THE EFFECT OF MODERATELY ELEVATED TEMPERATURE ON THE

FATIGUE LIVES OF NOTCHED $\left(K_T = 4\right)$ SPECIMENS

WHICH CONTAIN RESIDUAL STRESS

By

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Thesis submitted to the Graduate Faculty of the

Virginia Polytechnic Institute

in candidacy for the degree of

MASTER OF SCIENCE

in

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ABSTRACT

Fatigue tests were conducted on notched ($K_T = 4$) fatigue specimens of duplex annealed Ti-8Al-1Mo-1V sheet material (0.050 gage). Additional specimens were subjected to a single cycle of high nominal stress (called stress conditioning) prior to being tested in fatigue. Changes in fatigue lives as compared to the initial tests were noted. Further tests were made in which specimens were exposed to temperature between the stress conditioning and fatigue tests. The three temperatures were laboratory ambient (approximately 70° F), 300° F, and 550° F. The changes in fatigue life with exposure duration are noted for each temperature.

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IV. INTRODUCTION

During airplane flights at supersonic speeds, certain regions of the airplane will become hot due to aerodynamic friction. Notable of these regions is the wing skin. In addition, normal flight loads may induce residual stresses at points of stress concentration in the wing skin such as rivet holes, cut-out panels for interior access, etc. It is generally accepted that the residual stress in such areas provides a beneficial effect on fatigue life if it is compressive.

Almost all of the literature on the various facets of residual stress covers either room temperature behavior or the behavior of residual stresses at and above 1000° F. Since the approximate wing temperature associated with flight at Mach 3 is 550° F (ref. 8), the literature does not provide information about residual stress behavior in the temperature region of current interest.

The current project was initiated to establish preliminary information about the effect of moderately elevated temperature on the fatigue life of specimens containing residual stress. Notched ($K_T = 4$) specimens of a candidate material for supersonic transport use were used in the investigation. The investigation consisted of three general procedures. In the first, the fatigue life of the specimen was determined for a given fatigue loading. Secondly, a single cycle of high nominal stress was applied to other specimens prior to the fatigue test (which process will be termed stress conditioning throughout this report). The resultant change in fatigue lives due to the stress conditioning was noted. For the third phase, additional stress conditioned specimens were subjected to elevated temperature exposure for various durations prior to the fatigue test. The effect of the temperature cycle on the fatigue lives of the stress conditioned specimens was also noted and these fatigue lives were compared to the fatigue lives noted in the first two steps.

Although this procedure was indirect, it provided an adequate means for determining the effect of elevated temperature on residual stress for the purposes of this investigation.

V. LIST OF SYMBOLS

e	ultimate elongation of material measured on a 2-inch gage length after fracture, percent
E	modulus of elasticity of material for tensile loading of virgin specimen, ksi (see fig. A-1)
E'	modulus of elasticity of material for unloading after prior tensile loading, ksi (see fig. A-1)
E_S	secant modulus of material for tensile loading of virgin specimen, ksi (see fig. A-1)
E'_S	secant modulus of material for unloading after prior tensile loading, ksi (see fig. A-1)
kip	kilopound
ksi	kilopound per square inch
Kp	plastic stress concentration factor for initial tensile loading of notched specimen
Kp'	plastic stress concentration factor for unloading after prior tensile loading
K_T	theoretical elastic stress concentration factor
N	fatigue life, cycles
S	nominal applied stress, ksi
TUS	tensile ultimate strength of material, ksi
TYS	tensile yield strength of material at 0.2 percent offset, ksi
ϵ	strain, percent
ϵ_r	residual local strain at notch root, percent

ϵ_s	strain associated with secant modulus, E_S, percent
σ	local stress at notch root, ksi
σ_r	residual local stress at notch root, ksi

VI. LITERATURE REVIEW

The existence of residual stresses in metals is a well documented subject (see bibliography). The literature on the subject covers such facets as the development, measurement, redistribution and relaxation of residual stresses. Since the literature covers a diverse field of situations in which residual stresses occur, it seems helpful to classify the situations and accompanying residual stresses in a very general way. For the purpose of the ensuing discussion, the classification consists of a separation of the literature into two broad categories: (a) cases in which the residual stresses are inadvertently introduced such as machining, grinding, forming, etc., and (b) cases in which the residual stresses are intentionally introduced. This thesis will be concerned primarily with the latter category.

The primary objective of purposely introducing residual stresses into a structure is to improve the fatigue resistance of the structure to its service loadings. The improvement of fatigue resistance is accomplished by introducing compressive residual stresses into the fatigue sensitive locations (regions of stress concentration) of the structure. For a structure that experiences predominantly tensile service loadings, the compressive residual stress allows an improvement in fatigue resistance by causing an effective reduction of the service loadings due to the presence of the residual stress.

A number of researchers (refs. 1, 2, and 3) have shown that the fatigue resistance of useful structures can be improved by introducing compressive residual stresses into the structure. Heywood (ref. 1) reported that the fatigue lives of Meteor tailplanes can be increased fourfold if the structure is preloaded to 75 percent of its ultimate static failing load (U.S.F.L.). Heywood also noted that the fatigue lives of simulated structural joints increased by factors of up to ten when tested after preloading.

In a separate investigation at the Australian Defence Scientific Service Aeronautical Research Laboratories (refs. 2 and 3), Ford, Payne, et al., noted a fourfold increase of the fatigue lives of P-51D Mustang wings which had been preloaded in tension to between 85 and 90 percent of their U.S.F.L. The 85 to 90 percent preload range provided the optimum increase in fatigue lives of Mustang wings.

Other investigations (refs. 4, 5, and 6) have been made of the effect of residual stress on the fatigue lives of simple notched specimens as opposed to real structures. The results of these investigations also show that fatigue characteristics may be improved by the introduction of compressive residual stresses.

Rosenthal and Sines (ref. 4) have shown that the fatigue limit (at 10^7 cycles) of specimens of 61S-T was increased by approximately 30 percent due to prestressing. These specimens were prestressed in axial load and subsequently fatigue tested in bending. Rosenthal and Sines also conducted the same type of tests on annealed specimens of 61S. The effect of the prestress on the fatigue lives of the annealed specimens was much less than the effect on the heat treated alloy.

In another investigation, Taira and Murakami (ref. 5) report a progressive increase in fatigue limit proportional to the prestress magnitude for specimens of medium carbon steel (S45C). Taira and Murakami concluded that the residual stress introduced by prestressing was the principal factor responsible for increasing the fatigue limit. Taira and Murakami also found by use of the X-ray back reflection technique that the compressive residual stress introduced into their specimens relaxed progressively with fatigue cycling. The relaxation of residual stress was approximately 63 percent after 10^7 cycles at a maximum stress just below the fatigue limit of virgin specimens. At a stress which caused failure of the specimen in 10^6 cycles the relaxation was approximately 66 percent at 10^6 cycles. On the basis of the above two percentages, it seems that the rate of relaxation of the initial residual stress may depend on the amplitude of the fatigue stress. Even though the difference in the above percentages is small, the data reported by Taira and Murakami show a consistent trend.

A number of investigators have stated that the effect of residual stress on fatigue life is similar to the effect of mechanically applied mean stress. As a means of checking the degree of similarity, Morrow and Sinclair (ref. 6) conducted tests on unnotched specimens of SAE 4340. Morrow and Sinclair maintained constant strain limits throughout their tests and noted that the mean stress decreased as a function of the number of applied strain cycles. They also showed that the effect of cycling on the imposed stress varies with the hardness of the material being tested for applied stresses higher than the fatigue limit. The stresses decreased faster in the softer materials. The observation was made that the softer material undergoes a larger amount of plastic strain deformation per cycle and consequently accumulates more plastic strain deformation during a given number of cycles; the accumulation of plastic strain was proposed as the mechanism which allowed the mean stress to decrease.

The above discussions show the amount of effort that has been expended by researchers to learn the effects of residual stress on fatigue. This thesis is intended to allow recognition of another interesting facet of residual stress behavior.

VII. MATERIAL AND SPECIMENS

Material

The material used in this investigation was Ti-8Al-1Mo-1V titanium alloy in the duplex annealed condition. The duplex annealing procedure consists of heating to 1450° F for 8 hours, furnace cooling, heating to 1450° F for 15 minutes and air cooling. The heat treatment is applied to the material after rolling to sheet form. All sheets supplied by the manufacturer were of 0.050-inch nominal thickness. Table I lists the material properties pertinent to the investigation.

Specimens

The configurations of test specimens are given in figures 1 and 2. Figure 1(a) shows the configuration used to obtain the ordinary tensile data: ultimate tensile strength, 0.2 percent offset yield strength and elongation. Figure 1(b) shows the configuration used to obtain stress-strain data of the type used to make calculations of local stress. Specimens 1(a) and 1(b) are basically the same except that 1(b) has a shorter test section to increase the buckling strength of the specimen during compressive loading. Figure 2 gives the configuration of the fatigue specimen. The notch configuration represents an ellipse of the same minimum radius. The configuration of the simulated elliptical notch was determined by using the procedure developed by McEvily et al. (ref. 7) and has a theoretical elastic stress concentration factor, K_T, of 4.

The radii at the ends of the notch were made by successively increasing the drill size by increments of 0.003 inch starting with a

No. 35 (0.1100-inch) drill. The small drilling burrs remaining after the drilling operations were removed by rotating a conically shaped rubber abrasive composite lightly against the edges of the drilled holes. The deburring operation resulted in a 0.002 to 0.003-inch radius around the edges of the notch.

VIII. TESTING EQUIPMENT AND EXPERIMENTAL PROCEDURE

Tests for determining the tensile properties of the material were conducted in a 120-kip universal testing machine having a load cell in series with the specimen (fig. 1(a)). Stress-strain curves were automatically plotted by means of an x-y recorder. A signal from the load cell was used to actuate the stress axis on the recorder. The strain axis was fed by the output of a differential transformer (2-inch gage length) attached to the specimen. The ultimate elongation of the specimen was determined by measuring the distance after fracture between grid lines placed on the specimen before the test. All tensile and fatigue tests were conducted at room temperature.

Fatigue tests and cyclic stress-strain determinations were conducted in a hydraulically actuated machine in which loads were controlled through a closed-loop servo system. A schematic diagram of the machine is shown in figure 3 and a picture is presented in figure 4. Load amplitudes are adjustable by means of the electronic signal taken from variable resistors. These variable resistors are hereafter called "load pots." The two alternating-load pots can be preset to allow accurate loading of the test specimen from the first cycle of the test. The mean-load is determined by a third adjustable pot setting. The signal from one of the alternating-load pots adds to that from the mean-load pot and the other subtracts from it. All three of the pots are calibrated to the strain gaged weighbar to allow verification of loading accuracy. For the present tests, a 10-kip capacity weighbar was used.

The accuracy of loading by means of the above equipment is estimated to be within ±15 pounds or ±0.15 percent.

The testing machine may be operated in either a manual or an automatic mode. For fatigue tests the machine was operated in the automatic mode. For operation in the automatic mode, the electronic signal (load command) from one of the alternating-load pots operates the servo valve in the appropriate direction which causes loading to be applied to the specimen and weighbar via the hydraulic cylinder. As the loading on the weighbar increases, the output signal from one of the strain gage bridges (feedback signal) also increases. That signal is added algebraically to the load command which is of opposite polarity. When the feedback signal and the load command are of the same absolute value, the null detector emits a signal activating the solid-state switch. At that time the other alternating-load pot is activated. The signal from the newly selected pot actuates the servo valve in the opposite direction. The test thus proceeds by sequential selection of alternating-load pots.

In manual mode the machine may be used to apply static loads to the test specimen. In this mode the loading may be maintained at a constant value or manually varied in some pattern at the discretion of the operator. The machine was used in this way to obtain the cyclic stress-strain data which will be discussed at a later point. Specimens for these tests were of the type shown in figure 1(b). It was necessary to use guide plates with the specimens to prevent buckling under compressive loads. The guide plates consisted of two 1/4-inch-thick aluminum plates. The plates were shimmed apart at their edges by an amount slightly greater than the specimen thickness and were held together by a row of bolts along each vertical edge. The plates were lined on the inside with oiled paper to allow a minimum of friction between the plates and the specimen. Access holes were provided through the plates in the region of the specimen test section to allow passage of strain gage leads from the specimen to the strain monitoring equipment. The strain was measured on a commercial null-balancing indicator which read directly in microinches of strain. Loading was applied incrementally by means of the test machine. The resultant data were then plotted to give the desired stress-strain curve.

As mentioned earlier, the present work is an investigation of the effect of elevated temperature exposure on the fatigue life of specimens containing residual stress. All fatigue tests for this investigation were conducted at a constant amplitude stress range of 0-50 ksi. Generally, five specimens were tested for each test condition. The data shown in subsequent figures show the scatter limits (tick marks) and the geometric mean life (symbol) of the tests.

The first step was to determine the mean fatigue life at room temperature of specimens at the stress range of 0-50 ksi. The data thus obtained serve as a reference point for comparison with subsequent test results. For the second step, a single cycle of high nominal stress (axial tension or compression) was applied to other specimens which were subsequently tested in fatigue. Hereafter the application of the initial high stress cycle will be referred to as the conditioning of the specimens.

As will be discussed in a later section, the conditioning of the specimens produced a significant effect on the fatigue life. Those specimens conditioned by application of a 100-ksi stress cycle showed the greatest effect of the conditioning. For that reason, only specimens subjected to the 100-ksi conditioning treatment were used in the third (elevated temperature) phase of the investigation. Three temperatures were used in this part of the investigation: (1) laboratory ambient (approximately 70° F) was selected to determine the stability of the induced residual stresses in an ordinary temperature environment, (2) 300° F, and (3) 550° F since these are the approximate structural temperatures associated with flight at Mach 2 and Mach 3, respectively (ref. 8).

Specimen temperatures were achieved by removing them from the test machine after application of the conditioning cycle. Those specimens heated for less than 20 hours were then placed in a preheated "furnace" of the type shown in figure 5. A dummy specimen was put in the furnace during the heat-up and after conditioning of the test specimen, the dummy was removed as the test specimen was inserted. Those specimens heated for 20 hours or more were heated in an air circulating heat treatment oven and were placed there after application of the conditioning cycle. In either case the error in applied temperature from that desired was within $\pm 10^{\circ}$ F. The longest time of exposure to each of the above temperatures was 30 days.

IX. RESULTS AND DISCUSSION

The effect of specimen conditioning on fatigue life is shown in figure 6. The data point in figure 6 plotted at zero conditioning stress is the initial reference point. No conditioning cycles of magnitudes between zero and 50 ksi were applied since magnitudes smaller than the maximum fatigue stress can be expected to have no effect. The remaining data points were obtained by conditioning the specimens as indicated in the figure and subsequently failing the specimens in fatigue. The arrow and number by the symbol at 100 ksi indicate that two specimens tested at that conditioning stress did not fail within 10^6 cycles. Hereafter such specimens are called runouts. Data from runout specimens were not included in computations of geometric mean life. A tabulation of the data represented in figure 6 is given as table II.

As may be seen from figure 6, tensile conditioning increased the fatigue life and compressive conditioning decreased the fatigue life. Tensile conditioning stresses caused the material at the notch to yield appreciably which resulted in compressive residual stresses at the notch when the conditioning stress was removed from the specimen; larger tensile conditioning stresses produced larger compressive residual stresses. The compressive residual stress apparently depressed the local stress at the notch during subsequent fatigue cycling by an amount equal to the difference of residual stresses in conditioned specimens as compared to specimens which were not conditioned.

The residual stress could not be measured directly due to the small volume of plastically strained material at the notch. An estimation of the residual stress magnitude was made, however, by using the method of Crews and Hardrath (ref. 9). The method is reviewed in Appendix A. Table III presents the maximum and residual-local stresses (σ_{max} and σ_r, respectively) calculated by this method for each of the conditioning stress levels used. Also given in table III are the notch strains associated with the notch stresses. The strains were read from a stress-strain curve at the calculated stress.

The same method was used to calculate the local stress behavior occurring at the notch during the fatigue test. In this case the local stress due to the fatigue loading was added to the residual stress already present. The local stresses thus determined and the associated local strains (again from a stress-strain curve) are also presented in table III.

To verify the above argument concerning local stress depression during fatigue due to the presence of the residual stress, the local stress calculations from table III were plotted and are given in figure 7. It may be seen from the figure that for conditioning stress levels above 70 ksi, the local mean stress becomes compressive even though the applied nominal stress range is entirely tensile. The relative depression of the local mean stress with increasing magnitudes of conditioning stress was considered to be the factor responsible for increasing the fatigue life.

Again, as in figure 6, conditioning stress levels between zero and 50 ksi have no appreciable effect on the local stress behavior during fatigue. It must also be noted that the local stress behavior shown in figure 7 is only strictly applicable (a) during the first cycle of the fatigue test and (b) for a $K_T = 4$ specimen fatigued at a stress range of 0-50 ksi.

The fatigue life data obtained after exposing the specimens conditioned at 100 ksi to elevated temperatures are shown in figure 8. Table IV is a tabulation of the same data. At the left side of figure 8 corresponding to zero exposure time are plotted the original reference fatigue life and the fatigue life after application of a 100-ksi conditioning stress cycle. Both points are taken from figure 6. Symbols with arrows and numbers attached again indicate runouts whose lives were not included for computation of the geometric mean life. The time scale has been changed from linear to logarithmic at the 1-minute point so that a more legible representation of the data might be made for the very short exposure times. An additional scale of days has been added to facilitate reading the figure. The three curves in the figure are labeled according to the exposure temperature.

It was noted during the discussion of figure 6 that some specimens conditioned at 100 ksi did not fail within 10^6 cycles. Since after 30 days of exposure at 70° F other specimens also ran out, it seems apparent that the residual stresses induced by the conditioning were stable for that length of time. Another indication of the stability was that the shortest fatigue lives obtained after 10 days and 30 days of exposure at 70° F were not shorter than the lives of specimens tested immediately after conditioning. Exposure to 550° F, however, had a marked effect on the fatigue life even after very short durations of exposure. A similar but less pronounced effect was noted after exposure to 300° F. In an effort to explain the rapid effect of the exposure to 550° F by visual means, photomicrographs were made of the plastically strained notch material from specimens that had been exposed 30 days at 550° F. Inspection of the photomicrographs at a magnification of 800 diameters revealed no apparent difference between the exposed material and the material in the as-received condition.

As noted by figure 8, the fatigue lives after exposure did not return to the no-exposure life. A possible explanation for this phenomenon is that the recovered structure of the metal is stronger in fatigue than the original structure. This explanation would be valid even though the compressive residual stress had been reduced to zero by the recovery process.

Richards (ref. 10) stated that metallurgical recovery may cause sufficient change in residual stresses as to alter the properties of the material significantly and that any structural change associated with the recovery may not be optically discernible. The process of metallurgical recovery may occur at temperatures significantly below the recrystallization temperature. The recovery process is dependent on the duration of exposure, the temperature at which exposure takes place and the magnitude of the initial residual stress. Longer exposure durations, higher exposure temperatures and larger initial residual stresses all tend to increase the rate at which the recovery process takes place. These three considerations all agree qualitatively with the fatigue life behavior shown in figure 8. It is therefore reasoned that the behavior represented in figure 8 may be explained on the basis of metallurgical recovery.

It should be pointed out that an airplane flying at Mach 3 will be structurally loaded during the hot portion of the flight. This addition of stress, which acts as a driving force on processes such as recovery, may allow a more accelerated reduction of fatigue life than that noted in the present tests. Such an acceleration would not necessarily cause a greater reduction in the fatigue life.

The possibility exists that exposure to elevated temperature in itself might be responsible for a reduction in fatigue life even in the absence of residual stress. To evaluate the possibility, additional specimens were exposed to 550° F for 30 days without having been stress conditioned initially. The mean fatigue life of this group of specimens was compared to the original reference life. The mean life of the exposed specimens was slightly shorter than the original reference life (19,000 cycles compared to 26,000). The shortest life of the original reference group of specimens was 18,400 cycles compared to 16,600 cycles for the exposed specimens. Most of the lives of the exposed specimens fell within the lower half of the scatter band of the unexposed specimens. An explanation for the fact that the lives of the exposed specimens were shorter than those of the unexposed specimens may be based on two considerations. One is that the elevated temperature had a deleterious effect on the material. The other explanation is that in spite of care in preparation of the specimens, some residual stresses may have been inadvertently introduced; and the elevated temperature exposure allowed relaxation of the stresses. Of the two considerations the latter is probably the more reasonable explanation.

X. CONCLUSIONS

An investigation of the effect of elevated temperature on the fatigue lives of specimens containing residual stresses has been made. Although the investigation was carried out with only one type of specimen and one material, the trends noted are believed to be applicable to other specimen types and materials in a qualitative way.

The following conclusions are supported by the present investigation:

1. The application of a single cycle of conditioning stress to the notched specimens caused an appreciable change in fatigue life; conditioning stresses of greater magnitudes caused greater changes in fatigue life.

2. Analysis of the local stress behavior at the notch allowed a qualitative understanding of the fatigue behavior of conditioned specimens.

3. The residual stress introduced by the conditioning cycle was stable at 70° F within the 30-day period of investigation as determined by fatigue tests.

4. Exposure to moderately elevated temperature for short durations reduced the effect of the initial conditioning stress cycle on fatigue life.

5. Higher exposure temperatures caused a more rapid reduction of the effect of conditioning on fatigue life.

XI. ACKNOWLEDGMENTS

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XII. BIBLIOGRAPHY

The following bibliography is not intended to represent an exhaustive literature search. Instead it represents a realistic cross-section of the literature available on the many aspects of residual stresses, their causes and effects. As many of the articles listed contain information on several aspects of residual stresses, a completely exclusive cataloging could not be made on the basis of material content without repetition. Articles containing information about more than one aspect were therefore placed in the classification most relevant to the main topic. The following listing gives the general classifications chosen.

M-1 Residual stresses due to machining, fabrication processes or heat treating.

M-2 Residual stresses due to shot peening.

M-3 Mechanically imposed residual stresses.

M-4 The effects of residual stresses on fatigue.

M-5 Relief of residual stresses and stress relaxation.

M-6 Measurement of residual stresses.

M-7 General topics.

M-1

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XIV. VITA

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XV. APPENDIX A

METHOD OF CALCULATING LOCAL STRESSES

In 1950, Stowell (ref. 11) presented an expression with which to calculate the plastic stress concentration factor for a circular hole in an infinite plate under tension loading. In 1953, Hardrath and Ohman (ref. 12) generalized the Stowell expression to various notch geometries for the first quarter-cycle of loading. Recently Crews and Hardrath (ref. 9) have further extended Stowell's basic approach so that local stresses for loading subsequent to the first quarter-cycle may be calculated. The procedure thus developed was used in the present work to calculate local stresses and is explained below.

The general procedure consists of establishing a plotted curve of the relationship between K_p, the plastic stress concentration factor, and S, the nominal stress, which is unique for a given material and specimen geometry according to the equation:

$$K_p = \frac{\sigma}{S} \tag{A-1}$$

Combining the Hardrath-Ohman equation:

$$K_p = 1 + (K_T - 1)\frac{E_s}{E} \tag{A-2}$$

with equation (A-1), gives

$$S = \frac{\sigma}{1 + (K_T - 1)\frac{E_s}{E}} \tag{A-3}$$

Equation (A-3) is used to establish the relationship between K_p and S.

To establish the curve, values of E_s in terms of the associated stress and strain are substituted into equation (A-3) which is then solved for S. Equation (A-2) or the denominator of equation (A-3) yields the value of K_p which is associated with the nominal stress, S, just obtained.

After establishing the curve, one may enter at a prescribed value of nominal stress, read the corresponding value of K_p and determine the notch root stress, σ, by equation (A-1). The stress-strain curve necessary for the above calculations is shown as segment OA of the curve in figure A-1.

The same principle governing the above calculations for maximum notch root stress is used to calculate the residual stress at the notch root upon removal of the nominal stress. In this instance, the segment AB of the curve in figure A-1 is considered. Point A becomes the origin for purposes of calculation and the procedure is the same as that described above. Primes are added to the nomenclature during calculations concerned with segment AB to distinguish them from the preceding segment so that equations (A-2) and (A-3) become, respectively

$$K_p' = 1 \; (K_T - 1) \frac{E_s'}{E} \qquad \text{(A-4)}$$

$$S = \frac{\sigma}{1 + (K_T - 1) \frac{E_s'}{E}} \qquad \text{(A-5)}$$

A separate curve relating K_p' and S is established in the above manner.

The procedure may be continued for succeeding cycles of load application; an additional prime being added to the nomenclature to identify each specific half-cycle of loading.

For the present tests, it was assumed that the curves for loadings subsequent to point B had the same shape as the segment AB whether loading or unloading and no curves were obtained beyond point B. The curve shown in figure A-1 is for initial loading in tension and is therefore applicable to the present tests in which tensile conditioning stresses were analyzed.

The stress-strain curve shown in figure A-1 was obtained by taking strain gage readings from a specimen of the type shown in figure 1(b). A single strain gage was mounted at the geometrical center of each face of the specimen. The two gages were electrically connected in series so that the average strain reading of the two specimen faces was read.

The results of the calculations of local stress are shown in figure A-2 as plots of plastic stress concentration factor versus nominal stress, S. The lower curve in figure A-2, labeled K_p, was used for calculations during the first quarter-cycle of tensile loading. The higher curve was used for all subsequent loadings.

TABLE I.- SELECTED MATERIAL PROPERTIES OF DUPLEX

ANNEALED Ti-8Al-1Mo-1V SHEET (0.050 GAGE)

a. Mechanical properties

Sheet no.	TUS, ksi (b)	TYS at 0.2 percent offset, ksi (b)	Elongation, e, percent (a) (b)	Elastic modulus, E, psi (b)
30	150.4	136.9	12.5	17.2×10^6
34	151.0	136.9	12.7	16.9×10^6
35	149.1	135.3	12.3	16.6×10^6

(a) Measured after fracture over 2-inch gage length.
(b) Average of 16 tests per sheet.

b. Nominal chemical composition supplied by manufacturer

Constituent	C	Fe	N	Al	V	Mo	H	Ti
Percentage	0.026	0.11	0.11	7.9	1.0	1.1	0.003-0.006	Remainder

TABLE II.- FATIGUE LIFE DATA OBTAINED FROM NOTCHED SPECIMENS

AFTER STRESS CONDITIONING

Conditioning stress, ksi	Specimen No.	Fatigue life, cycles	Geometric mean life, cycles
None	TC30A81	18,390	25,300
	TC34A63	20,730	
	TC30A74	21,710	
	TC30A80	24,320	
	TC34A16	24,860	
	TC34A97	29,480	
	TC30A79	34,430	
	TC30A38	39,000	
+60	TC30A42	20,290	28,280
	TC30A24	26,360	
	TC30A1	28,660	
	TC30A37	34,020	
	TC30A49	35,500	
-60	TC30A46	22,680	24,080
	TC30A20	24,240	
	TC30A94	24,290	
	TC30A54	24,320	
	TC30A88	24,650	
+80	TC30A29	37,250	44,590
	TC30A45	38,250	
	TC30A30	47,280	
	TC30A19	48,390	
	TC30A64	54,090	
+100	TC30A47	96,650	144,800
	TC30A96	118,440	
	TC30A13	150,940	
	TC30A87	152,050	
	TC35A59	157,020	
	TC30A39	166,650	
	TC30A22	193,880	
	TC30A48	$>10^6$	
	TC30A8	$>10^6$	
-100	TC30A70	14,860	16,250
	TC30A83	15,700	
	TC30A23	15,910	
	TC30A17	16,520	
	TC30A71	18,500	

TABLE III.- CALCULATED* LOCAL STRESSES AND STRAINS ASSOCIATED WITH THE STRESS CONDITIONING CYCLE AND FATIGUE STRESS CYCLE FOR NOTCHED SPECIMENS OF Ti-8Al-1Mo-1V ALLOY

Conditioning stress, S, ksi	Local stresses and strains associated with conditioning-stress cycle				Local stresses and strains associated with the fatigue-stress cycle (0-50 ksi) subsequent to the stress conditioning cycle			
	Local stress, σ, ksi		Local strain, ϵ, percent		Local stress, σ, ksi		Local strain, ϵ, percent	
	maximum	residual	maximum	residual	maximum	minimum	maximum	minimum
50	136.5	-52.0	1.15	0.03	136.5	-52.0	1.15	0.03
60	138.6	-75.0	2.10	0.72	113.5	-75.0	1.84	0.72
80	140.8	-108.8	3.56	1.68	79.7	-108.8	2.80	1.68
100	146.0	-124.0	5.70	3.05	64.5	-124.0	4.17	3.05

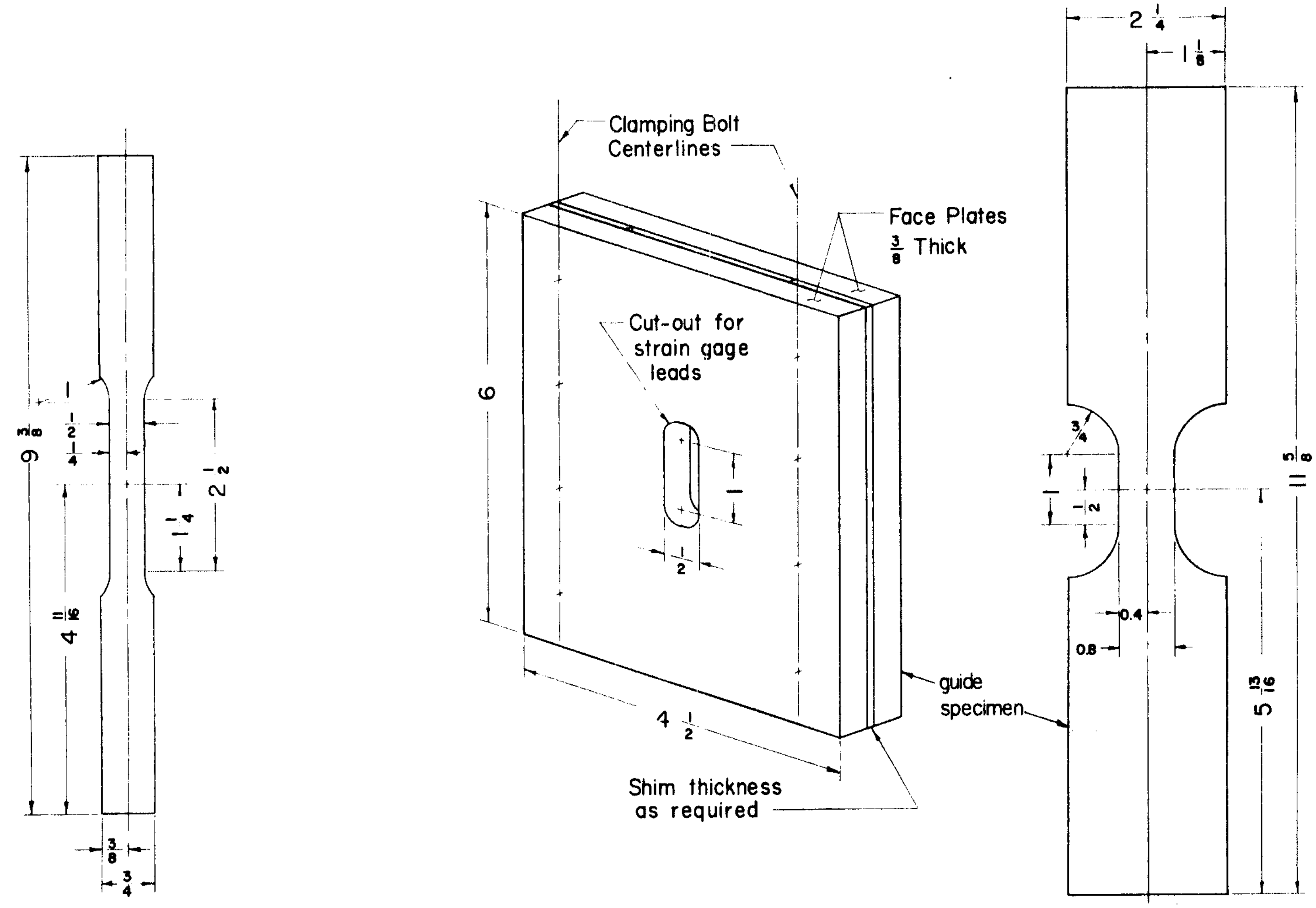
*Calculated using the method of Crews and Hardrath (ref. 9).

TABLE IV.- FATIGUE LIFE DATA OBTAINED AFTER EXPOSURE OF STRESS CONDITIONED SPECIMENS (100 KSI ONLY) TO ELEVATED TEMPERATURES

Exposure conditions		Specimen number	Fatigue life, cycles	
Temperature, °F	Duration, min		Individual	Geometric mean
70	14,400 (10 days)	TC34A64	119,000	135,300
		TC34A23	123,000	
		TC34A88	169,250	
		TC34A51	$>10^6$	
		TC34A50	$>10^6$	
	43,200 (30 days)	TC35A11	127,000	214,560
		TC34A84	185,000	
		TC34A91	420,540	
		TC34A90	$>10^6$	
		TC34A11	$>10^6$	
300	1	TC35A46	85,840	115,600
		TC35A52	96,850	
		TC35A74	114,200	
		TC35A13	187,570	
		TC35A78	$>10^6$	
	6	TC35A92	88,110	126,600
		TC35A81	103,360	
		TC35A45	119,850	
		TC35A29	148,170	
		TC35A85	153,780	
		TC35A53	165,290	
	60	TC35A33	58,870	79,020
		TC35A30	73,710	
		TC35A31	76,040	
		TC35A80	90,070	
		TC35A62	103,730	
	14,400 (10 days)	TC34A12	73,130	96,340
		TC34A46	83,500	
		TC34A45	102,260	
		TC34A56	105,580	
		TC34A47	125,760	
	43,200 (30 days)	TC34A80	61,360	79,220
		TC34A17	72,770	
		TC34A95	75,300	
		TC34A72	79,020	
		TC34A10	117,350	

TABLE IV.- FATIGUE LIFE DATA OBTAINED AFTER EXPOSURE OF STRESS CONDITIONED SPECIMENS (100 KSI ONLY) TO ELEVATED TEMPERATURES - Concluded

Exposure conditions		Specimen number	Fatigue life, cycles	
Temperature, °F	Duration, min		Individual	Geometric mean
550	0.1	TC35A55 TC35A39 TC35A86 TC35A24 TC35A65	66,500 76,620 80,180 121,390 126,610	91,110
	1	TC35A83 TC35A93 TC35A75 TC35A94 TC35A7	58,410 66,160 66,840 67,480 74,990	66,570
	60	TC35A41 TC35A48 TC35A49 TC35A16 TC35A66	52,070 54,330 61,460 62,580 62,680	58,450
	360 (6 hours)	TC35A2 TC35A42 TC35A47 TC35A32 TC35A36 TC35A68	38,360 51,450 57,220 65,890 79,540 79,960	60,140
	1200 (20 hours)	TC34A70 TC34A31 TC35A26 TC34A96 TC34A62 TC34A13	56,550 56,610 60,680 64,770 68,730 88,430	65,150
	7200 (5 days)	TC34A2 TC34A75 TC34A3 TC34A99 TC34A5	23,350 49,380 50,890 55,430 58,910	45,340
	14,400 (10 days)	TC30A32 TC30A41 TC30A51 TC30A92 TC34A61	37,410 44,850 45,390 48,760 50,550	45,150
	43,200 (30 days)	TC30A33 TC30A43 TC30A55 TC30A14 TC30A72	39,330 40,610 41,200 43,290 45,820	41,990



(a) Tensile specimen.

(b) Sheet compression specimen and antibuckling guide.

Figure 1.- Specimens used to determine strength properties of duplex annealed Ti-8Al-1Mo-1V sheet (0.050 gage).

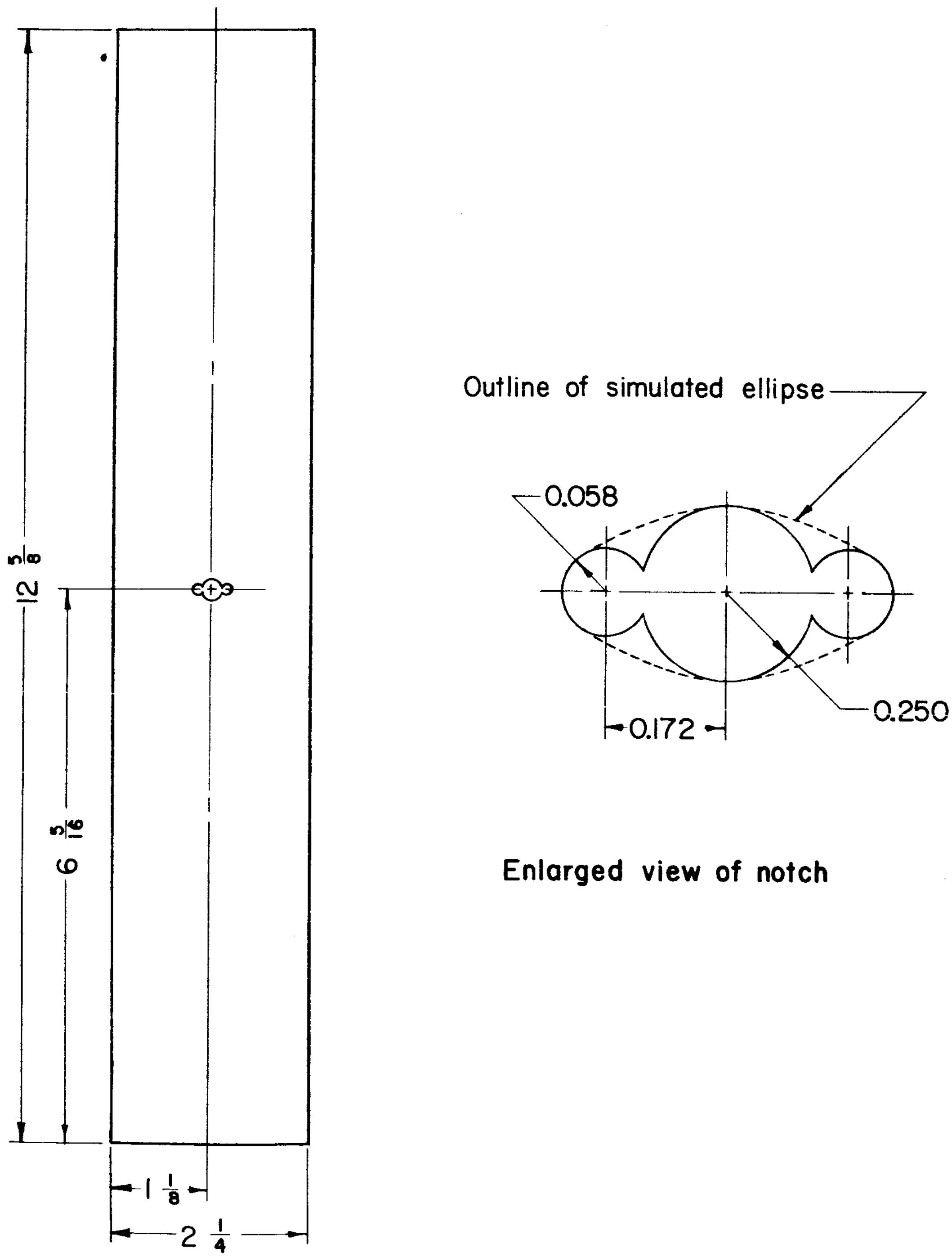


Figure 2.- Notched fatigue specimen $\left(K_T = 4\right)$. Duplex annealed Ti-8Al-1Mo-1V sheet (0.050 gage).

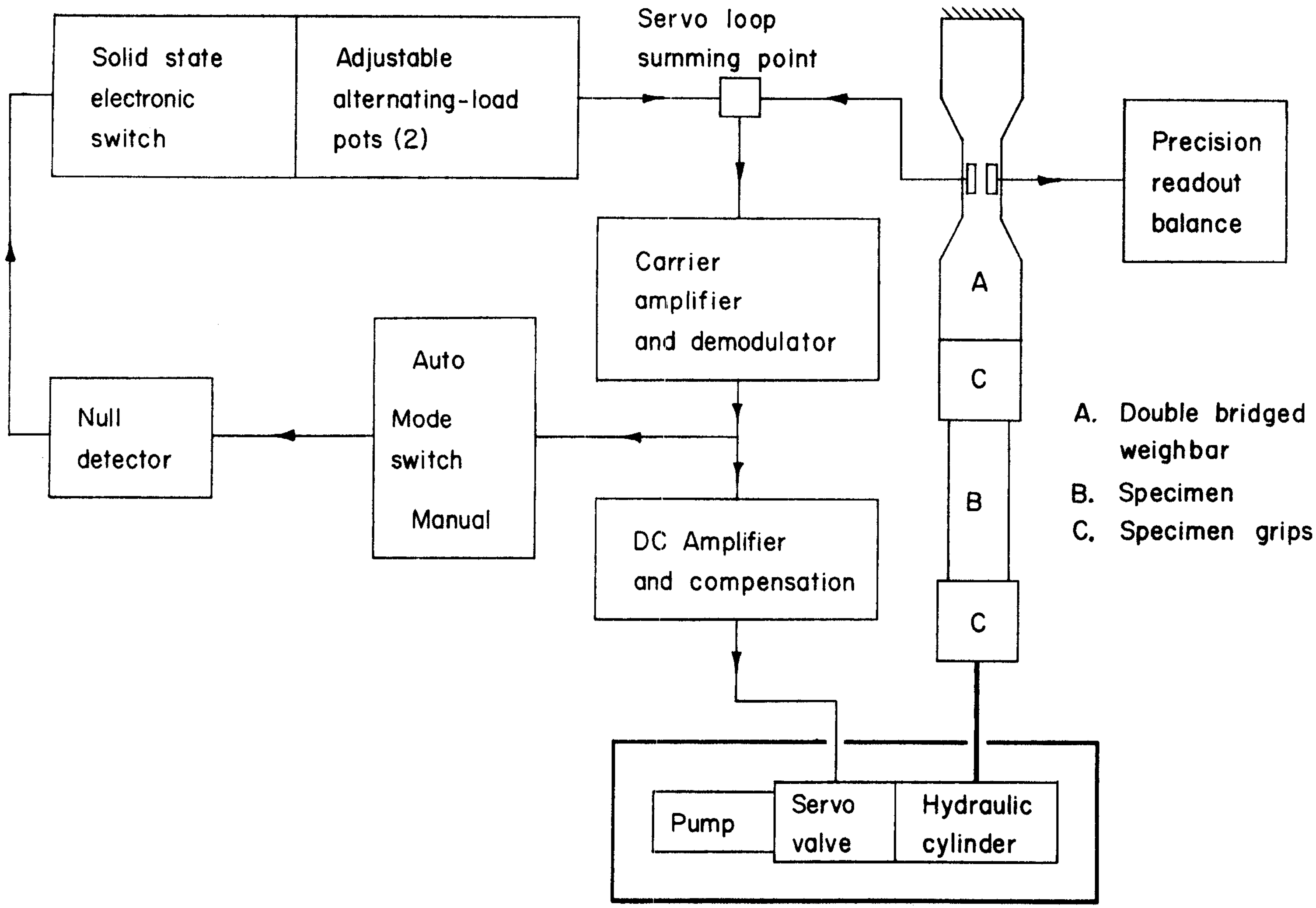


Figure 3.- Closed-loop servo-hydraulic fatigue testing machine schematic.

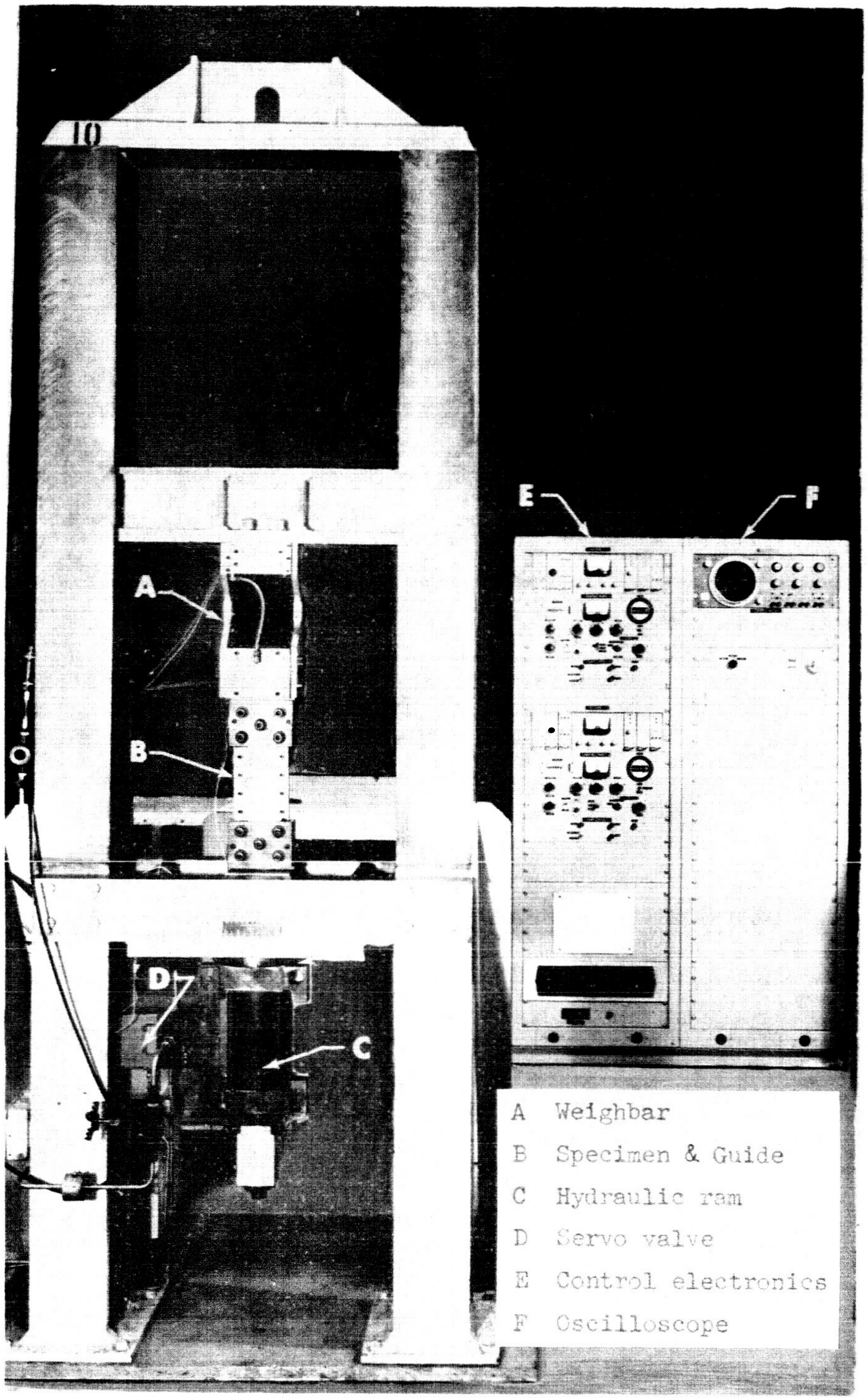
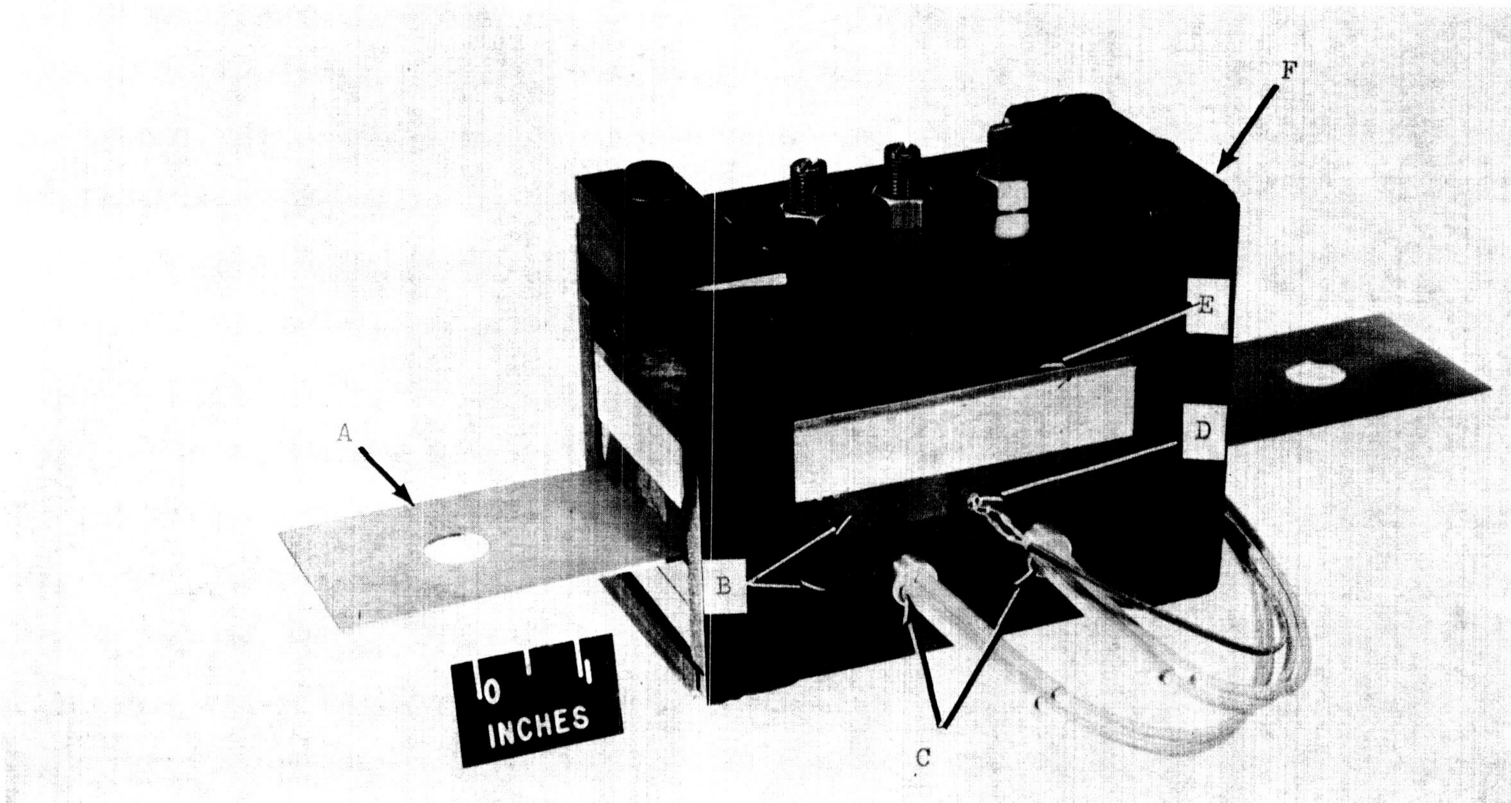


Figure 4.- Photograph of closed-loop servo-hydraulic fatigue testing machine and control console.



A Specimen
B Carbon slabs
C Resistance heating elements
D Thermistor temperature sensor
E Pressure plate for use when furnace acts as guide plate
F Supporting frame

Figure 5.- Photograph of apparatus used for short-duration specimen heating.

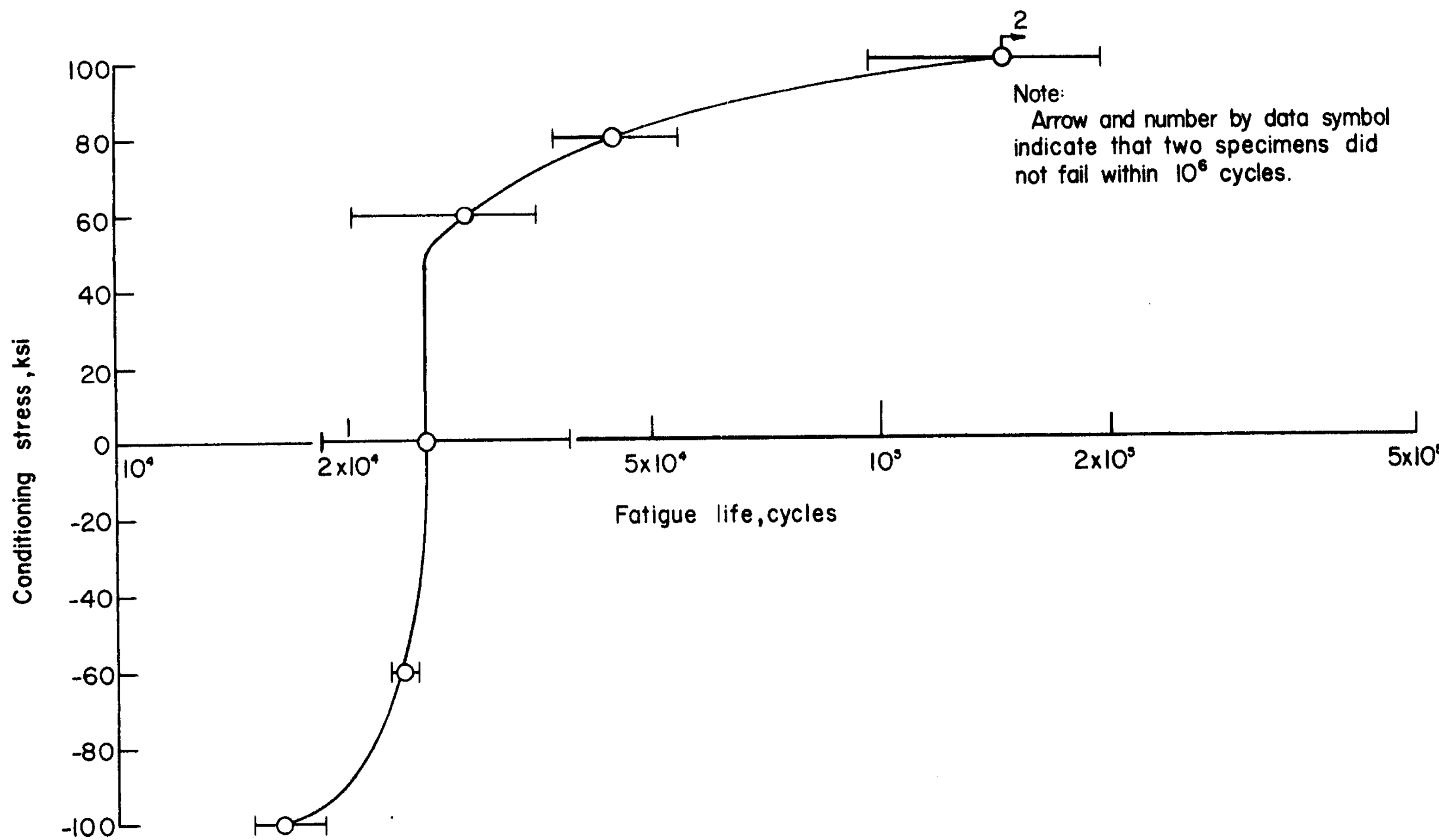


Figure 6.- The effect of a single cycle of conditioning stress on the room temperature fatigue life (at 0-50 ksi) of notched $\left(K_T = 4\right)$ fatigue specimens of Ti-8Al-1Mo-1V alloy sheet (0.050 gage).

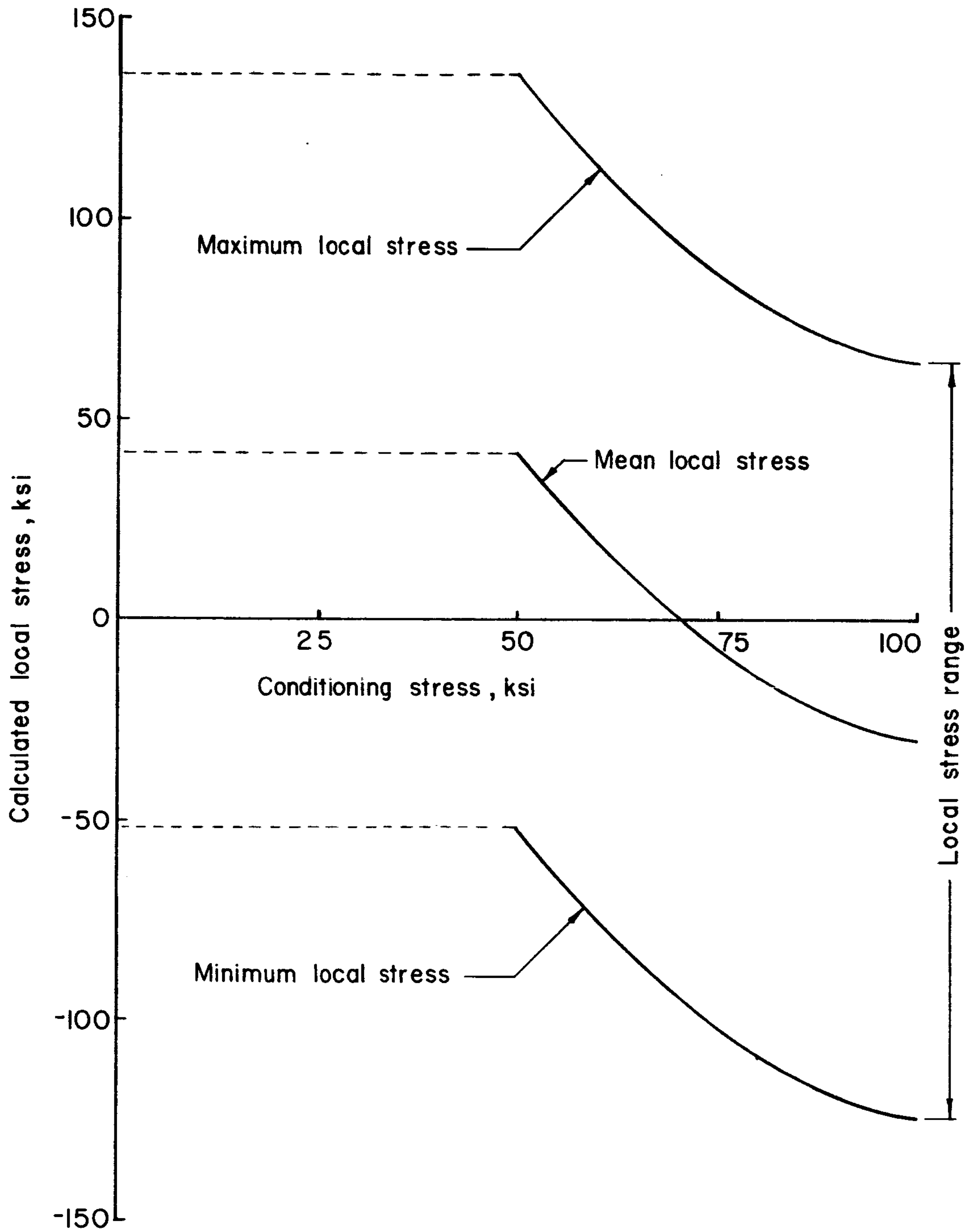


Figure 7.- Initial local stress conditions during fatigue loading (0-50 ksi) after application of conditioning stress cycle to notched $\left(K_T = 4\right)$ specimens of Ti-8Al-1Mo-1V alloy.

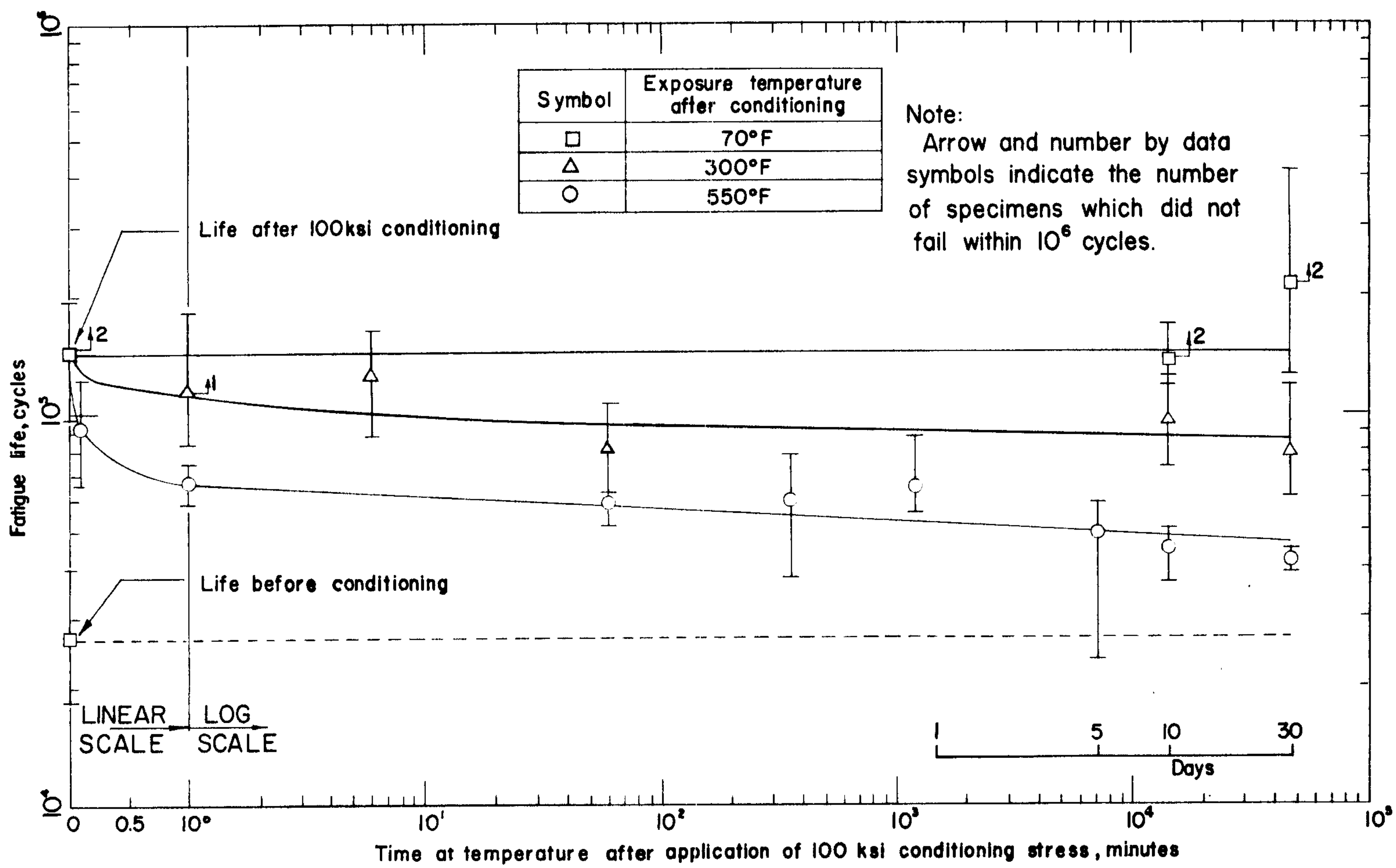


Figure 8.- The effect of exposure to elevated temperature on the fatigue life (at 0-50 ksi) of stress conditioned specimens of Ti-8Al-1Mo-1V alloy sheet (0.50 gage) at room temperature.

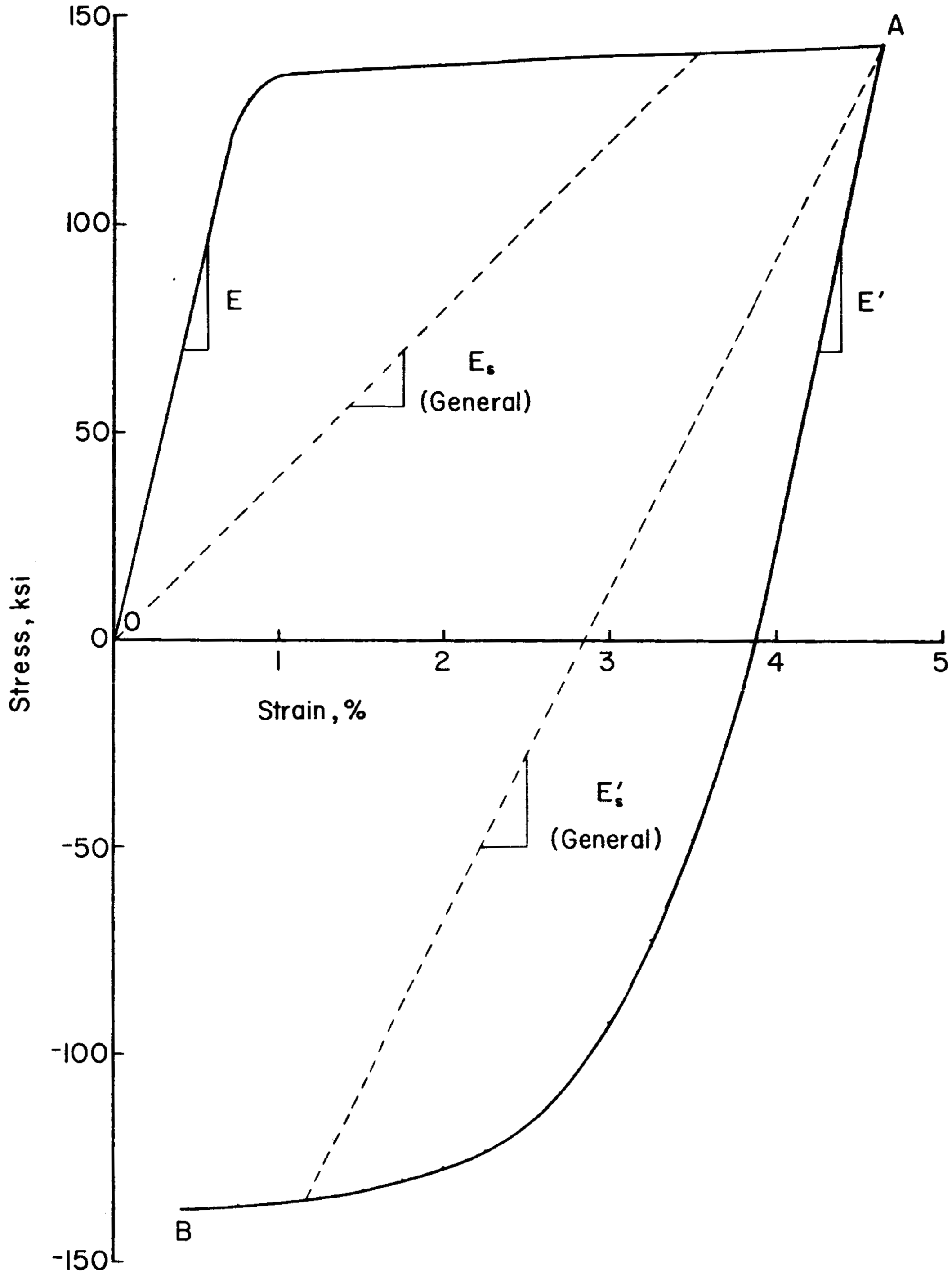


Figure A-1.- Characteristic stress-strain curve of duplex annealed Ti-8Al-1Mo-1V sheet (0.050 gage).

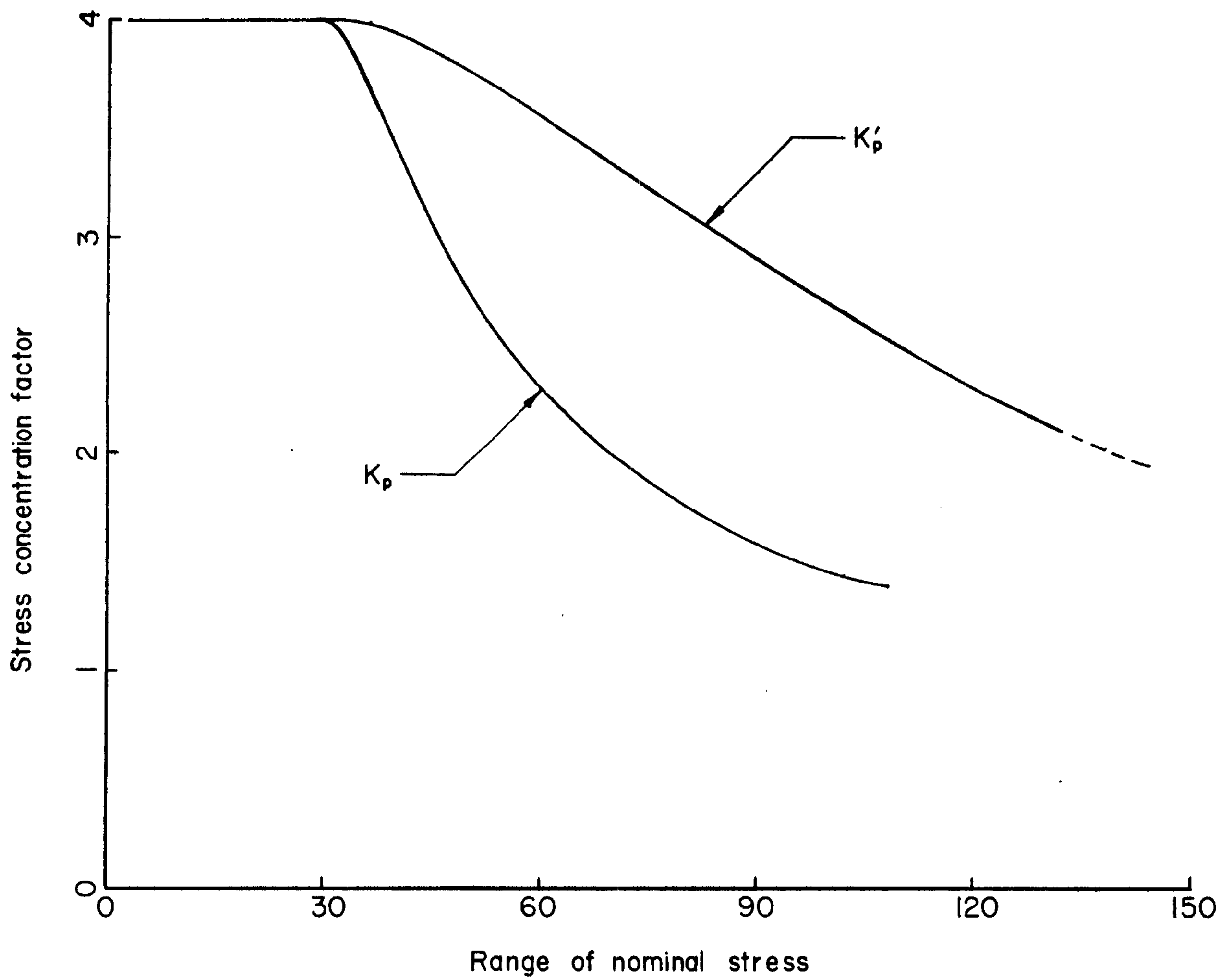


Figure A-2.- Relations between plastic stress concentration factors and nominal applied stress for notched $\left(K_T = 4\right)$ specimens of duplex annealed Ti-8Al-1Mo-1V sheet (0.050 gage).