodic Coatings (Conform to MIL-M-45202 with post-treatments)	Type IIA3 (HAE Heavy):0.8 - 1.2 mil (0.02 - 0.03 mm) thick with approximately 0.5 mil (0.012 mm) magnesium material removed for every 1 mil (0.025 mm) of coating thickness
	Type IA2 (HAE Light):0.2 - 0.4 mil (0.0051 - 0.010 mm) thick with approximately 0.5 mil (0.012 mm) magnesium material removed for every 1 mil (0.025 mm) of coating thickness
	Type IID (DOW 17 Heavy):0.8 - 1.2 mil (0.02 - 0.03 mm) thick with approximately 0.5 mil (0.012 mm) magnesium material removed for every 1 mil (0.025 mm) of coating thickness
	Type IC (DOW 17 Light):0.2 - 0.4 mil (0.0051 - 0.010 mm) thick with approximately 0.5 mil (0.012 mm) magnesium material removed for every 1 mil (0.025 mm) of coating thickness

Table IV (Continued)

Condition	Description
Organic Coatings	
A	Epoxy primer (MIL-P-23377C) + aluminum pigmented acrylic lacquer (total thickness = 5.0 mils (0.127 mm) per side)
B	Epoxy primer (MIL-P-52192B) + alkyd topcoat (total thickness = 5.5 mils (0.140 mm) per side)
C	Epoxy seal (proprietary) + chromate primer (MIL-P-8585) + alkyd topcoat (total thickness = 5.2 mils (0.132 mm) per side)
D	Epoxy primer (MIL-P-23377C) + polysulfide primer + polyurethane (MIL-P-83286B) (total thickness = 5.4 mils (0.137 mm) per side)
E	Chloro-rubber (proprietary) + chromate primer + polyurethane (MIL-P-83286B) (total thickness = 5.3 mils (0.134 mm) per side)

Table V

R.R. Moore Rotating Beam Fatigue Test Specimen Fabrication Procedure

1. Cut blanks from cast plate.
2. Cut blank to exact length and turn to 1/2-in. (12.7 mm) diameter on center.
3. Re-center with controlled depth; drill and tap both ends.
4. Rough turn center section to 0.040-in. (1.0 mm) oversize.
5. Finish turn with cuts in the order of 0.014-in. (0.35 mm) and 0.006-in. (0.15 mm), respectively.
6. Machine tapers.
7. Polish with #400 wet or dry polishing paper.

2. R.R. Moore Fatigue Test Procedure

The standard R.R. Moore rotating beam fatigue test was chosen for this phase of the program. It is ideally suited for screening testing because of its high speed and good reproducibility of test method. Cyclic frequency is about 10,000 rpm so that runouts of 2×10^7 cycles can be achieved in a little more than a day. The R.R. Moore rotating beam fatigue test specimen is shown in figure 1. Table V describes the fabrication details. Test specimens, 220 AZ91, 170 ZE41, and 170 EZ33, were machined from cast plates 3-5/8 in. wide x 12-in. long x 5/8-in. thick (92 x 302 x 15.8 mm). The plates were sectioned into specimen blanks and identified according to the scheme shown in figure 2. All specimens were machined at NADC.

The rotating beam fatigue test equipment used is shown in figures 3 and 4. Test stresses in the specimen are accurately achieved using dead weight loading which produces a constant moment along the length of the test specimen. The test load to be applied is determined from the test stress desired and the minimum specimen test section diameter (minimum cross sectional area). The greatest stress occurs at the surface of the minimum diameter and during each test cycle each point on the specimen surface sees a complete sinusoidal stress cycle ranging from the maximum cyclic test stress in tension to the maximum cyclic test stress in compression (load ratio, R, = -1 = minimum cyclic stress/maximum cyclic stress). Stresses within the specimen diminish to zero at the specimen neutral axis.

The R.R. Moore specimens tested were of two sizes with respect to test section minimum diameter and radius. Initially, 560 specimens were fabricated according to the specifications shown in figure 1, except that the minimum test section diameter was 0.387-in. (9.8 mm) with a 10-in. (254 mm) radius. This size was based on considerations of material strength, machine loading capacity, and the need for some reduced section to preclude grip failures.

Due to the low strength level of the magnesium alloys, test machine capacity provided no real limitation on design so that a maximal diameter was chosen to minimize stress concentration effects and to provide a maximum cross sectional area for best representation possible of the bulk material. However, during the first tests on the as-machined control set many specimens failed near the .480-in. (12.2 mm) taper diameter in the grip rather than at the minimum test section diameter. These failures occurred primarily in the low stress - high cyclic life regime and were attributed to fretting fatigue.

Some minor fretting damage at the grip taper is normal for this test due to the action of dynamic strains in the contact points at the grip taper, however, the fretting between the magnesium and steel surfaces is much more severe than normally experienced in tests of other materials. This problem necessitated redesign of the specimen for a smaller test section diameter that would provide consistently valid high cycle failures. Analysis of the data indicated a close design relationship between fretting damage susceptibility, test load level, and test machine minimum loading limitations. This led to the conclusion that only a very small range of values around 0.300-in. diameter would yield satisfactory testing of magnesium rotating beam specimens. The redesigned specimen shown in figure 1 was decided upon having a minimum test section diameter of 0.305-in. (7.7 mm) with a 5-1/4-in. (133 mm) radius. Typical finished specimens are shown in figure 30.

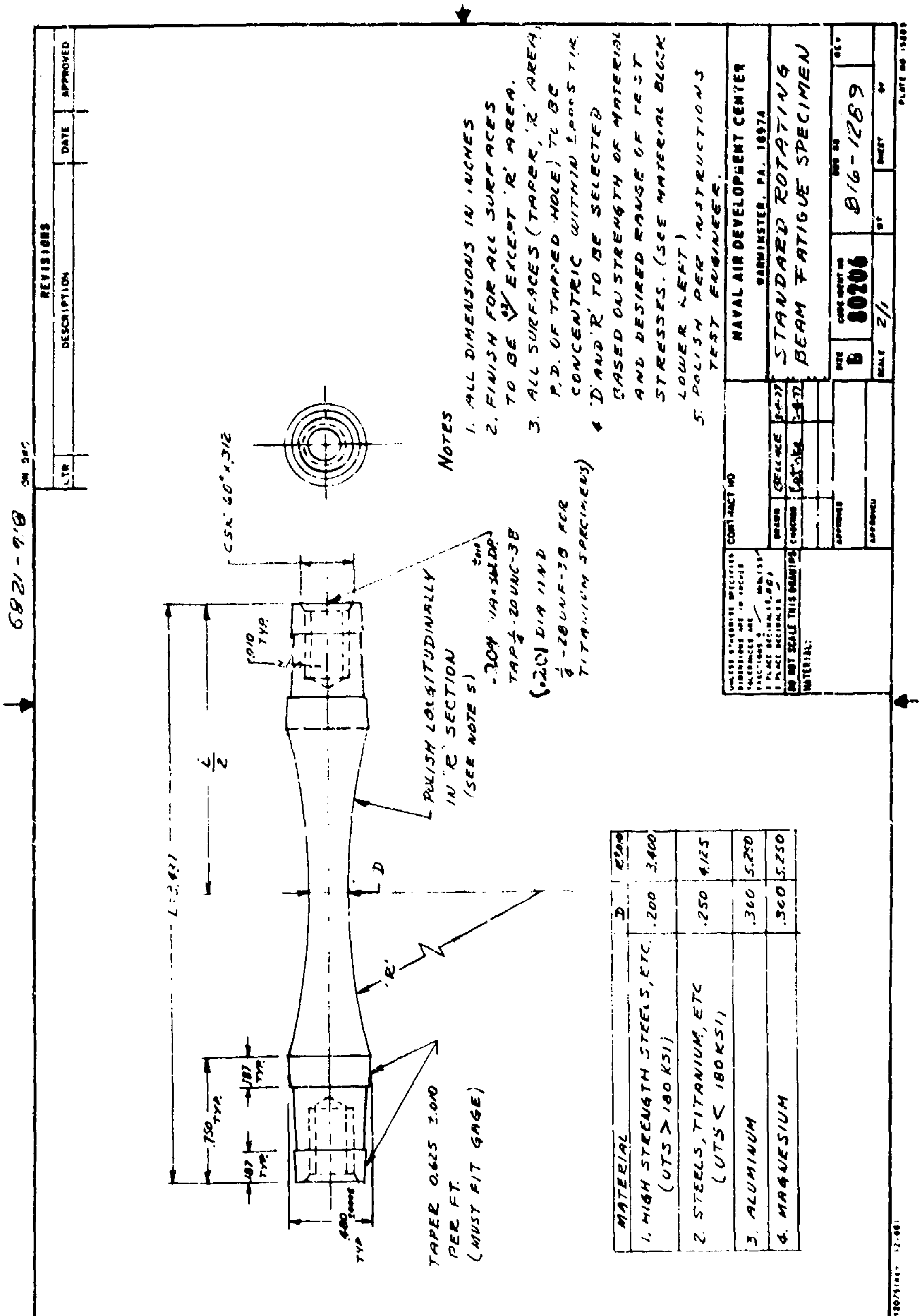


Figure 1 - R. R. Moore Rotating Beam Fatigue Test Specimen

All specimens were numbered; each specimen number determined by the alloy number, plate number, and location in the plate from which it was taken. Specimens taken from each plate were numbered 1 to 16 depending upon their location with respect to the plate numbered end: The #1 specimen being from the numbered end.

Example:

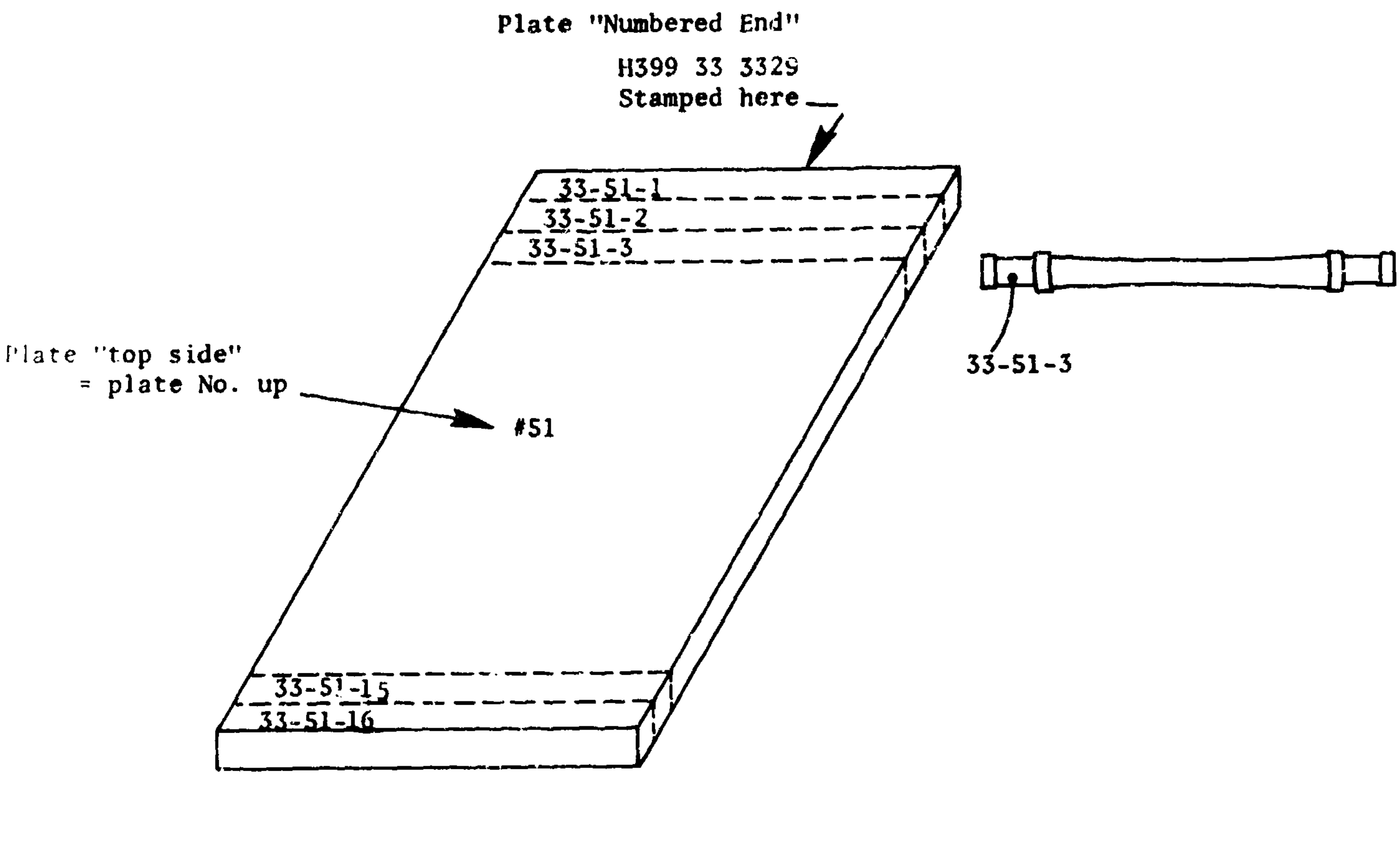


Figure 2. Magnesium Cast Plate Sectioning for R. R. Moore Specimens; and Identification Scheme

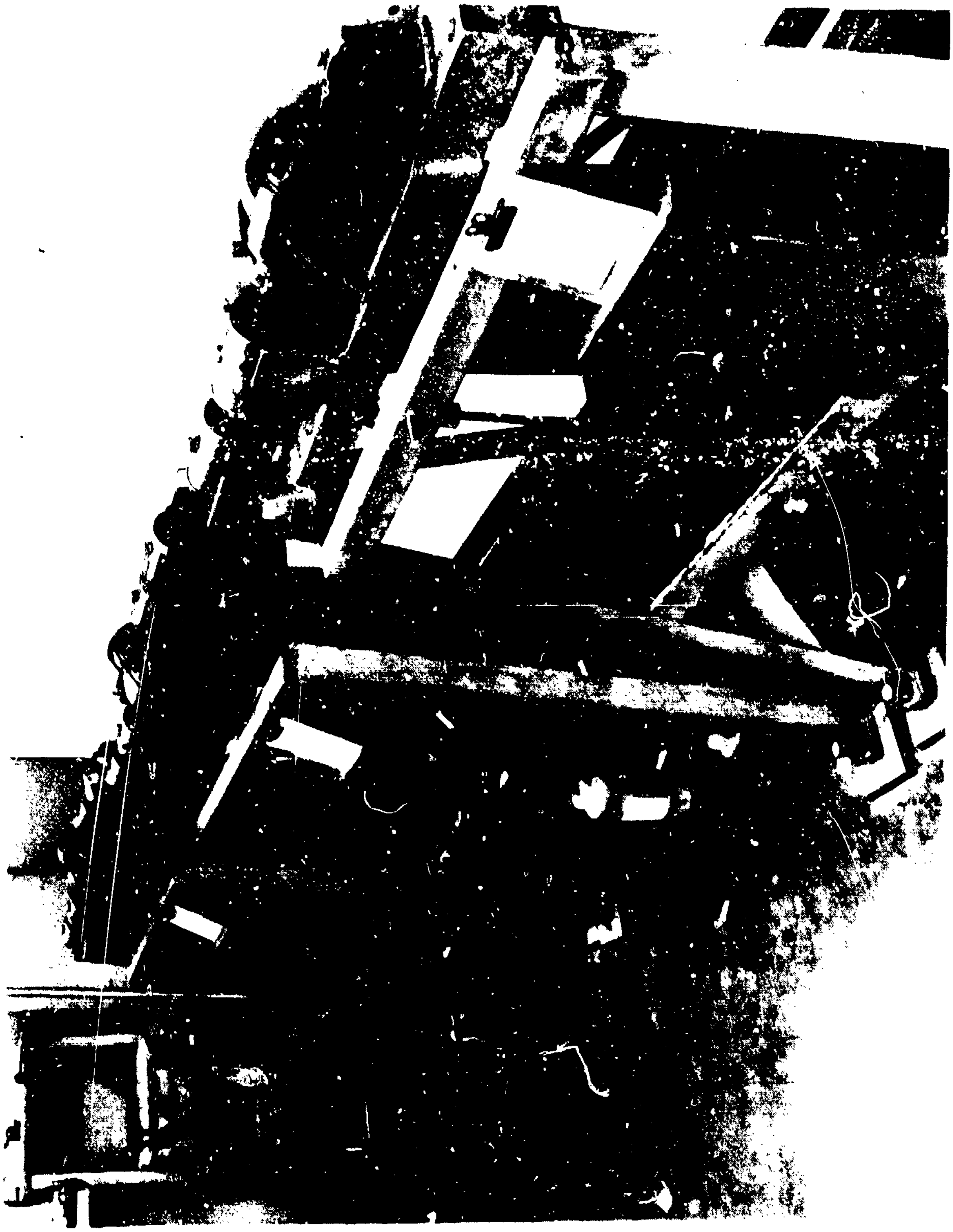


Figure 3 - R. R. Moore Rotating Beam Fatigue Test Facility

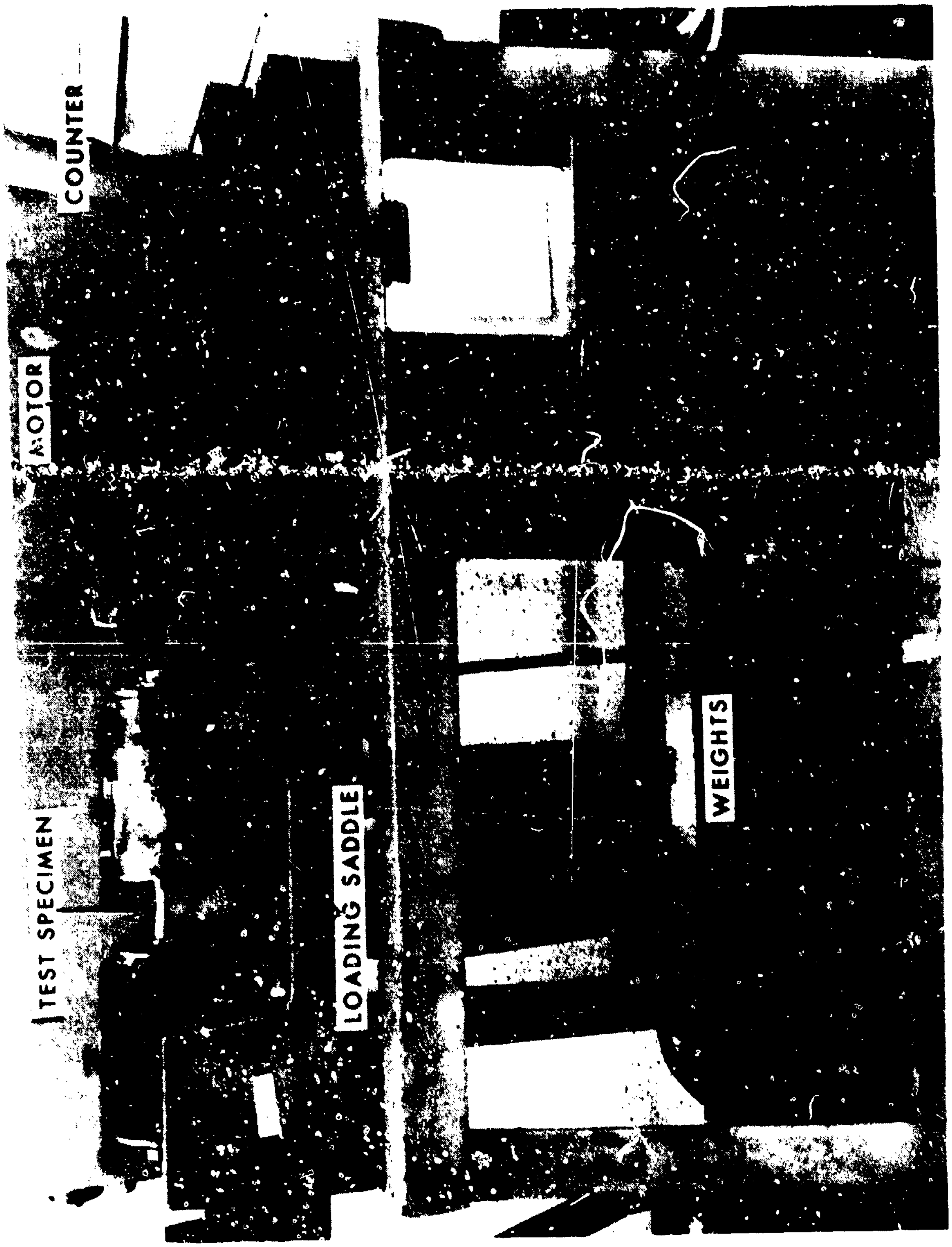


Figure 4 - Close-Up of R. R. Moore Rotating Beam Fatigue Test Machine

A total of 286 specimens were reduced in diameter from 0.387-in. (9.8 mm) to 0.305-in. (7.7 mm) for the purpose of testing in the low stress - high cycle area of the stress - life curve where susceptibility to fretting fatigue taper failure is greatest. The remainder of the specimens were left at 0.387-in. (9.8 mm) test section diameter for testing in the high stress - low cycle regime. From Peterson, reference (6), the difference in theoretical stress concentration factor between the two specimen designs was considered negligible since it was only in the order of .1 - .2%.

Later in the testing program 60 extra R.R. Moore specimens (20 from each alloy) were machined to the new design requirements (0.305-in. (7.7 mm) diameter) for test conditions M24 and M25 (HAE light and heavy coatings without prior shot peening or pickling).

A computer program was utilized to produce a random selection of specimens for final disposition into the various test groups (M1 through M23 in table III). All specimens were subsequently processed (peened, pretreated, coated, etc.) in two lots according to whether or not they were 0.387-in. (9.8 mm) or 0.305-in. (7.7 mm) in diameter. The four 0.387-in. (9.8 mm) diameter high stress - low cycle specimens from each group were processed first followed by the five or six 0.305-in. (7.7 mm) diameter low stress - high cycle specimens from each group.

For all test conditions, stress - cyclic life (S-N) curves were generated - primarily to provide comparison of the effects of the various surface treatments on the fatigue strength of the substrate magnesium alloy material. Nine specimens were utilized to generate each S-N curve. Tests were terminated if no failure occurred after 2 x 10^7 cycles. Test stresses were based on specimen dimensions in the as-polished condition prior to any coating application or pretreatment processing.

For the last 60 specimens dimensional changes accompanying processing of each test condition were monitored. These are shown in table VI for the three alloys with HAE light and heavy coatings.

Tests of As-Cast Surfaces

1. Test Conditions

In this phase of the program the intent was to evaluate the best coating system possibilities as applied to as-cast surfaces of the magnesium alloys. Since ultimate utilization would be on cast helicopter housings this was a more realistic test of the coatings. Closer simulation of the actual end use environment was provided in several of the tests by exposure of specimens to high humidity or salt fog prior to fatigue testing.

The corrosion preventive systems to be used in this phase were selected based on the results of the R.R. Moore fatigue screening tests as well as the results of the Frankford Arsenal corrosion tests, reference (7). Table VII summarizes the conditions tested in this phase of the program. The coatings were applied utilizing the same processes used in the R.R. Moore tests. Specimens in test conditions 6, 7, and 8 (table VII) were exposed to 7 day/5% salt fog environment conforming to ASTM-B-117 before fatigue testing. Likewise, specimens

Table VI

Dimensional Changes Due to HAE Anodic Coatings

- from test conditions M24 and M25 with coatings applied without prior acid pickling
- from 0.305-in. (7.7 mm) diameter test specimens
- median values

Coating	AZ91 Δ dia. mils (mm)	AZ91 Coating Thick. (1) mils (mm)	ZE41 Δ dia. mils (mm)	ZE41 Coating Thick. (1) mils (mm)	EZ33 Δ dia. mils (mm)	EZ33 Coating Thick. (1) mils (mm)
HAE Heavy	+0.8 (0.020)	0.8 (0.020)	+1.5 (0.038)	1.5 (0.038)	+1.5 (0.038)	1.5 (0.038)
HAE Light	+0.5 (0.013)	0.5 (0.013)	+0.3 (0.008)	0.3 (0.008)	+0.2 (0.005)	0.2 (0.005)

(1) Assuming 0.5 mil (0.012 mm) magnesium material removed for every 1 mil (0.025 mm) of coating thickness.

Table VII

Test Conditions for the Sheet Flexure Fatigue Tests of As-Cast Surfaces

Test Condition (C)	1	2	3	4	5	6	7	8	9	10	11	12	13
As Cast	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Alkaline Cleaned		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
DOW 7			✓			✓			✓				
DOW 17 Heavy				✓			✓			✓			✓
HAE Heavy					✓			✓			✓	✓	
Salt Fog						✓	✓	✓					
High Humidity									✓	✓	✓		
1/8-in. Thick	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
1/4-in. Thick												✓	✓

in test conditions 9, 10, and 11 were exposed to 7 day/high humidity (distilled water fog) environment before fatigue testing. All environmental exposures were performed at the Frankford Arsenal.

2. Sheet Flexure Fatigue Test Procedure

The standard sheet flexure fatigue test was used in this phase. This test utilizes flat specimens in a repeated bending cyclic loading mode and was, therefore, very suitable for tests of as-cast surfaces. Frequency of the test machine is 1730 cpm and thus a runout of 10^7 cycles required four days of continuous operation. In order to control testing time and expense, only the AZ91 and ZE41 alloys were used in this phase. AZ91 because it is the current alloy used in the helicopter housings to which the new alloys must be compared and ZE41 because it showed the best fatigue and corrosion resistant performance in the previous tests. In the exposure tests, only the AZ91 alloy was used in order to further control the magnitude of the program and also because the ZE41 alloy had shown to be least susceptible to corrosion degradation in the Frankford Arsenal corrosion test program.

Two specimen sizes were tested - 1/8-in. (3.2 mm) and 1/4-in. (6.4 mm) thick - as shown in figures 5a and 5b. Most tests were run with the 1/8-in. (3.2 mm) thick specimens because a greater number of test machines were available but some 1/4-in. (5.4 mm) thick tests were desired because this thickness is more representative of the actual housings. All specimens were prepared at NADC from 1/4-in. (6.4 mm) thick cast plates supplied by the Frankford Arsenal. The 1/8-in. (3.2 mm) thick specimens required approximately 1/8-in. (3.2 mm) material removal which was accomplished by grinding from one side of the plate only. Care was exercised to protect the final as-cast test surface from receiving any processing or fabrication abuse. Fabrication of the 1/8-in. (3.2 mm) and 1/4-in. (6.4 mm) thick specimens was according to the procedures listed in table VIII. Typical finished specimens are shown in figures 45 and 46. As with the R. R. Moore tests, the final disposition of specimens into the various test groups (C1 through C13 in Table VII) was made on a random selection basis.

The small, 1/8-in. (3.2 mm) thick, specimens were run in 40 lb. (178 kN) capacity sheet flexure fatigue test machines while the larger, 1/4-in. (6.4 mm) thick, specimens were run in a 150 lb. (668 kN) capacity sheet flexure fatigue test machine. This equipment is shown in figures 6, 7, and 8. The specimens are designed so that the center straight sided tapered portion represents an area of constant stress - that is, the moment arm and cross sectional area increase proportionately as the distance from the point of load application so that stress remains constant. Constant deflection is maintained by the test machine rotating eccentric for the duration of the test.

S-N curves were generated for all test conditions, about nine specimens per curve. The cyclic frequency was 1730 cpm and tests were terminated if no failure occurred after 10^7 cycles. Test stresses were based on dimensions of the as-cast specimens prior to applying any surface conditioning or coatings. A load ratio of R = .1 was used to ensure that, for the 1/8-in. (3.2 mm) thick specimens, failure initiated at the as cast surface rather than at the machined bottom surface.

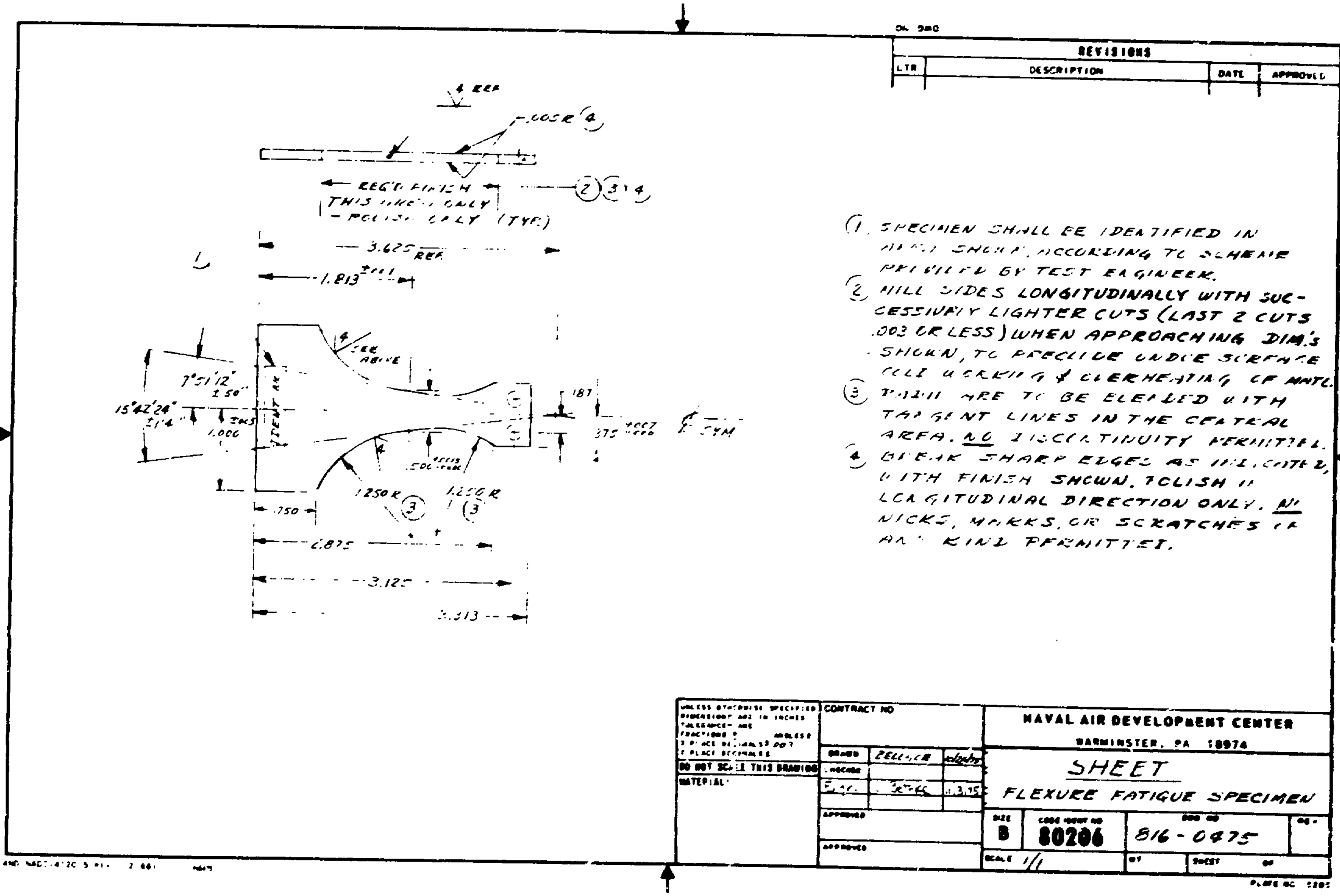


Figure 5(a) - 1/8-In. (3.2mm) Thick Sheet Flexure Fatigue Test Specimen

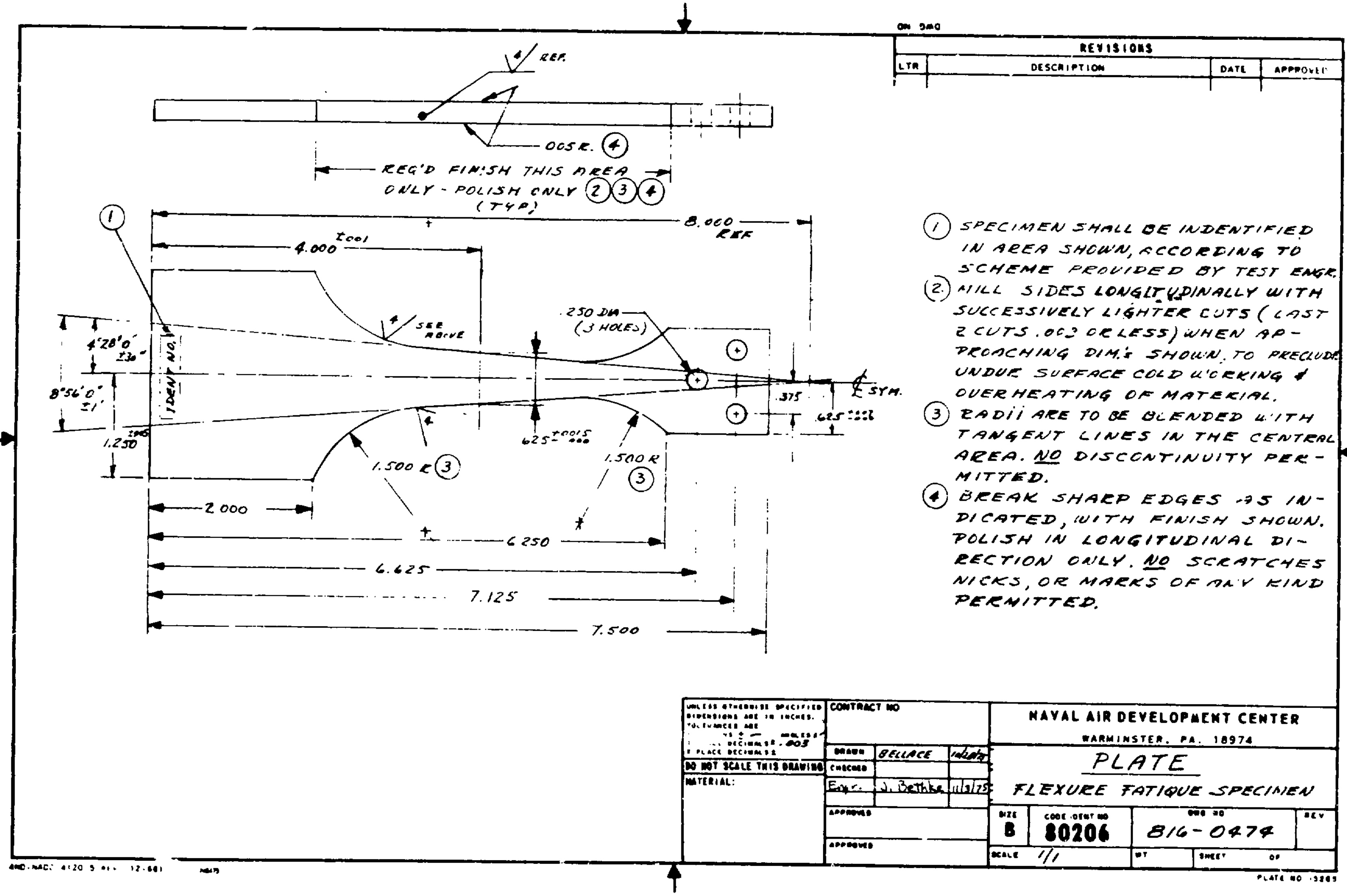


Figure 5(b) - 1/4-In. (6.4mm) Thick Sheet Flexure Fatigue Test Specimen

Table VIII

Sheet Flexure Fatigue Specimen Fabrication Procedure

1/8-in. (3.2 mm) Thick Specimens

1. Surface grind 4-1/4 in. x 7-1/4 in. x 1/4 in. thick (108 mm x 184 mm x 6.4 mm thick) cast plate to 1/8-in. (3.2 mm) final thickness. All material to be removed from bottom surface.

2. Lay out plate for four test specimens and identify.

3. Cut plate into four specimen blanks.

4. Cut contour using engraving machine and 4X pattern:

   a) rough cut specimen from blank to 0.004-in. (0.1 mm) oversize; stepping down through thickness in 0.005 to 0.010-in. (0.125 - 0.250 mm) increments.

   b) finish cut to final dimensions in two passes.

5. Drill and deburr end holes.

6. Break edges and polish sides in longitudinal direction using #500 emery paper.

1/4-in. (6.4 mm) Thick Specimens

1. Same as for 1/8-in. (3.2 mm) thick specimens except:

   a) no surface grinding of the 5-1/4-in. x 8-in. x 1/4-in. thick (133 mm x 203 mm x 6.4 mm thick) cast plate is required,

   b) lay out plate for two specimens,

   c) use 2X pattern.

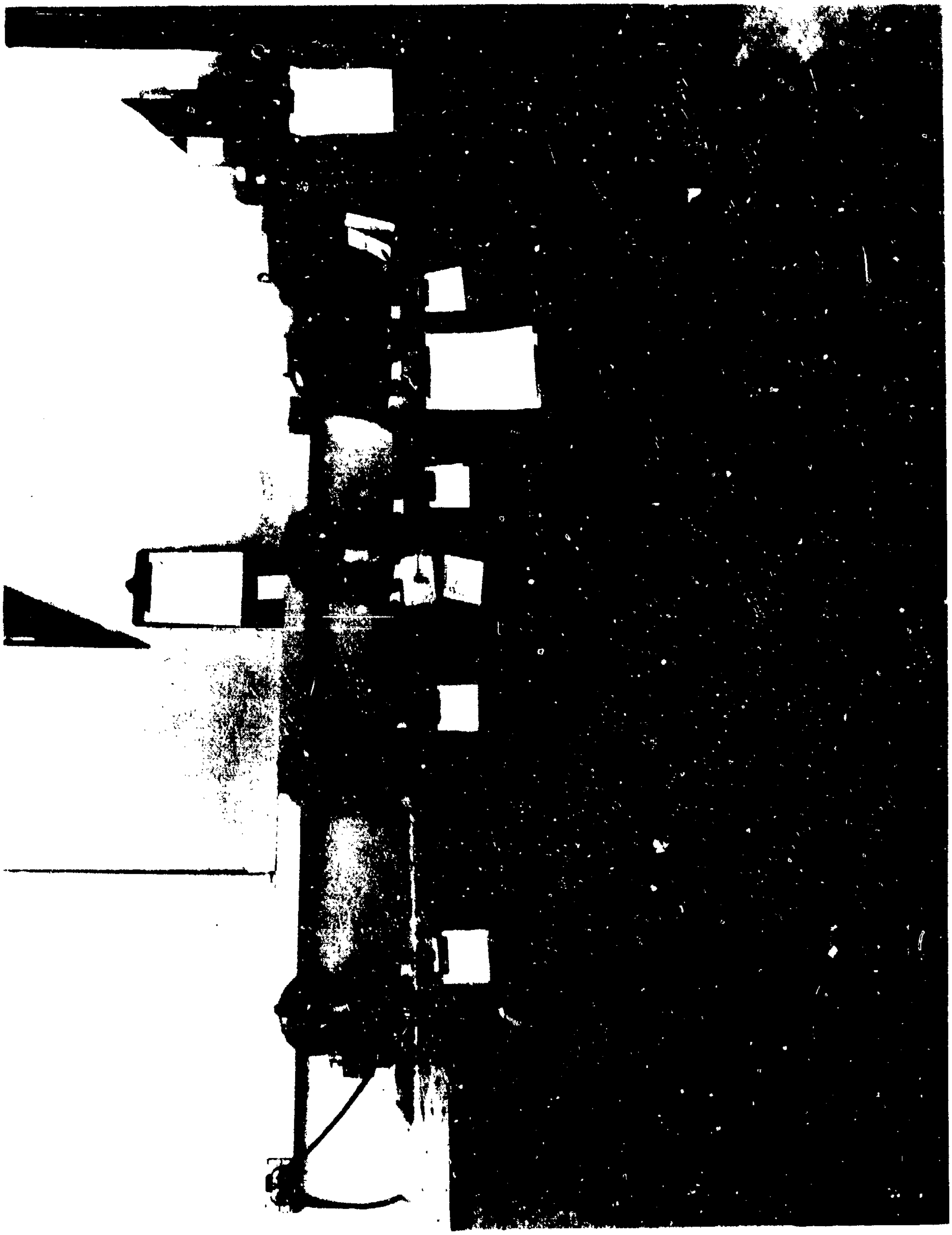


Figure 6 - Sheet Flexure Fatigue Test Facility

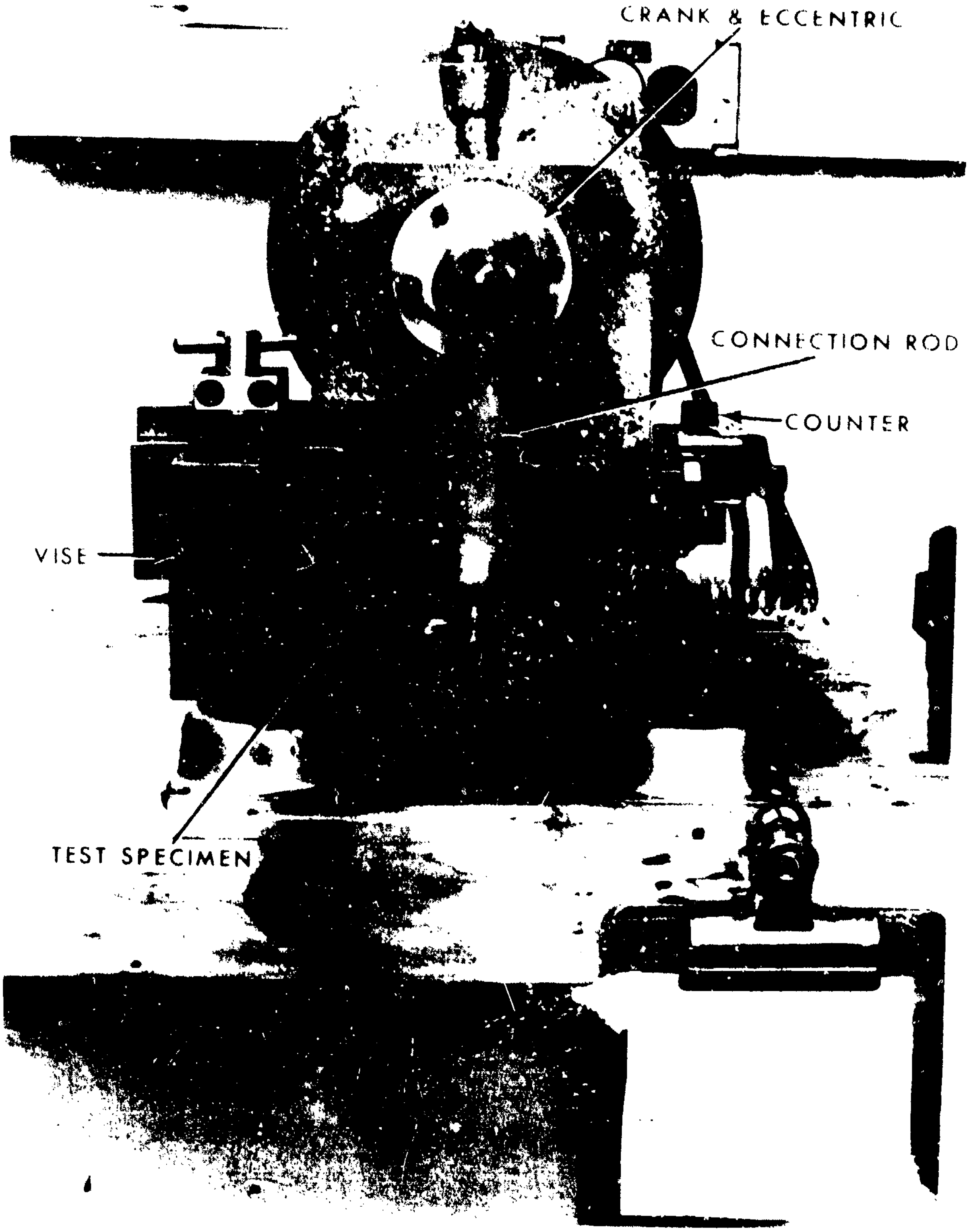


Figure 7 - Close-Up of 40 Lb. (178 N) Capacity Sheet Flexure Test Machine Showing Test in Progress

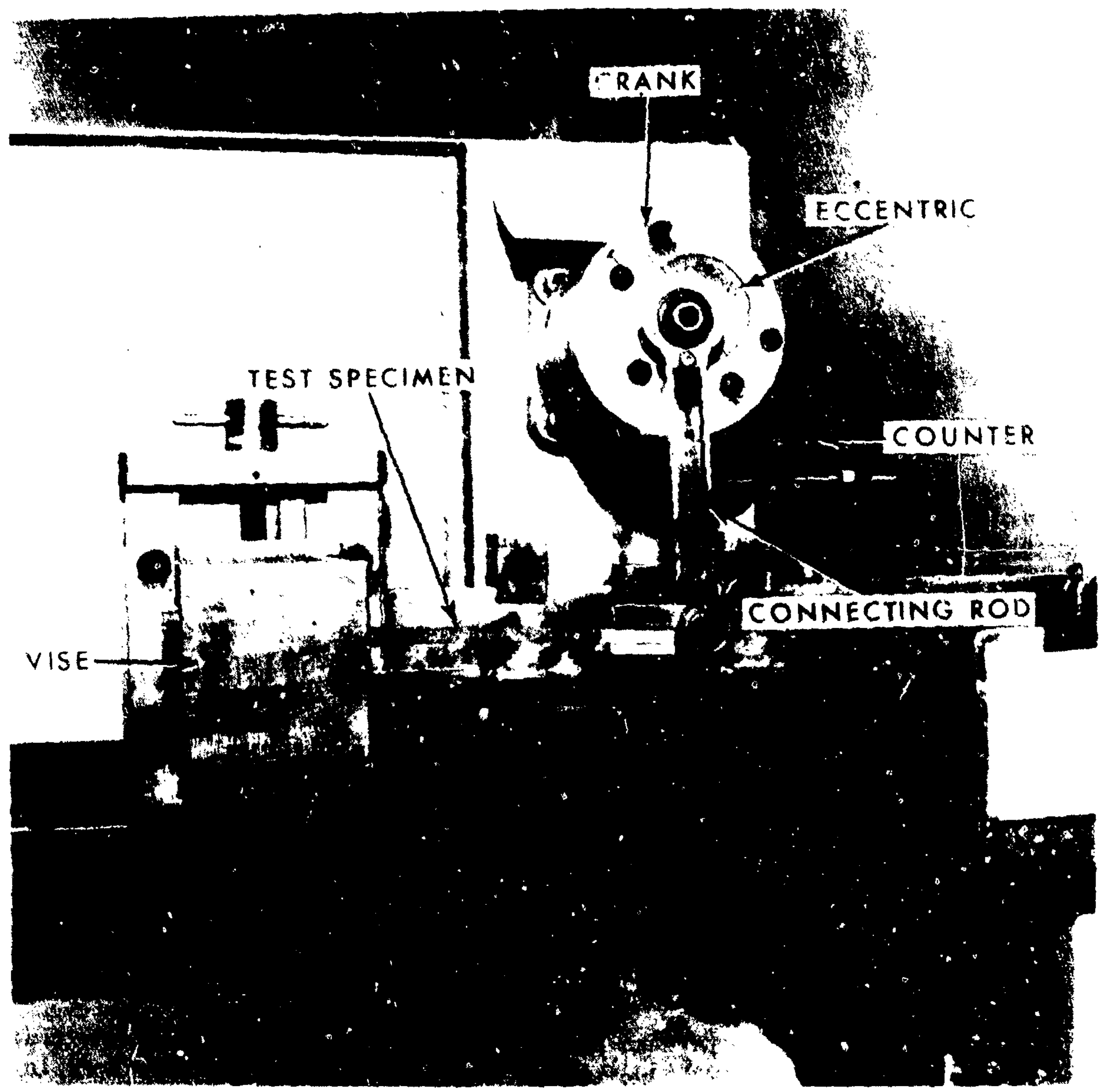


Figure 8 - Close-Up of 150 Lb. (668 N) Capacity Sheet Flexure Fatigue Test Machine

RESULTS OF TESTS

R.R. Moore Screening Tests

Results of the R.R. Moore specimen tests are presented in figures 9 - 29 and are summarized in table IX. Typical failures for the large and small sized R.R. Moore specimens and representative fracture surfaces for low and high cyclic life are shown in figures 30 and 31, respectively. Each S-N figure shows all the valid data points obtained for one test condition (test conditions as per table III) for the alloys tested at that condition. Faired (sketched) stress - life (S-N) curves were drawn through the data points for each alloy and the fatigue strength at 2 x 10^7 cycles estimated for each.

For the ZE41 and EZ33 alloys, and in general the AZ91 alloy, the complete S-N curve is defined by two straight lines intersecting at the fatigue limit stress of the alloy for the particular test condition. Three test conditions of AZ91 alloy (M1, M24, and M25 - the only test conditions in which specimens were neither peened nor pickled) do not fit this description but rather are better described by a smooth parabolic curve. Failure does not occur below the fatigue limit stress. In actuality, this horizontal straight line portion of the S-N curve is not a line but an area of finite stress width representing a scatter band resulting from the statistical nature of the fatigue phenomena (reflecting the intrinsic variability of fatigue life data as well as any material, processing, and testing variables that have not been controlled or balanced in the testing procedures). Information about the statistical width of this band was not determined for these tests because of the great number of specimens that would be required to do so. The slopes of the upper straight line portion of the S-N curves generally fell into two groups for each alloy according to whether or not specimens were shot peened. These are as follows:

Condition	Slope, $\frac{\text{ksi}}{\text{log cyclic life}}\left(\frac{\text{MPa}}{\text{log cyclic life}}\right)$		
	AZ91	ZE41	EZ33
Peened	4.8 ± .6 (33.1 ± 4.5)	6.2 ± .8 (42.7 ± 5.5)	4.0 ± .4 (27.6 ± 2.8)
Unpeened	6.6 ± .8 (45.5 ± 5.5)	8.2 ± 1.0 (56.5 ± 6.9)	5.2 ± .4 (55.8 ± 2.8)

This is consistent with expectations since treatments which affect the substrate surface affect the crack nucleation stage of fatigue and therefore are most influential in the low stress - high cyclic life tests; hence the observed effect of peening to decrease the stress - cyclic life slope.

The need for using specimens of two different diameters was described earlier. While the effect of size in fatigue is real, the difference between the two specimen sizes utilized in this program was considered to be small enough so as to be

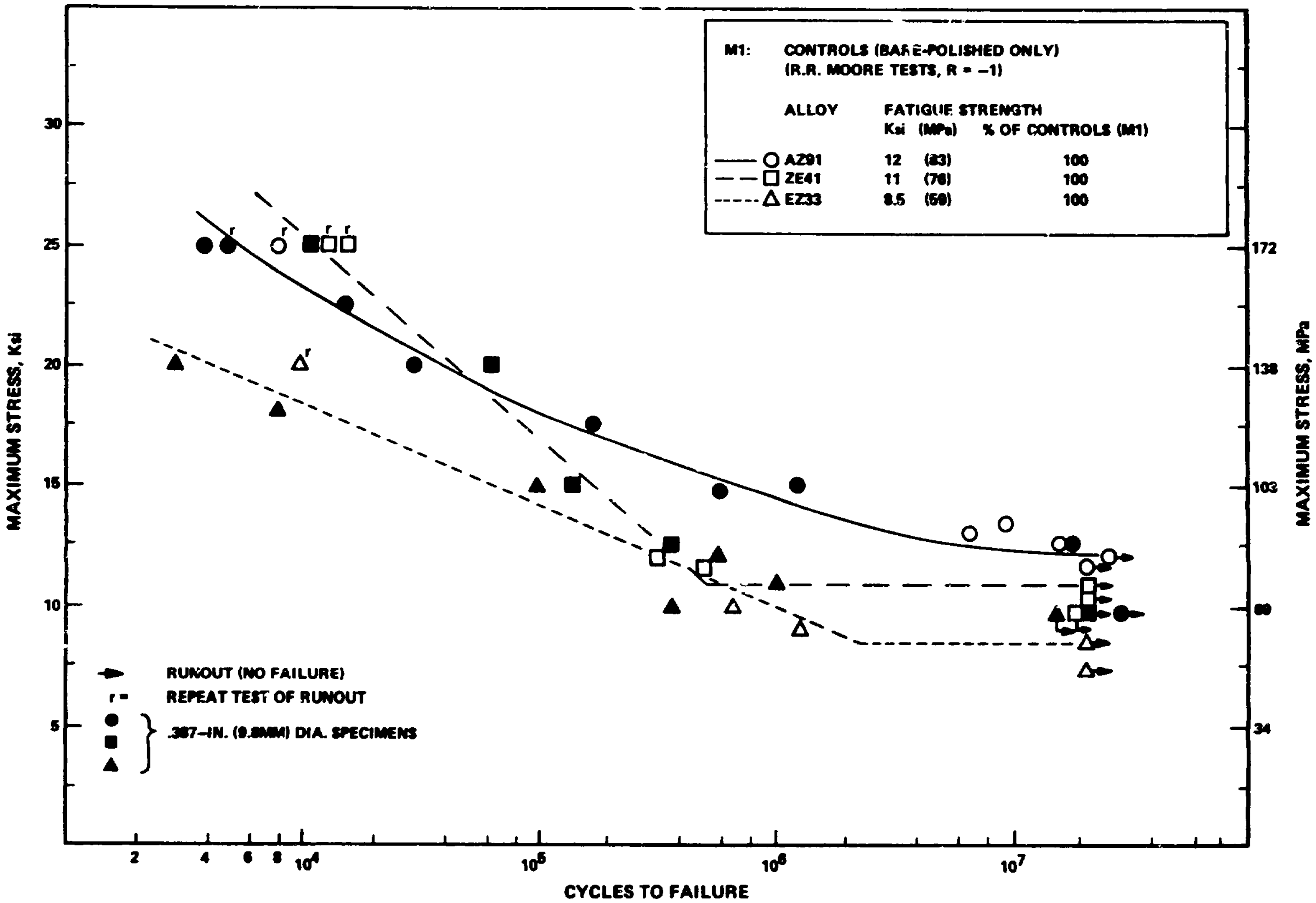


Figure 9 - R. R. Moore Fatigue Test S-N Curves

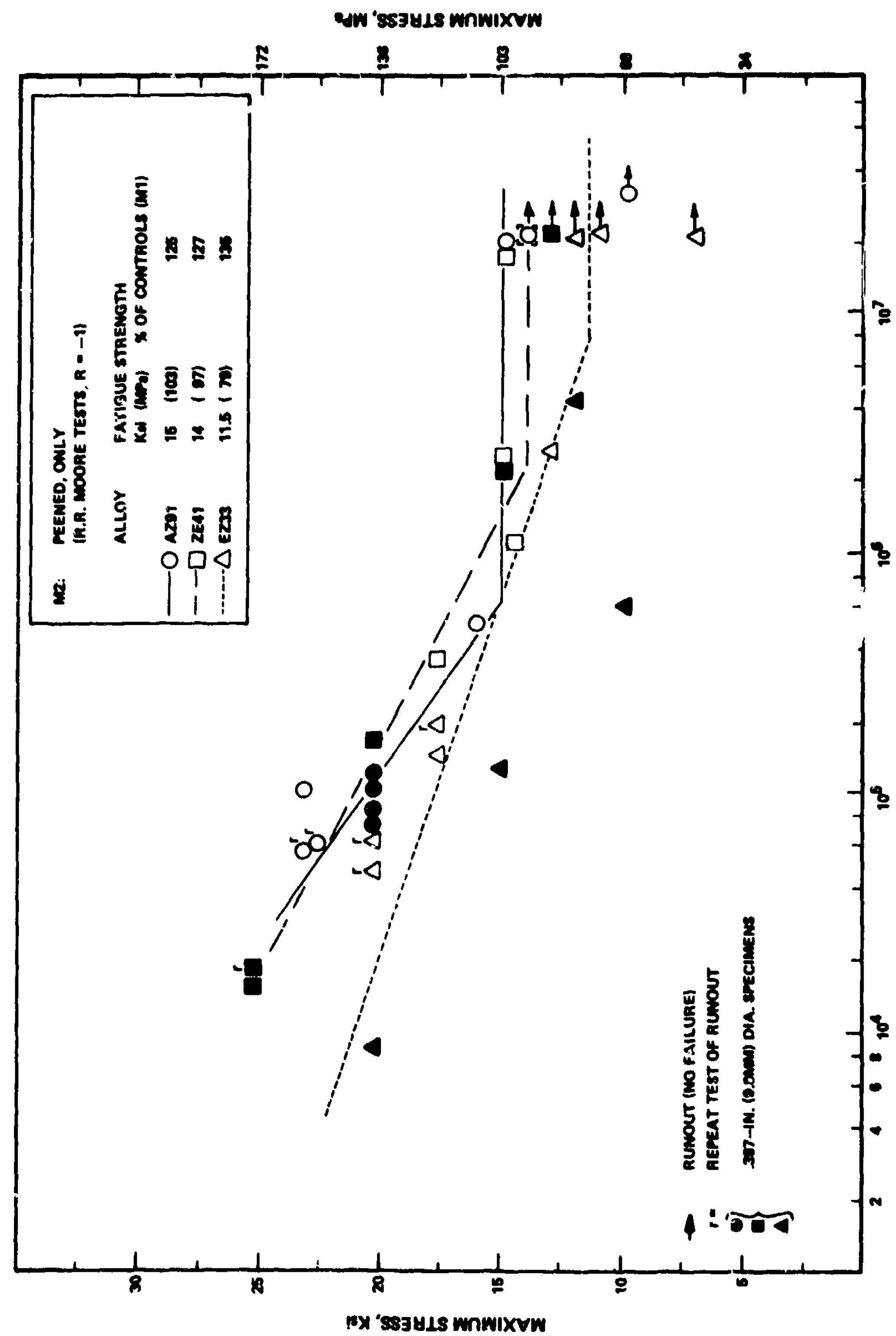


Figure 10 - R. R. Moore Fatigue Test S-N Curves

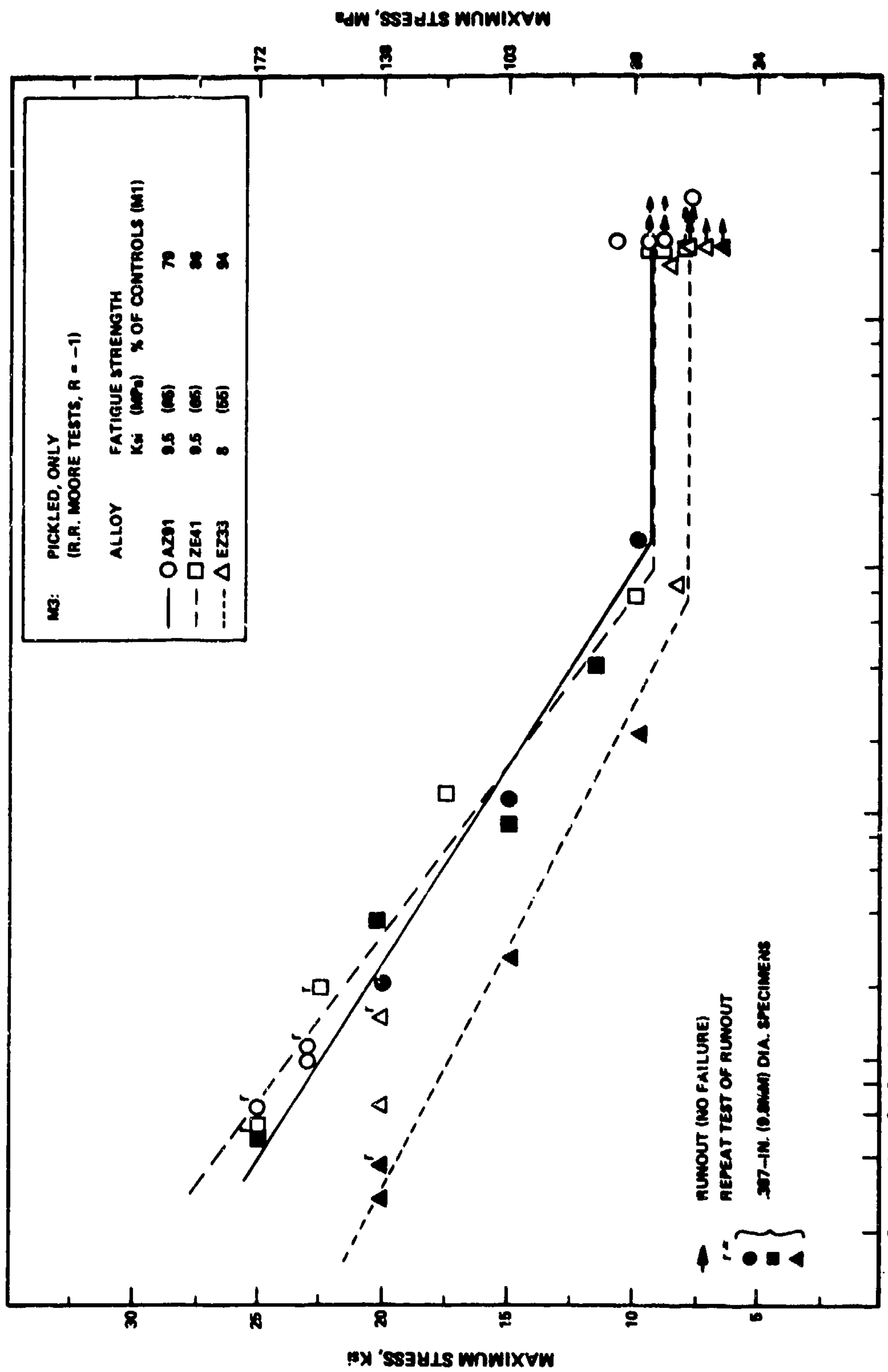


Figure 11 - R. R. Moore Fatigue Test S-N Curves

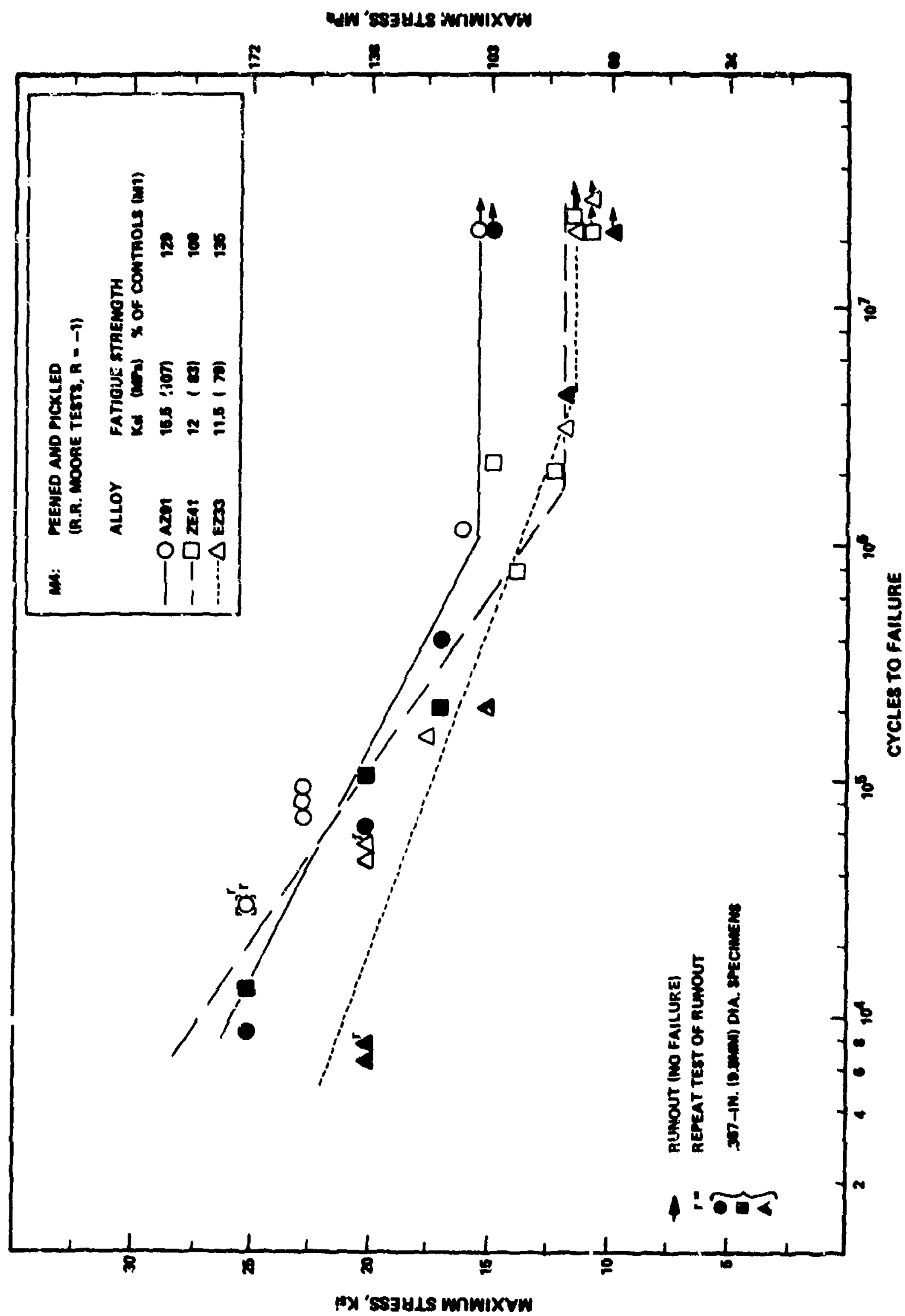


Figure 12 - R. R. Moore Fatigue Test S-N Curves

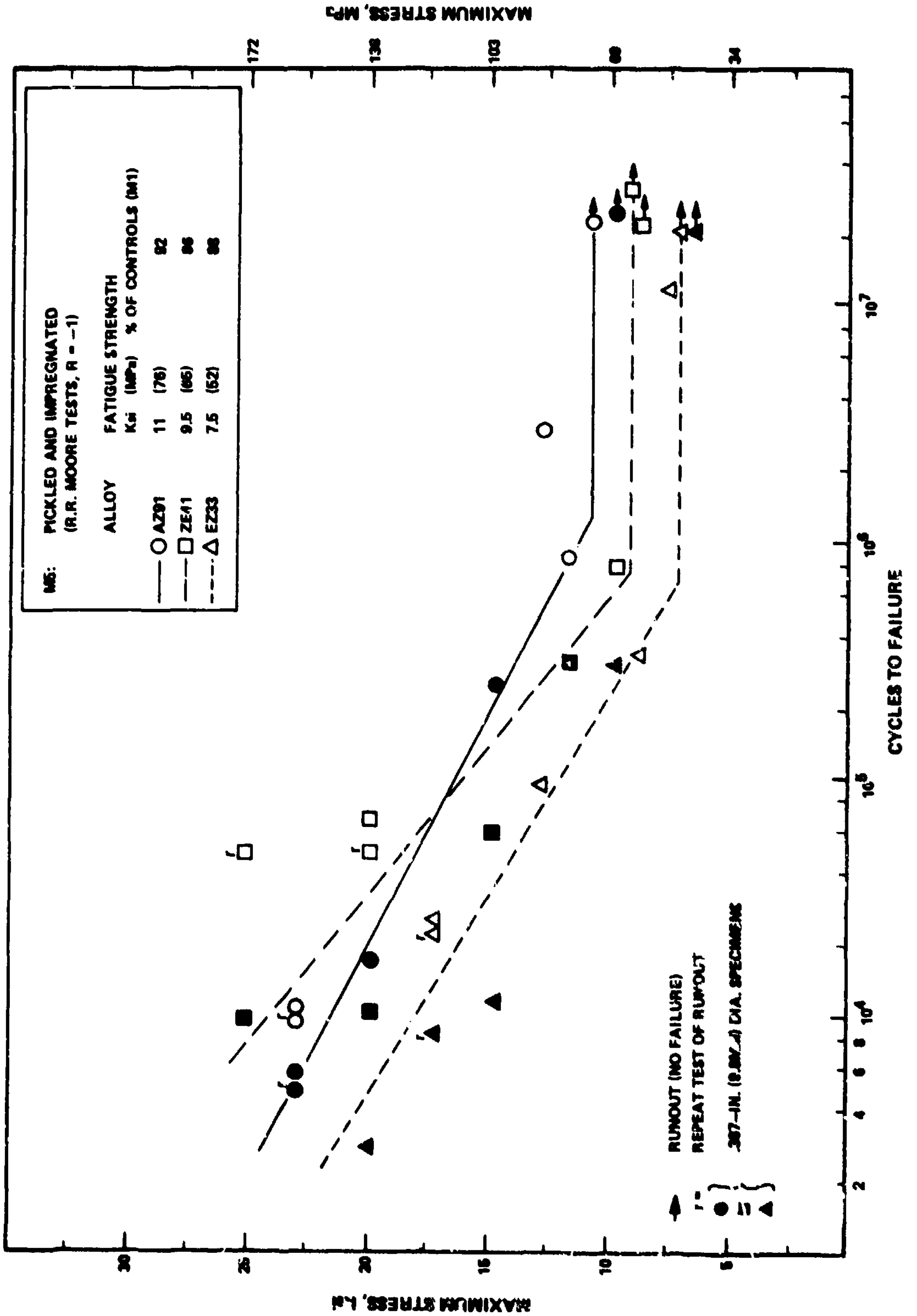


Figure 13 - R. R. Moore Fatigue Test S-N Curves

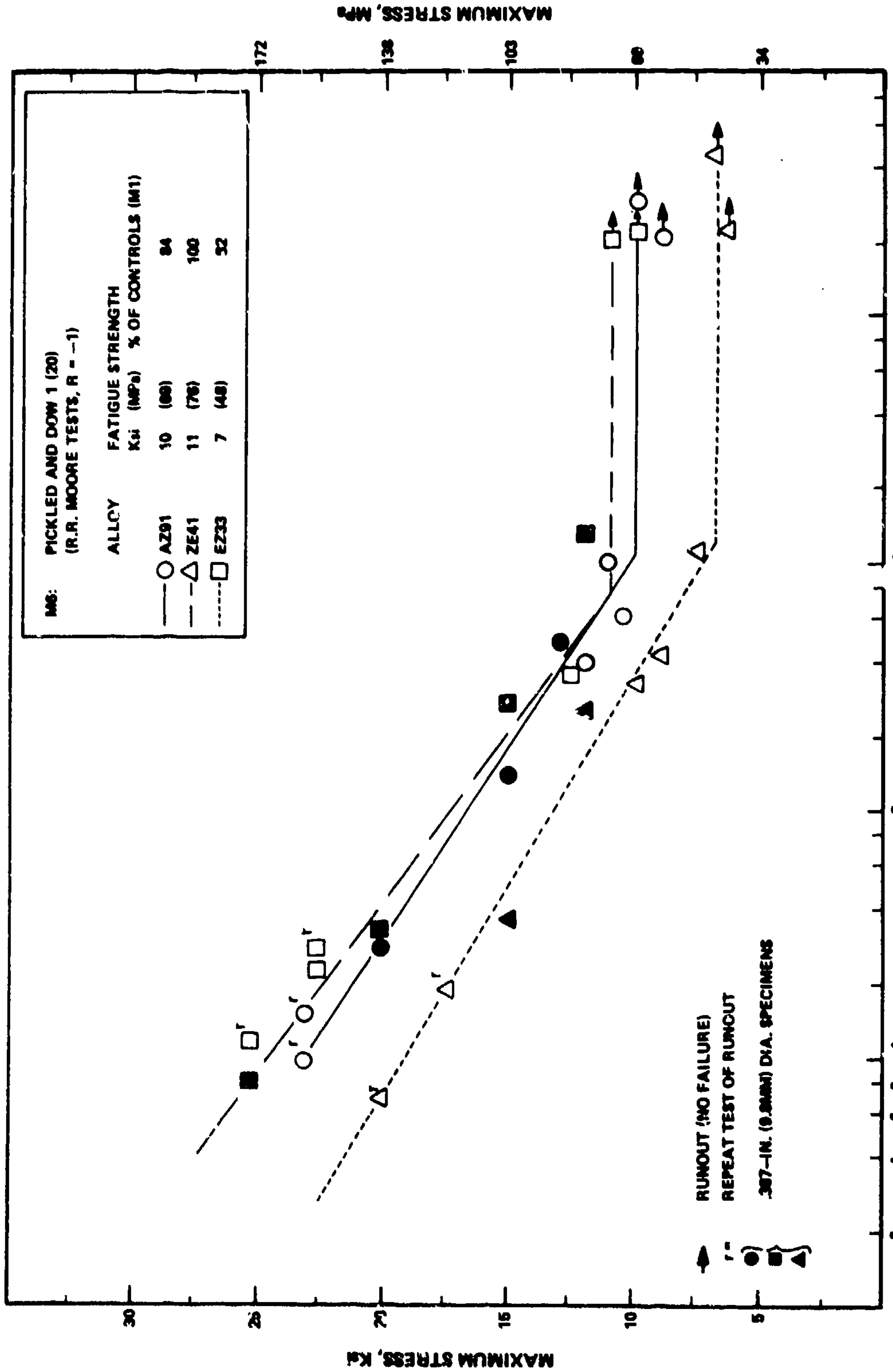


Figure 14 - R. R. Moore Fatigue Test S-N Curves

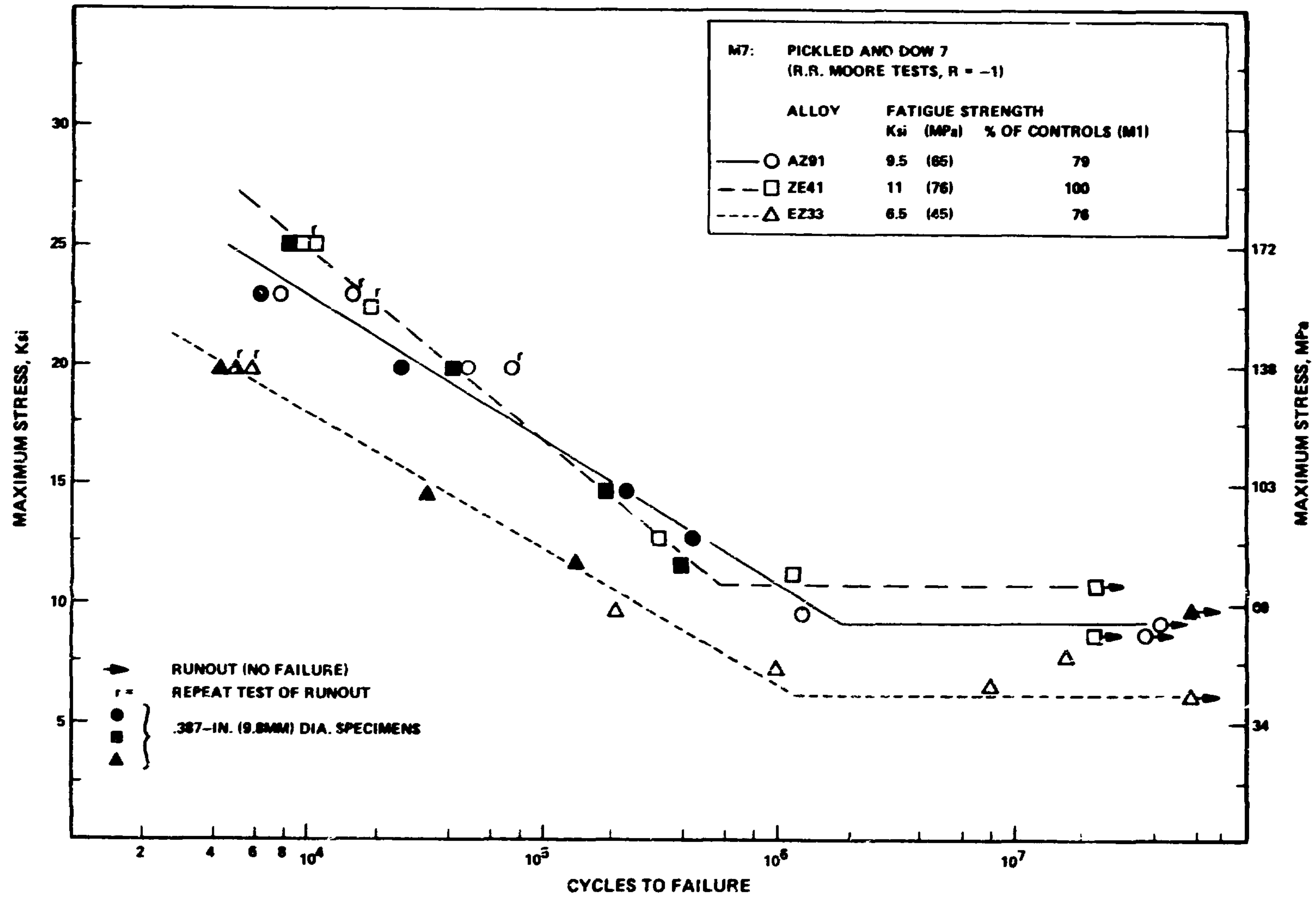


Figure 15 - R. R. Moore Fatigue Test S-N Curves

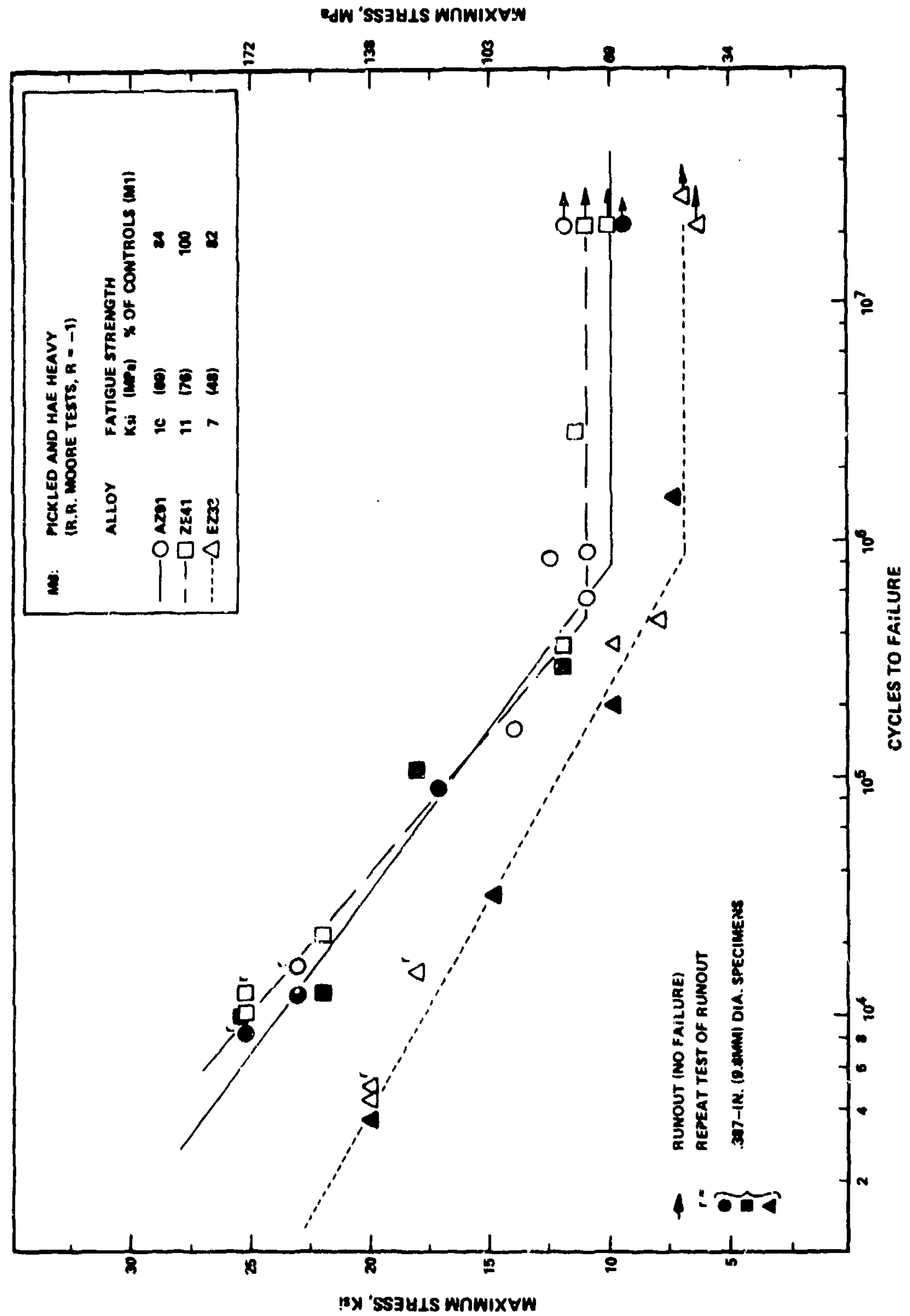


Figure 16 - R. R. Moore Fatigue Test S-N Curves

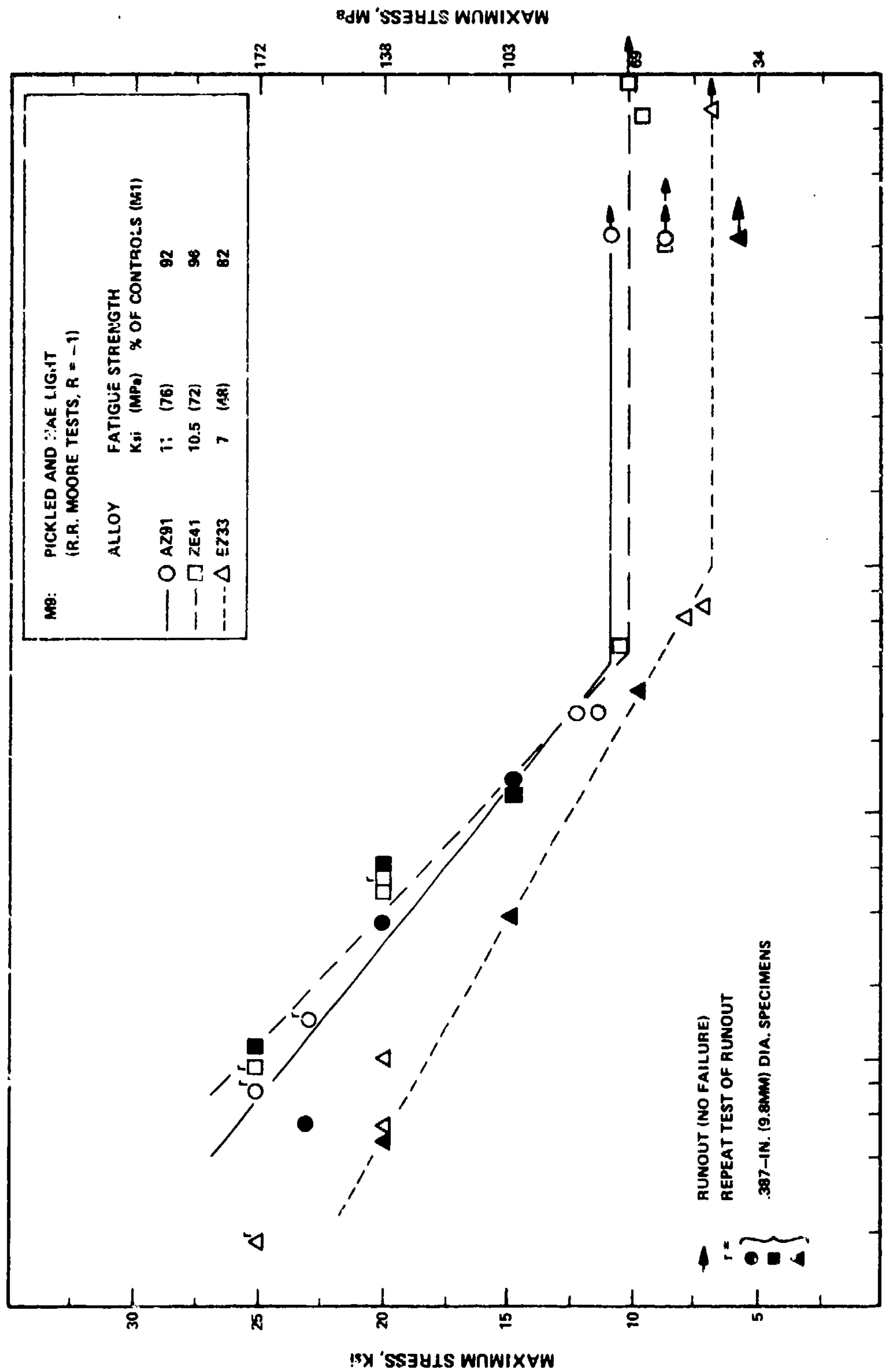


Figure 17 - R. R. Moore Fatigue Test S-N Curves

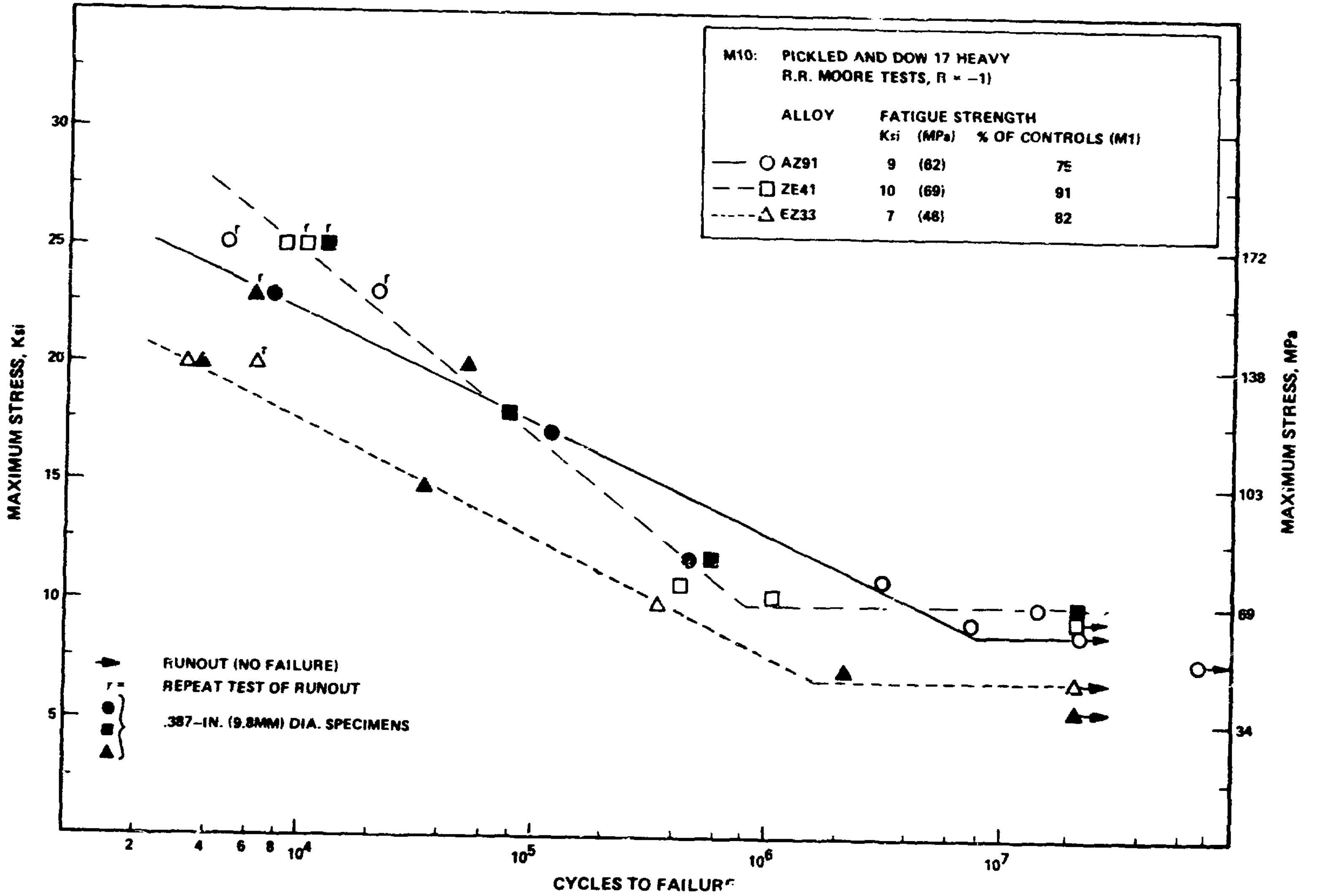


Figure 18 - R. R. Moore Fatigue Test S-N Curves

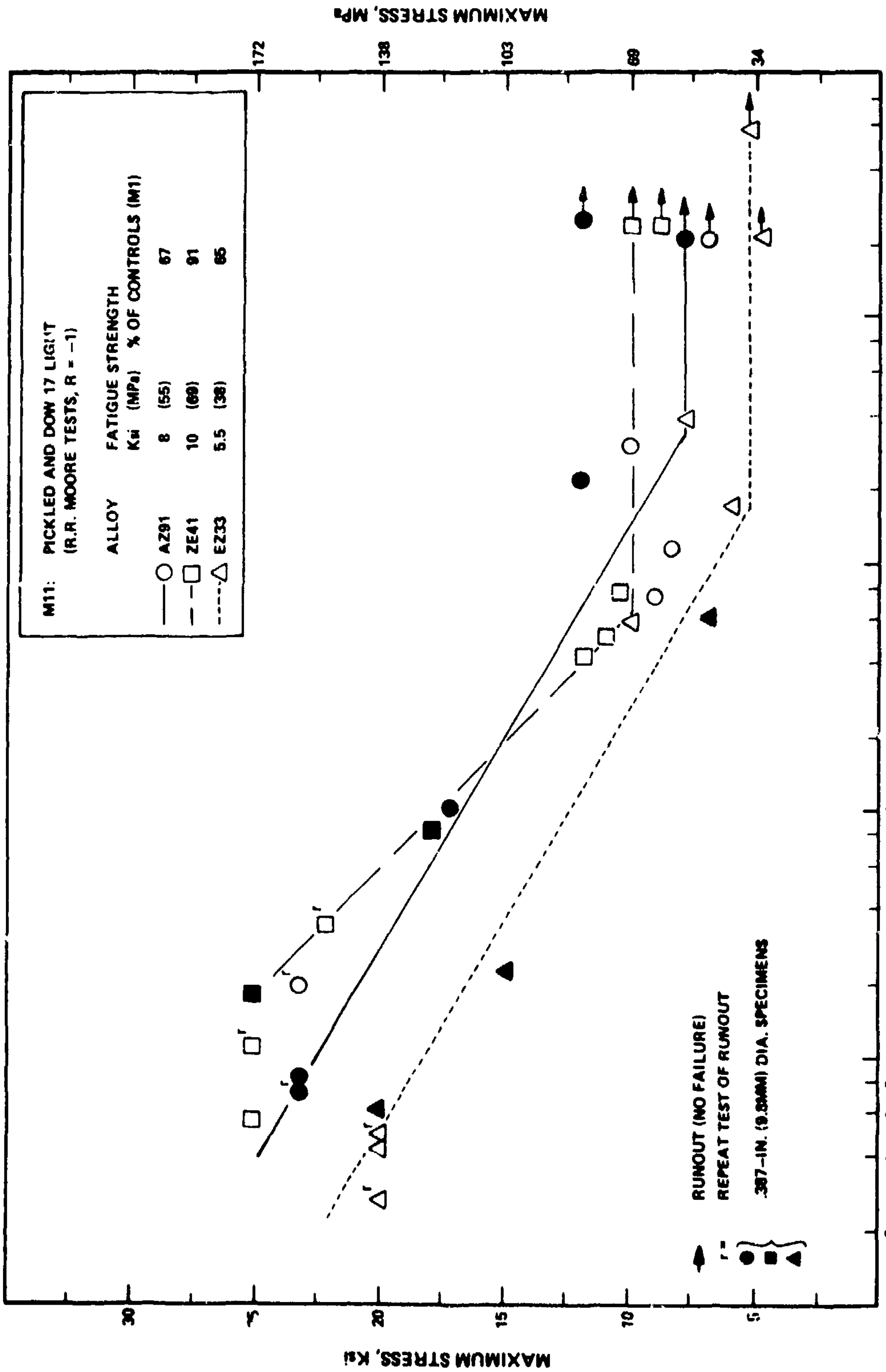


Figure 19 - R. R. Moore Fatigue Test S-N Curves

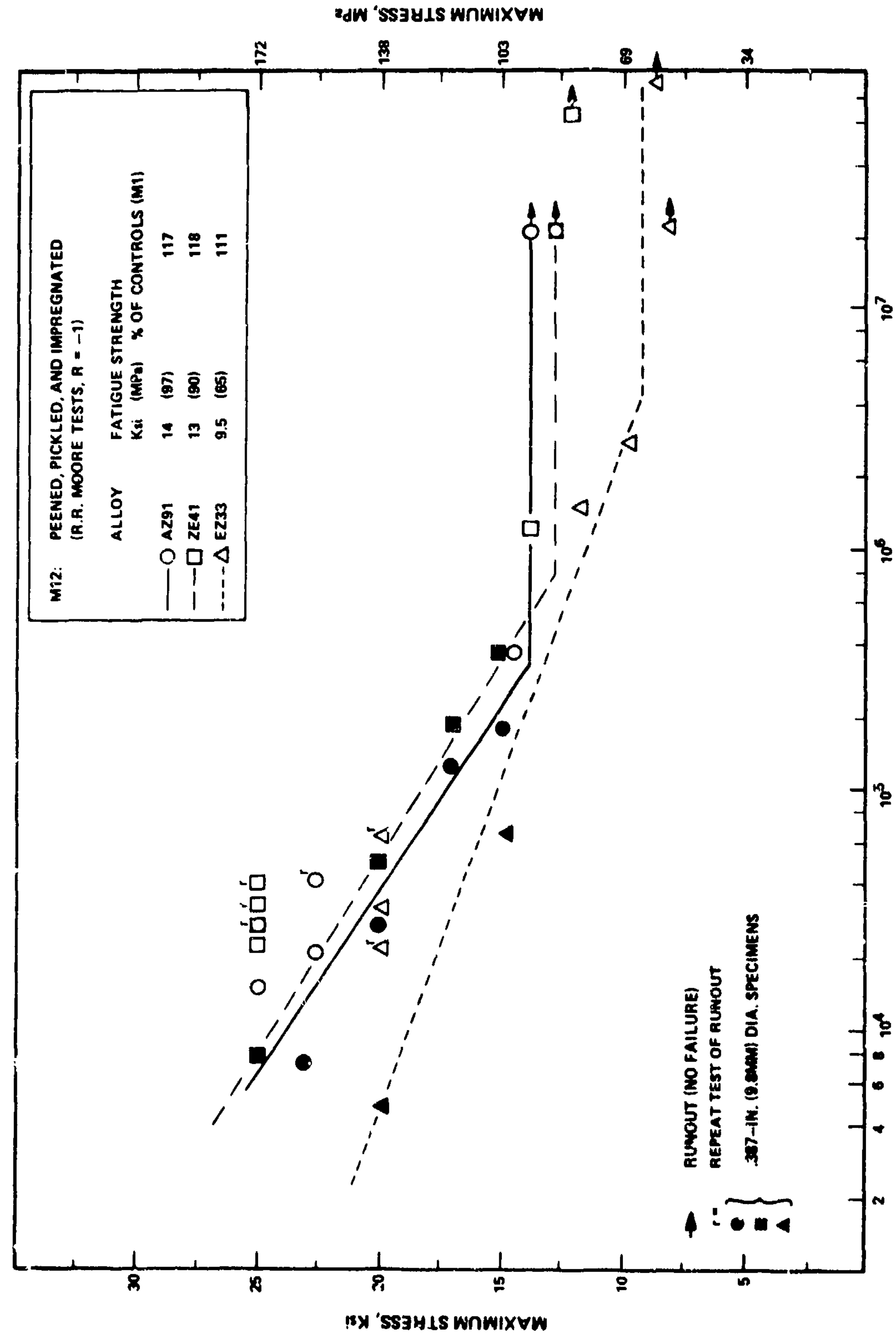


Figure 20 - R. R. Moore Fatigue Test S-N Curves

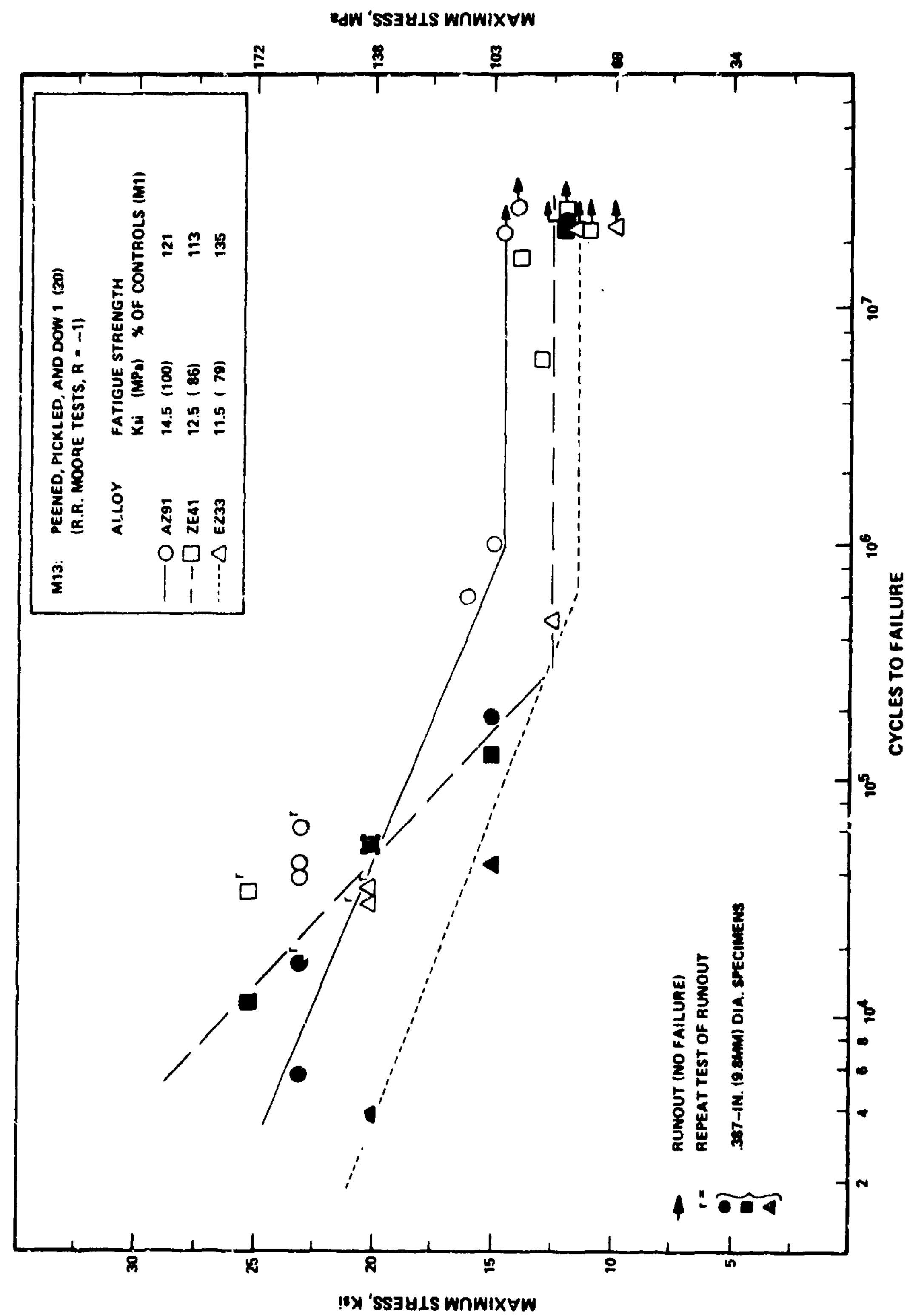


Figure 21 - R. R. Moore Fatigue Failure Test S-N Curves

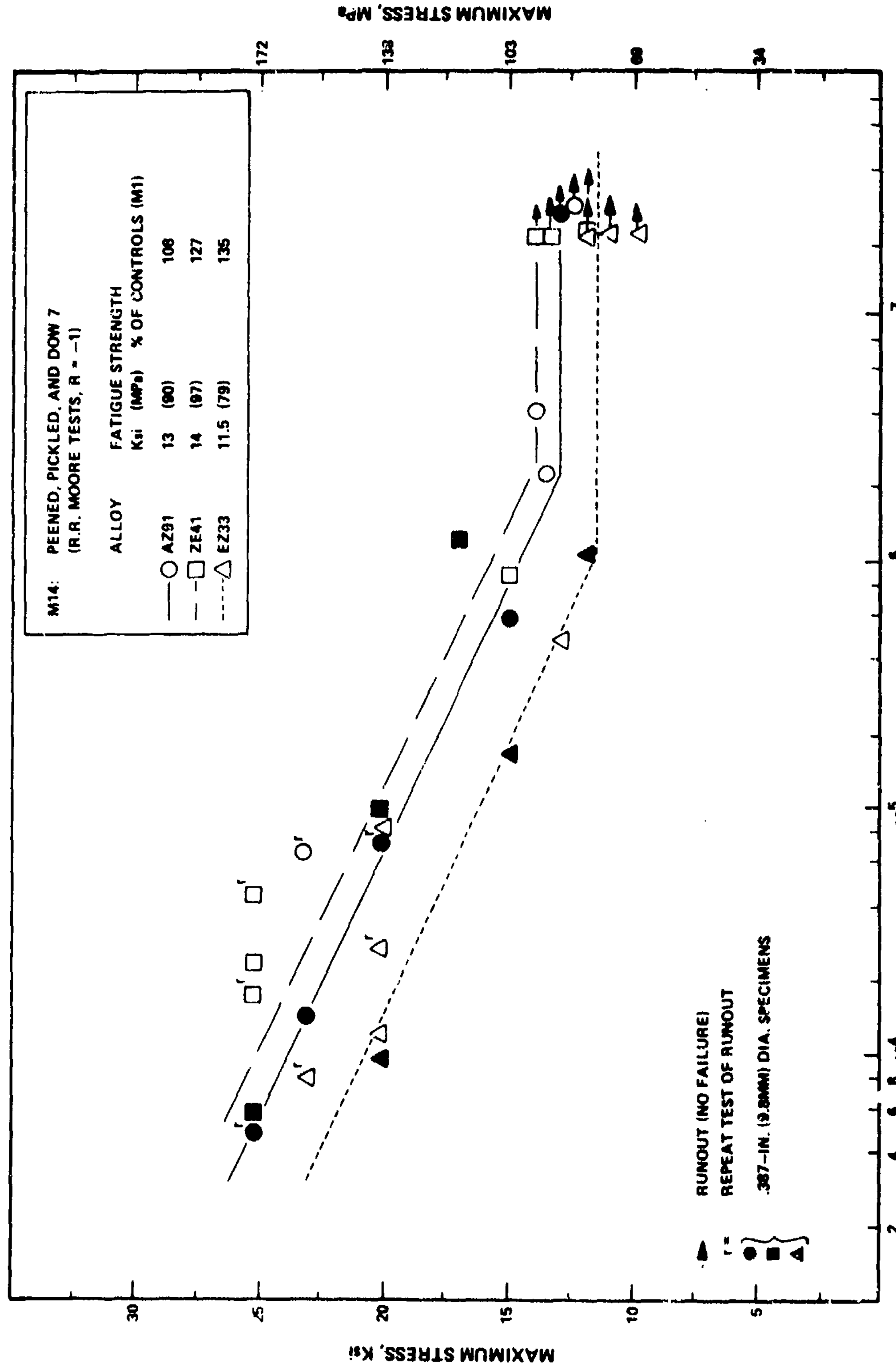


Figure 22 - R. R. Moore Fatigue Test S-N Curves

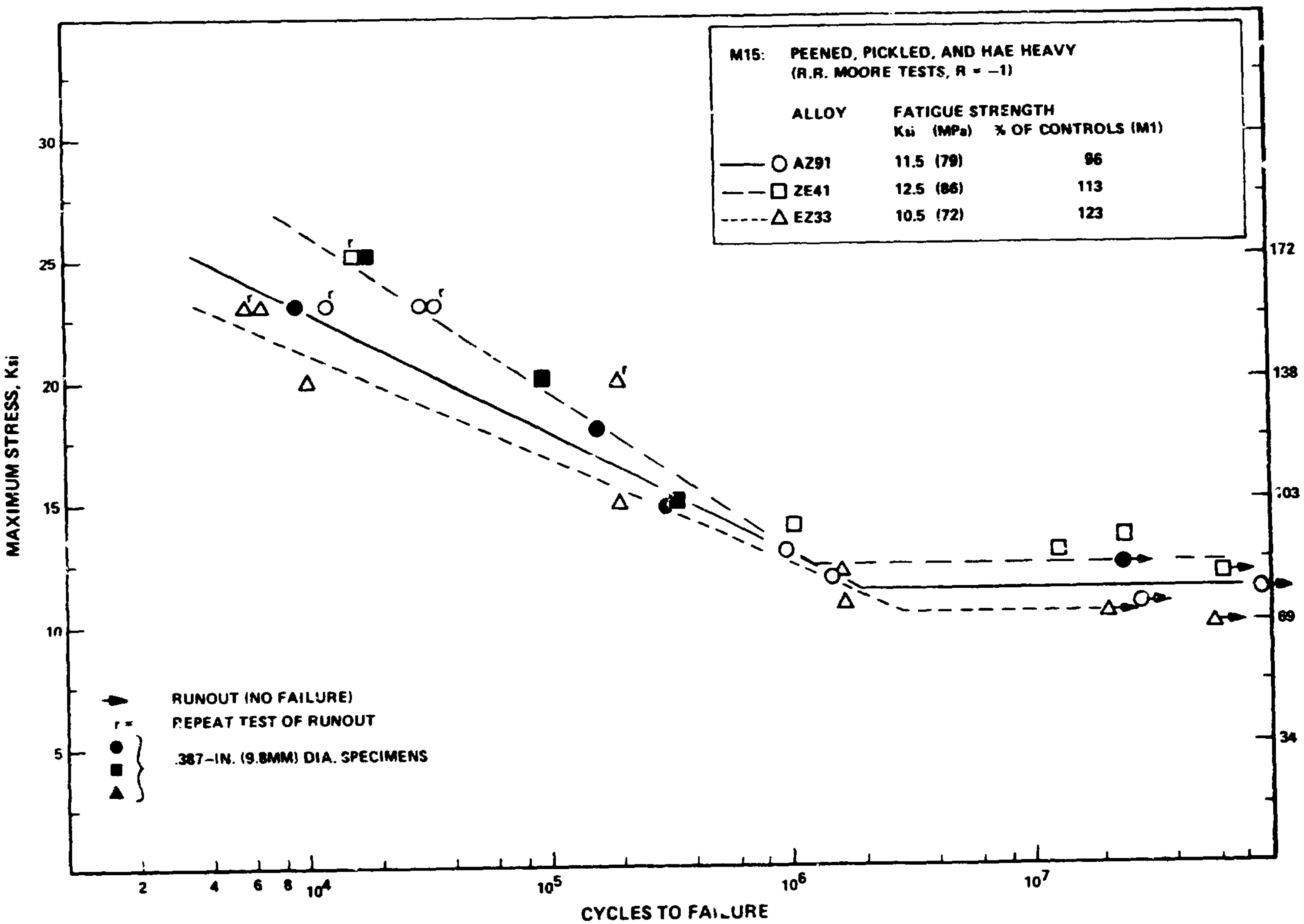


Figure 23 - R. R. Moore Fatigue Test S-N Curves

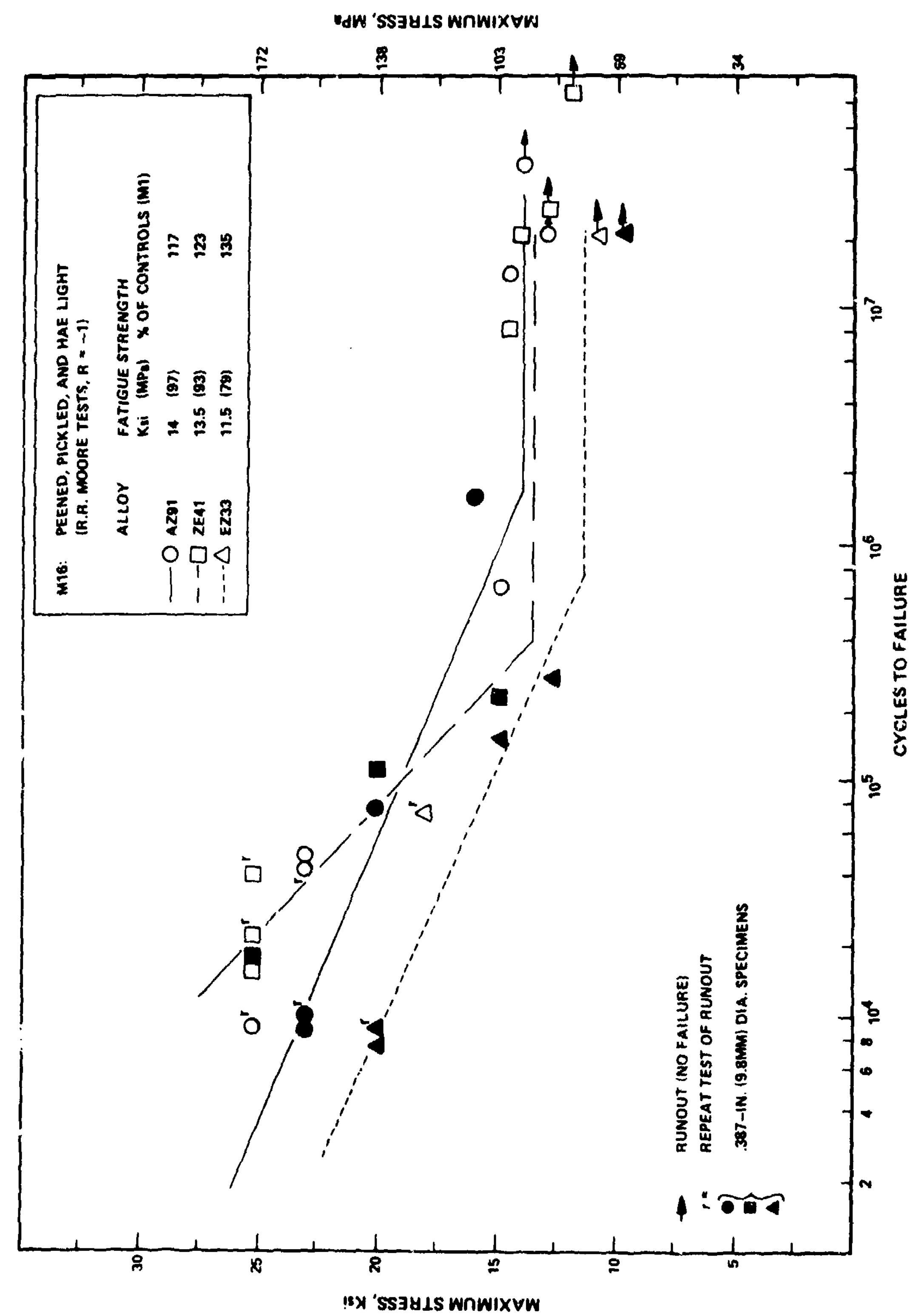


Figure 24 - R. R. Moore Fatigue Test S-N Curves

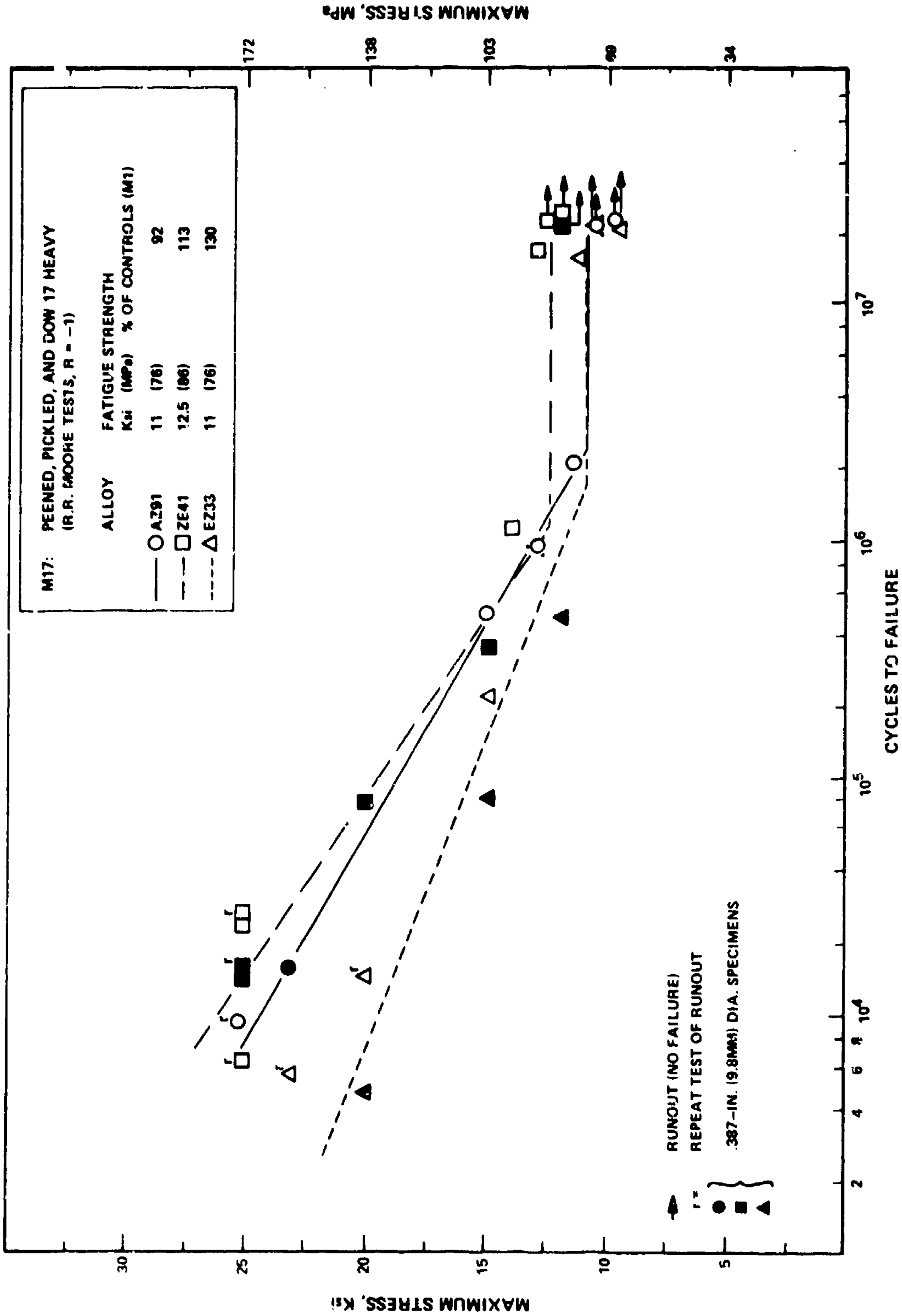


Figure 25 - R. R. Moore Fatigue Test S-N Curves

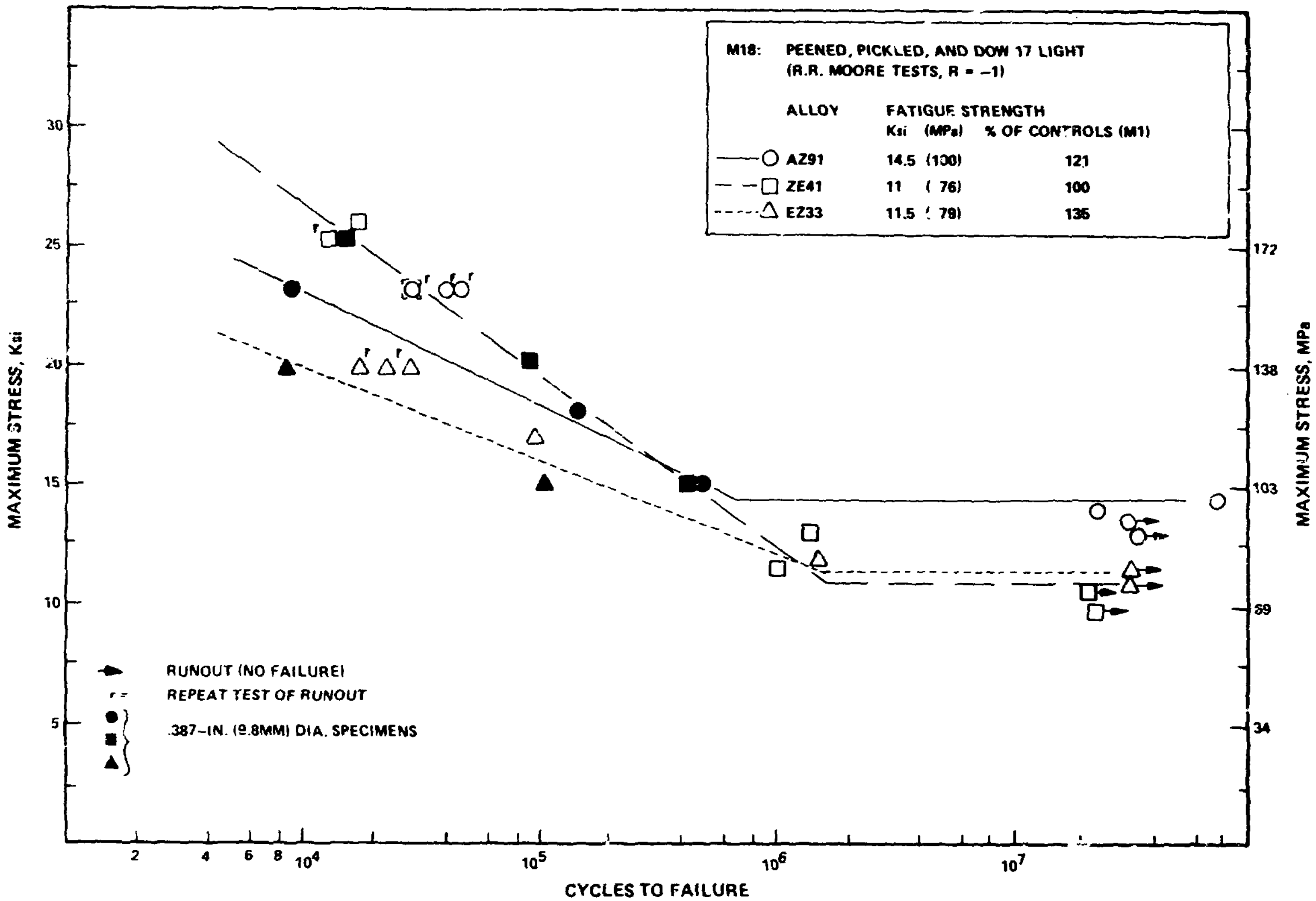


Figure 26 - R. R. Moore Fatigue Test S-N Curves

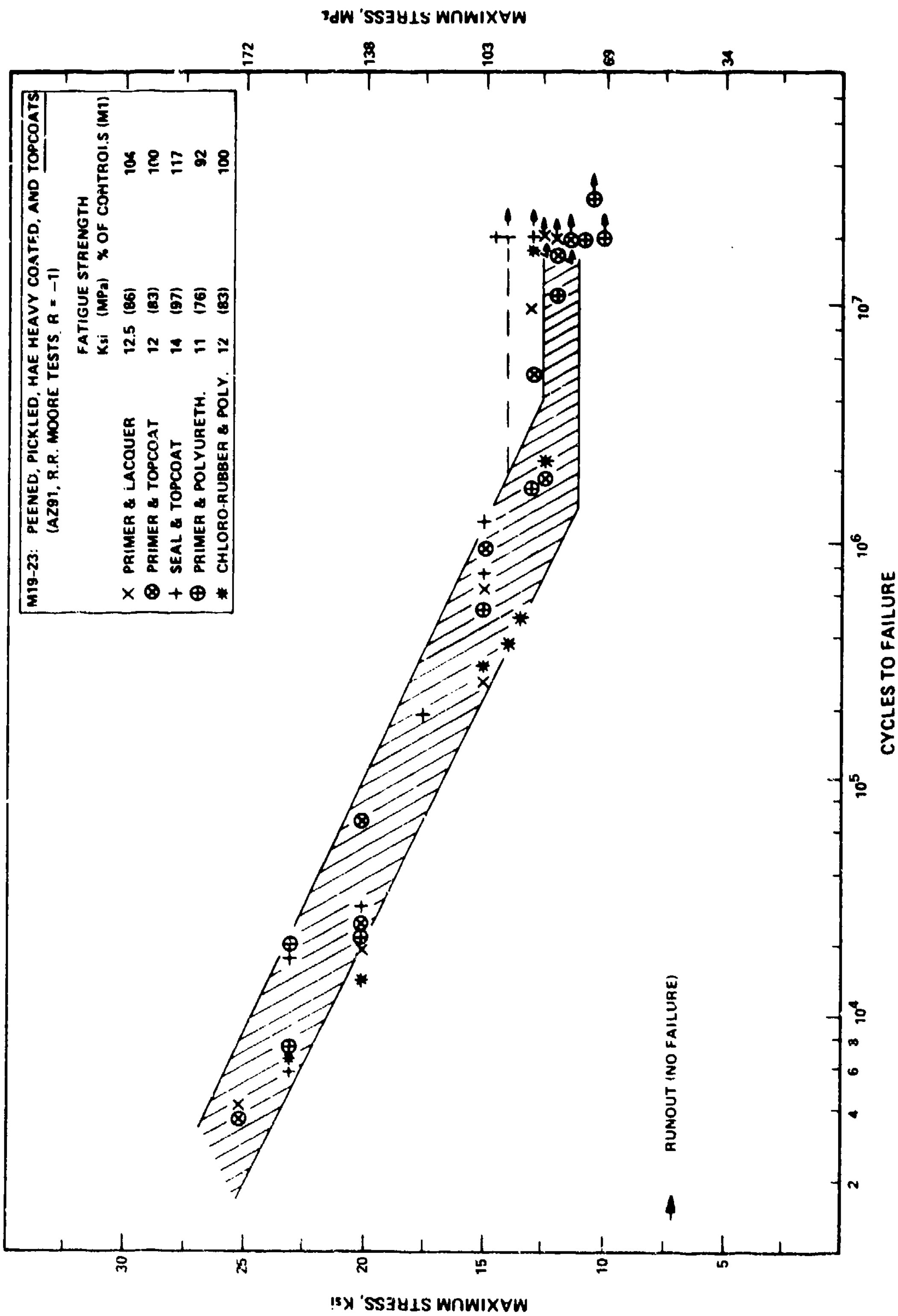


Figure 27 - R. R. Moore Fatigue Test S-N Curves

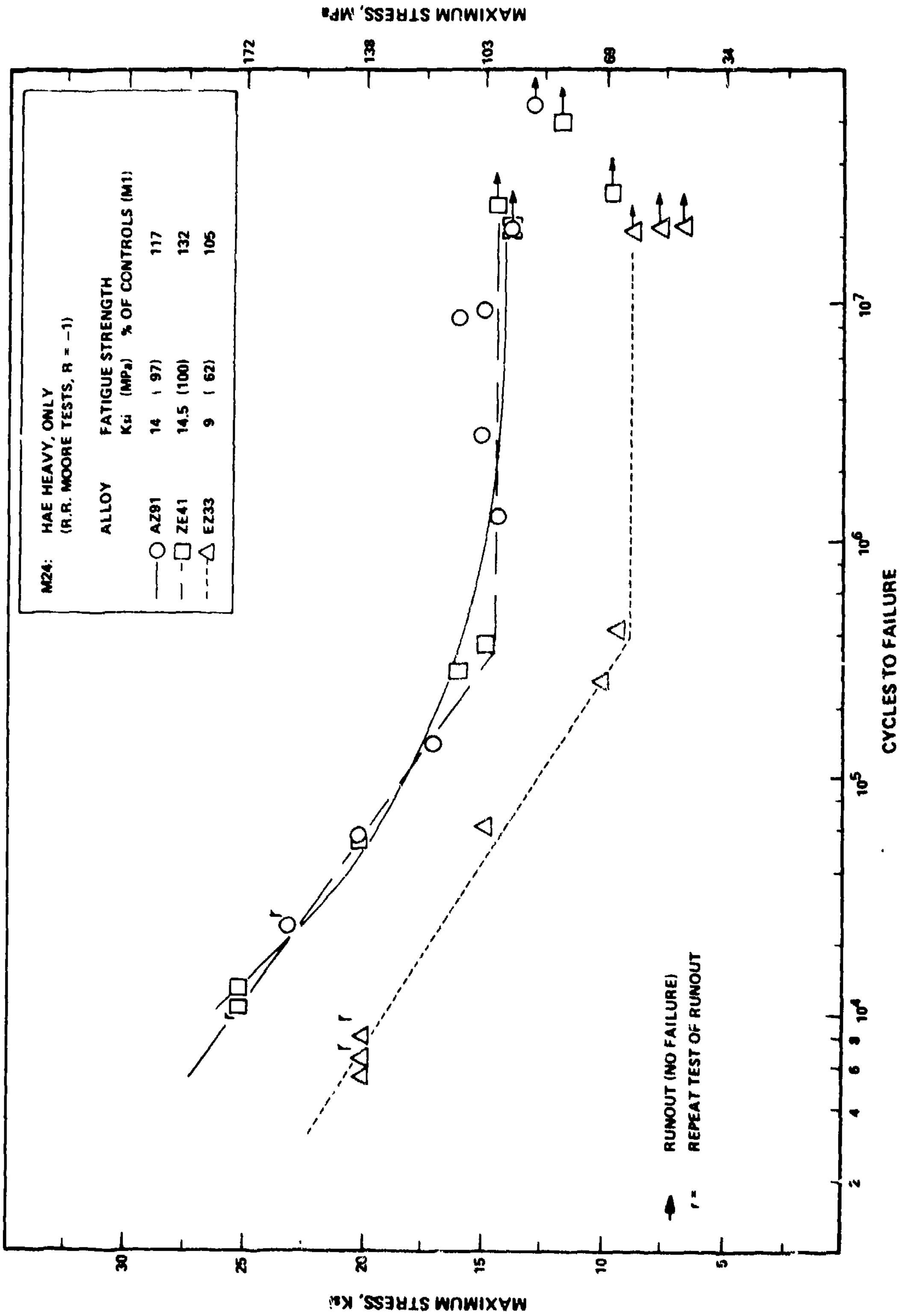


Figure 28 - R. R. Moore Fatigue Failure Test S-N Curves

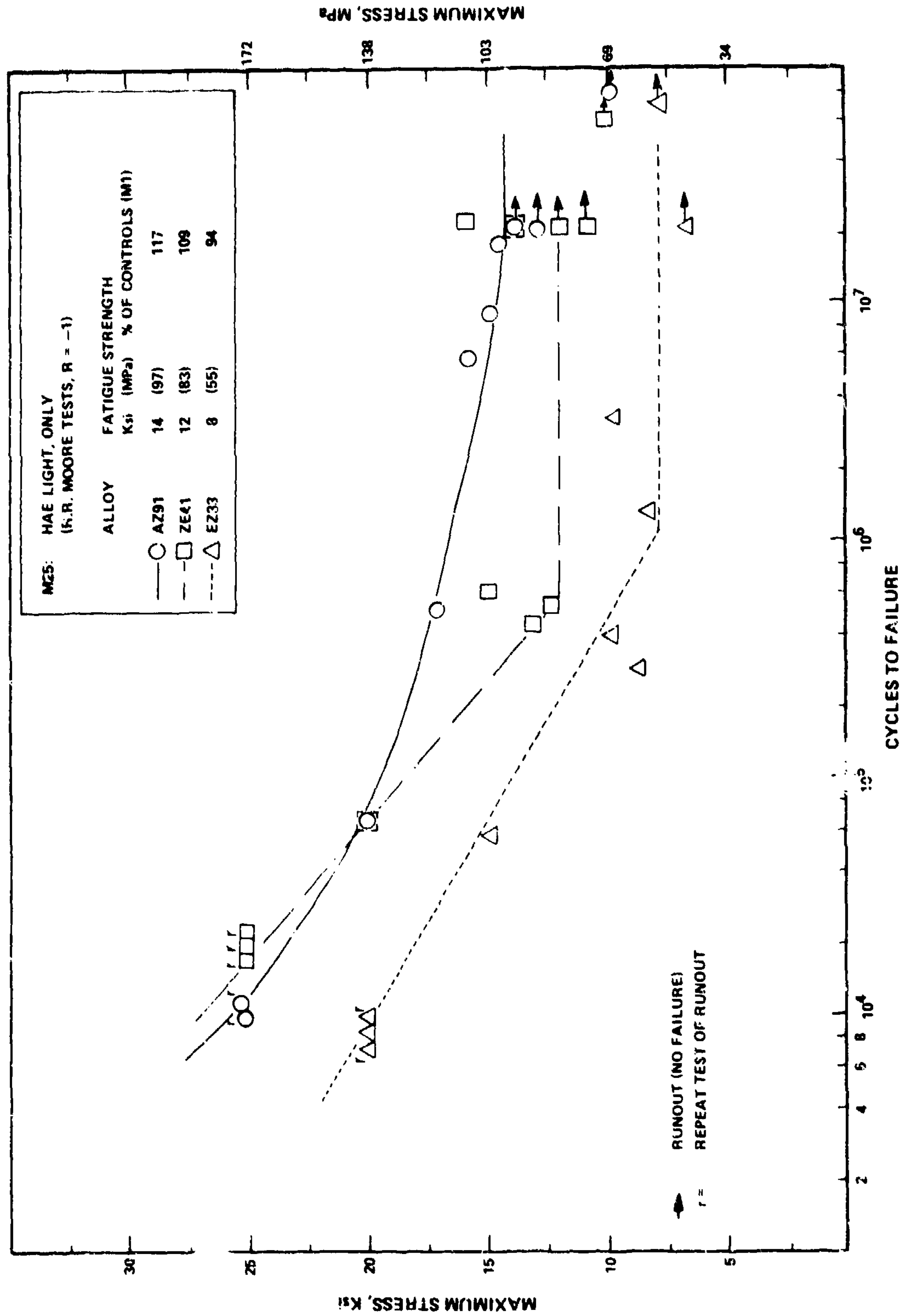


Figure 29 - P. R. Moore Fatigue Test S-N Curves

Table IX

Summary of R. R. Moore Fatigue Test Results

Condition, M	1	3	5	2	4	12	6	7	13	14	8	9	10	11	15	16	17	18	19	20	21	22	23	24	25
Fatigue Strength																									
AZ91 (ksi)	12	9.5	11	15	15.5	14	10	9.5	14.5	13	10	11	9	8	11.5	14	11	14.5	12.5	12	14	11	12	14	14
(MPa)	(83)	(65)	(76)	(103)	(107)	(97)	(69)	(65)	(100)	(90)	(69)	(76)	(62)	(55)	(79)	(97)	(76)	(100)	(86)	(83)	(97)	(76)	(83)	(97)	(97)
ZE41 (ksi)	11	9.5	9.5	14	12	13	11	11	12.5	14	11	10.5	10	10	12.5	13.5	12.5	11	-	-	-	-	-	14.5	12
(MPa)	(76)	(65)	(65)	(97)	(83)	(90)	(76)	(76)	(86)	(97)	(76)	(72)	(69)	(69)	(86)	(93)	(86)	(76)						(100)	(83)
EZ33 (ksi)	8.5	8	7.5	11.5	11.5	9.5	7	6.5	11.5	11.5	7	7	7	5.5	10.5	11.5	11	11.5	-	-	-	-	-	9	8
(MPa)	(59)	(55)	(52)	(79)	(79)	(65)	(48)	(45)	(79)	(79)	(48)	(48)	(48)	(38)	(72)	(79)	(76)	(79)						(62)	(55)
% of Controls (M1)																									
AZ91	100	79	92	125	129	117	84	79	121	108	84	92	75	67	96	117	92	121	104	100	117	92	100	117	117
ZE41	100	86	86	127	109	118	100	100	113	127	100	96	91	91	113	123	113	100	-	-	-	-	-	132	109
EZ33	100	94	88	135	135	111	82	76	135	135	82	82	82	65	123	135	130	135	-	-	-	-	-	105	94
Condition, M	1	3	5	2	4	12	6	7	13	14	8	9	10	11	15	16	17	18	19	20	21	22	23	24	25
	Controls	Pickled, only	Pickled & Impregnated	Peened, only	Peened & Pickled	Peened, Pickled, & Impregnated	Pickled & DOW 1 (20)	Pickled & DOW 7	Peened, Pickled, & DOW 1 (20)	Peened, Pickled & DOW 7	Pickled & HAE Heavy	Pickled & HAE Light	Pickled & DOW 17 Heavy	Pickled & DOW 17 Light	Peened, Pickled, & HAE Heavy	Peened, Pickled, & HAE Light	Peened, Pickled, & DOW 17 Heavy	Peened, Pickled, & DOW 17 Light	Peened, Pickled, HAE Heavy & Primer + Lacquer	Peened, Pickled, HAE Heavy & Primer + Topcoat	Peened, Pickled, HAE Heavy & Seal + Topcoat	Peened, Pickled, HAE Heavy & Primer + Poly.	Peened, Pickled, HAE Heavy & Chloro-rubber & Poly.	HAE Heavy, only	HAE Light, only

41-8-11 41-19-16 33-51-13 33-50-14

Figure 30 - Typical R. R. Mc[illegible] Rotating Beam Fatigue Test Specimens, Large and Small Diameter; and Representative Failures. Specimens at Left are With the HAE Heavy Anodic Coating (M8). Failed Specimens are Coated With the DOW 17 Light Anodic Coating (M11).

33-51-13

33-50-14

Figure 31 - Representative Fractures of High (Bottom Specimen: 622,000 Cycles) and Low (Top Specimen: 25,000 Cycles) Cyclic Life; Same DOW 17 Light Coated Specimens as Shown in Figure 30.

of no significant influence on the test results. A critical evaluation of the test data supports this assumption in general. Although some effect may seem apparent, the data, itself, is conflicting and is confused by the inability to differentiate between effects due to size and effects caused by the fact that the specimens were processed in two separate groups (that is, manufactured, treated, and coated at different times).

Of the conditioning treatments evaluated, both pickling and shot peening proved to have significant effect on the fatigue strength of all three alloys: yielding 5 to 20% decrease with pickling (M3) and 25 to 35% increase with peening (M2) depending upon the alloy. Also, pickling after peening (M4) had little effect on the peened fatigue strength. The effect of the polystyrene impregnation after pickling differed for the peened (M12) and unpeened (M5) conditions. For the pickled and impregnated specimens there appears to be little effect, generally. Applied over surfaces peened prior to pickling, however, impregnation appears to reduce slightly the fatigue strength - at least for the AZ91 and EZ33 alloys. This reduction could be attributed to the 300°F (149°C) cure temperature required by impregnation causing stress relief of the peened surfaces. In fact, MIL-S-13165B (Shot Peening of Metal Parts, 31 Dec 1966) and MIL-P-81985(AS) (Peening of Metals, 18 Oct 1974) both restrict post peening operation temperatures of magnesium parts to under 200°F (93°C).

The unpeened chromate coating data, except for the ZE41 alloy, showed reduced fatigue strength from the bare controls, M1 (20 to 25% reduction). On unpeened ZE41 alloy surfaces, however, these coatings showed no deleterious effect. Peened and chromate coated data showed significant reduction, compared to the peened only condition, only for AZ91 with the DOW 7 coating, which reduced fatigue strength by 17%, and ZE41 alloy with the DOW 1 coating which showed a 14% reduction in fatigue strength. Interestingly, in general the ZE41 chromate coating data showed comparable strength to the controls and 5 to 20% increased fatigue strength compared to the pickled only and peened and pickled surfaces. In general, the test results indicated very little difference between the chromate conversion coatings, DOW 1/DOW 20 (M6 and M13) and DOW 7 (M7 and M14).

For all the anodic coating tests, (M8 - 11, 15 - 18) the data showed reduced fatigue strength from the bare (M1) and peened (M2) controls (0 to 35% reduction). However, when compared to the pickled only or peened and pickled surfaces (M3 and M4, respectively) degradation due to the coatings did not necessarily occur. Thus, for the ZE41 alloy an improvement in fatigue strength of up to 15% was observed with the anodic coatings applied to both peened and unpeened, pickled surfaces. For the EZ33 alloy there was very little influence on peened and pickled surfaces but on pickled only surfaces a 10 to 30% reduction in fatigue strength occurred due to these coatings. On peened and pickled surfaces of AZ91 the anodic coatings were deleterious with significant reduction (35 to 40%) seen with the thick anodic coatings. On pickled only AZ91 material the HAE coating showed slight benefits (5 to 10%) and the DOW 17 coating showed slight degradation (5 to 10%). None of the anodic coatings proved consistently best, although for the unpeened condition the HAE coatings yielded better results. Also, except for the AZ91 peened surfaces, there was no significant difference between the thick and thin coatings. AZ91 peened surfaces with thin anodic coatings were 25 to 30% better than with thick coatings whereas a difference of only 5 to 10% occurred with the ZE41 and EZ33 alloys. This, in spite of the fact that the difference in coating thickness between the heavy and light applications was apparently much less for the AZ91 than for the other two alloys (see Table VI). In the unpeened conditions very little difference between heavy and light coatings occurred and in several cases the heavy coating showed better results.

Conditions M24 and M25 provided direct evaluation of the effects of the HAE anodic coatings applied directly to untreated substrate magnesium surfaces - thus avoiding the complications due to peening or pickling. A marked increase in fatigue strength of 10 to 30% resulted for the ZE41 and AZ91 alloys compared to the bare controls (M1) while the fatigue strength of EZ33 remained approximately unchanged with these coatings.

Except for the epoxy seal system (M21) the organic coatings (M19 - M23) had no discernible effect on the already peened, pickled, and HAE heavy coated surfaces (M15) of AZ91 alloy. The epoxy seal topcoat system indicated a beneficial effect Several of the organic coated specimens showed degradation in the coating after testing at high stress levels. Degradation occurred only at the higher test strains - 3000 $\mu\epsilon$ or greater. The M19 topcoat showed a coarsening effect which was severe at 25 ksi (172 MPa) but an integral coating was still maintained. Two M20 specimens had several coating cracks near the fracture after testing at 20 ksi (138 MPa) and 25 ksi (172 MPa). One M21 test specimen showed some slight blistering of the coating in the center section after testing at 23 ksi (158 MPa). The M22 coating showed perhaps, the most severe degradation since, for two specimens tested at 20 ksi (138 MPa) and 23 ksi (158 MPa) stress, the coating actually peeled off near the fracture exposing the HAE anodic undercoating.

Sheet Flexure Tests of As-Cast Surfaces

Results of the sheet flexure fatigue tests are presented in figures 32 - 44 and are summarized in Table X. Typical failures for the small and large sized specimens and representative fracture surfaces are shown in figures 45 - 48, respectively. Each S-N figure shows all the valid data points achieved for one test condition (test condition as per Table VII). Faired stress - cyclic life curves were drawn through the data points and the fatigue strength estimated for each alloy and test condition. For all conditions of both alloys (AZ91 and ZE41) the complete S-N response curve is defined by two straight lines intersecting at the fatigue limit stress of the alloy for the particular test condition. The slope of the upper straight line portion of these curves for both alloys and all test conditions was 11.2 ± 2.2 ksi/log cyclic life (77.4 ± 15.1 MPa/log cyclic life). In every case the ZE41 alloy fatigue life was greater than that for AZ91.

The same considerations for data scatter described for the R. R. Moore tests also hold true for the sheet flexure fatigue tests. Additionally, the existence of the as-cast surface increases the potential of scatter associated with the determination of the sheet flexure fatigue strength. This is due to the lack of control on specimen surface finish - the as-cast surface from the manufacturer being the test surface, and also the random occurrence of casting flaws of various severity at or near the surface. Both of these factors were not present with the R. R. Moore machined specimen tests but are representative of the material as it is actually used in the housings. Examples of these flaws are seen in figures 47 and 48. All flaws were in the form of voids or pores at or near the surface.

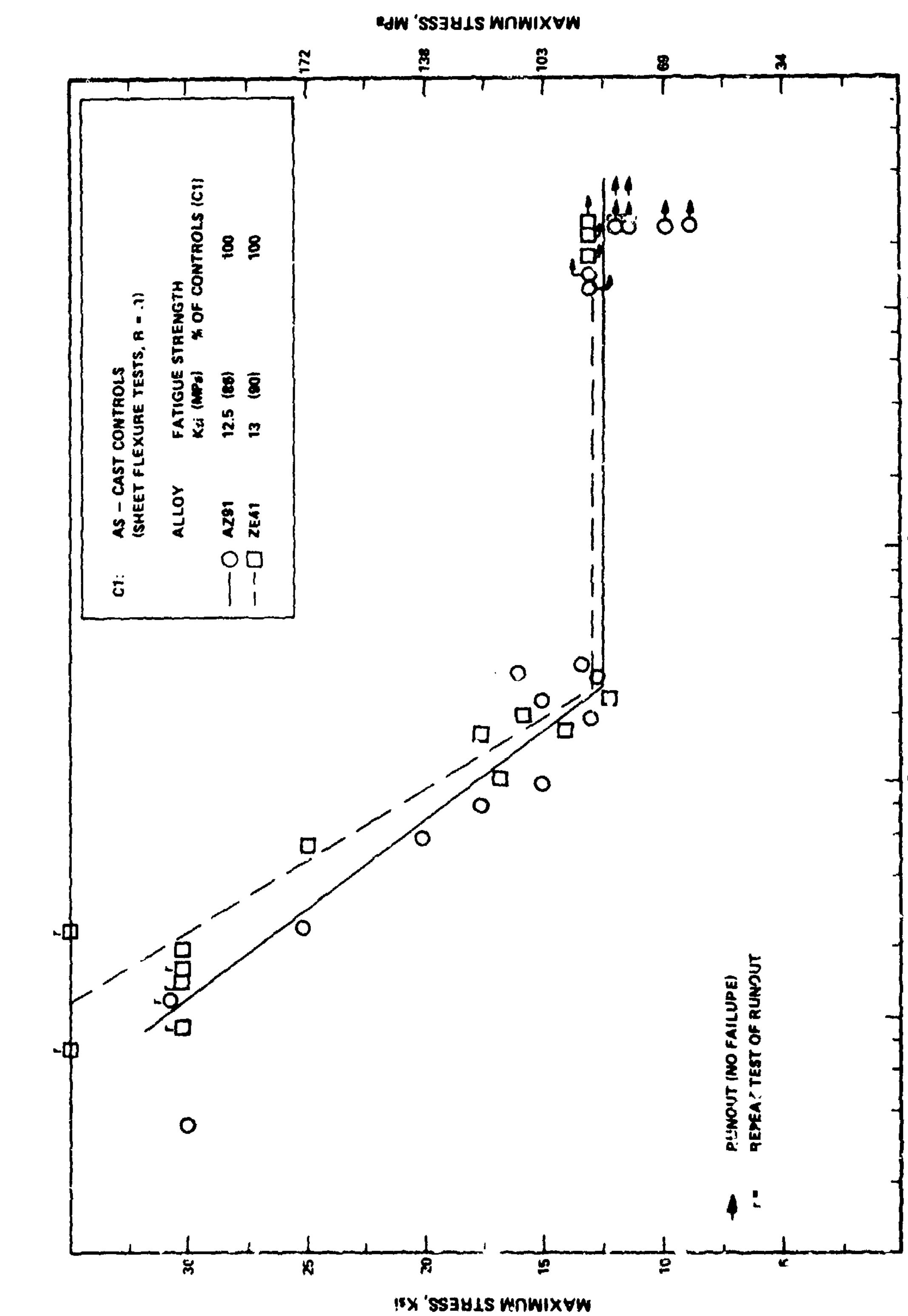


Figure 32 - Sheet Flexure Fatigue Test S-N Curves

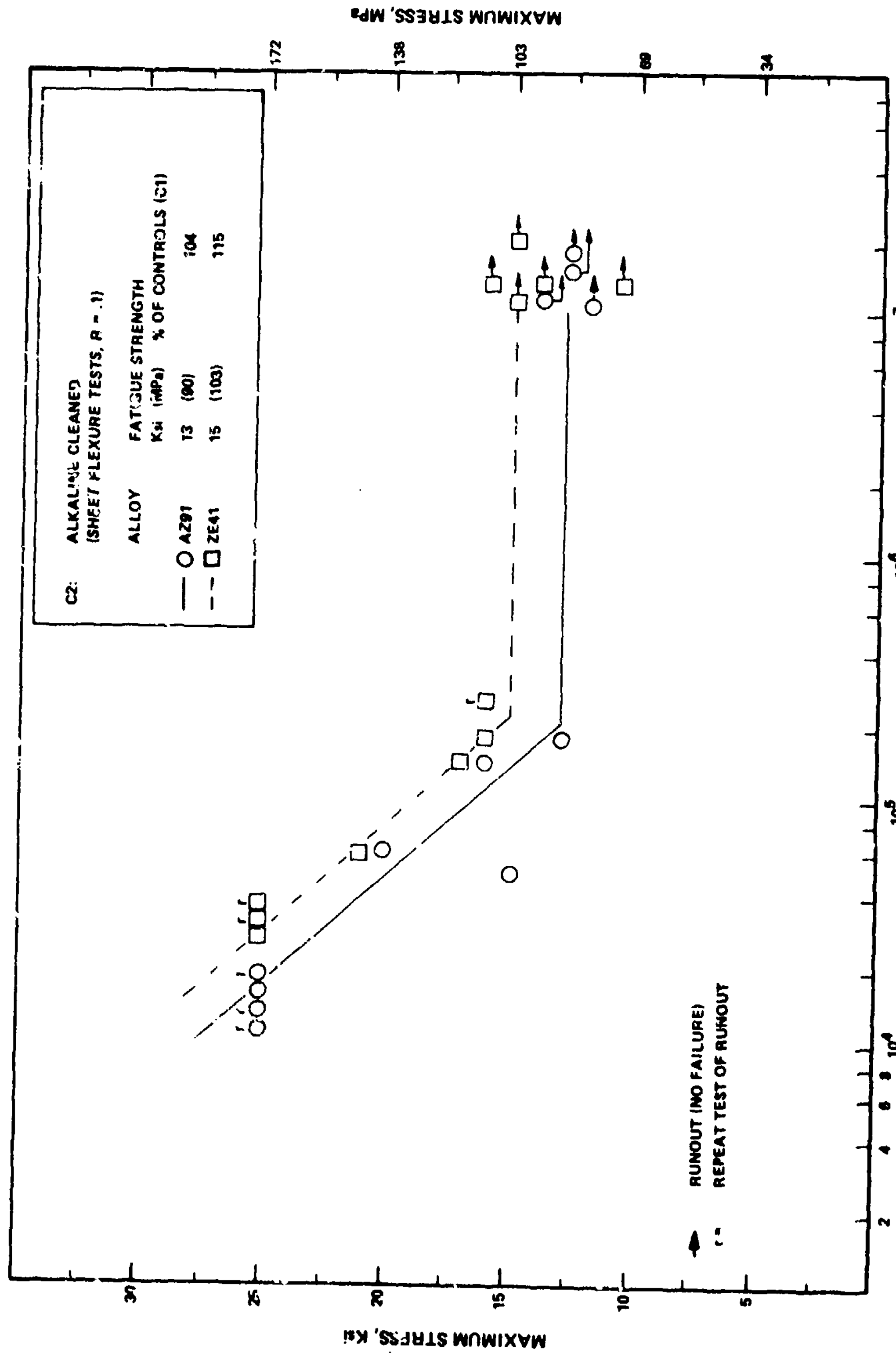


Figure 33 - Sheet Flexure Fatigue Test S-N Curves

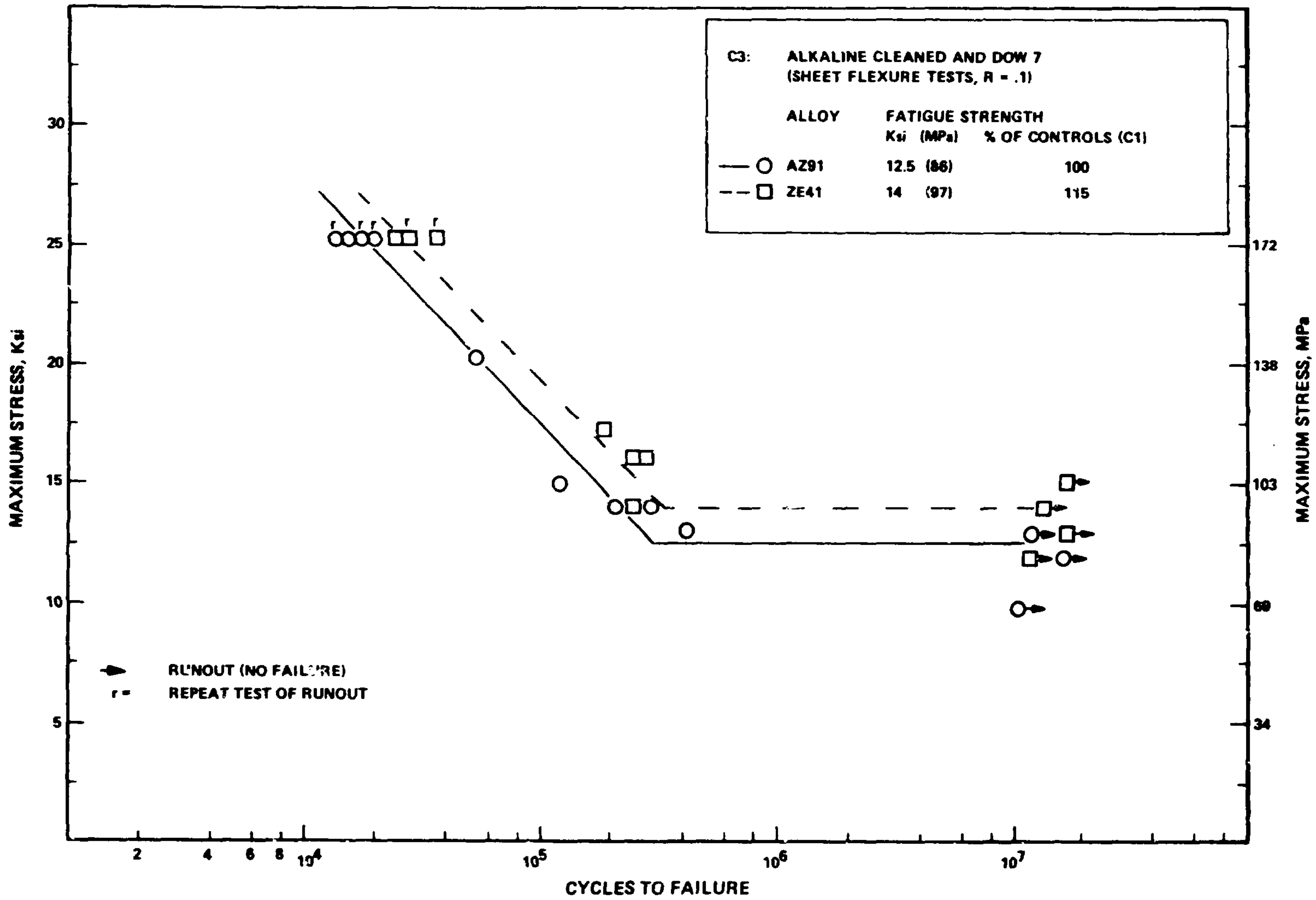


Figure 34 - Sheet Flexure Fatigue Test S-N Curves

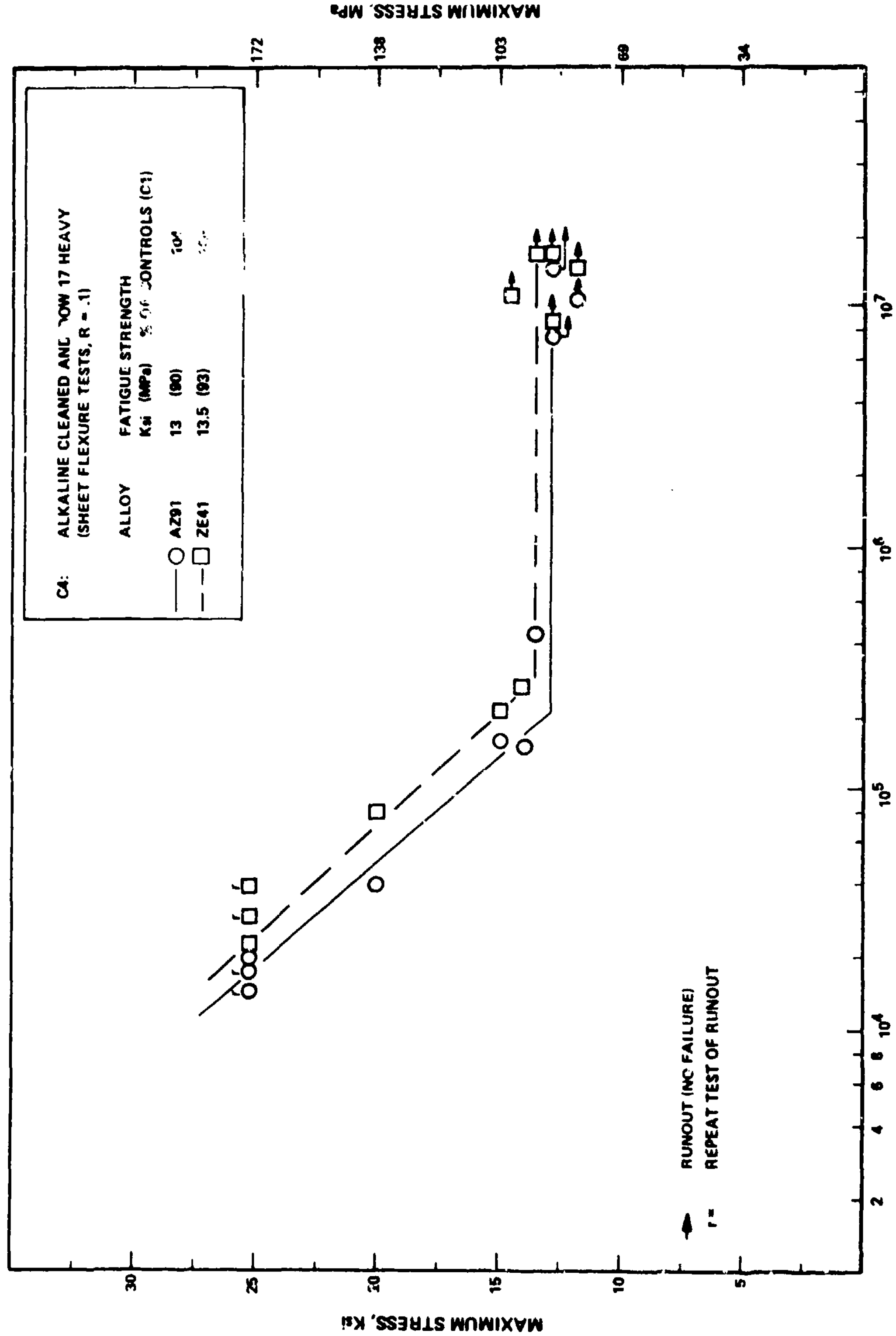


Figure 35 - Sheet Flexure Fatigue Test S-N Curves

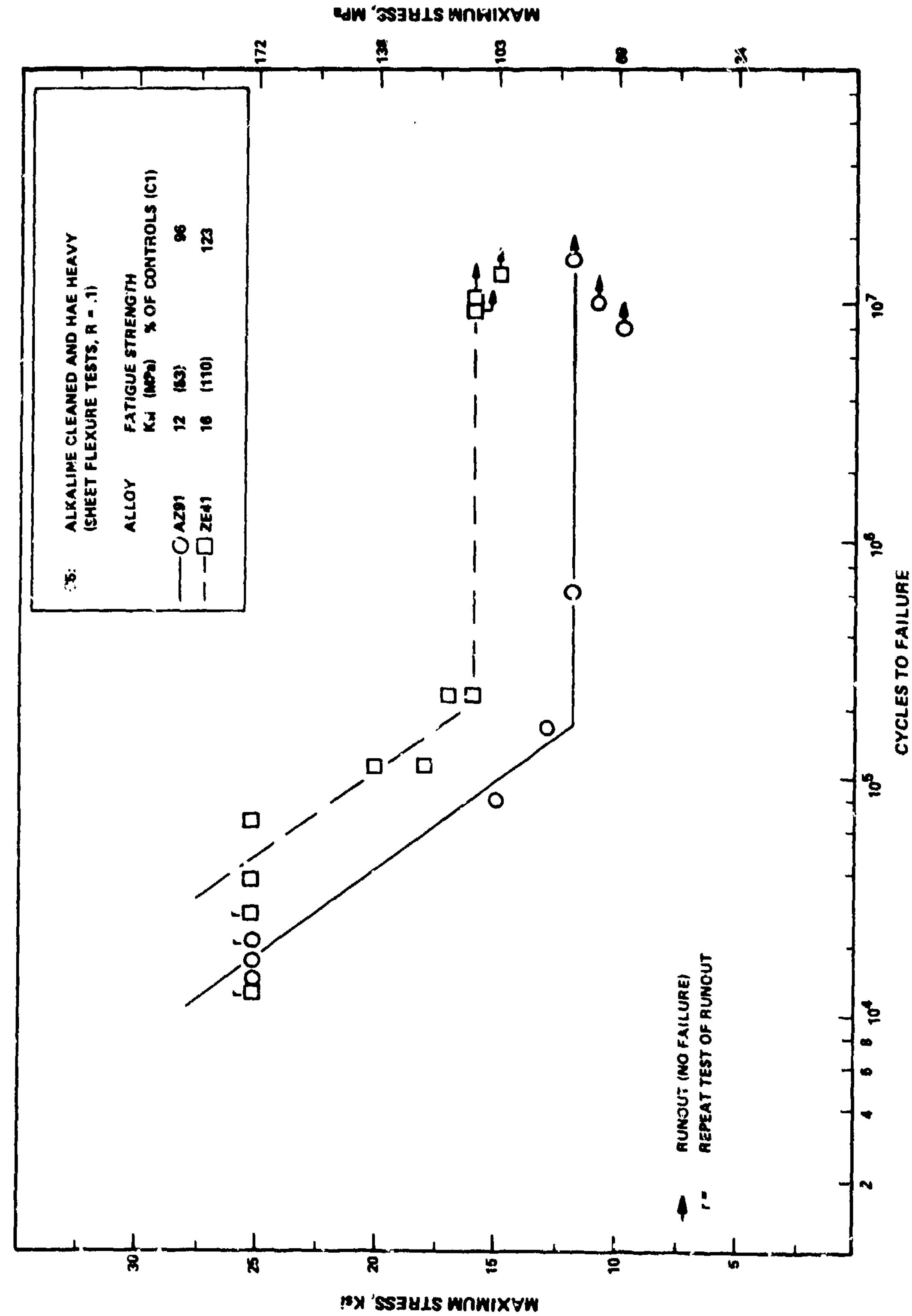


Figure 36 - Sheet Flexure Fatigue Test S-N Curves

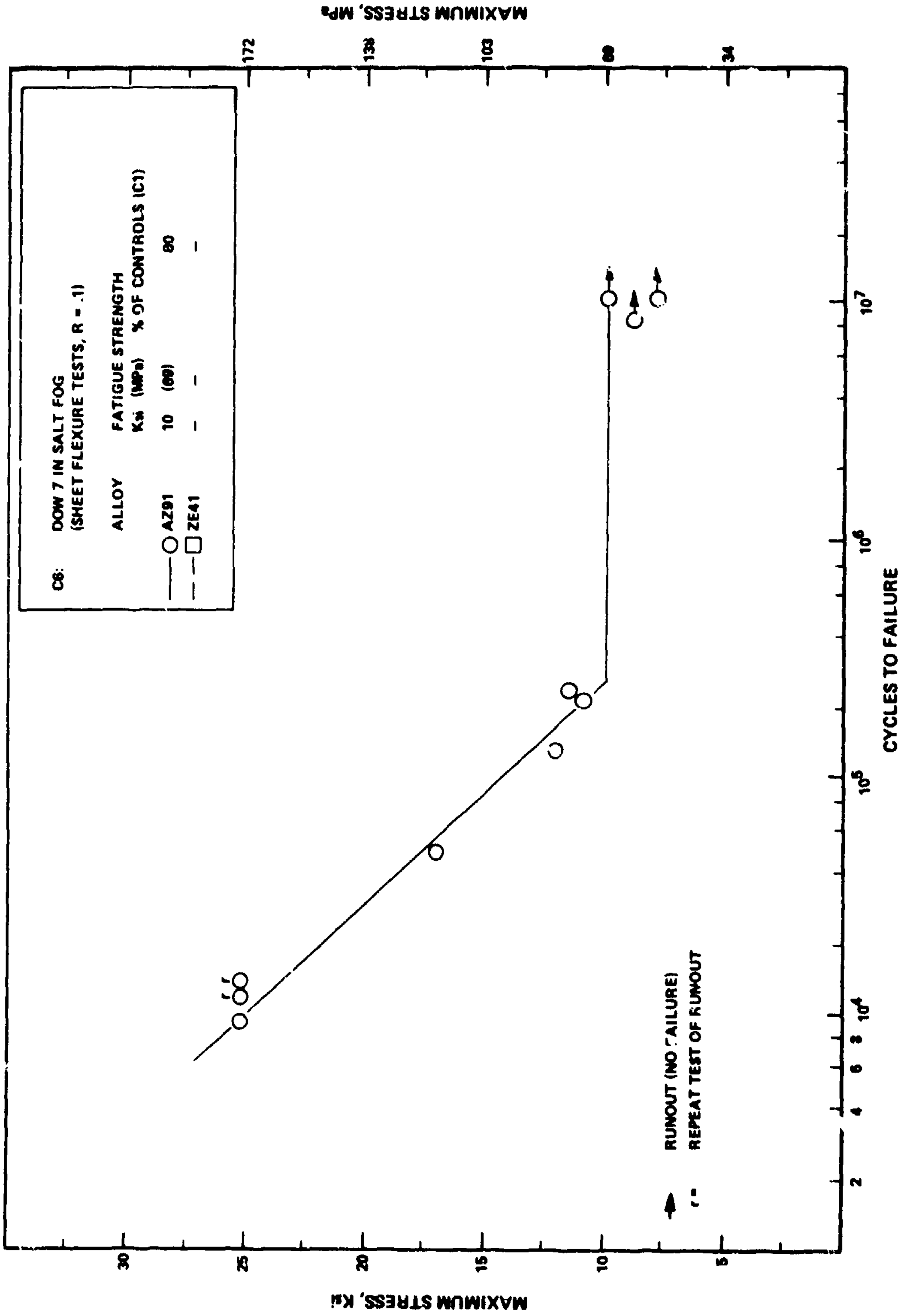


Figure 37 - Sheet Flexure Fatigue Test S-N Curves

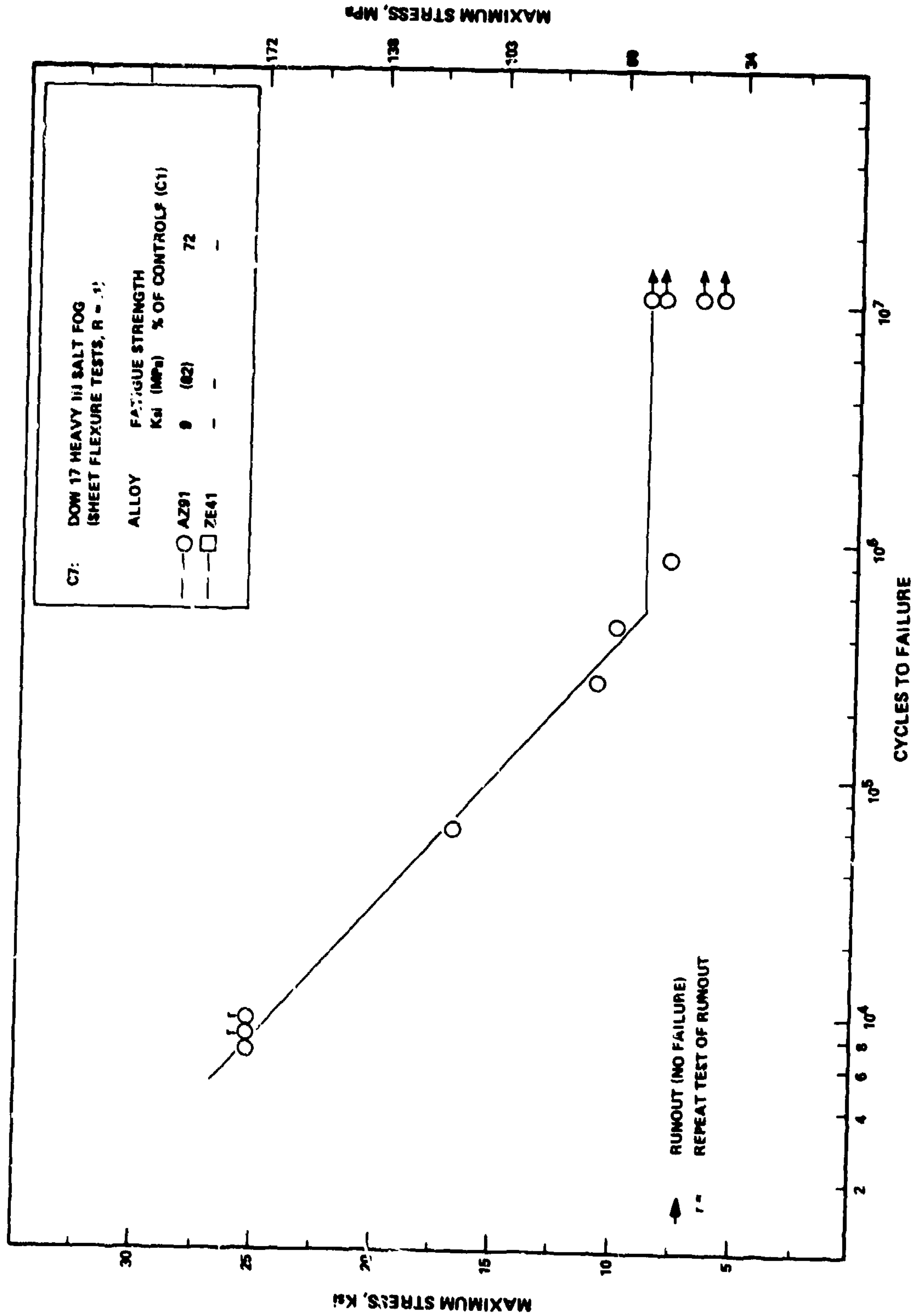


Figure 38 - Sheet Flexure Fatigue Test S-N Curves

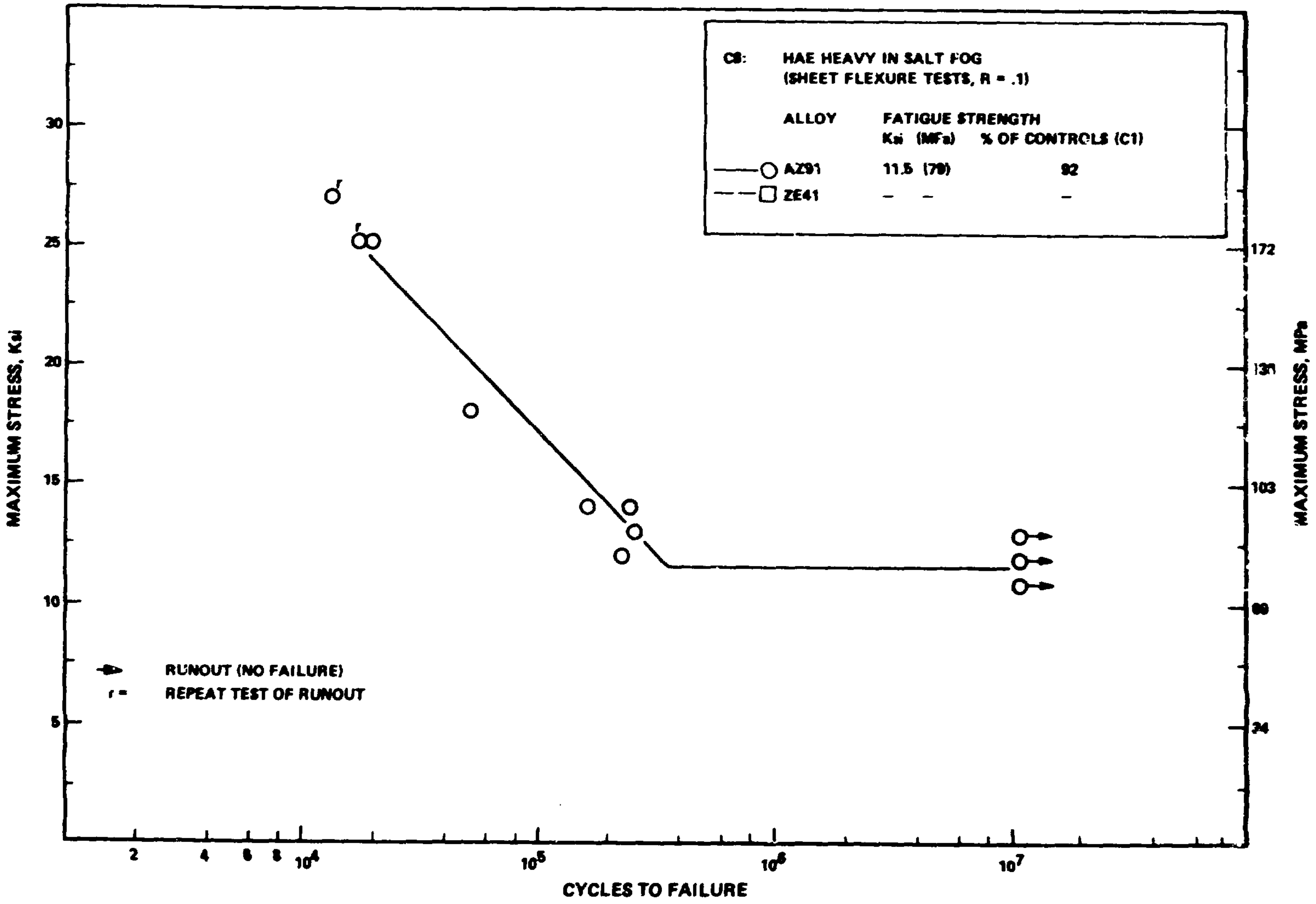


Figure 39 - Sheet Flexure Fatigue Test S-N Curves

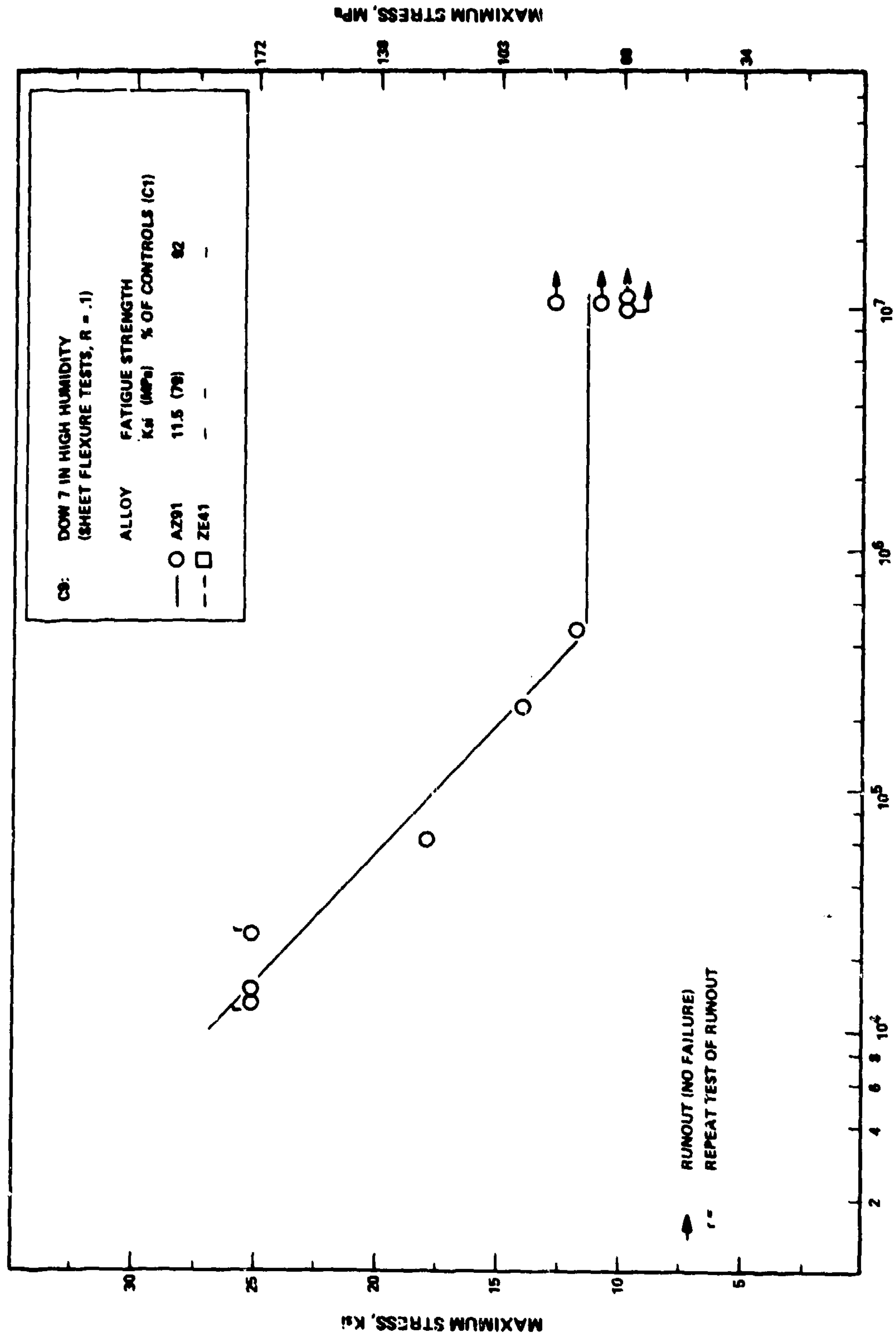


Figure 40 - Sheet Flexure Fatigue Test S-N Curves

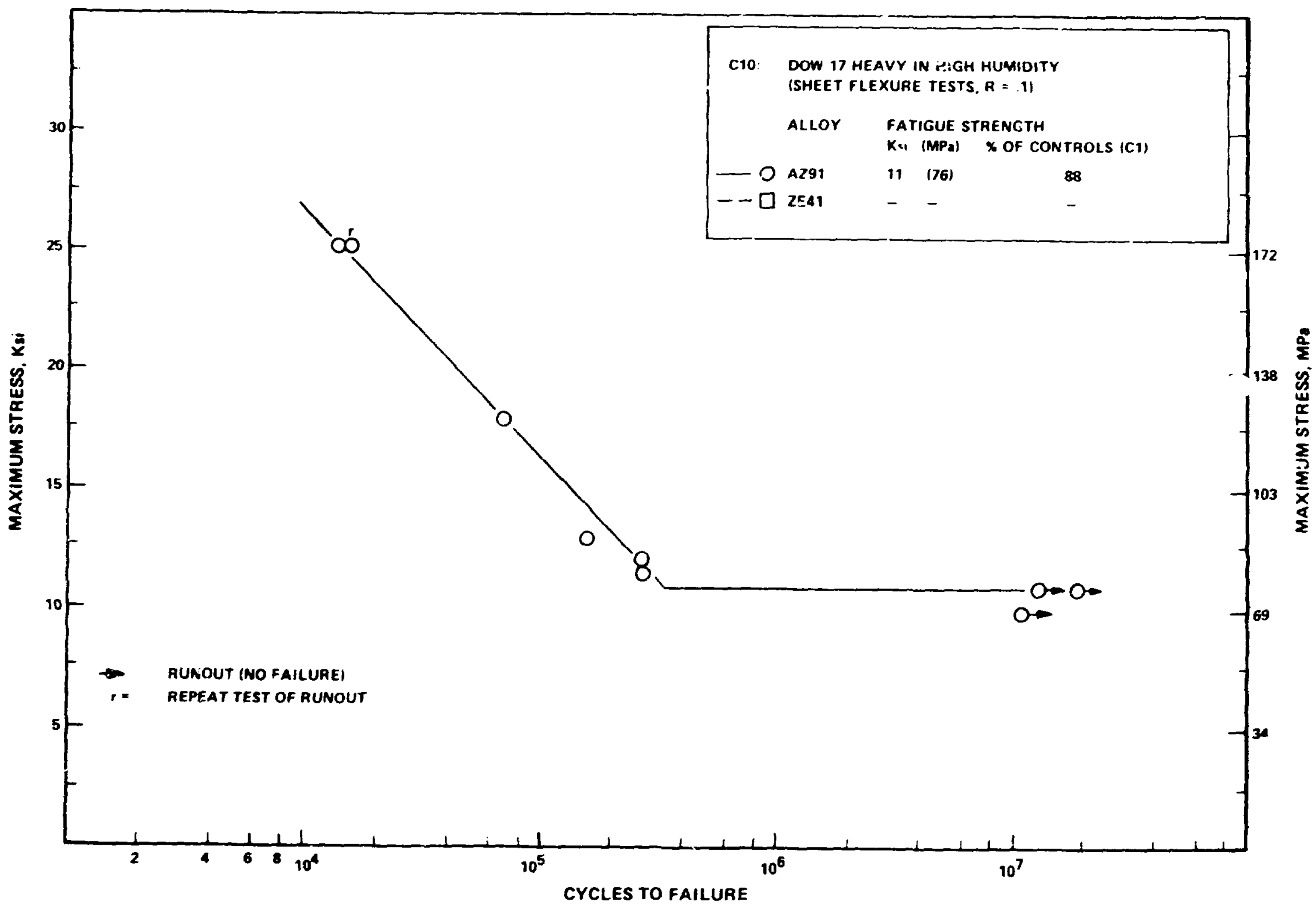


Figure 41 - Sheet Flexure Fatigue Test S-N Curves

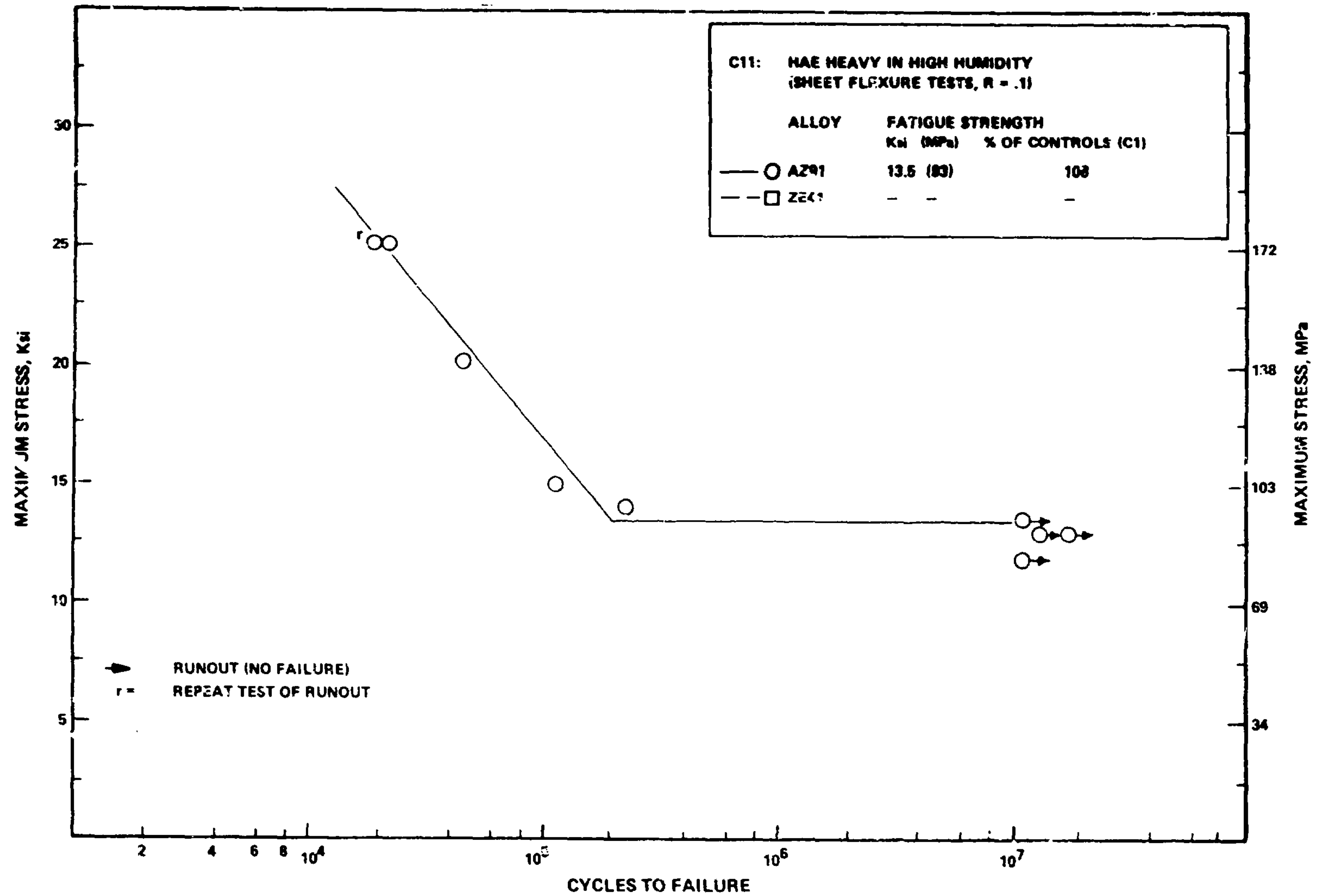


Figure 42 - Sheet Flexure Fatigue Test S-N Curves

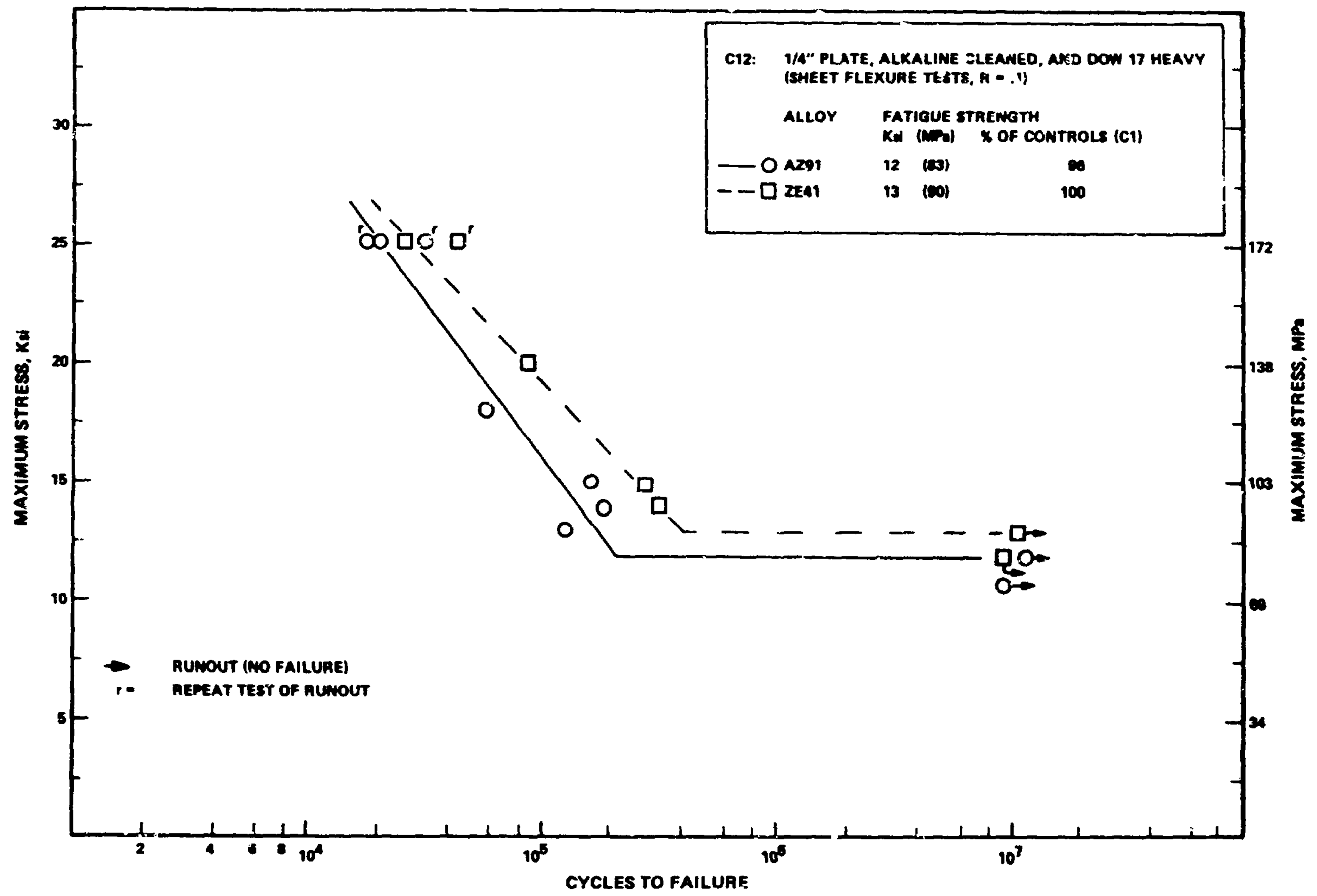


Figure 43 - Sheet Flexure Fatigue Test S-N Curves

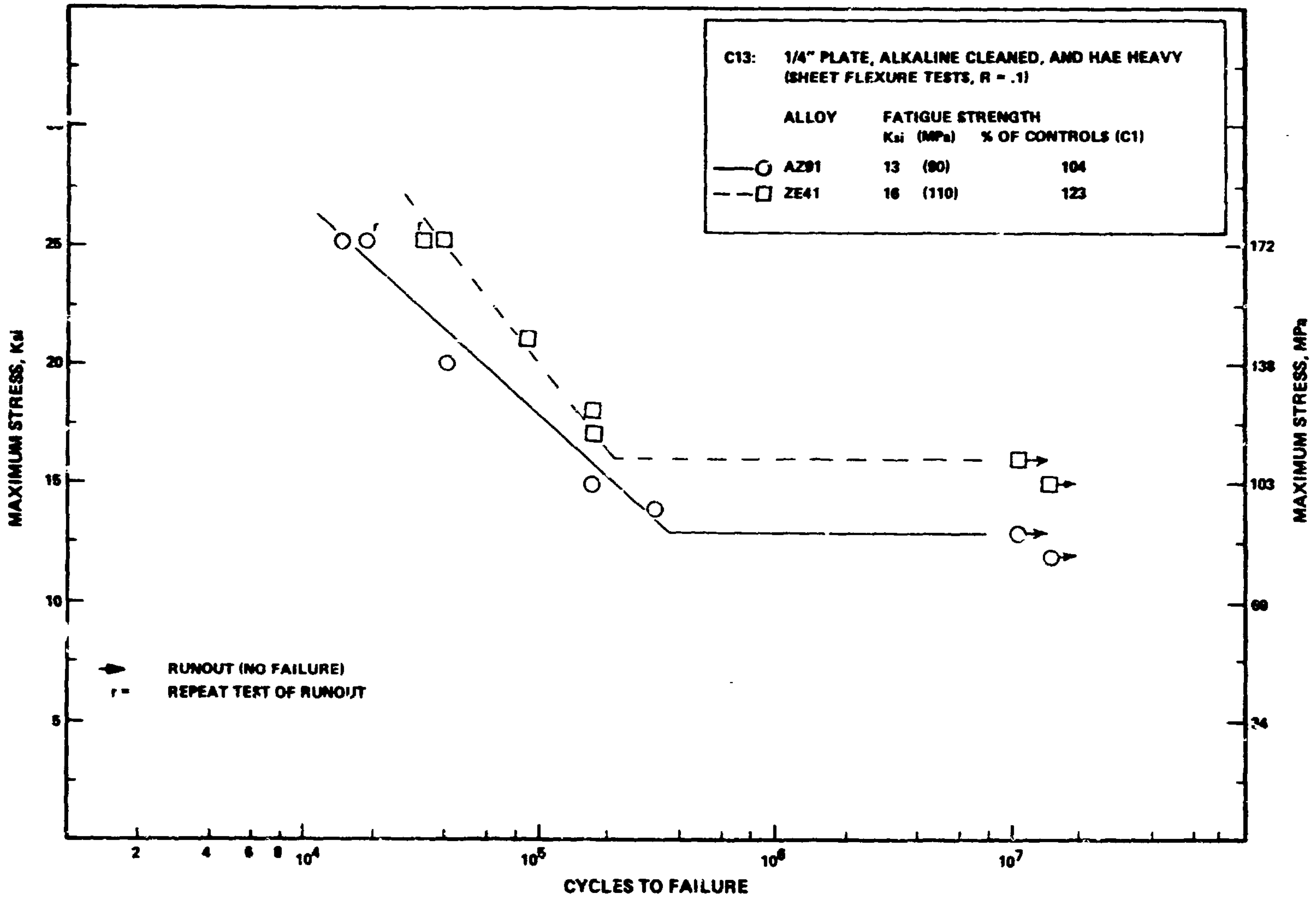
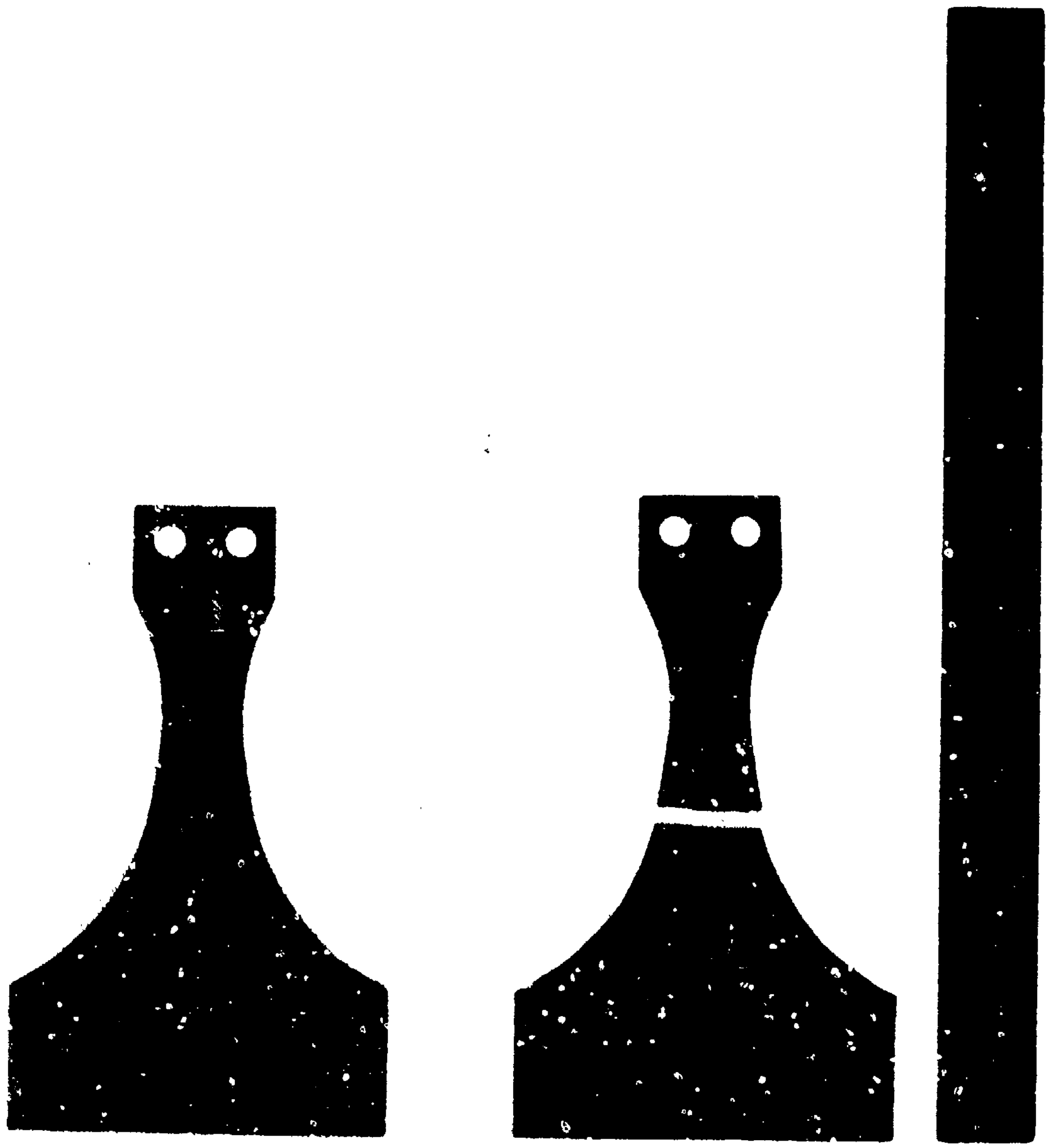


Figure 44 - Sheet Flexure Fatigue Test S-N Curves

Table X

Summary of Sheet Flexure Fatigue Test Results

Condition, C	1	2	3	4	5	6	7	8	9	10	11		12	13
Fatigue Strength														
AZ91 (ksi)	12.5	13	12.5	13	12	10	9	11.5	11.5	11	13.5		12	13
(MPa)	(86)	(90)	(86)	(90)	(83)	(69)	(62)	(79)	(79)	(76)	(93)		(83)	(90)
ZE41 (ksi)	13	15	14	13.5	16	--	--	--	--	--	--		13	16
(MPa)	(90)	(103)	(97)	(93)	(110)								(90)	(110)
% of Controls (C1)														
AZ91	100	104	100	104	96	80	72	92	92	88	108		96	104
ZE41	100	115	115	104	123	--	--	--	--	--	--		100	123
Condition	1	2	3	4	5	6	7	8	9	10	11		12	13
	As-Cast Controls	Alkaline Cleaned	Alk. Cleaned & DOW 7	Alk. Cleaned & DOW 17 Heavy	Alk. Cleaned & HAE Heavy	DOW 7 in Salt Fog	DOW 17 Heavy in Salt Fog	HAE Heavy in Salt Fog	DOW 7 in High Humidity	DOW 17 Heavy in High Humidity	HAE Heavy in High Humidity		1/4" plate, Alk.Cleaned & DOW 17 Heavy	1/4" plate, Alk.Cleaned & HAE Heavy



4-62-3 4-56-1

Figure 45 - Typical 1/8-In. (3.2mm) Thick Sheet Flexure Fatigue Test Specimen and Representative Failure. Specimens are ZE41 Alloy, HAE Heavy Anodic Coated (C5).

Figure 46 - Typical 1/4-In. (6.4mm) Thick Sheet Flexure Fatigue Test Specimen and Representative Failure. Specimens are AZ91 Alloy, HAE Heavy Coated (C13).

4-66-2 (C3)

4-53-2 (C3)

4-56-1 (C5)

Figure 47 - Representative Fractures of 1/8-In. (3.2mm) Thick Sheet Flexure Fatigue Test Specimens With and Without Fracture Initiation at Surface Casting Flaws; All Three Specimens Failed After About 200,000 Cycles.

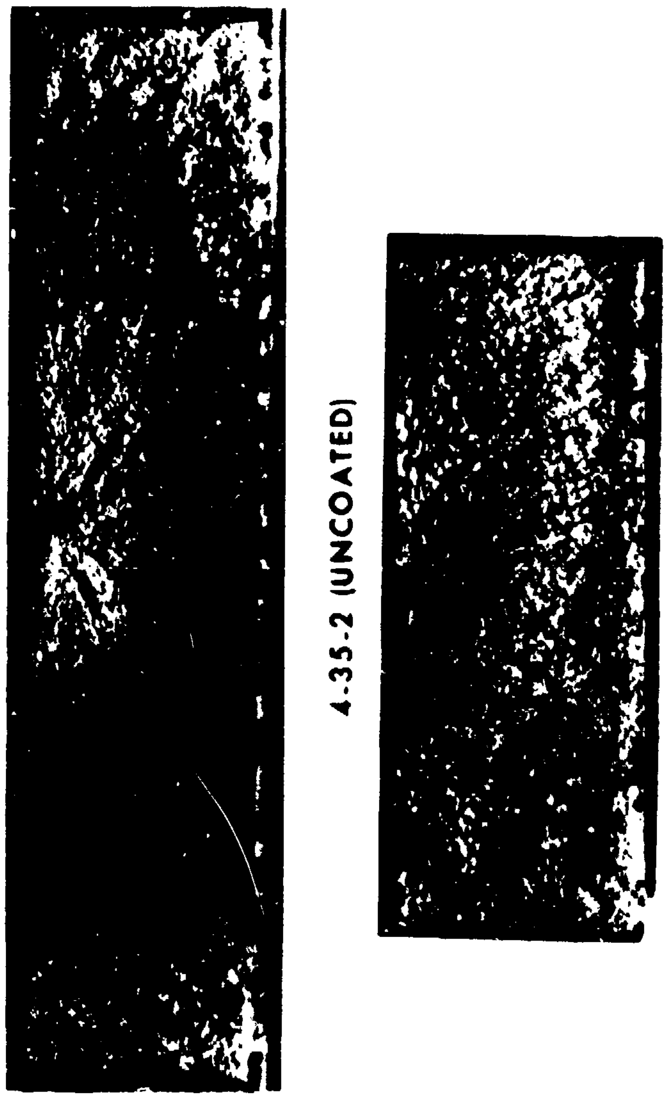


Figure 48 - Representative Fractures of 1/4-In. (6.4mm) Thick Sheet Flexure Fatigue Test Specimens With and Without Fracture Initiation at Surface Casting Flaws.

For the AZ91 alloy, the treated specimens (C2 through C5) showed no discernible effect on fatigue strength compared to the bare control set (C1) (±5%). For the ZE41 alloy, fatigue strength was increased 5 to 25% by the alkaline cleaning and coatings (C2 through C5). The effects of salt fog and high humidity exposure on the fatigue strength of coated AZ91 alloy are shown by the data of tests C6 through C8 and C9 through C11, respectively. Both environments are detrimental - the salt fog exposure significantly so (10 to 30% reduction). The high humidity exposure provided only slight (10%) reduction except with the HAE heavy anodic coating where a 10% improvement actually occurred. Typical surface corrosive damage resulting from these exposures is shown in figures 49 - 52, which also show unexposed specimens for comparison. Figures 53 - 56 present the fracture surfaces of the specimens of figures 49 - 52 showing the surface corrosion and pitting damage - which in some cases caused multiple crack initiation sites.

The large sized, 1/4-in. (6.4 mm) thick, plate specimen data for both AZ91 and ZE41 alloys with heavy HAE and DOW 17 anodic coatings show results consistent with those obtained on the small flexure specimens in regard to fatigue strength and relative worth of the coatings.

DISCUSSION

Pretreatments

Th[illegible]ificant effects of acid pickling and shot peening on substrate magnesi[illegible]igue are clearly shown by the R.R. Moore specimen results. Table XI shows the major influence of these processes: all pickled (unpeened) conditions showed reduced fatigue strength (all changes are "minus") while the peened conditions generally showed increased fatigue strength (most changes are "plus"), irrespective of the follow-up processing or coatings applied. Thus, the dominant influence of pickling and peening compared to the other treatments and coatings seems obvious.

The very deleterious effect of acid pickling on ferrous substrate materials is described and documented by Harris, reference (8), and is attributed primarily to surface roughening - even when no intercrystalline corrosion attack occurs. Surface roughness, as measured in rms, is increased many fold - but also, the nature of the surface roughening, i.e., sharp notches, is very severe. Similar effects are seen to occur with aluminum alloys. Eggwertz and Jarfall, reference (9), describe considerable reduction in the fatigue strength of 7079 aluminum alloy bar stock due to pickling - with or without a following anodic treatment. Both studies cite the time and temperature of pickling as the controlling factors on the magnitude of the subsequent effect on substrate fatigue. Because of these effects, and their dependence on process details, pickling is also seen as possibly providing a significant influence on the variation observed in the R.R. Moore screening test results.

The general benefits of shot peening on metallic substrate fatigue properties are well documented, reference (3); while the beneficial effects in regard to coated ferrous and titanium substrates are described by Jankowsky, et al.,

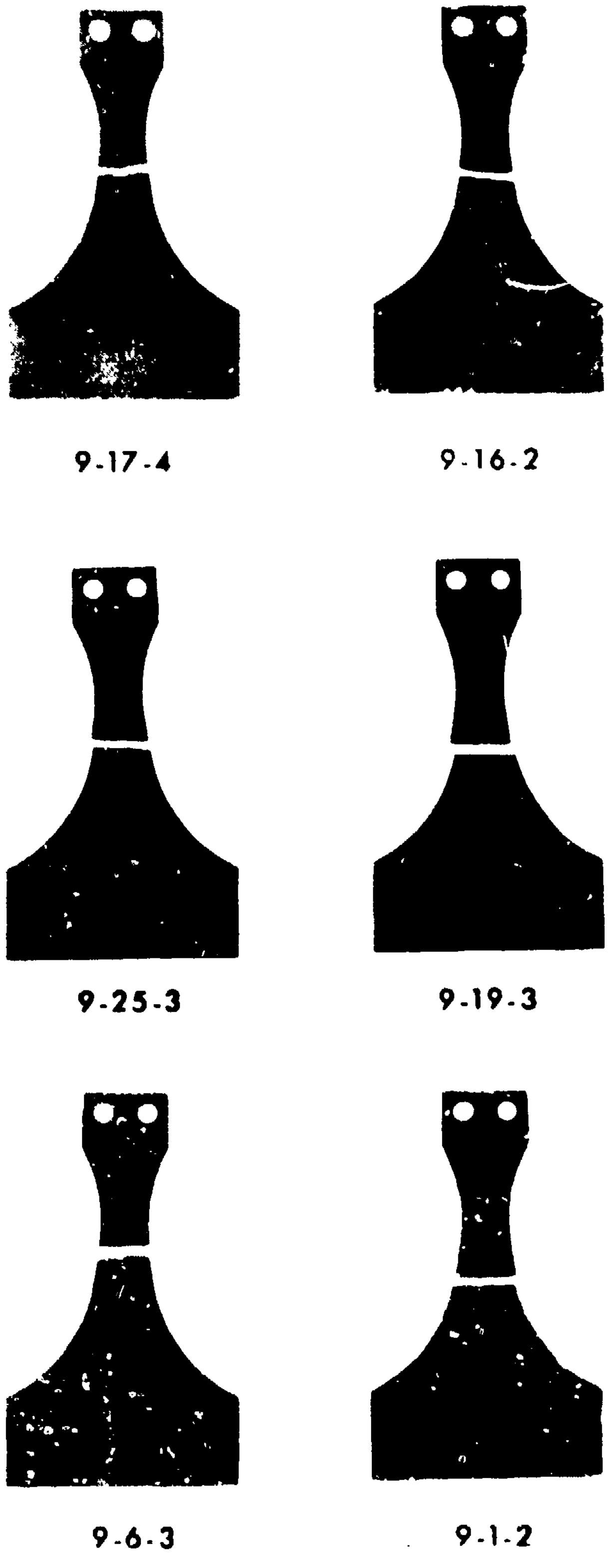


Figure 49 - Exposed (Right) and Unexposed (Left) Specimens With HAE (C11), DOW 7 (C9), and DOW 17 (C10) Coatings (Top to Bottom) Showing Very Little Surface Corrosion After 7 Days in High Humidity Environment.

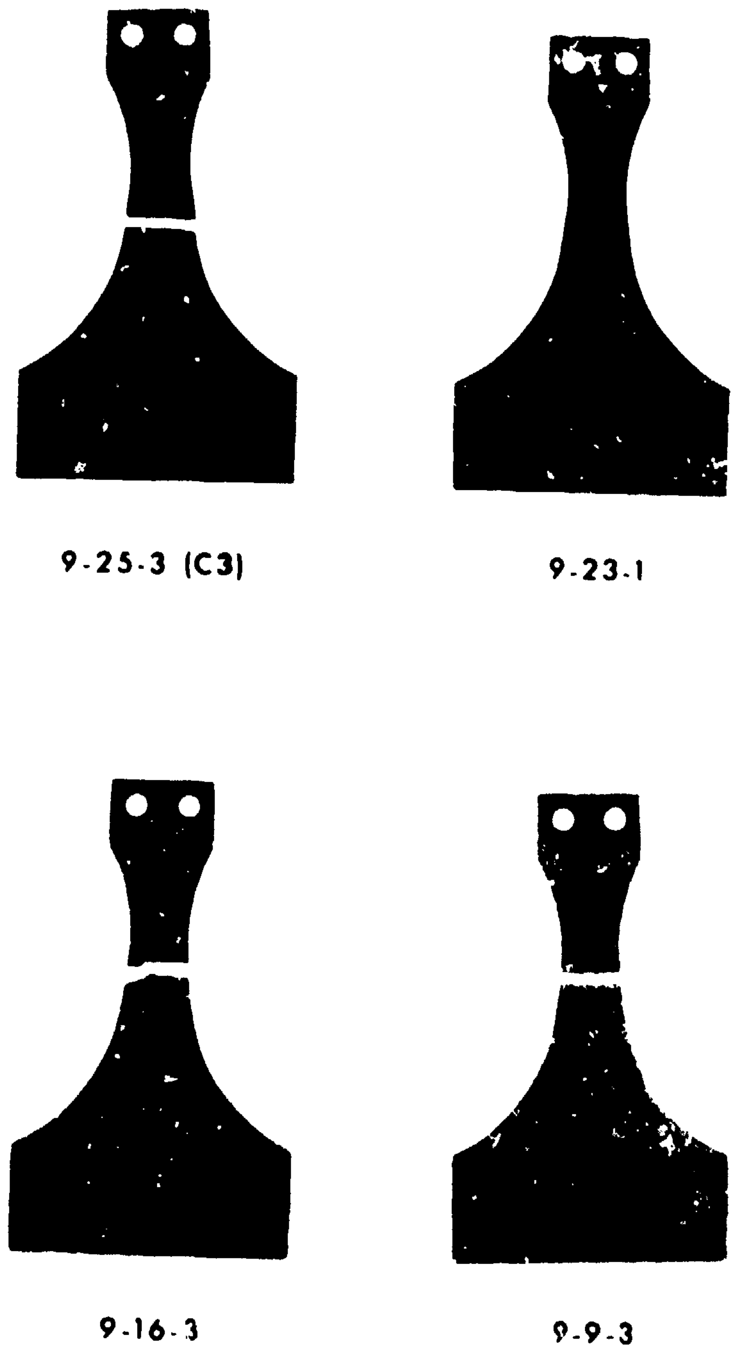


Figure 50 - Exposed and Unexposed (Upper Left Only) Specimens With DOW 7 Coating (C6) Showing Light to Heavy Range of Surface Corrosion Typical After 7 Days in 5% Salt Fog Environment.

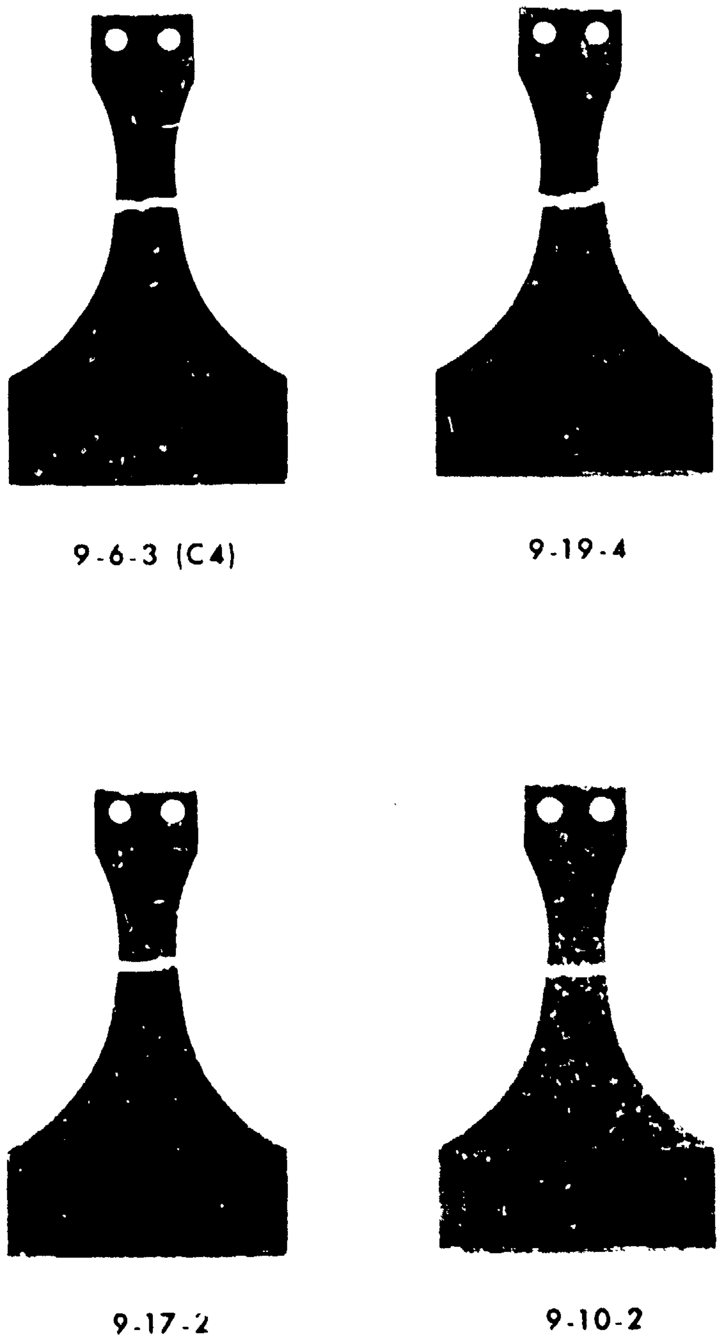


Figure 51 - Exposed and Unexposed (Upper Left Only) Specimens With DOW 17 Heavy Anodic Coating (C7) Showing Light to Heavy Range of Surface Corrosion Typical After 7 Days in 5% Salt Fog Environment.

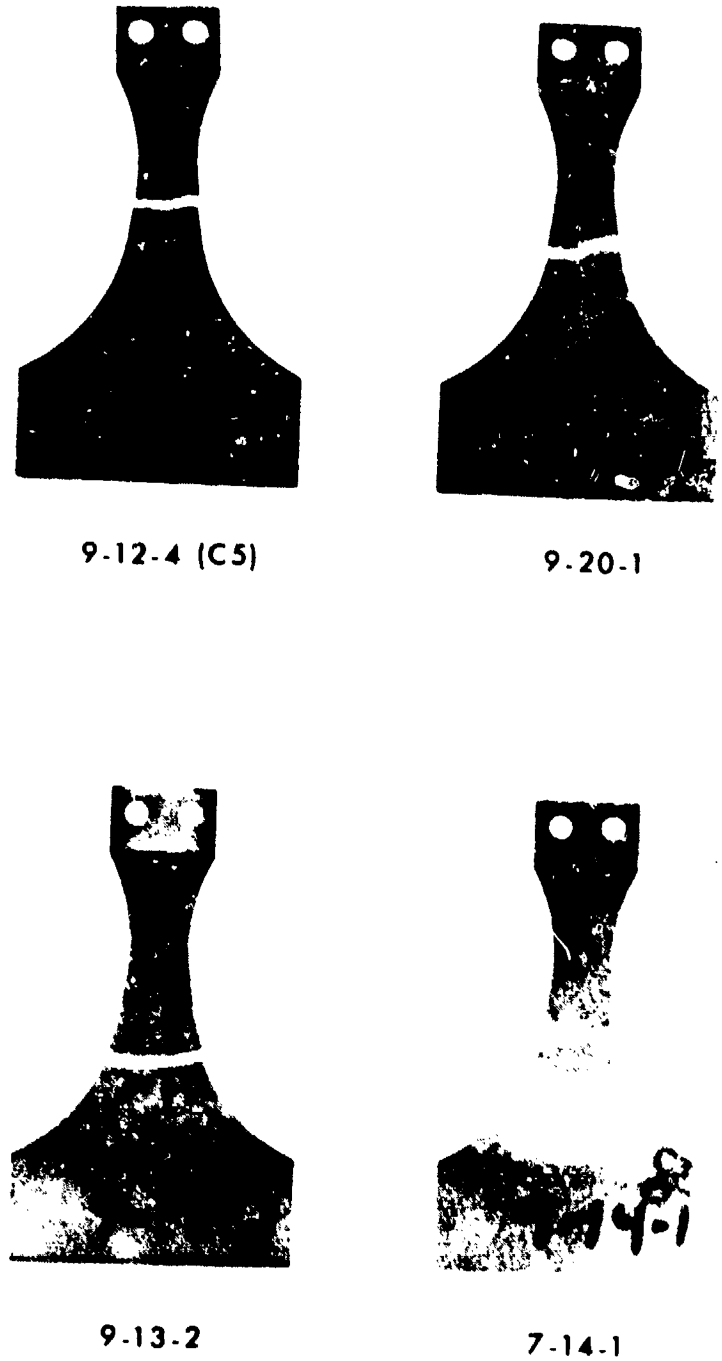


Figure 52 - Exposed and Unexposed (Upper Left Only) Specimens With HAE Heavy Anodic Coating (C8) Showing Light to Moderate Range of Surface Corrosion Typical After 7 Days in 5% Salt Fog Environment.

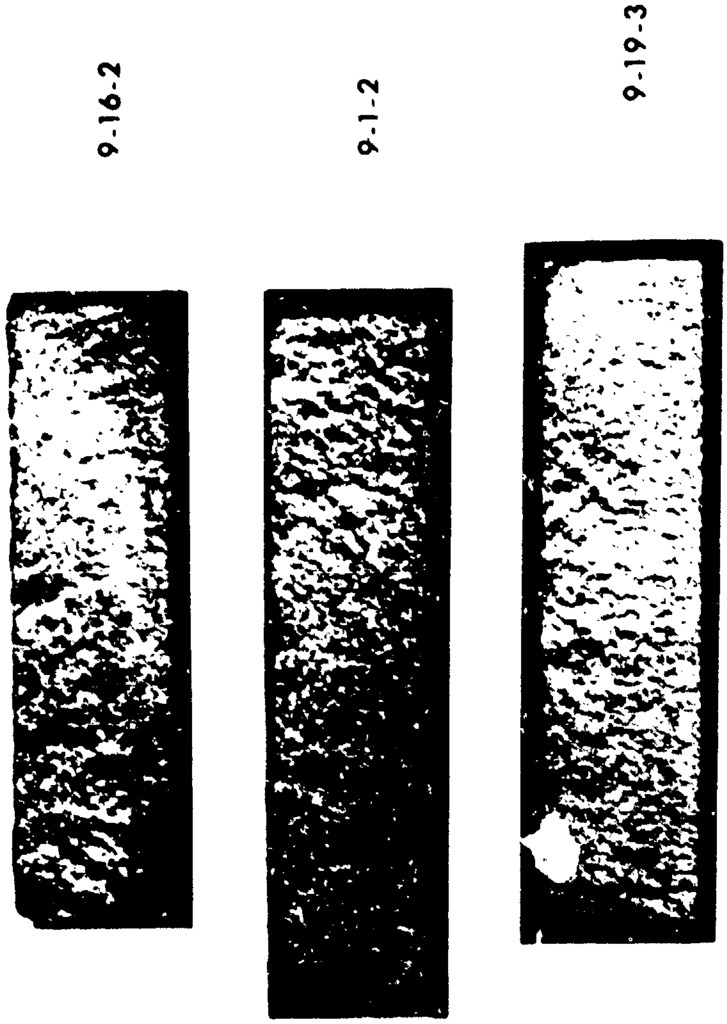


Figure 53 - Fracture Surfaces of the High Humidity Exposure Specimens of Figure 49, With HAE, DOW 17, and DOW 7 Coatings (Top to Bottom).

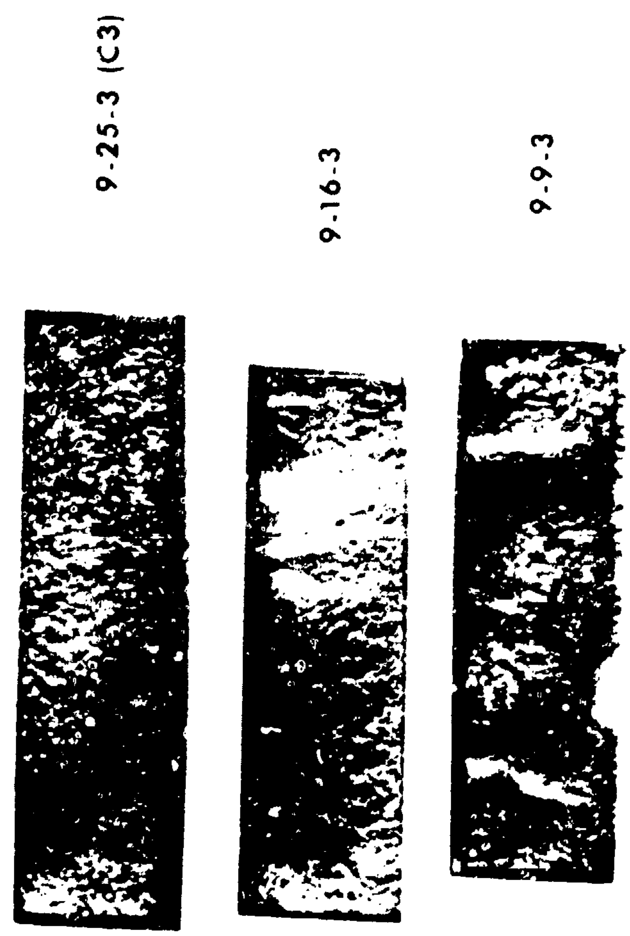
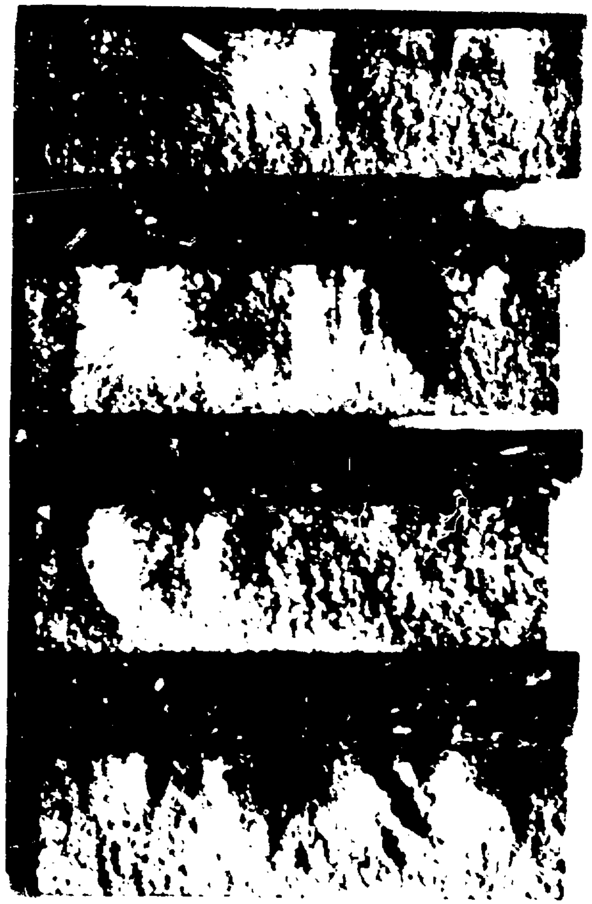


Figure 54 - Fracture Surfaces of the Salt Fog Exposure Specimens of Figure 50, With DOW 7 Coating.



9-6-3 (C4)

9-19-14

9-17-2

9-10-2

Figure 55 - Fracture Surfaces of the Salt Fog Exposure
Specimens of Figure 51, With DOW 17 Coating.

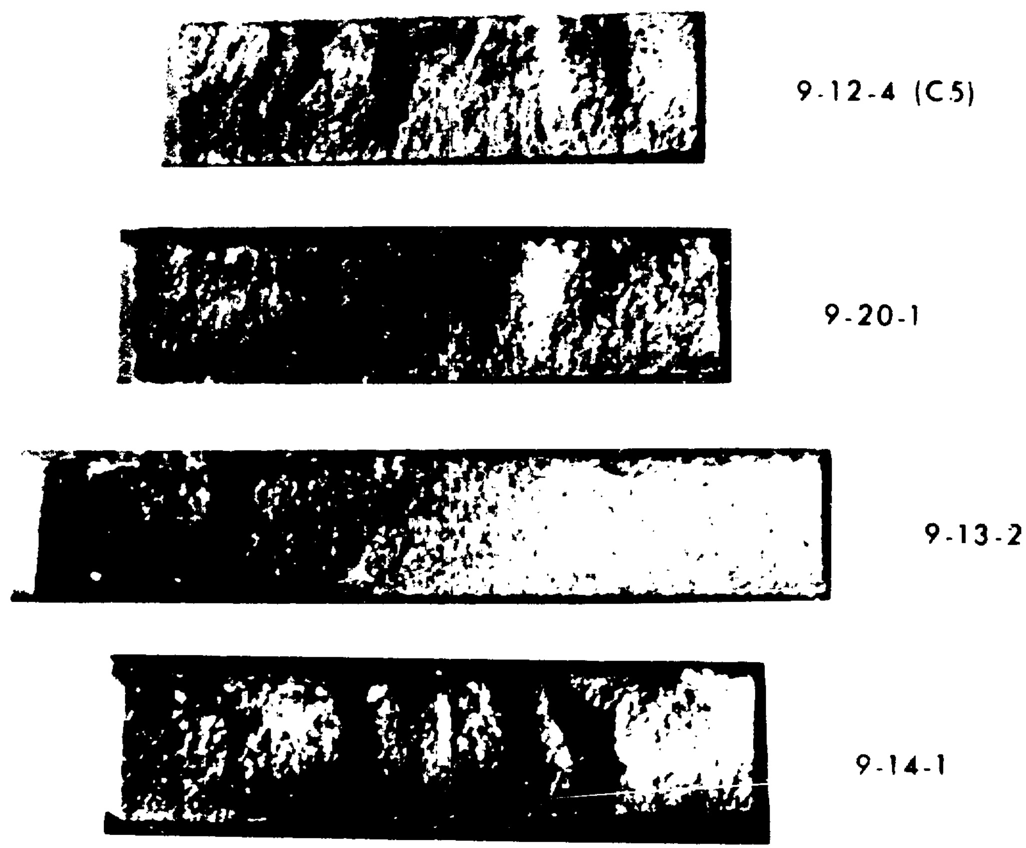


Figure 56 - Fracture Surfaces of the Salt Fog Exposure
Specimens of Figure 52, With HAE Coating.

Table XI

Influence of Surface Preparations and Coatings
on Fatigue Strength of Magnesium Rotating Beam Specimens

Test Specimen Group	% Change from Controls* (M1)		
	AZ-91	ZE-41	EZ-33
As Polished - Control Set	0	0	0
Pickled - only	-20%	-15%	-5%
- Impregnated	-10	-15	-10
- Chromate Coated	-15 to 20	0	-20 to 25
- Anodic Coated - Thin	-10 to 35	-5 to 10	-20 to 35
- Anodic Coated - Thick	-15 to 25	-0 to 10	-20
Peened - only	+25	+25	+35
Peened & Pickled - only	+30	+10	+35
- Impregnated	+20	+20	+10
- Chromate Coated	+10 to 20	+10 to 25	+35
- Anodic Coated - Thin	+20	+0 to 25	+35
- Anodic Coated - Thick	-5 to 10	+15	+25 to 30
- HAE Thick with Topcoats	-10 to +15	---	---
As Polished & HAE Thin or Thick Coated	+15	+10 to 30	-5 to +5

* % increase (+) or decrease (-) in fatigue strength at 20 x 10^6 cycles

reference (4). The literature on shot peening of magnesium is very limited but beneficial effects are also shown to occur provided the peening is done properly, reference (5). Benefits from glass bead peening of wrought magnesium are described in reference (2).

Coatings

It is apparent from the R.R. Moore screening test data that the coatings are generally subordinate to peening and pickling in their influence on the magnesium substrate material fatigue properties. The effects of the coatings, therefore, were not as clearly defined - especially when the previously mentioned scatter factors are considered. Thus, in the screening tests, no coating performed significantly or consistently best, although the HAE coating appeared to have generally better performance. In the sheet flexure fatigue tests on as-cast surfaces, however, the HAE coating more clearly demonstrated better performance over the DOW 17 and DOW 7 coatings - including excellent resistance to the corrosive environments. This is shown in table XII.

Surprisingly, the anodic coatings were not necessarily deleterious to the fatigue strength of these magnesium alloys. Because of the potential surface etching effect and residual tensile stresses and porosity in the as-applied coating itself, these coatings have been considered to be deleterious to substrate fatigue properties. In general, hard surface coatings and electrodeposited metals have a deleterious effect on structural materials fatigue properties, references (4) and (8).

Limited previous fatigue studies dealing with anodic coatings on magnesium also indicated a deleterious effect, references (1) and (2), but did not evaluate the effects of pickling or differentiate between the separate effects of the pickling and the anodic coatings. In this present study, pickling is seen to be the major detriment in the standard application of the anodic coatings with a superimposed separate, lesser effect of the anodic coatings apparently depending upon the substrate alloy and other preconditioning treatments (i.e., shot peening). In this regard, it is noteworthy that in the unpeened anodic and chromate coated R.R. Moore tests of ZE41 alloy very little or no degradation was observed in fatigue strength compared to the bare control set and there was actually improved strength compared to the pickled only data. Similar examples can be seen in some cases of the other alloys and with peened surfaces.

The potential for improvement in fatigue properties possible with the anodic coatings is shown directly by the results of test conditions M24 and M25 where no pickling or peening was utilized. In two alloys, ZE41 and AZ91, the coatings provided significant improvement over bare surfaces. Applied to the EZ33 alloy surfaces, the coatings had no deleterious effect. Perhaps part of this beneficial effect can be attributed to the load carrying ability of the coating in this application since the magnesium substrate strength does not represent a significant mismatch with the coating (that is, the strength of the substrate and coating are comparable) and this might also tend to minimize premature crack initiation in, or propagation from, the coating to the substrate. Protection from atmospheric corrosion also presents a real benefit.

Table XII

Influence of Anodic Coatings and Corrosive Exposure
on the Fatigue Strength of Magnesium
Sheet Flexure Specimens With As-Cast Surfaces

Test Specimen Group	% Change from Controls* (C1)	
	AZ-91	ZE-41
As Cast - Controls	0	0
Alkaline Cleaned - only	+5	+15
- DOW 7 Coated	0	+10
- D[illegible] 17 Thick Coated	+5	+5
- [illegible] Thick Coated	-5	+25
Salt Fog Exposure		
- DOW 7 Coated	-20	--
- DOW 17 Thick Coated	-30	--
- HAE Thick Coated	-10	--
High Humidity Exposure		
- DOW 7 Coated	-10	--
- DOW 17 Thick Coated	-10	--
- HAE Thick Coated	+10	--

* % change increase (+) or decrease (-) in fatigue strength at 10×10^6 cycles

The sheet flexure fatigue tests showed results similar to the R.R. Moore tests with respect to the coating effects - indicating no degradation due to the coatings and possibly some benefit. In this regard, less obvious coating effects would be expected in the sheet flexure tests because the pores and irregularities in the surface of a casting may be the dominating influence.

There is some inconsistency in the coatings data with respect to the relative worth of the various coatings, pre-treatments, coating thickness, etc. Possibly these inconsistencies might reflect variations in the basic coating process details and indicate the importance of these details to the acceptability of the deposited coating. The use of two R.R. Moore test specimen sizes, the subsequent need to process and test in two separate lots, variation in coating thicknesses apparently achieved (table VI), and large variations in surface corrosion damage achieved for each coating during salt fog exposures, all suggest that, even for the same coating, real differences in the processing existed. For aluminum alloys, the importance of the anodic coating process details to subsequent substrate fatigue properties has been reported by Eggwertz and Jarfall, reference (9), and Beitel, reference (10). They have shown that process details such as type of acid bath, bath temperature and voltage, and time of workpiece in the bath are important; and that subsequent substrate fatigue properties are not necessarily degraded - and can be significantly improved.

Thus, while the results of this study do not establish a clearly optimum coating system for these magnesium alloy castings, they do show the minor influence these coatings generally have on the substrate fatigue strength, demonstrate that this influence can be beneficial, and indicate that the influence might be maximized by maximizing the coating process details.

Alloys

Of the three alloys, EA33 showed the least effect of acid pickling and greatest beneficial response to shot peening. It showed the most consistent effect of the chromate and anodic coatings, which was deleterious, but not significantly so in the peened conditions and not at all on unpeened and unpickled surfaces. ZE41 alloy was moderately influenced by acid pickling but had good response to peening. The chromate and anodic coatings were not detrimental - but rather provided improved fatigue strength. The AZ91 alloy was the most degraded by pickling - but showed good response to peening. The chromate and anodic coatings data were the most inconsistent and provided generally deleterious influences which, in some cases were significant. Coating degradation of peened surfaces was worse than for the other two alloys but on bare surfaces increased fatigue strength occurred. Thus, the ZE41 alloy appears to have the best response with applied coatings. In both the screening and flexure fatigue tests, coated ZE41 fatigue strength was greater than for the other two alloys.

ACKNOWLEDGEMENTS

Appreciation is expressed to Mr. W. Worden, Mr. F. Perry, and Mr. J. Stewart who effectively and efficiently handled and tested the very large number of specimens involved with this program. Mr. A. Gallaccio and Mr. M. Pelensky of the Frankford Arsenal provided important technical coordination with the corrosion test phase of the AVSCOM program including the provision of specimen coatings and treatments, specimen environmental exposures, and preliminary magnesium shot peening data. The valuable assistance Mr. J. Rinnovatore of the Frankford Arsenal provided as contract monitor is also recognized.

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