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Hole Coining to Prevent Fatigue Failures

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There are several other mechanical means known for putting compressive stresses in the surface - the most well-known being cold working by surface rolling, abrasive barrel tumbling, and shot peening. Heat treating operations, carburizing, nitriding may also introduce some beneficial stresses into the surface. Further processing of the metal part, such as machining or grinding unbalances these internal stresses and can result in harmful tensile stresses, seriously reducing fatigue strength. Residual stress, therefore, is seen as an agent which can work for you or against you.

COMPARISON TESTS IN COINING OF MONOBLOC AND SIMPLE JOINTS:

Figure 1 illustrates the appearance of a typical coined hole. Note that when the failure eventually occurred it was at a site some distance away from the hole. To show the significant increase in fatigue life from hole coining, S/N curves of coined holes, uncoined holes and plain specimens of flat monobloc type are compared in Figure 2. The coined holes are comparable to plain specimens in respect to fatigue life. This virtually eliminates the stress concentration factor at the hole.

The critical relationships between the many variables which enable coining to induce beneficial residual compressive stress at the hole edge were derived empirically, i.e., by many fatigue tests and photoelastic studies. For each range of material thickness, there is a correct range of values for the following variables.

1. Coining depth
2. Groove radius
3. Distance between coined groove and hole edge
4. Spacing between two coined holes, as well as coined to uncoined holes, relative to the major load direction.

It cannot be too strongly emphasized that if these variables are not exactingly observed, the expected fatigue life improvement will not be obtained. For example, if the coining groove is made too deep for a thin member, the member may be susceptible to internal shear cracking under the groove area as shown in Figure 3. Tool misalignment could aggravate this condition even further. In turn, groove depths too shallow will show no worthwhile improvement in fatigue life. The amount of compressive residual stress that can be obtained for a given groove depth is dependent upon groove radius. The greater the radius, the greater will be the compressive stress. There is definitely an optimum range of groove depth in relation to material thickness.

HOLE COINING TO PREVENT FATIGUE FAILURES

INTRODUCTION:

Functional needs of modern aircraft and missile components demand that metals work harder and more effectively than ever before. Metals react to stresses imposed upon them whether by manufacturing processes or by service, and when the stresses are repeatedly applied, the metal may reach its fatigue limit and fail.

How can we give metals a built-in resistance to fatigue? The Douglas Company has used for many years a process designated as "coining." Very simply, it is the impressing of a groove around an opening such as a bolt hole, slot, or window frame.

Essentially, coining produces compressive residual stress adjacent to these high stress points. It is known that serious fatigue troubles have generally been the result of unusually high stress concentration factors existing in significant structural members. One of the primary origins of fatigue failure in structure is associated with holes and cut-outs. These holes may be bolt and rivet attachment holes; passage holes for control line, plumbing or other equipment; or access doors and windows. These locations represent a stress concentration and the effect of the concentration can be severe. A major step toward improving the overall fatigue life of any structure, therefore, can be achieved by improving the detailed fatigue resistance of the hole itself. Coining is offered as a means of significantly improving fatigue life without adding additional weight and without necessitating major design changes. Failures may not occur at the same locations in coined structural specimens as in comparable uncoined specimens, since coining often strengthens the vital areas so successfully that failures are ultimately found in regions of lower stress. Coining is the addition of an impressed groove around a hole or other open configuration. A die or rolling wheel is used under pressure to form the groove. The formation of the groove causes displacement of the metal toward the center of the opening. The metal adjacent to the opening is simply forced inwardly so that it is usually necessary to ream out the hole to its original diameter if a fastener is to be inserted.

Both photoelastic and x-ray diffraction studies have verified that a favorable compressive residual stress at the hole edge is the factor in coining which is responsible for the fatigue life improvement. Under cyclic tension loading of structure it is a well recognized fact that control of residual stress is an important factor in the control of fatigue strength, i.e., a residual compressive stress lowers the applied mean stress and hence the fatigue life is improved. Designers are becoming increasingly aware that residual tensile stresses sometimes rob them of some of the potential strength of load-carrying members.

The directions of the principal stresses induced by coining are circumferential and radial with respect to the hole. Inside the coining circle, both principal stresses are compressive. Outside the coining circle, the circumferential stress is tension and the radial stress is compressive. The magnitude of the surface stresses are graphed in Figure 4 and illustrate this relationship.

Fatigue tests show that coining substantially improves the fatigue life, but when the hole spacing or the edge clearance is small, coining can decrease life rather than increase it. It was shown in the preceding figure that tensile residual stresses are produced in the tangential direction in the field outside the coined circle. Therefore, a minimum spacing must be observed between coined holes and also between coined and adjacent uncoined holes.

Because of possible relaxation effects which may decrease the fatigue life improvement of coined hole specimens, fatigue tests were performed on some specimens immediately after hole processing and on others after a delay of approximately one year. S/N curves were derived for aluminum alloy materials 7079-T6, 2014-T6 alclad, 2014-T6 bare, 2024-T4 bare, and 7075-T6. Tests were conducted on both the coined and uncoined conditions for comparison purposes. The fatigue test results are shown in Figures 5 through 9. The comparative fatigue test results on coined hole specimens showed that a delay in testing did not decrease the fatigue life improvement for any of the materials investigated. It was found that coin grooving of both surfaces of material .050" in thickness tended to induce shear cracking. Grooving on <u>one</u> side only, however, of 1/4" holes in 7075-T6 sheet, .050" to .067" thickness, significantly increased fatigue life over that of uncoined specimens while reducing the propensity to cracking. S/N curves are presented in Figure 10.

Recent fatigue tests conducted on titanium alloy 6 Al - 4 V using simple central hole monobloc specimens showed a considerable increase in life for the coined holes versus the uncoined holes. The following fatigue test results were obtained.

Max. Stress K.S.I.	Axial Tension	Hole Size	Cycles to Failure, Uncoined	Cycles to Failure, Coined
60	R = + .2	.25	55,000	~~5×10^6~~
			55,000	4.5×10^6
			59,000	9.8×10^6
				8×10^6 *

* NO FAILURE

Comparative fatigue tests were conducted on specimens which were V-notched and edge-roll coined versus uncoined, and the former showed significant increases in fatigue life. The results and a photograph of the specimen are presented in Figure 11.

The Douglas Company has conducted numerous coined-joint fatigue tests, both simple and complex. A few examples are described here.

In the underwater full scale fuselage tests on the DC-8, machined aluminum window supporting plates were installed both with and without coined edges and holes, for comparison purposes. During testing, cracks originated at the uncoined window attach holes beginning between 30,000 and 40,000 cycles. Such a crack progressed completely through the plates and into the skin areas, necessitating repair after 60,000 cycles. The first crack in the fully coined window plates was detected (underwater) at 113,079 cycles and had progressed to a length of only 7/16" at 140,405 cycles when the test was terminated.

It is estimated that 140,000 cycles is the equivalent of approximately 40 to 120 years of ordinary service. The coining had substantially slowed up the crack growth rate as well as forestalling any cracking for a long initial period. The retardation of the crack growth rate can be explained by the high compressive field produced by coining.

A typical coined and rolled groove edged DM-8 window is shown in Figure 12.

Fatigue tests of plain, steel-bushed, and coined pin-loaded holes in a 7075-T6 alloy were conducted. The steel-bushed hole contained an average interference fit of .0026". The specimen consisted of a 0.875" thick plate loaded at each end by a 7/8" diameter pin (bolt). These tests were undertaken to improve the fatigue strength of the DC-8 flap support. The fatigue test loading range was a net tension stress of 14,350 psi maximum to 2870 psi minimum and a bearing stress of 34,400 psi maximum to 6,880 psi minimum. The results and the specimen configuration are shown in Figure 13. It is interesting to note that all the plain and bushed specimens underwent complete failure by fracturing at the diameter of the hole normal to the applied load, whereas the coined specimens developed cracks because of bolt breakage at 225,770 cycles. These cracks, which extended from the hole edge to the vicinity of the bottom of the coined groove, were found by visual examination to have undergone little or no propagation at conclusion of testing.

Double strap joint fatigue tests were conducted on 7075-T6 bare material, uncoined versus coined specimens; the fatigue results are shown in Figures 14 and 15. Spectrum loaded fatigue test results of the double strap joint are presented in Figure 16; a substantial increase in fatigue life was recorded for the coined specimens.

Riveted thin sheet joint specimens offer a direct comparison of coined vs. uncoined riveted joints in thin skin. The coining on the skin was on the inside only (opposite the countersink for the upset rivet head). The failures in all cases (coined and uncoined) originated in the rivet holes in the skin at the first row of rivets in the stringer. Improvement in average life of the coined joints was over three times that of the uncoined. A photograph of the joint is presented in Figure 17 with the results of the fatigue tests.

Consider the fatigue tests of an extruded Y-section stringer joint. Coining in this joint as in most others involving complex bolted and lockbolted joints shows displacement of the failure from the original area (edge of lockbolt hole) to some other part of the joint, or the delay of the failure until a greater life has been registered. The failure from the lockbolt hole is displaced in the coined assembly to a fretting failure which starts outside the hole at a higher life. A photograph of this joint is presented in Figure 18 with fatigue test results.

Testing of a series of double shear fatigue specimens, made from an X 2020 aluminum alloy with 3/8" diameter holes, which were both coined and uncoined for comparison purposes, proved the benefit of using the coining process. At a low level of stress, 33,000 P.S.I., an increase in fatigue life of 10 times was obtained on a single load level basis for longitudinal specimens. Tests conducted on specimens which had been subjected to temperatures up to 300°F. for times up to 100 hours indicated that the beneficial results of coining were only slightly reduced by these temperatures or by time-at-temperature.

S/N fatigue curves of these tests are shown in Figure 19.

Coining in complex joints normally does not show the great increases in fatigue life associated with coining of simple unfilled loaded holes. A variety of reasons may be given for the difference. For example, interference fit attachments such as huckbolts normally have a high fatigue life and normally fail outside the hole from fretting, so coining may or may not improve the fatigue life of such an attachment hole. In addition, many other factors are normally present in joints to obscure the effects of coining. In general, if an uncoined joint is failing from an attachment hole which on subsequent test specimens is coined, the life will be at least equal to, and normally somewhat greater than, before coining and the failure will in most cases originate at a different location in the joint.

Summing this up, the use of coining in complex joints tends to protect the particular hole which has been coined and to throw the failure onto the next weakest link "fatigue-wise" in the joint with increases in fatigue life dependent on the relative difference between fatigue concentration factors within the joint. Obviously, a well designed joint with high fatigue life cannot be improved as much as one where the attachment hole represents a high stress concentration compared to all other concentrations in the joint.

To determine whether coining has any effect on the resistance of the high-strength aluminum alloys to stress corrosion cracking, a series of coined specimens were exposed to alternating immersion in salt water. Coining showed no tendency to induce stress corrosion cracking during a 6 months exposure, after which time these tests were discontinued.

The tests described above are but a few examples from the total number of tests conducted over a period of several years. Coining has been incorporated in production in the past on the DC-6/7, and currently on the DC-8. The coining is performed at room temperature after heat treatment and straightening of the part. The equipment used for coining is either the stationary squeezer or the portable squeezer type. Parts with tapers of as great as 10° are readily coined with swivel type coining dies. Figures 20 to 22 show examples of stationary and portable types of tooling.

To sum up, then, coining can markedly increase the fatigue life of structural members if certain established optimum conditions are observed with respect to the following variables:

A. Relationship of groove depth to material thickness

B. Relationship of groove radius to material thickness

C. Distance between groove and hole edge

D. Minimum spacing of coined holes and coined-to-uncoined holes

Extensive tests by the Douglas Company have established an optimum range of tolerances and permissible variations for each of the above relationships as applied for production coining. If these variables are not correctly controlled, the result may be no improvement in fatigue life or even a damaging effect.

The coining process outlined above is a proprietary development of Douglas Aircraft Company, Inc.

FIGURE I. AXIAL FATIGUE SPECIMEN "HOLE COINED"

NOTE: FAILURE OCCURRED AWAY FROM HOLE

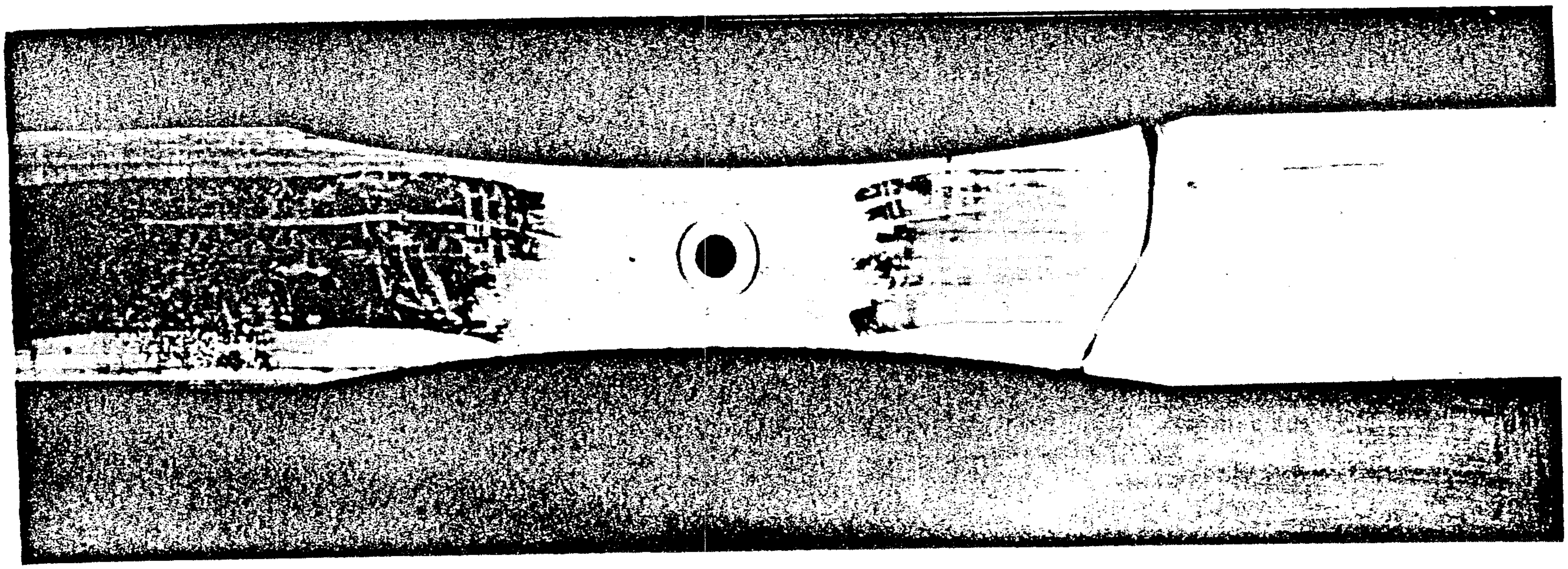


FIGURE 2. COMPARISON CURVE OF 7075-T6, 1/8 IN. THICK EXTRUSION, WITH HOLES COINED AND UNCOINED. STRESS RATIO = +.2

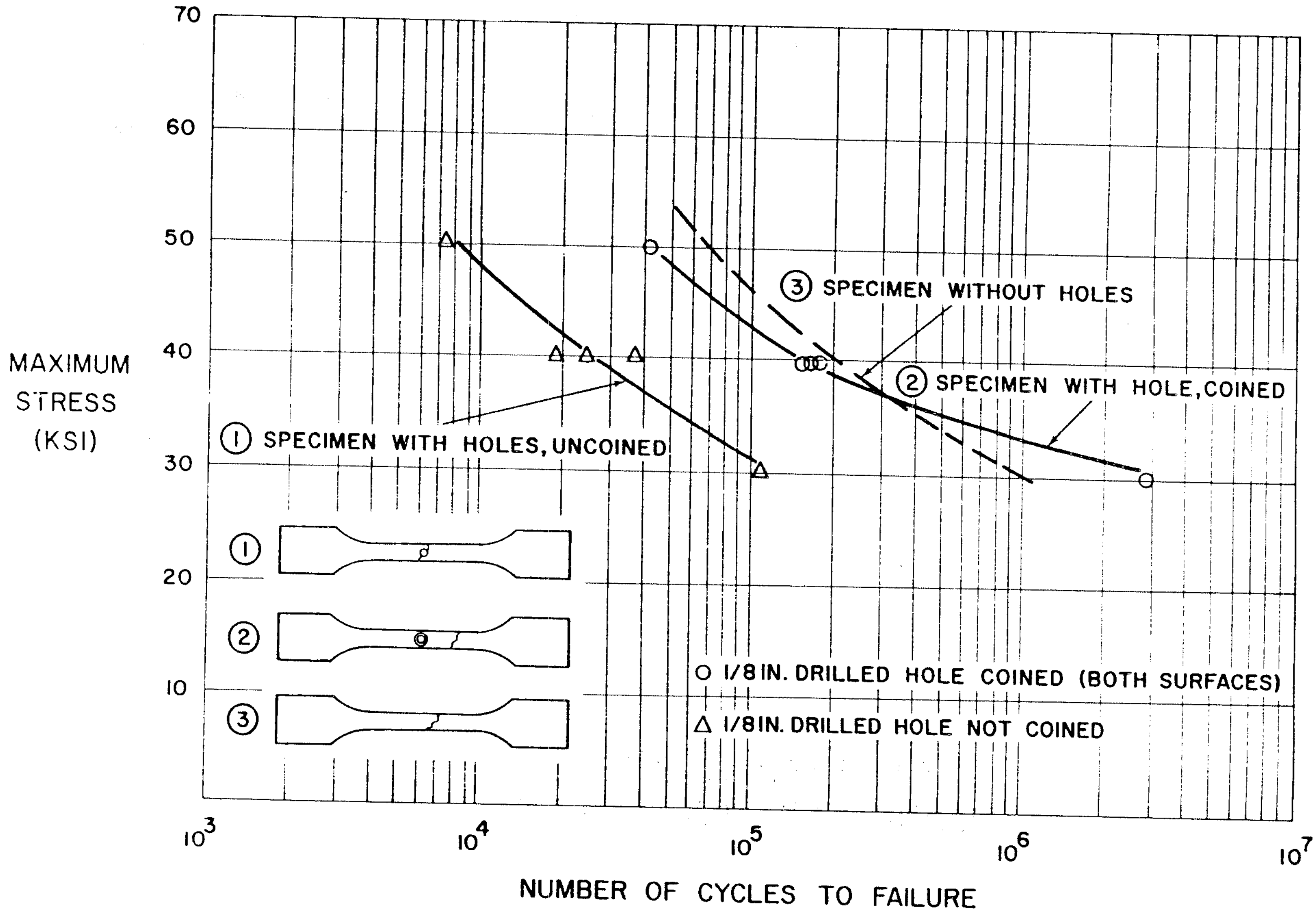
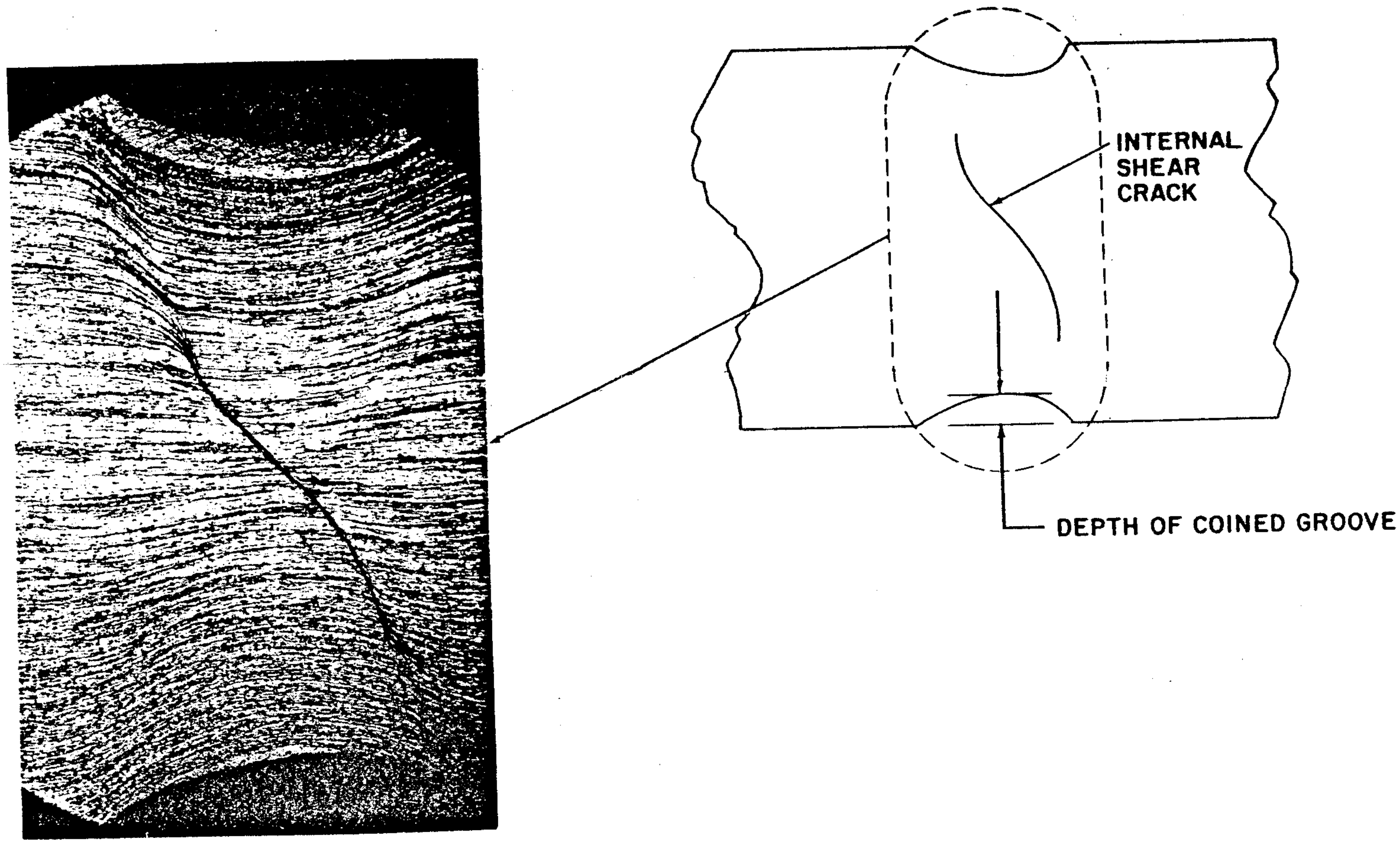
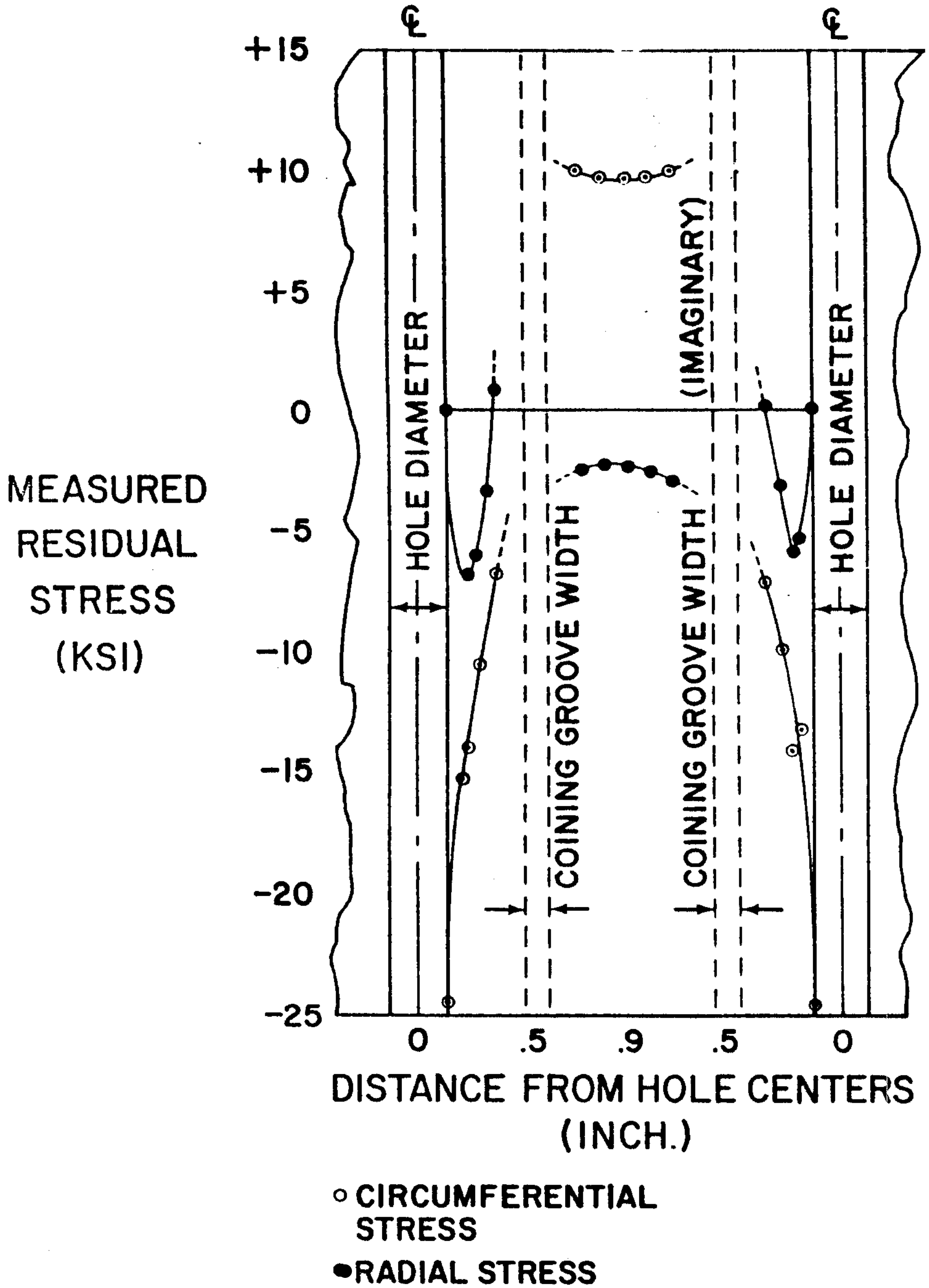


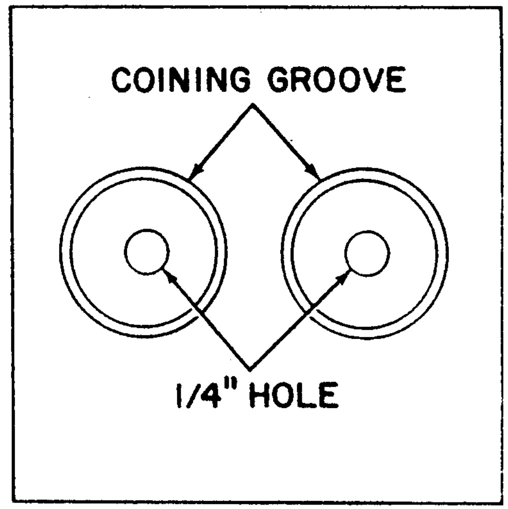
FIGURE 3. INTERNAL SHEAR CRACK



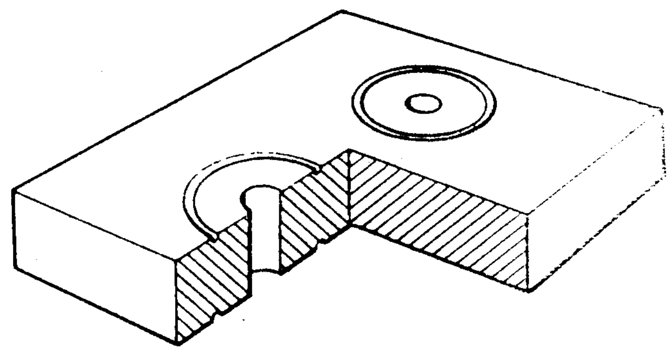
MAGNIFIED 50 TIMES

FIGURE 4. STRESS PATTERN DUE TO HOLE COINING TWO HOLE SPECIMEN.





PLAN VIEW



CUTAWAY VIEW

FIGURE 5. EFFECT ON FATIGUE LIFE OF A ONE YEAR DELAY IN TESTING OF COINED HOLE SPECIMENS.

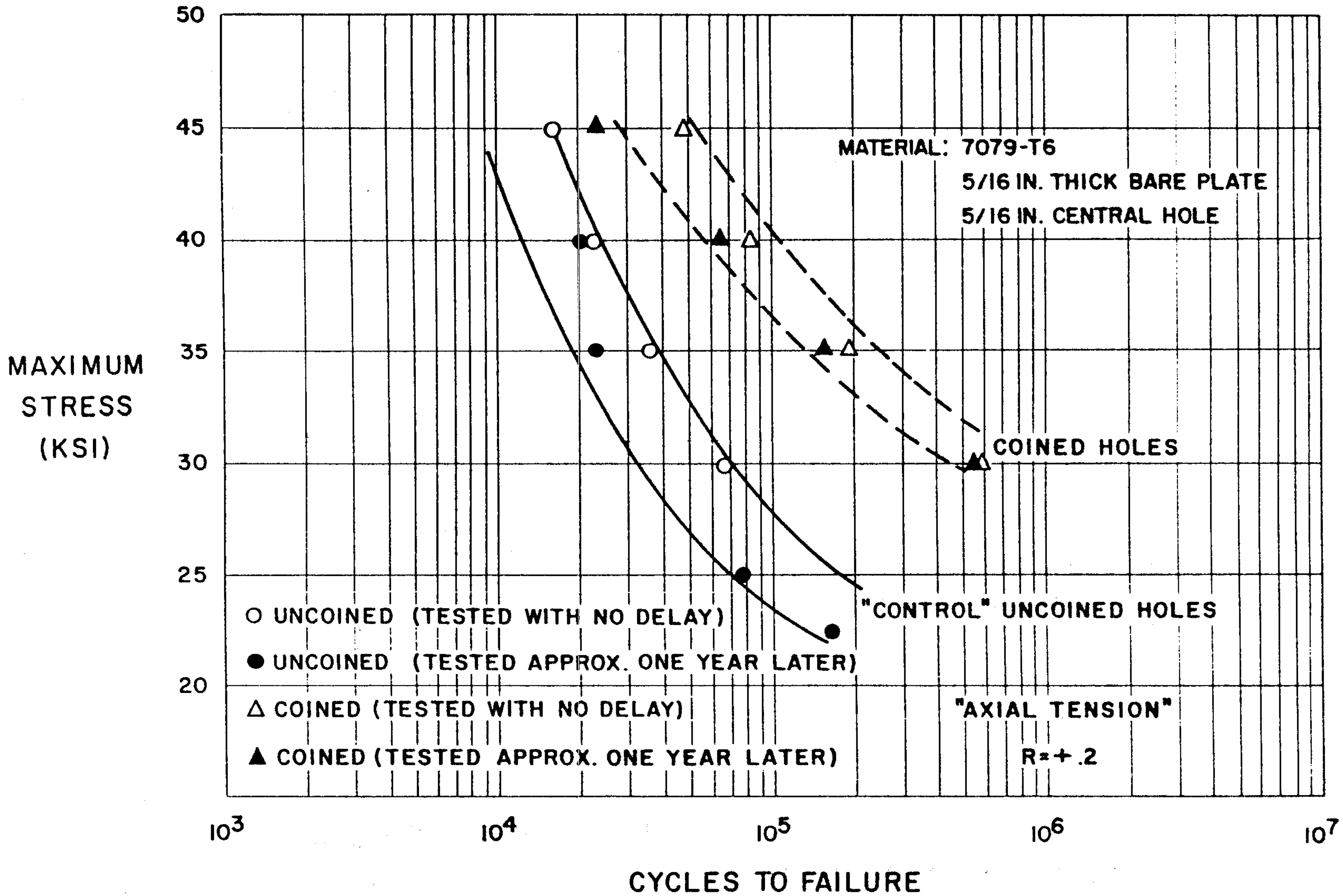


FIGURE 6. EFFECT ON FATIGUE LIFE OF A ONE YEAR DELAY IN TESTING OF COINED HOLE SPECIMENS.

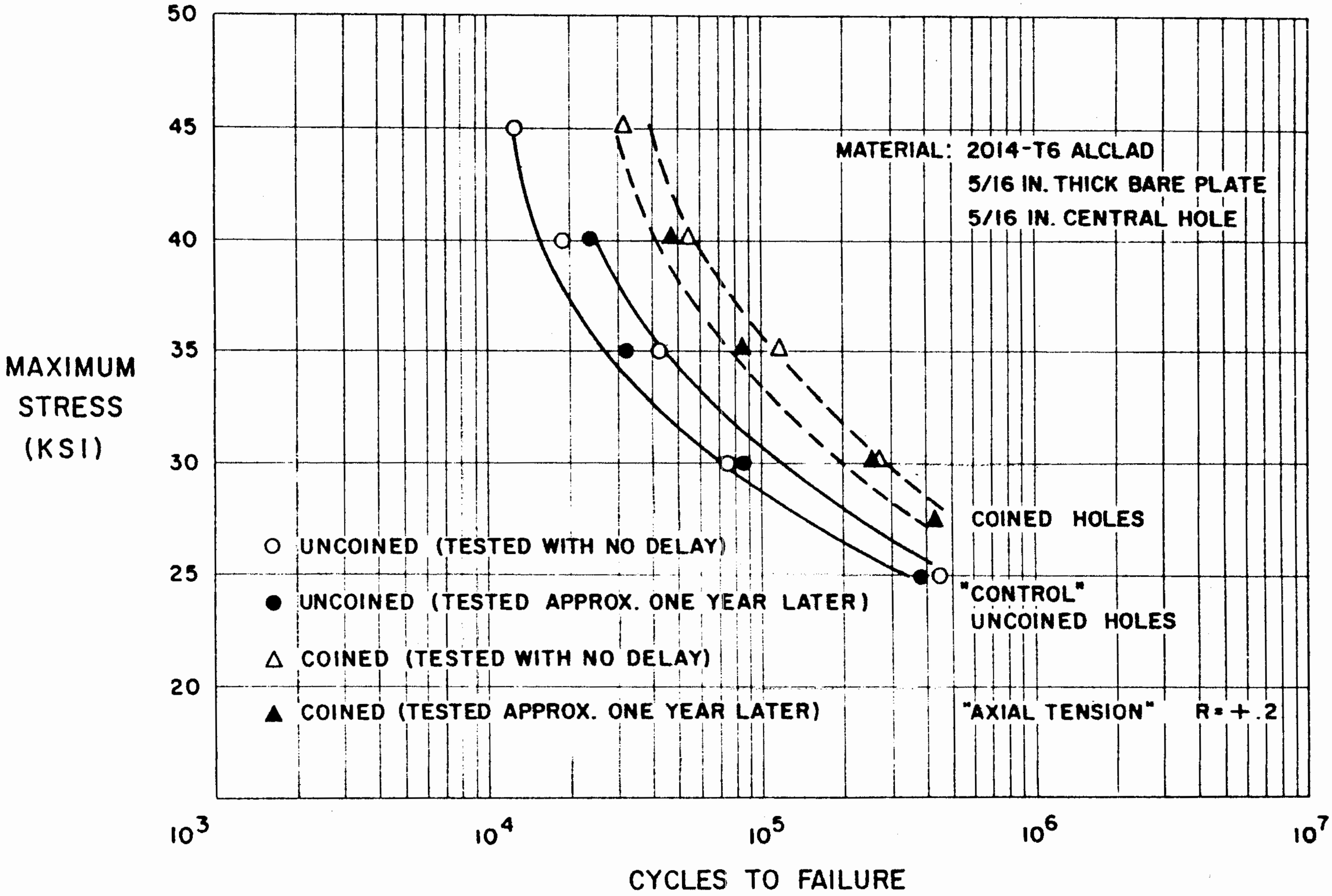


FIGURE 7. EFFECT ON FATIGUE LIFE OF A ONE YEAR DELAY IN TESTING OF COINED HOLE SPECIMENS.

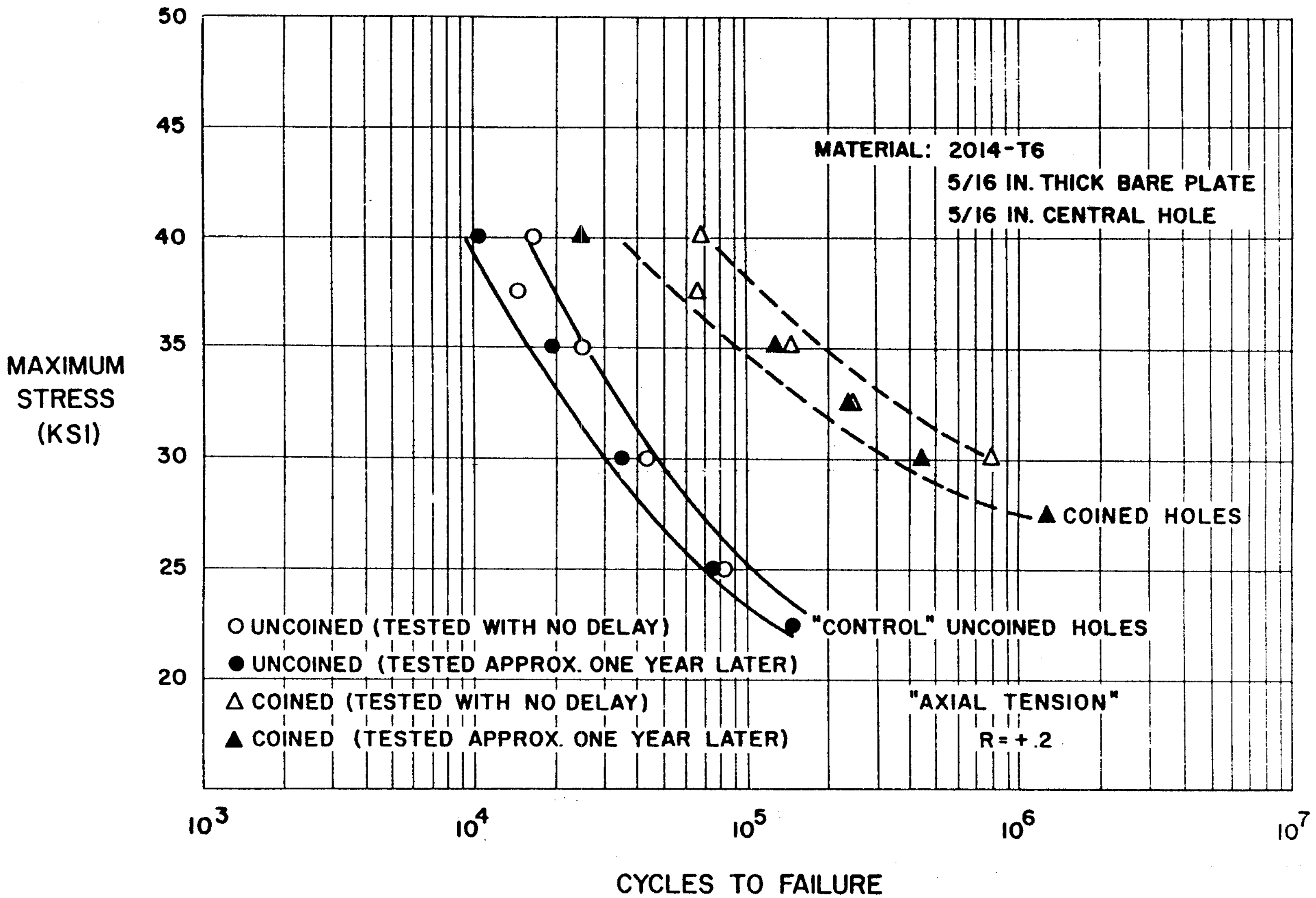


FIGURE 8. EFFECT ON FATIGUE LIFE OF A ONE YEAR DELAY IN TESTING OF COINED HOLE SPECIMENS.

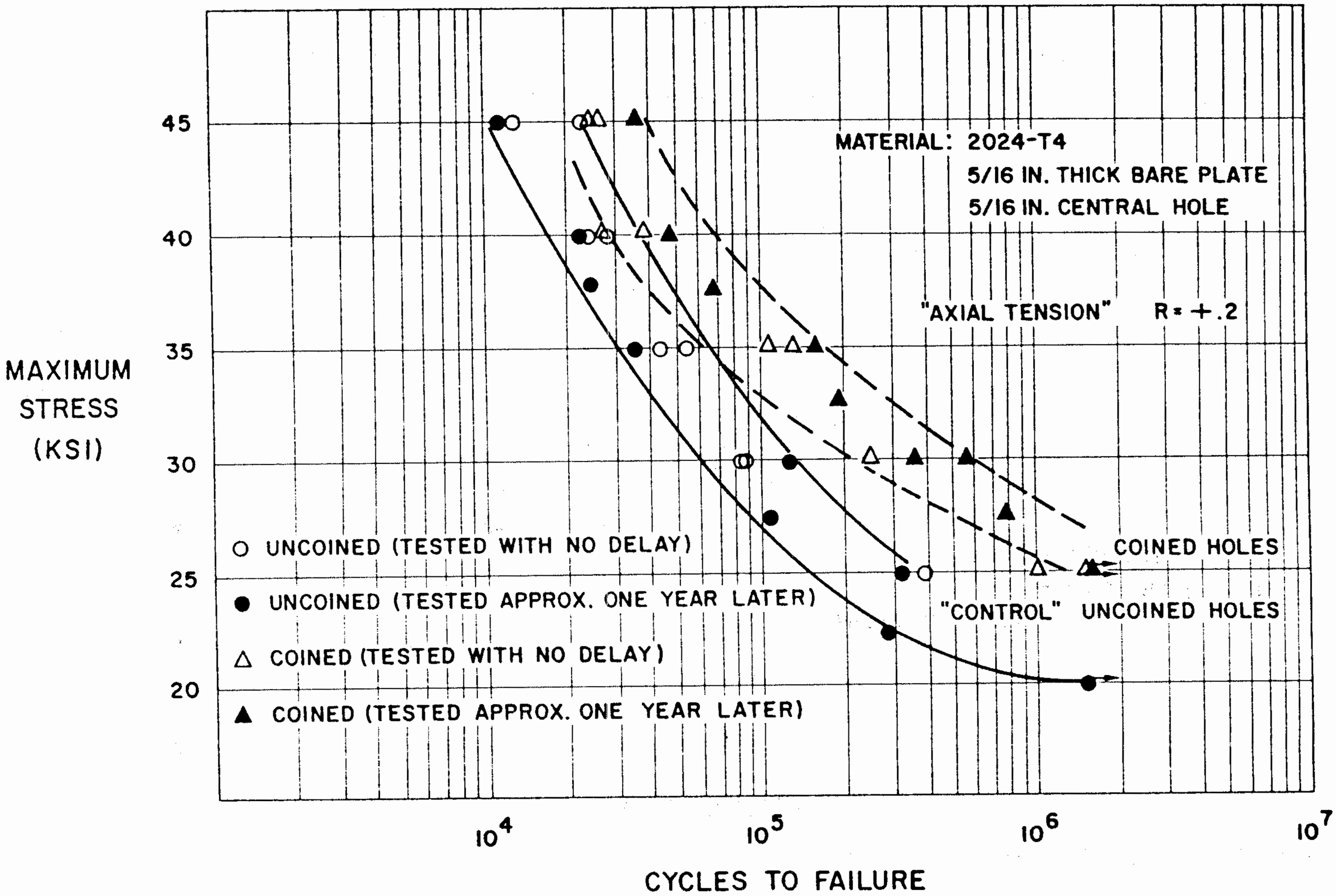


FIGURE 9. EFFECT ON FATIGUE LIFE OF A ONE YEAR DELAY IN TESTING OF COINED HOLE SPECIMENS.

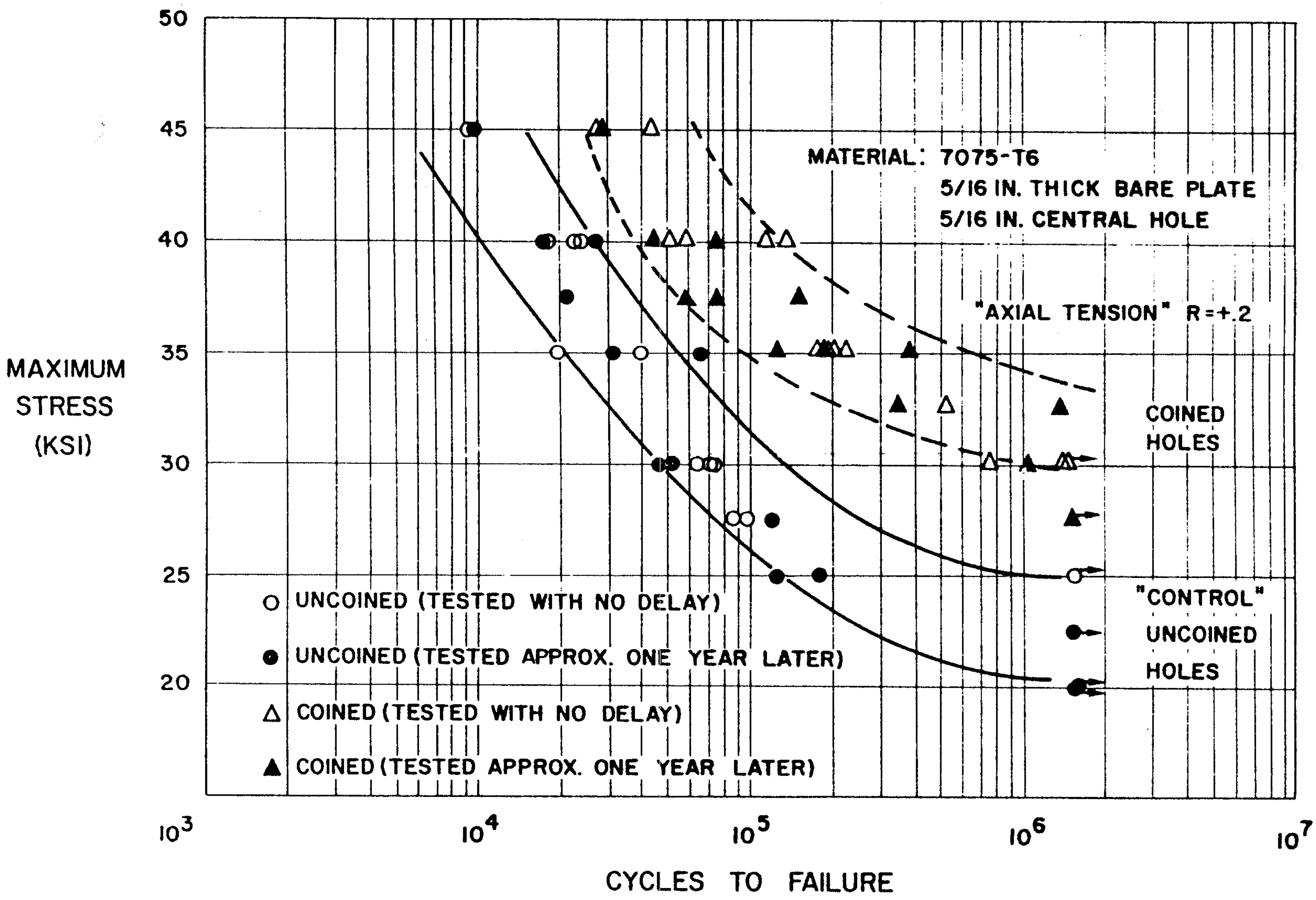


FIGURE 10. EFFECT ON FATIGUE LIFE OF COINING ONE SIDE ONLY ON MATERIAL .050 IN. AND .067 IN. THICKNESS. AXIAL TENSION FATIGUE TESTS "HOLE" COINING.

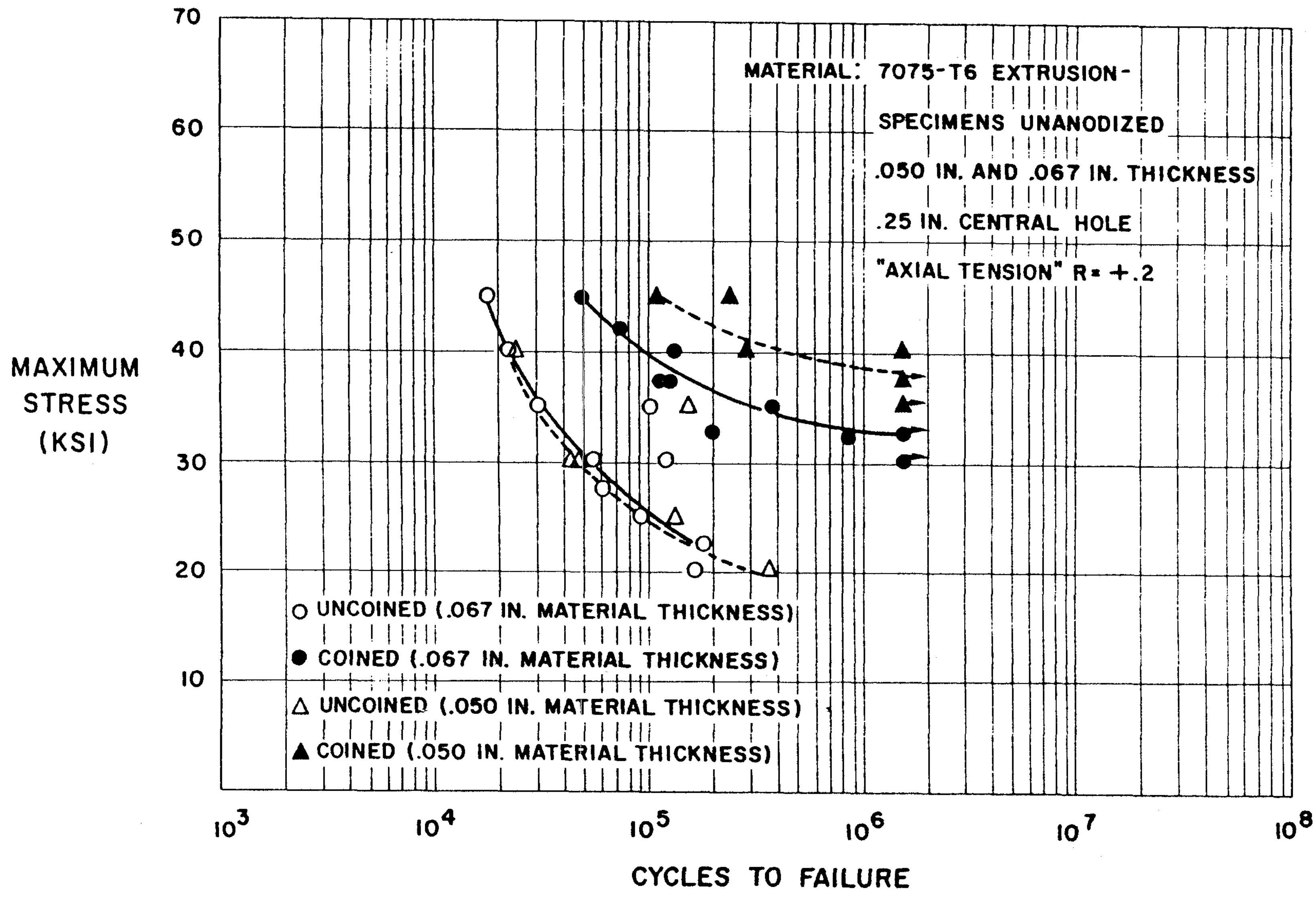
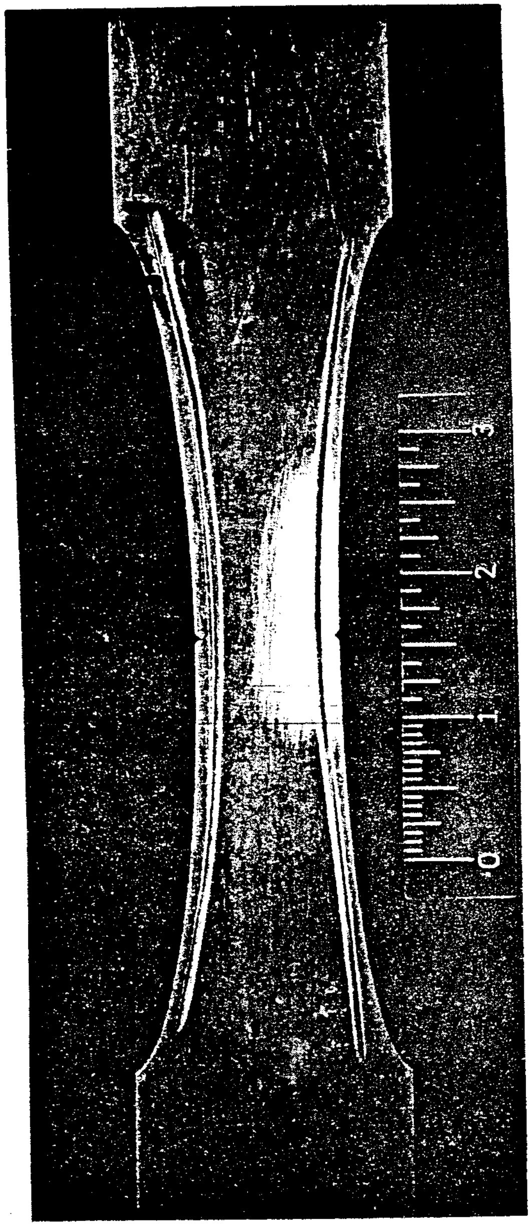
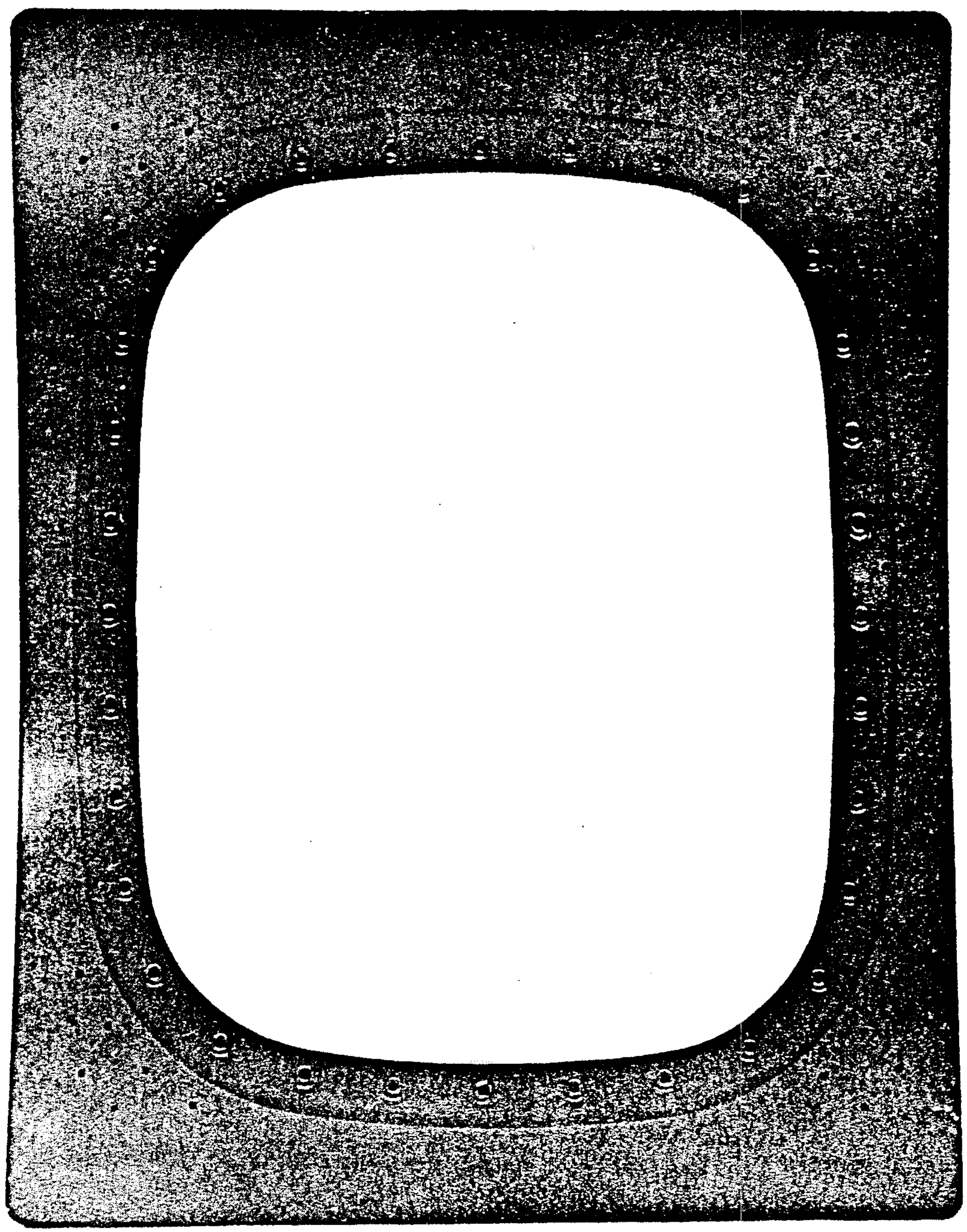


FIGURE 11. ALUMINUM ALLOY 7075-T6 SHEET, EDGE ROLL GROOVED AND V-NOTCHED



"AXIAL TENSION", R= +.2				
MATERIAL THICKNESS	GROOVE CONDITION	NOTCH	MAX. STRESS K.S.I.	LIFE RATIO GROOVED UNGROOVED
.102" BARE	ONE SIDE	V-NOTCHED BEFORE GROOVING	20	>7
.102" BARE	ONE SIDE	V-NOTCHED AFTER GROOVING	20	>20
.102" BARE	BOTH SIDES	V-NOTCHED BEFORE GROOVING	25	>450
.062" ALCLAD	ONE SIDE	V-NOTCHED BEFORE GROOVING	20	>84
.062" ALCLAD	BOTH SIDES	V-NOTCHED BEFORE GROOVING	20	>82

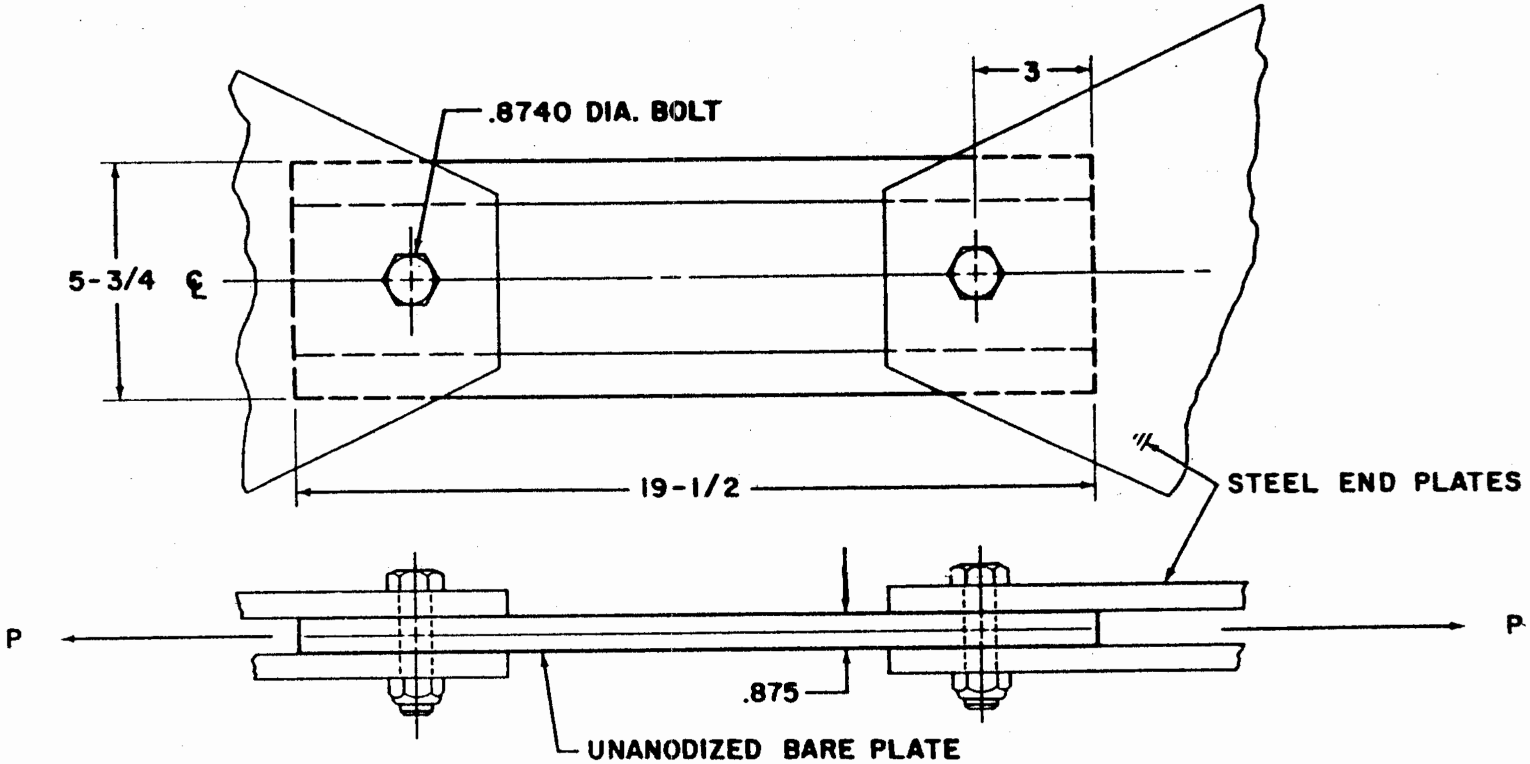
FIGURE 12. COINED AND GROOVED WINDOW DOUBLER, DC-8



UNCOINED DOUBLER CRACKED AT BOLT HOLE, 215,000 CYCLES

COINED AND GROOVED DOUBLER HAD NO FAILURE AT 682,800 CYCLES.

FIGURE 13. SPECIMEN DIAGRAM AND FATIGUE TEST RESULTS.



FATIGUE TEST RESULTS, CYCLES TO FAILURE

	PLAIN, UNCOINED HOLE	BUSHED HOLE	COINED HOLE
1.	18,100	114,970	532,170*
2.	22,810	124,000	862,950*
3.	14,680	95,400	575,750 N. F.

*TEST STOPPED, SMALL CRACKS.

FIGURE 14. COINED FATIGUE SPECIMEN

SPECIMEN MADE FROM BARE 7075-T6

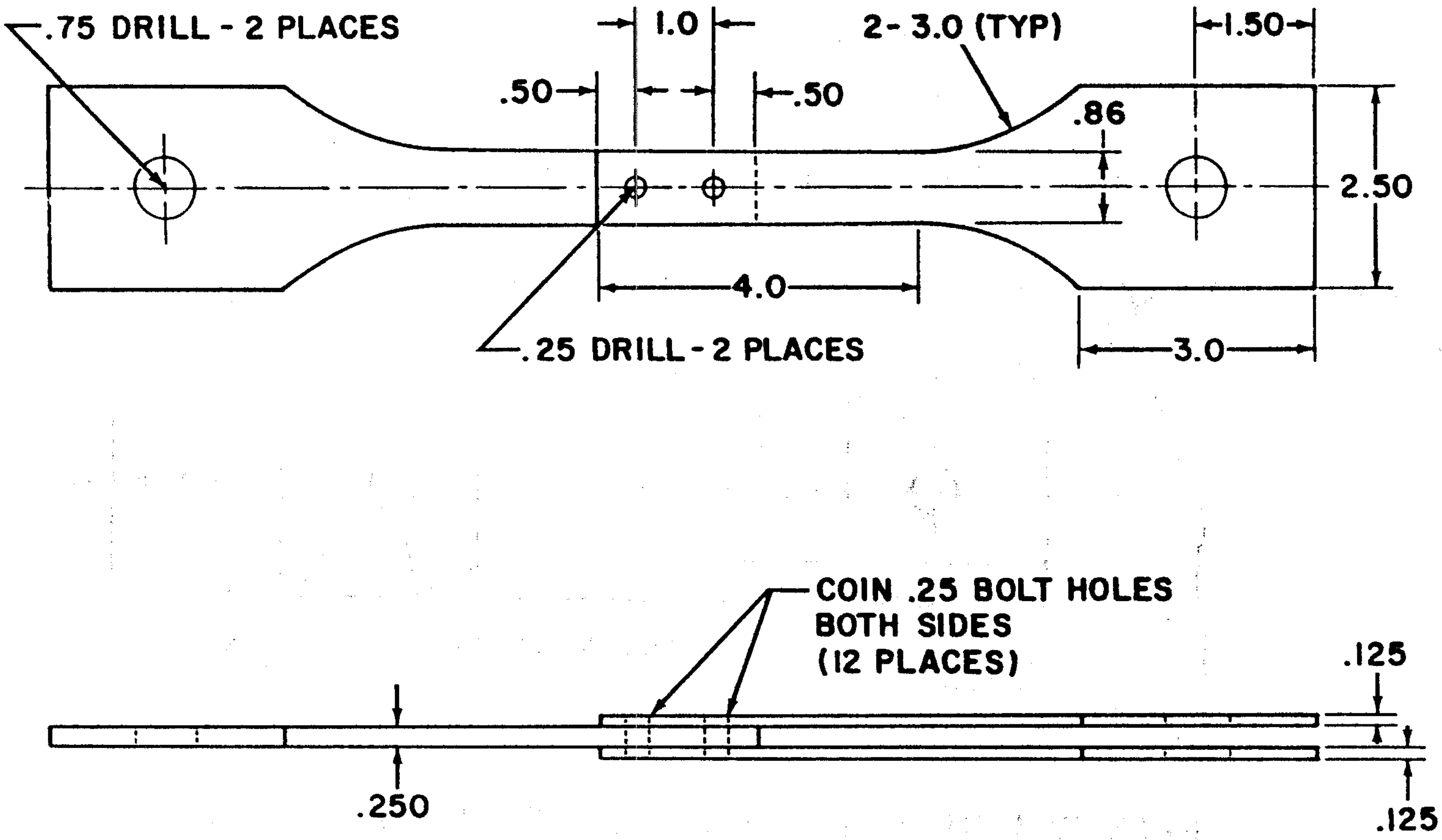


FIGURE 15. RESULTS OF FATIGUE TESTS OF DOUBLE STRAP JOINTS

"AXIAL TENSION" R = + .2

SPECIMENS WITH TWO BOLTS

CONDITION	MAX. STRESS	CYCLES TO FAILURE
UNCOINED	45,000	6,000/12,000
"	25,000	79,000/240,000
COINED	45,000	51,000*/53,000*
"	25,000	182,000*
"	25,000	870,000

LOADED TO YIELD LOAD PRIOR TO CYCLING

CONDITION	MAX. STRESS	CYCLES TO FAILURE
UNCOINED	25,000	267,000
"	45,000	18,000/40,000
COINED	25,000	421,000*
"	44,800	35,000
"	45,000	66,000*

*FAILED AT LOADING HOLE

NOTE: FATIGUE TESTS CONDUCTED BY CHANCE VOUGHT AIRCRAFT INC. DALLAS, TEXAS

FIGURE #16. RESULTS OF TESTS TO FATIGUE SPECTRUM

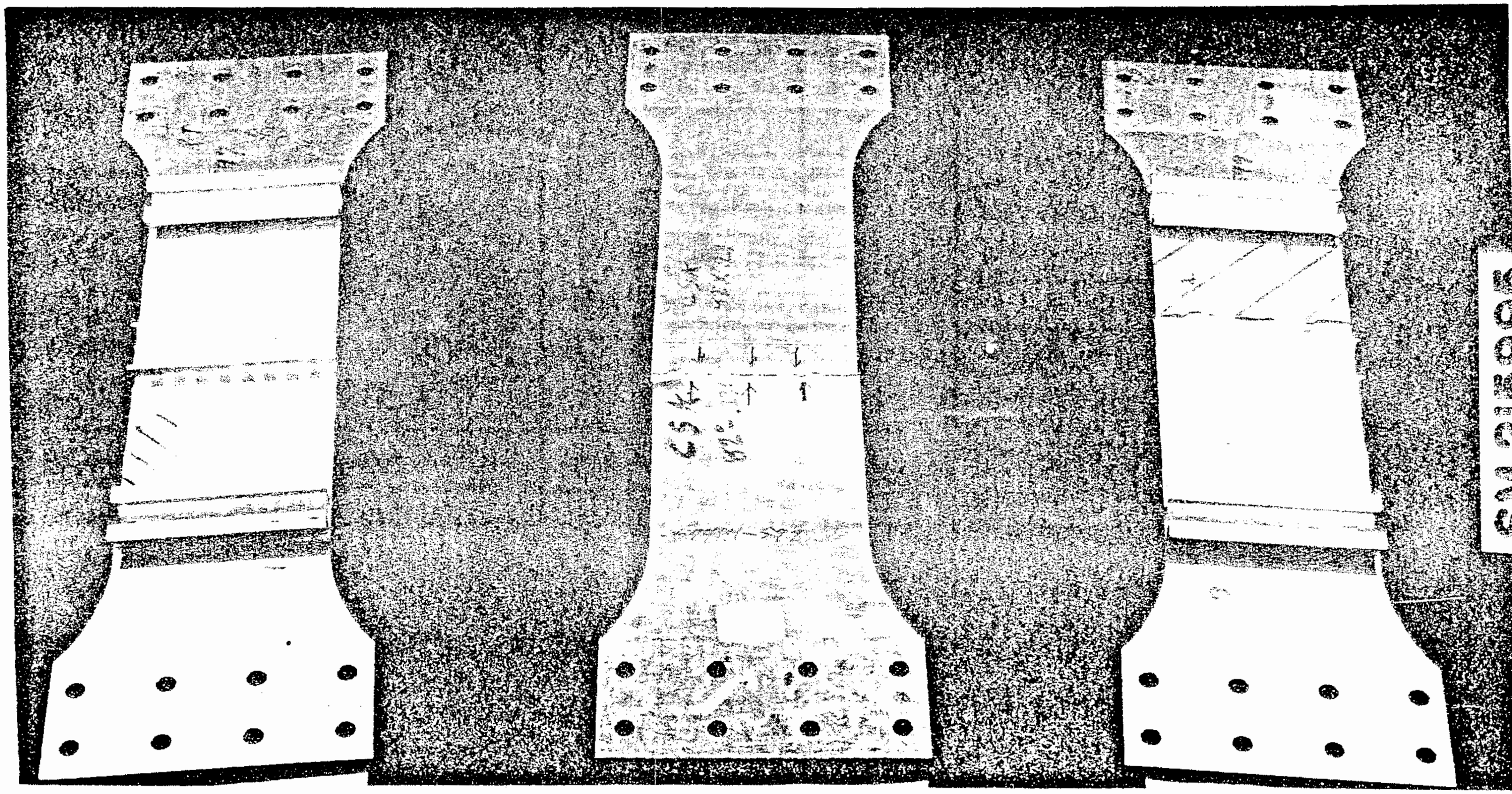
SPECTRUM USED (VALUES FOR ONE BLOCK)

$f_{MAX.}$	$f_{MIN.}$	f_{CYCLES}
45,000	6,750	3
38,250	6,750	17
31,500	6,750	65
24,750	6,750	172

	NO. OF BLOCKS TO FAILURE	
SPECIMENS WITH SINGLE BOLT	COINED	UNCOINED
1. FAILED		192
2. FAILED		194
3. FAILED	392	
4. FAILED	887	
5. FAILED	712	

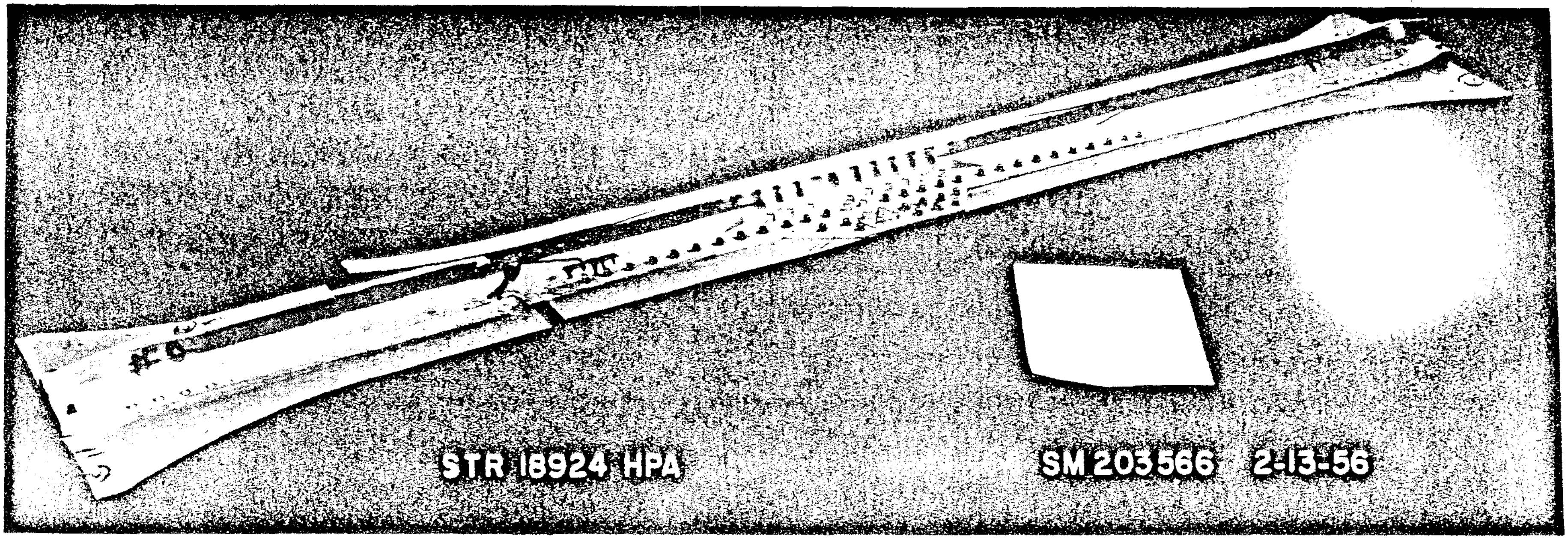
NOTE: FATIGUE TESTS CONDUCTED BY CHANCE VOUGHT AIRCRAFT INC. DALLAS, TEXAS

FIGURE 17 LONGITUDINAL FUSELAGE SKIN SPLICE



PART DESCRIPTION	ALTERNATING STRESS	SPECIMEN	LIFE CYCLES, UNCOINED	LIFE CYCLES COINED
.050 2014-T6 SKIN, .025"	4,400-22,000	1	39,030	
BEADED DOUBLER, 5	PSI GROSS	2	129,010	
RIVETS IN BEADED AREA	AREA STRESS	3	82,270	
(45° BEAD), 7075-T6		4	86,740	
SPLICE STRINGER AD-5		AVG	84,200	
RIVETS		1		312,770
SAME EXCEPT STRINGER COINED		2		244,990
BOTH SIDES AND SKIN COINED ON SIDE OPPOSITE COUNTER		1A		231, 650
		AVG		263, 136

FIGURE 18 Y SECTION STRINGER JOINT



PART DESCRIPTION	ALTERNATING STRESS	SPECIMEN	LIFE CYCLES, UNCOINED	LIFE CYCLES COINED
.125" SKIN, .078"-.125" Y SECTION STRINGER, 1/4 DIA. LOCKBOLTS.	4,400 22,000 PSI GROSS AREA STRESS	1 2 AVG.	109,500 117,500 113,060	
SAME AS ABOVE EXCEPT FIRST THREE LOCKBOLT HOLES IN EACH ROW COINED		1		154,460

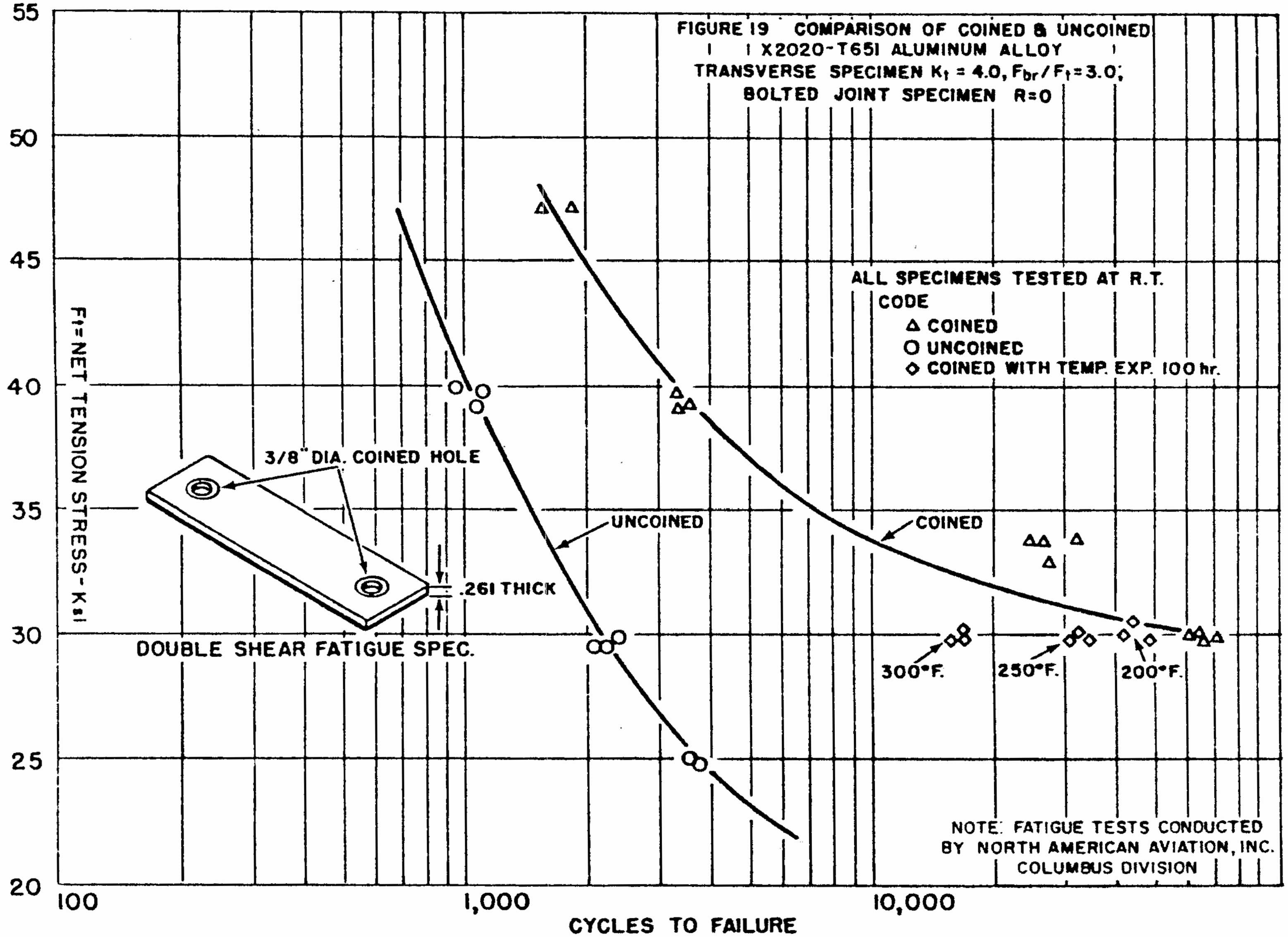


FIGURE 19 COMPARISON OF COINED & UNCOINED
X2020-T651 ALUMINUM ALLOY
TRANSVERSE SPECIMEN K_t = 4.0, F_{br}/F_t = 3.0;
BOLTED JOINT SPECIMEN R=0
ALL SPECIMENS TESTED AT R.T.
CODE
Δ COINED
O UNCOINED
◇ COINED WITH TEMP. EXP. 100 hr.
3/8" DIA. COINED HOLE
.261 THICK
DOUBLE SHEAR FATIGUE SPEC.
UNCOINED
COINED
300°F.
250°F.
200°F.
F_t=NET TENSION STRESS-Ksi
55
50
45
40
35
30
25
20
100
1,000
10,000
CYCLES TO FAILURE
NOTE: FATIGUE TESTS CONDUCTED
BY NORTH AMERICAN AVIATION, INC.
COLUMBUS DIVISION

FIGURE 20. STATIONARY SQUEEZER USED FOR COINING FUEL TRANSFER SLOTS