https://ntrs.nasa.gov/search.jsp?R=19660009121 2020-03-16T23:27:54+00:00Z

FACILITY FORM 602

N66-18410 (ACCESSION NUMBER) (THRU)

101 (PAGES) 1 (CODE)

CR 70590 (NASA CR OR TMX OR AD NUMBER) 17 (CATEGORY)

GPO PRICE $ _____

CFSTI PRICE(S) $ _____

Hard copy (HC) $4.00

Microfiche (MF) .75

ff 653 July 65

DEVELOPMENT OF STRESS RELIEF TREATMENTS FOR HIGH STRENGTH ALUMINUM ALLOYS

By

G. M. Orner & S. A. Kulin

Contract No. NAS8-11091
PR 1-4-50-01166-01 (1F)
CPB 02.1212-64

Annual Report No. 2

13 August 1964 - 13 August 1965

September 1965

MATERIALS RESEARCH AND DEVELOPMENT

MANLABS, INC.

21 ERIE STREET
CAMBRIDGE 39
MASSACHUSETTS

DEVELOPMENT OF STRESS RELIEF TREATMENTS FOR HIGH STRENGTH ALUMINUM ALLOYS

By

G. M. Orner & S. A. Kulin

Contract No. NAS8-11091
PR 1-4-50-01166-01 (1F)
CPB 02.1212-64

Annual Report No. 2

13 August 1964 - 13 August 1965

September 1965

MATERIALS RESEARCH AND DEVELOPMENT

MANLABS, INC.
21 ERIE STREET
CAMBRIDGE 39
MASSACHUSETTS

FOREWORD

This report was prepared by ManLabs, Inc. under Contract No. NAS8-11091, PR 1-4-50-01166-01 (1F), CPB 02.1212-64, "Development of Stress Relief Treatments for High Strength Aluminum Alloys", for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the Technical direction of the Propulsion and Vehicle Engineering Laboratory, Materials Division of the George C. Marshall Space Flight Center with Mr. W.B. McPherson acting as project manager.

ABSTRACT

1844/10

The response of residual stress, strength and toughness of three high strength aluminum alloys subjected to time-temperature treatments has been characterized. Residual stress distributions in a variety of alloys in several thicknesses were measured in both the as-heat-treated and stress-relieved conditions. It is shown that the rate of residual stress-relief in aluminum alloys is highly dependent on the relief history of the particular stress under consideration. Furthermore, it is demonstrated that a stress increment added to an existing stress undergoing a time temperature treatment will relieve at a rate that is characteristic for the material, i.e., the rate of stress-relief for the stress increment is independent of both the magnitude of the previously existing stress and the amount of relief the previously existing stress has already sustained. A mechanism for residual stress-relief with microstrain playing the major role is proposed. This mechanism is capable of explaining the behaviors observed in a wide variety of experiments which were conducted in an attempt to shed light on the mode of stress-relief in high strength aluminum alloys.

TABLE OF CONTENTS

		Page
ABSTRACT		
I.	INTRODUCTION	1
	A. Background	1
	B. Objective and Scope	1
II.	MATERIALS	3
III.	EXPERIMENTAL PROCEDURES	4
	A. Measurement of Residual Stress-Relief	4
	B. Measurement of Residual Stress Distribution	6
	C. Tensile Testing	10
	D. Fracture Toughness Testing	10
	E. Welding	10
IV.	EXPERIMENTAL RESULTS	11
	A. Relief of Residual Stresses by Time-Temperature Treatments	11
	B. Effect of Time-Temperature Treatments on the Mechanical Properties of Aluminum Alloys	11
	1. Tensile Properties	11
	2. Fracture Toughness Properties	12
	C. Residual Stress Magnitude and Distribution	12
	1. 7075-T6 Plate and Forgings	18
	2. 7178 Forgings	19
	3. Stress Distribution in Other Alloys	19
	D. Stress-Relief	19
	E. Mechanisms of Stress-Relief	20
	1. Effect of Previous Stress-Relief History	20
	2. Effect of Heat-Treated Condition on Rate of Residual Stress-Relief	22
	3. Creep Back Experiments	23
	4. Discussion of Mechanisms of Residual Stress-Relief	24

TABLE OF CONTENTS (Cont)

		Page
V.	WELDING STUDIES (Subcontracted to M.I.T. Welding Laboratory)	27
	A. Introduction	27
	B. Materials	27
	C. Experimental Procedures	27
	D. Experimental Results and Discussion	28
VI.	SUMMARY AND CONCLUSIONS	32
	A. Summary	32
	B. Conclusions	32
References		34

ILLUSTRATIONS

Figure		Page
1	Modified Split-Ring Specimen for Measurement of Relief of Residual Stress	35
2	Specimen for Measuring Residual Stress-Relief in 1 inch Thick Plate	36
3	Tensile Specimen	37
4	Apparatus Used to Cool Tensile Specimens to -320°F During Testing	38
5	Residual Stress Relief Characteristics of Forged 7178-T6 Aluminum	39
6	Effect of Time and Temperature on Remaining Residual Stress for 7106-T63 Plate Stressed Initially to 40 ksi	40
7	Effect of Time and Temperature on Remaining Residual Stress for 7039-T651 Plate Stressed Initially to 40 ksi	41
8	Effect of Time and Temperature on the Yield Strength of Forged 7178-T6 at Room Temperature	42
9	Effect of Time and Temperature on the Yield Strength of Forged 7178-T6 at -320°F	43
10	Effect of Time and Temperature on the Yield Strength of Forged 7178-T6 at -423°F	44
11	Effect of Time and Temperature on the Yield Strength of 7106-T63 Plate at Room Temperature	45
12	Effect of Time and Temperature on the Yield Strength of 7106-T63 at -320°F	46
13	Effect of Time and Temperature on the Yield Strength of 7106-T63 at -423°F	47
14	Effect of Time and Temperature on the Yield Strength of 7039-T651 at Room Temperature	48
15	Effect of Time and Temperature on the Yield Strength of 7039-T651 at -320°F	49
16	Effect of Time and Temperature on the Yield Strength of 7039-T651 at -423°F	50

ILLUSTRATIONS (Cont)

Figure		Page
17	Effect of Time and Temperature on the Tensile Strength of Forged 7178-T6 at Room Temperature	51
18	Effect of Time and Temperature on the Tensile Strength of Forged 7178-T6 at -320°F	52
19	Effect of Time and Temperature on the Tensile Strength of Forged 7178-T6 at -423°F	53
20	Effect of Time and Temperature on the Tensile Strength of 7106-T63 Plate at Room Temperature	54
21	Effect of Time and Temperature on the Tensile Strength of 7106-T63 at -320°F	55
22	Effect of Time and Temperature on the Tensile Strength of 7106-T63 at -423°F	56
23	Effect of Time and Temperature on the Tensile Strength of 7039-T651 at Room Temperature	57
24	Effect of Time and Temperature on the Tensile Strength of 7039-T651 at -320°F	58
25	Effect of Time and Temperature on the Tensile Strength of 7039-T651 at -423°F	59
26	Relationship Between Remaining Residual Stress and Loss of Tensile Yield Strength at Room Temperature for Various Time-Temperature Treatments for Forged 7178-T6	60
27	Relationship Between Remaining Residual Stress and Loss of Ultimate Tensile Strength at Room Temperature for Various Time-Temperature Treatments for Forged 7178-T6	61
28	Relationship Between Remaining Residual Stress and Loss of Tensile Yield Strength at Room Temperature for Various Time-Temperature Treatments for 7106-T63 Plate	62
29	Relationship Between Remaining Residual Stress and Loss of Ultimate Tensile Strength at Room Temperature for Various Time-Temperature Treatments for 7106-T63 Plate	63
30	Relationship Between Remaining Residual Stress and Loss of Yield Strength at Room Temperature for Various Time-Temperature Treatments for 7039-T651 Plate	64

ILLUSTRATIONS (Cont)

Figure		Page
31	Relationship Between Remaining Residual Stress and Loss of Ultimate Tensile Strength at Room Temperature for Various Time-Temperature Treatments for 7039-T651 Plate	65
32	Effect of Time and Temperature on the Impact Fracture Toughness of Forged 7178-T6 at Room Temperature	66
33	Effect of Time and Temperature on the Impact Fracture Toughness of 7178-T6 at -320°F	67
34	Effect of Time and Temperature on the Impact Fracture Toughness of 7106-T63 Plate at Room Temperature	68
35	Effect of Time and Temperature on the Impact Fracture Toughness of 7106-T63 at -320°F	69
36	Effect of Time and Temperature on the Impact Fracture Toughness of 7039-T651 at Room Temperature	70
37	Effect of Time and Temperature on the Impact Fracture Toughness of 7039-T651 at -320°F	71
38	Residual Stress Distributions Through the Thickness in 1 inch Thick 7075-T6 Rolled Plate (1), Reheat-Treated Forged Plate (2) and As-Received Forged Plate (3)	72
39	Effect of Quench Bath Temperature on Residual Stress. Effect of Fabrication Variables on Residual Stress	73
40	Residual Stress Distribution Through the Thickness of 1.3 Thick 7178 Forging, As-Received (O) and After Stress-Relieving at 350°F for 100 Hours (□)	74
41	Residual Stress Distribution Through the Thickness of 2.4 Thick 7178 Forging, As-Received (O) and After Stress-Relieving at 350°F for 100 Hours (□)	75
42	Residual Stress Distribution Through the Thickness of 3.3 Thick 7178 Forging, As-Received (O) and After Stress-Relieving at 350°F for 100 Hours (□)	76
43	Residual Stress Distribution Through The Thickness in 3/4 inch Thick 2219-T6 as Heat-Treated	77
44	Residual Stress Distribution Through The Thickness in 2 inch Thick 2219-T6 Plate as Heat-Treated	78

ILLUSTRATIONS (Cont)

Figure		Page
45	Residual Stress Distribution Through the Thickness in 2 inch Thick 7039-T6 as Heat-Treated	79
46	Effect of Time and Temperature on Residual Stresses in Forged 7178, As-Received (□), Re-solution Treated, Quenched and Aged in Unstressed Condition (□) and Re-solution Treated, Quenched and Aged Under Simulated Residual Quench Stresses (O)	80
47	Effect of Time and Temperature (400°F) on Stress in 7075-T651 Stressed to Two Initial Stress Levels and With Additional Stress Increments Added During the Time-Temperature Treatment . . .	81
48	Effect of Initial Maximum Stress Level on Remaining Stress in 7075-T6 Stressed to 7.5 and 20 ksi	82
49	Effect of Time at Temperature on the Rate of Residual Stress-Relief in 7075-T651 at 400°F	83
50	Effect of Time and Temperature (500°F) on Stress in 6061-T651 Stressed to Two Initial Stress Levels and with Additional Stress Increments Added During the Time-Temperature Treatment . . .	84
51	Effect of Heat Treatment on the Rate of Residual Stress-Relief at 400°F in 6061-T6 Subjected to Reversed Stress Cycling (Modified Ring Type Specimens)	85
52	Effect of Heat Treatment on the Rate of Residual Stress-Relief at 400°F in 6061-T6	86
53	Effect of Alternate Loading and Unloading at 400°F for 24 Hour Periods on Residual Stress-Relief in 6061-T6	87
54	Effect of Alternate Loading and Unloading at 400°F for 24 Hour Periods on Residual Stress-Relief in 7075-T6	88
55	Per Cent "Creep Back" as a Function of Prior Residual Stress in 7075-T6	89
56	Plastic Deflection of a 6061-T651 Stress-Relief Specimen Subjected to Time-Temperature (400°F) Treatments with a Reversal of Stress (15 ksi max.) Every 24 Hours	90
57	Plastic Deflection of a 7075-T651 Stress-Relief Specimen Subjected to Time-Temperature (400°F) Treatments with a Reversal of Stress (37.5 ksi max.) Every 24 Hours	91

TABLES

Table No.		Page
1	Procedure for the Measurement of the Relief of Residual Stress Using the Modified Split-Ring Specimen (Figure 1)	5
2	Effect of Time and Temperature on Elongation and Reduction of Area for 7178-T6 Forged Material	13
3	Effect of Time and Temperature on Elongation and Reduction of Area for 7039-T651 Plate	14
4	Effect of Time and Temperature on Elongation and Reduction of Area for 7106-T63 Plate	16
5	Residual Stresses in Bead-on-Plate Circle Welds in Aluminum	29
6	Residual Stresses in Bead-on-Plate Circle Welds in Aluminum	30
7	Average Remaining Residual Stress % After a Stress-Relief of 400°F for 2 Hours	31

I. INTRODUCTION

A. Background

This report covers the work accomplished during the second 12 month period of a program to investigate residual stresses in high strength aluminum alloys and their relief by means of time-temperature treatments.

During the first twelve month period, a specimen was developed for measuring the rate at which stress-relief occurs during time-temperature treatments. Using this specimen, the time-temperature stress-relieving characteristics of six high strength aluminum alloys were determined over a range of temperatures and for times up to 100 hours. The effects of time-temperature treatments on the tensile and fracture toughness properties were also determined. It was found that the rate of residual stress-relief expressed as a percentage of the initial stress, is largely independent of the magnitude of the initial stress. The rate of stress-relief was shown to be highly dependent on temperature, time and to the amount of stress-relief that has already taken place. Furthermore, it was shown that in most of the heat treatable alloys, moderate amounts of residual stress-relief can be obtained without seriously affecting the tensile strength properties. In the single work-hardened alloy investigated, it was found that essentially complete residual stress-relief can be obtained with little effect on tensile strength properties. Through the thickness, residual stress analyses made on plate and forged materials, reveal that, although essentially equi-biaxial residual stresses exist in the aluminum alloys heat-treated to the T6 condition, the residual stresses existing in the work-hardened alloy, 5456-H343, vary considerably with respect to rolling direction. Residual stress analyses of multiple pass butt weldments indicate low residual stress values due to welding. The time-temperature residual stress-relieving characteristics of welded material were shown to differ only slightly from those of the parent plate.

B. Objective and Scope

The primary objective of this program was to develop stress-relief treatments for forgings, plate and welded stock of high strength aluminum alloys and to study their stress-relief behavior with respect to previous history.

In addition, a concurrent objective was to determine the effect of time-temperature stress-relieving treatments on the tensile and fracture toughness properties of these alloys. From these data, optimum time-temperature stress-relieving treatments for a specific application can be obtained for each of the alloys investigated.

A secondary objective was to determine quantitatively the residual stress distributions in plate, welded plate and in forgings of various thicknesses.

In addition to the six high strength aluminum alloys already under study, three alloys of current interest were selected, i.e., 7178-T6, 7106-T63 and 7139-T6.

Particular emphasis was placed on the effect of specimen history since it was shown previously that the rate of residual stress-relief is highly dependent on the amount of residual stress that has already been relieved.

II. MATERIALS

Studies were conducted on three new alloys, 7178-T6 in the form of forgings, 7039-T6 and 7106-T63 in the form of rolled plate.

The 7178-T6 forgings were procured from the Wyman-Gordon Company in the form of pancakes having nominal thicknesses of 1/2, 1, 2 and 3 inches. The diameter of these forgings ranged from 8 inches for the 1/2 inch thickness to 18 inches for the 3 inch thickness.

The Alcoa alloy, 7106-T63 was in very short supply (except in one ton minimum lots per thickness from the Aluminum Company of America). Eventually, however, one sheet each of 1/2 and 1 inch thicknesses was obtained from the Southwest Research Institute.

The Kaiser alloy, 7039-T6 was obtained free of charge in all necessary thicknesses through the courtesy of the Kaiser Aluminum Company.

III. EXPERIMENTAL PROCEDURES

A. Measurement of Residual Stress-Relief

The design of one type of stress-relief specimen used is a modification of the "split-ring" specimen used by Brown and Cohen (1*) and Oding (2) and is illustrated in Figure 1. The function of the screw at the heavy end of the specimen is to apply a stress of predetermined value in the ring portion of the specimen; the stress in the arms is considered to be negligible. The eccentricity of the ring is designed to give essentially the same maximum surface stress at any point around the circumference. Since this specimen is stressed by bending, stresses vary in magnitude from zero at the neutral axis to a maximum at the surfaces. Furthermore, because of the considerable radial thickness of the ring, the internal surface stresses are greater than the external surface stresses and of opposite sign. Although it can be argued that a uniaxial tensile specimen would be preferable to this bend specimen because of the stress gradients in the latter, it would be considerably more difficult to use from an experimental standpoint. Furthermore, during the first phase of this program, it was found that the per cent of stress-relief in aluminum alloys was largely independent of the applied stress level. Thus, the stress gradient in this specimen is believed to have little effect on the results.

The difference in stress between the inner and outer surfaces of the ring was calculated and later experimentally verified by strain gauges. For this specimen design, the magnitude of the external surface stress is 0.58 times the internal surface stress. The internal surface stress is equal to 185 psi times the distance the arms are spread in thousandths of an inch. Thus, any desired stress may be imparted to the specimen by spreading the arms at precalculated amounts. As shown in Figure 1, reference marks are scribed on the arms of the specimen and a traveling stage microscope is used to measure the distance between the marks.

The steps employed in using this specimen to determine the effect of time-temperature treatments on residual stress are outlined in Table 1.

During the second phase of this program a new specimen was designed for the determination of residual stress-relief and is shown in Figure 2. A value for residual stress is obtained by measuring the deflection of the specimen after it is cut as shown in Figure 2 to relieve the residual stresses. The thickness of this specimen is thought to be of little consequence except when specimens are to be fully heat-treated (i.e., any heat treatment including solution treating and quenching). In this case it is considered necessary to have the specimen thickness at least equal to that

*Underscored numbers in parentheses designate References given at end of report.

TABLE 1

PROCEDURE FOR THE MEASUREMENT OF THE RELIEF OF RESIDUAL STRESS USING THE MODIFIED SPLIT-RING SPECIMEN (FIGURE 1)

1. Determine desired stress level and measure no-stress distance, S, between scribe marks.

2. By adjustment of the screw, increase the separation of the scribe marks by the distance calculated to give the desired stress level. The new total distance between the scribe marks is S_1.

3. Hold at temperature in a suitable liquid bath for a predetermined time.

4. Allow specimen to cool to ambient temperature, loosen screw and measure the distance (S_2) between the scribe marks.

5. Calculate the per cent of stress-relief by the formula:

$$\frac{S_2-S}{S_1-S} \times 100$$

6. Reset gap between scribe marks to distance S_1 and reheat for an additional time period.

7. Repeat above procedure until the cumulative time at temperature reaches 100 hours.

of the parent plate in order to simulate more closely the quench rates that prevail in full size plates. Thus, where no heat treatment or only a stress-relieving treatment is required, specimen thickness is held to 1/4 inch.

This specimen was chosen for the following reasons:

1. It was shown previously that, when measurements of the relief of residual stress are required, measurements taken at one point (e.g., on the surface) can be very misleading particularly if large residual stress gradients are present. This can be explained by the fact that the changes in surface strains during the stress-relief treatments are influenced by the changes in internal strains during these treatments. Thus, a measurement based on stress-relief over the entire section is necessary.

2. The method used previously, i.e., making through the thickness residual stress analyses on as-heat-treated and on as-heat-treated and stress-relieved specimens and taking the average stresses, is very time consuming and costly.

3. Although this specimen cannot give absolute values for residual stress, it can give accurate values for the average percentage change in residual stress.

B. Measurement of Residual Stress Distribution

For the purposes of this program, a relatively simple method for the accurate determination of residual stress distribution was employed. The selection of this method for the determination of residual stress distribution was made based on the following assumptions:

1. Residual stresses in the direction normal to the surfaces of the plate are essentially zero, because in areas remote from the edges the processing of the plate is consistent in all locations. Therefore, identical residual stress patterns exist at all points and since the plate is at rest their net effect is zero. It follows then that these stresses are equal to zero.

2. The residual stresses parallel to the surface on heat-treated plates are equi-biaxial. This assumption is based on the fact that these stresses result from heat treatment which is a nondirectional process.

The validity of these assumptions was demonstrated by the results of investigations documented in the report submitted for the first twelve month period of this program (3).

The following experimental method of residual stress determination was used. A narrow strip, approximately 1/4 inch thick, was machined from the center of the plates to be studied. These materials supplied in the

T651 (i.e., stress-relieved) condition, were reheat-treated to the T6 condition in the form of 10 inch square plates. Thus, the specimen used was 1/4 x 1 x 10 inches. By cutting this thin strip from the plate, the transverse strains were relieved and, although corrections for these would be required in the calculations, experimental measurements of only the longitudinal strains were required.

An SR-4 strain gauge was positioned longitudinally in the geometrical center of each side (i.e., machined cross sectional surface) of the test specimen. The two gauges were connected in series and thus, effectively compensated for the effect of any bending of the specimen that might occur. The active length and width of these gauges is 3/4 inch and 5/32 inch, respectively. The resistance of the gauges was measured on a Baldwin SR-4 Type N strain indicator which reads strain changes directly in μ inch/inch.

After measuring the resistance of the gauges, a thin layer (.025 inch) was carefully machined from each edge of the specimen (i.e., from the original plate surface) in a shaping machine, using a very sharp tool and limiting the depth of the final cut to .005 inch. By removing an equal amount of material from both the top and bottom surfaces of the specimen, bending was avoided and the calculations could be greatly simplified. After removal of the two layers, the strain gauges were remeasured, the strain change noted and converted directly to stress (i.e., stress change in remaining part of specimen) by the following formula:

$$\Delta\sigma = E\Delta e$$

where $\Delta\sigma$ = Stress change

E = Young's modulus

Δe = Strain change

Since the force change resulting from the stress change in the remaining part of the specimen was exactly balanced by the force resulting from residual stress in the layer removed, the relationship between the two stress values was inversely proportional to their cross-sectional areas, hence

$$\sigma_l = \Delta\sigma \frac{T - 2t}{2t} = E\Delta e \frac{T - 2t}{2t} \qquad (1)$$

where σ_l = Average stress in layers removed

T = Original specimen width

t = Thickness of each layer removed

Since the stress in the layers removed was uniaxial, whereas before the specimen was cut it was equi-biaxial, a correction $(1 + \nu / 1 - \nu^2)$ for the effect of transverse stress had to be made.

Therefore,

$$\sigma_o = \frac{1+\nu}{1-\nu^2}\sigma_l = \frac{1+\nu}{1-\nu^2} E \Delta e \frac{T-2t}{2t} \quad (2)$$

where σ_o is the original stress existing in the layer removed from the plate.

The same procedure was followed for each succeeding pair of layers removed. However, for each pair of these layers a correction for the effect of the stress in the preceding (removed) layers was made. This correction is simply equal to the sum of the strain changes in the remaining section resulting from the removal of all the previous layers. The residual stress in the xth layer to be removed, uncorrected for transverse stress is given by:

$$\sigma_x = E \Delta e_x \frac{T-2xt}{2t} - (\Delta e_1 + \Delta e_2 \text{ --- } + \Delta e_{x-1}) \quad (3)$$

This method of residual stress analysis assumes that the residual stress distribution is identical from either surface to the center of the plate. Furthermore, since the center section of the specimen is used to carry the strain gauges, the last approximately 0.1 inch cannot be machined away and hence, the residual stress in this area must be estimated. This is of little consequence, however, because the rate of change of residual stress near the mid-thickness position is normally very low.

The assumption that the stresses parallel to the surface of heat-treated aluminum plate are equi-biaxial, does not apply to the work-hardened 5456-H343 alloy. Since the residual stresses in this material result from cold work (i.e., rolling, which is a directional process as opposed to heat-treating which is nondirectional), a directional effect was anticipated and specimens were cut from both the longitudinal and transverse orientations. Calculations for residual stresses in the strip specimens were made using Eq. (3) above. However since the residual stresses in this alloy are not equi-biaxial, the correction used previously for the effect of the transverse stress (which exists in the plate, but is relieved in the strip specimen) does not apply. The following correction was used for the effect of transverse stress in each layer removed:

$$\sigma_l = E(1.223\,\sigma_{l_1} + .370\,\sigma_{t_1}) \quad (4)$$

where

σ_l = Residual stress in the longitudinal direction in the original plate.

σ_{l_1} = Residual stress as determined from the strip specimen cut in the longitudinal direction.

σ_{t_1} = Residual stress as determined from the strip specimen cut in the transverse direction.

E = Young's modulus.

ν = Poisson's ratio.

The derivation of Eq. (4) is given below:

ϵ_l and ϵ_t = Residual strains in longitudinal and transverse directions in plate material (biaxial case).

ϵ_{l_1} and ϵ_{t_1} = Residual strains in longitudinally and transversely oriented strip specimens (uniaxial case).

σ_l, σ_t, σ_{l_1} and σ_{t_1} = The stresses corresponding to the strain values ϵ_l, ϵ_t, ϵ_{l_1} and ϵ_{t_1}.

(In the uniaxial case, the stresses and strains are simply related to each other by Young's modulus, in the biaxial case they are not.)

$$\text{i.e.,} \qquad \epsilon_{t_1} = \frac{\sigma_{t_1}}{E} \tag{5}$$

$$\text{and} \qquad \epsilon_t = \frac{\sigma_t}{E} - \frac{\nu \sigma_l}{E} \tag{6}$$

But, $\epsilon_t = \epsilon_{t_1}$ because (neglecting end effects which are nonexistent in the center of the length of the strip specimen) there can be no change in the length of the strip specimen when it is cut from the plate since the average axial stress remains equal to zero.

$$\frac{\sigma_{t_1}}{E} = \frac{\sigma_t - \nu \sigma_l}{E} \quad \text{(Eqs. (5) and (6))}$$

$$\text{i.e.,} \qquad \sigma_t = \sigma_{t_1} + \nu \sigma_l \tag{7}$$

$$\text{similarly} \qquad \sigma_l = \sigma_{l_1} + \nu \sigma_t \tag{8}$$

$$\sigma_t = \sigma_{t_1} + \nu [\sigma_{l_1} + \nu \{\sigma_{t_1} + \nu (\sigma_{l_1} + \nu \ldots)\}]$$

$$\text{i.e.,} \qquad \sigma_t = \sigma_{t_1} (1 + \nu^2 + \nu^4 + \nu^6 \ldots) + \sigma_{l_1} (\nu + \nu^3 + \nu^5 \ldots)$$

Assuming a value for Poisson's ratio of .33 :

$$\sigma_t \cong 1.122\ \sigma_{t_1} + .370\ \sigma_{l_1}$$

$$\sigma_l \cong 1.122\ \sigma_{l_1} + .370\ \sigma_{t_1}$$

C. Tensile Testing

Tensile test specimens with a nominal gauge length of 2 inches and a gauge diameter of 1/4 inch were used to determine the as-heat-treated tensile properties and the changes in these properties resulting from time-temperature stress-relief treatments. Details of this specimen are illustrated in Figure 3.

The details of the experimental arrangement used for testing at -320°F are shown in Figure 4. Initially, specimen elongation for yield strength determinations were obtained by the use of SR-4 strain gauges cemented to the specimens. It was found, however, that good agreement ($\pm$ ~1%) for yield load could be obtained by using an extensometer which measured cross-head movement. For reasons of economy and the fact that at this low temperature the strain gauges occasionally loosened from the specimen before the .2% strain was reached, cross-head movement was used for the determination of .2% yield load in all subsequent tests at -320°F.

Tensile testing at -423°F was carried out by the Convair Division of General Dynamics.

D. Fracture Toughness Testing

Fracture toughness measurements were made using the fatigue pre-cracked Charpy impact test. The significance of this test has been well established at this laboratory and elsewhere (4, 5). The test is conducted in the same manner as the conventional Charpy test except that:

1. V-notches are sharpened by fatigue cracking to a depth of approximately .030 inches.

2. The results are evaluated in terms of energy per square inch of fracture area, i.e., in-lbs/in^2, termed W/A.

Standard size specimens, .394 inch square were used throughout this program. Specimens tested at -320°F were cooled in liquid nitrogen for several minutes before being transferred to the impact machine and broken; a procedure requiring only two or three seconds. The impact testing was performed using a MLI machine of special design (CIM-24) which has high accuracy and reliability.

E. Welding

The alloys used for welding investigations in this phase of the program were 5456-H343, 7106-T63, 7039-T651 and 2219-T651.

During the initial phase of the program, all welding on 2014-T651 and 6061-T651 was accomplished by multi-pass built welds using the MIG process. It was found, however, that this technique produced welds which had nonuniform residual stresses from one weld to another. For this reason, the welding portion of this phase of the program was carried out using circular, single-pass, bead-on-plate welds by the MIG process.

IV. EXPERIMENTAL RESULTS

A. Relief of Residual Stresses by Time-Temperature Treatments

The residual stress-relieving characteristics of 7178-T6 forgings, 7106-T63 plate and 7039-T651 plate, as determined by the modified split ring specimen, are presented in Figures 5, 6 and 7.

It is interesting to note that there is little difference in the curves obtained for all three alloys. A comparison of these results with those obtained on the 7075-T651 and the 7079-T6 alloys (3) shows almost identical behavior.

All of the seven series alloys investigated have comparable zinc content and, in addition, are all aged at approximately the same temperature. This explains the similarity of stress-relief characteristics and it would appear that the minor differences in composition among the several alloys have little effect on stress-relieving characteristics.

B. Effect of Time-Temperature Treatments on the Mechanical Properties of Aluminum Alloys

1. Tensile Properties

The effect of time-temperature treatments on the tensile yield and ultimate strength of 7178-T6, 7106-T63 and 7039-T651 at room temperature, -320°F and -423°F are presented in Figures 8 through 25. The relatively high strength and low ductility of 7178-T6 is demonstrated at all test temperatures in contrast to the relatively low strength and high ductility of the other two alloys.

With respect to loss of tensile strength with time-temperature treatments, these data are typical of those found for the other seventy series alloys. The 7106-T63 and 7039-T651, of relatively low strength to start with, appear to overage about as readily as the other alloys tested. This is an unexpected result in view of the high strength levels reported in as-welded joints in these materials.

Figures 26 through 31 illustrate the relationship between remaining residual stress and both loss of yield and loss of ultimate strengths for 7178-T6, 7106-T63 and 7039-T651, after various time-temperature treatments when tested at room temperature. These figures clearly show the loss of strength which must be expected for any particular reduction in residual stress. For moderate amounts of residual stress-relief, i.e., about 40%, a loss of approximately 10% can be expected in both yield and ultimate strengths in all three alloys. It is interesting to note that, with the possible exception of the 7178-T6 material the relationship between remaining residual stress and loss of strength for each alloy is essentially independent of the particular time-temperature treatment used to obtain a given reduction in residual stress.

The very high strength and low ductility of the 7178 alloy in the as-received condition has resulted in almost identical values for yield and ultimate strength when tested at -320°F and -423°F (Figures 9, 10, 18 and 19). Ductility rises rapidly however, as the severity of the time-temperature treatment increases and is reflected by an increasing ultimate strength/yield strength ratio. Ductility measurements (per cent elongation and reduction in area) were made on all three alloys and are presented in Tables 2 through 4. Note the very low ductility values recorded for the 7178-T6 material in the as-received condition when tested at the lower temperatures.

2. Fracture Toughness Properties

Fracture toughness measurements, using the pre-cracked Charpy test, were made on all three materials after a variety of time-temperature treatments. The object of these tests was to indicate toughness trends and provide assurance that no dangerous loss of this material property results from any of the time-temperature stress-relieving treatments employed. Throughout the entire investigation it has been found that, with a few rather insignificant exceptions, fracture toughness in the fully heat-treated alloys being studied is enhanced rather than degraded by the stress-relieving treatments.

Charpy tests of the 7106 and 7039 alloys indicated a severe laminated condition in both these materials. When cracks were propagated in a direction normal to the original plate surface severe splitting across the path of fracture occurred resulting in fictitiously high W/A values and excessive scatter. The data presented for these two alloys were obtained from specimens cut and notched so that crack propagation was parallel to the plate surfaces and across the major rolling direction. Thus, the effect of the laminations was minimized, but even so, scatter was severe and the values obtained should only be used as indications of fracture toughness trends. Fracture toughness in these two alloys is in all cases very high and increases with time-temperature treatments. Curves illustrating the effect of time-temperature treatments on fracture toughness at room temperature and at -320°F for 7178, 7106 and 7039, are presented in Figures 32 through 37.

The fracture toughness values of the 7178-T6 material when tested at room temperature and -320°F in the as-received condition are lower than those of any of the other alloys tested. However, in agreement with the results obtained on the other alloys, fracture toughness is enhanced by time-temperature stress-relieving treatments.

C. Residual Stress Magnitude and Distribution

In order to determine the magnitude and distribution of residual stresses in plate and forgings, both in the as-received and in the stress-relieved conditions, it was necessary to make through-the-thickness stress analyses. This technique is described in Section III .

TABLE 2

EFFECT OF TIME AND TEMPERATURE ON ELONGATION AND REDUCTION OF AREA FOR 7178-T6 FORGED MATERIAL

Aging Time (hrs)	As Rec. EL	As Rec. RP	Aging Temperature 300°F Elong. %	300°F RA %	350°F Elong. %	350°F RA %	400°F Elong. %	400°F RA %	450°F Elong. %	450°F RA %	Test Temperature (°F)
As Received	8.0	6.5									Room Temperature
	2.5	1.5									
2			8	18	4.5	7.5	11	32	9.5	25	Room Temperature
			12	18	8	7	7	15	10	50	
5			5	6.5	6	14	10	11	10	42	Room Temperature
			9	17	8	14	10	11	10	40	
25			8.5	13.5	12	29	12	18	11	25	Room Temperature
			8.5	13.5	12	14	12	41	12.5	47	
100			6.5	3	9.5	11	12	41	--	--	Room Temperature
			9	11	8	6	10	11	--	--	
As Received	0.5	1									-320
	1.5	2									
2			2.5	2	1	0	6.0	5.0	5.5	8.5	-320
			2.5	0	1	1	10	15.0	7	7	
5			1	2	3	2.5	10	9	7	6.5	-320
			1	0	6	8	10	18	12	27	
25			1	0	5	2.5	8	10	--	--	-320
			3	7	5	2	16	29	--	--	
100			7	6	11	17	16	30	--	--	-320
			4.5	4.5	11	17	9	13	--	--	
As Received	0.5	1.0									-423
	1	1.5									
5			1	1	3	5.5	9	10	--	--	-423
			1.5	2.5	0	1.0	4	2.0	--	--	
25			3	4.0	4	4.0	10.5	10.5	--	--	-423
			4	5.0	4.5	6.0	9	10.0	--	--	
100			3.5	4.0	5.5	7.0	14.5	28.0	--	--	-423

TABLE 3

EFFECT OF TIME AND TEMPERATURE ON ELONGATION AND REDUCTION OF AREA FOR 7039-T651 PLATE

Aging Time (hrs)	As Rec. EL	As Rec. RA	Aging Temperature 300°F Elong. %	300°F RA %	350°F Elong. %	350°F RA %	400°F Elong. %	400°F RA %	Test Temperature (°F)
As Received	10	41							Room Temperature
	10	29							
2			10	32	10	35	12	55	Room Temperature
			10	30	10	39	13	39	
5			10	30	11	38	12	43	Room Temperature
			10	38	11	43	13	44	
25			12	36	11	56	13	57	Room Temperature
			10	45	11	56	15	41	
100			12	47	11	50	15	49	Room Temperature
			12	50	11	55	15	57	
As Received	14	28							-320°F
	13	23							
2			13	30	16	23	19	42	-320°F
			15	25	14	33	19	27	
5			15	26	17	27	23	26	-320°F
			14	25	17	38	20	~ 4	
25			14	22	19	35	23	33	-320°F
			14	21	19	36	23	32	
100			17	19	19	44	22	30	-320°F
			16	35	19	31	23	41	

TABLE 3 (Cont)

EFFECT OF TIME AND TEMPERATURE ON ELONGATION AND REDUCTION OF AREA FOR 7039-T651 PLATE

Aging Time (hrs)	As Rec. EL	As Rec. RA	Aging Temperature 300°F Elong. %	300°F RA %	350°F Elong. %	350°F RA %	400°F Elong. %	400°F RA %	Test Temperature (°F)
As Received	17	21.5							-423°F
	18	21.0							
5			11.5	21.0	19	25.0	18	21.5	-423°F
			17	25.5	20	21.5	23	25.0	
25			17.5	24.5	18.5	24.0	24	29.0	-423°F
			17	22.0	21.0	21.5	13	28.0	
100			17.5	25.5	18.5	22.0	22	21.5	-423°F

TABLE 4

EFFECT OF TIME AND TEMPERATURE ON ELONGATION AND REDUCTION OF AREA FOR 7106-T63 PLATE

Aging Time (hrs)	As Rec. EL	As Rec. RA	Aging Temperature 300°F Elong. %	300°F RA %	350°F Elong. %	350°F RA %	400°F Elong. %	400°F RA %	450°F Elong. %	450°F RA %	Test Temperature (°F)
As Received	11	37									Room Temperature
	11	36									
2			11	42	11	35	12.5	51	14	50	Room Temperature
			11	35	11	31	11	50	14	52	
5			11	33	11	50	14	52	15	49	Room Temperature
			11	43	11	43	14	53	15	58	
25			12	39	14	50	14	59	15	46	Room Temperature
			11	49	12.5	53	14	47	15	53	
100			12.5	44	12.5	50	15	58	--	--	Room Temperature
			12.5	48	12.5	50	14	55	--	--	
As Received	14	10.5									-320°F
	11.5	14.0									
2			14	18	--	--	19	36	21	38	-320°F
			15.5	30	--	--	--	45	21	34	
5			14	31	--	--	19	37	--	33	-320°F
			14	21	--	--	19	31	23	44	
25			14	25	--	--	19	31	23	30	-320°F
			14	28	--	--	19.5	39	26	28	
100			15	24	--	--	14.5	33	--	--	-320°F
			15	24	--	--	14.5	42	--	--	

TABLE 4 (Cont)

EFFECT OF TIME AND TEMPERATURE ON ELONGATION AND REDUCTION OF AREA FOR 7106-T63 PLATE

Aging Time (hrs)	As Rec. EL	As Rec. RA	Aging Temperature 300°F Elong. %	300°F RA %	350°F Elong. %	350°F RA %	400°F Elong. %	400°F RA %	450°F Elong. %	450°F RA %	Test Temperature (°F)
As Received	15	24									-423°F
	17	25									
5			15	20	20	21	16.5	19.5	--	--	-423°F
			16.5	25	20	21.5	19.0	36.5	--	--	
25			13.5	19.5	20	28.5	25.0	35.5	--	--	-423°F
			15.0	20.0	20	28	25.5	25.5	--	--	
100			20.0	24.5	22.5	24.5	20.5	24.5	--	--	-423°F

1. 7075-T6 Plate and Forgings

In earlier work (3), it was shown by through-the-thickness residual stress analyses, that the residual stresses in rolled 7075-T6 plate were much higher than in forged 7075-T6 plate. This unexpected result was questioned and the following additional work was carried out. A piece of the 7075-T6 forged plate was machined down to one inch thick, resolutionized and quenched in water at about 60°F. A through-the-thickness stress analysis was conducted on a coupon cut from the center of this forging. Curves showing the residual stress distributions in this coupon together with those from coupons cut from the same forging before reheat treatment and from a reheat-treated 1 inch thick plate, are presented in Figure 38. Note that the reheat treatment greatly increased the residual stresses in the forging, although the residual stresses in the reheat-treated rolled plates are still considerably higher. Thus, it appears that heat treating variables can have a very significant effect on residual stress. The fact that the residual stresses in the reheat-treated forging were lower than those observed in the rolled plate may be due to a size effect. The rolled plate coupon was 10 inch square whereas the forging (which was the largest piece of 1 inch thick forging available) had maximum measurements of about 8 inch x 10 inch. One of the long edges of the forging was part of a 7-1/2 inch radius circle so the overall size of this piece was even smaller than the maximum measurements indicate.

In order to further confirm the observed variations in residual stresses between forged and rolled material and to investigate the effect of heat treatment variables on residual stresses, an experiment was conducted using 1 inch square by 5 inch long specimens. The specimens were solution treated and quenched in groups of 4, wired together side by side with dummy specimens around the periphery to simulate as closely as possible the quench conditions pertaining to one inch thick plate. The results from these tests scattered so badly that no useful conclusions could be drawn. The reason for the scatter was believed to be unequal cooling during quench resulting from the formation of steam pockets. The experiment was therefore repeated, each specimen being quenched independently in a brine solution to minimize the formation of steam pockets. Since these specimens were cooled equally on all four sides during quench, identical residual stresses would be expected on each face. Thus, each specimen could be split in two directions, normal to each other, and two measurements made for residual stress. Specimens were tested in duplicate, hence, 4 values for each condition were available for plotting. These data for 7075-T6 are presented in the bar graph of Figure 39. Note the much lower residual stress in the forged material and the effect of quench bath temperature on residual stress. The maximum residual stress values are nominal values and were calculated assuming that the residual stress decreased uniformly from surface to center of specimen.

2. 7178 Forgings

The through-the-thickness residual stress distributions both before and after stress-relief for three thicknesses of 7178-T6 forgings are presented in Figures 40 through 42. These forgings were circular in shape, about 15 inches in diameter, with thicknesses of 1.3, 2.4 and 3.3 inches. The magnitude and distribution of residual stress, including the maximum stress values, are approximately the same for each thickness. This is in contrast to the results obtained on 7075-T6 forgings where an increase in maximum stresses was observed with increasing thickness (3).

3. Stress Distribution in Other Alloys

Data have been obtained by residual stress analyses in the through-the-thickness direction for two thicknesses of 2219-T6 plate, and are presented in Figures 43 and 44. It can be seen that higher residual stresses occur in the thicker plate as was observed in the 7075-T6 forgings. Note also that the residual tensile stresses in the central portion of the 2 inches thick plate initially increase from the center outwards. This behavior was not observed in the other heat-treated alloys and the reason for this result is not clear.

Figure 45 illustrates the residual stress distribution through the thickness of a 2 inch thick plate of 7039-T6 in the as-received condition.

D. Stress-Relief

In order to determine the effect of time-temperature treatments on the residual stresses in plate, an evaluation of the residual stress distributions through the thickness of the plates in the as-received and in the stress-relieved condition was made. For this purpose the average residual stress values, disregarding sign, were taken as a measure of the effective magnitude of residual stress. These values were obtained by dividing the sum of the areas between the curve and abscissa by the plate thickness. Values for per cent residual stress remaining were calculated and compared with predicted results obtained from modified split-ring specimens, subjected to similar time-temperature treatments.

The remaining residual stress vs. time curves obtained from modified split-ring specimens clearly show that the rate of stress-relief in aluminum decreases rapidly with increasing amounts of stress-relief. Since the residual stresses in heat-treated plate occur during the quench following solution treatment and are partially relieved during the subsequent aging treatment, the residual stresses resulting from heat treatment of plate would be expected to relieve more slowly during subsequent time-temperature treatments than the new (i.e., not partially relieved) stresses induced in the modified split-ring specimens. Thus, for predicting the remaining residual stress in heat-treated plate, after a particular time-temperature treatment, it is necessary to duplicate in the modified split-ring

specimen a residual stress that had been subjected to the same thermal-mechanical history experienced by the residual stresses in the heat-treated plate. The procedure used for this purpose is described in the following section where data are presented for the 7178-T6 alloy.

The residual stress-relieving characteristics of 7178-T6 forgings, as determined with the modified split-ring specimen, are presented in Figure 5. A comparison of these results with those obtained from 7075-T6 (Figure 10 in Annual Report #1) shows essentially identical behavior; the curves from one alloy practically superimposing on those of the other at each temperature. Figure 46 illustrates the effect of prior relief on the rate of residual stress-relief that occurs during the aging part of the heat treating cycle. In this experiment two modified split-ring specimens in forged 7178 were solutionized and water quenched. The arms of all four specimens were then plastically spread about .05 inch to relieve quench induced residual stresses in the test sections. One specimen was then stressed to its yield strength to simulate, with a stress of known magnitude, the actual residual stresses that would occur in plate due to the quench. Both specimens were then aged. After aging, the stressed specimen was unloaded and both the remaining stress and the amount of stress-relief that had occurred during the aging was determined. This specimen was then restressed, exactly as before unloading and the companion specimen was stressed to the same stress value. The effect of time-temperature treatments (350°F for times up to 25 hours) on the residual stresses in these specimens was determined. Note in the figure that the specimen aged in the stressed condition relieves more slowly than the specimen aged in the unstressed condition, reflecting the effect of the previous relief (occurring during aging) on the rate of subsequent stress-relief. In this case, the amount of residual stress-relief which resulted from the aging treatment was 16%. Note also, on the lower curve of Figure 46, that the results from the as-received material superimpose on the results from the reheat-treated specimen, aged in the unstressed condition.

As can be seen by reference to the upper curve of Figure 44, the remaining residual stress, as determined under the conditions described above, was 54 per cent. This value may be compared with the 65, 64 and 74% obtained by through-the-thickness analyses made on the three thicknesses of forged 7178 material (see Figures 40, 41 and 42).

E. Mechanisms of Stress-Relief

1. Effect of Previous Stress-Relief History

It has been demonstrated and reported in earlier progress reports that the percentage rate at which residual stress-relief occurs in aluminum is largely independent of the magnitude of the residual stress. As stress-relief progresses, however, the rate of relief decreases very rapidly until after 100 hours, little change is taking place. Since overaging, evidenced by the loss of tensile strength, occurs concurrently with stress-relief and as the rate at which it occurs also decreases with time at temperature, it would seem logical to assume that stress-relief might be associated with local volume

changes resulting from the overaging phenomenon. Such, however, does not appear to be the case. In the stress cycling experiments (see Figures 105 and 106, 1st Annual Report), where stresses were reversed every 24 hours, the rate of stress-relief was just as fast on the last cycle as on the first, in spite of the fact that overaging was proceeding much more slowly during the last cycles.

In order to try and shed some light on the mechanism involved, a carefully controlled experiment was run, using six of the modified ring type specimens, all stress-relieved simultaneously in the same salt bath with temperature controlled to $\pm 2^{\circ}F$ or better. One object of this experiment was to determine whether any one of a series of multiple stresses applied to a specimen at different times during a time-temperature treatment would relieve at the same rate as a single stress of the same magnitude applied to an otherwise unstressed specimen. This experiment closely simulated the stress cycling experiment, referred to above, except that the successive stresses were all applied in the same direction, care being taken not to exceed the lowering yield strength of the material.

The experimental details were as follows: six identical modified ring type specimens were cut from one piece of rolled 7075-T651 plate; four of these specimens were stressed to 20 ksi and two were stressed to 7.5 ksi. The six specimens were placed in a salt bath at $400^{\circ}F$ in pairs at 30 minute intervals to allow time for their removal at selected staggered time intervals for measurement of remaining stress, restraining and return to the bath. Each pair was removed and measured after elapsed times of 1 hour, 5 hours and 24 hours. Two of the specimens loaded initially to 20 ksi and the two loaded initially to 7.5 ksi were, thereafter, removed and measured at 24 hour intervals until a total stress-relieving time of 144 hours was accumulated. The remaining two specimens (loaded initially to 20 ksi) were given an additional load of 7.5 ksi and returned to the salt bath. Measurements of remaining residual stress on these two specimens were made after accumulated times of 1, 5 and 24 hours. This procedure was repeated every 24 hours until these specimens had been subjected to a total time at temperature of 144 hours.

The data, remaining residual stress vs. time at temperature for all six specimens are plotted in Figure 47. Note the excellent reproducibility of the results, particularly in the lower two curves. Also, immediately apparent from Figure 47 is the similarity in the shape of the curves obtained for each 24 hour period from the two specimens whose stress levels were cyclically increased every 24 hours. The similarity in the shape of these curves helps to confirm previous observations that the rate of residual stress-relief is a function of the previous history of the particular residual stress itself rather than that of the material. Furthermore, these curves suggest that within the yield strength of the material any applied stress, subjected to a time-temperature treatment, will relieve at a rate that is largely independent of the existence of other stresses and of the previous history of the material, being dependent essentially on its own time-temperature history.

If this suggestion is valid, it should be possible to predict the remaining stress in the multistressed specimens at any time during their time-temperature treatment from the data obtained from the singly stressed specimens. For example, using the data from the singly stressed specimens, the remaining stress in the multistressed specimens after 96 hours at temperature is made up as follows:

20 ksi subjected to 400°F for 96 hours - remaining stress = 3.6 ksi
7.5 ksi subjected to 400°F for 72 hours - remaining stress = 1.7 ksi
7.5 ksi subjected to 400°F for 48 hours - remaining stress = 1.8 ksi
7.5 ksi subjected to 400°F for 24 hours - remaining stress = 2.2 ksi

Total = 9.3 ksi

This value, 9.3 ksi, agrees well within the limits of expected experimental error with the 9.6 ksi actually observed in the specimens. Several similar calculations have been made for various time periods and the results are plotted as filled circles in Figure 47. Note the generally good agreement for all of these points.

In Figure 48 a replot of the two lower curves of Figure 47, where remaining residual stress is plotted as a percentage of the initial stress, illustrates the near independence of the fractional rate of stress-relief with stress magnitude.

Figure 49 illustrates the changing rate of residual stress-relief with time at 400°F in 7075-T651. This curve was obtained from the curve in Figure 47 which depicts remaining residual stress as a function of time at temperature, starting with an initial stress of 20 ksi. The slope of the curve in Figure 47 was measured at selected time intervals and divided by the stress remaining at that time, giving rate of stress-relief in ksi per hour per ksi of remaining stress (i.e., in units of hr^{-1}). Note how rapidly the rate of relief decreases with time during the first few hours.

The results illustrated in Figure 50 may be compared with those of Figure 47. They are the results from an identical experiment conducted in another alloy, 6061-T651. Note that very similar results were obtained although agreement between predicted and actual remaining residual stresses is not as good as that found for 7075-T651.

2. Effect of Heat-Treated Condition on Rate of Residual Stress-Relief

Results from previously run experiments have suggested that heat-treated condition has a comparatively small effect on the rate at which stress-relief takes place. For example, it was shown that the rate of residual stress-relief in welded specimens is almost identical to that observed in the original plate. This behavior was unexpected because intuitively one would expect the occurrence of any metallurgical change (during stress-relief treatment) to favor residual stress-relief. An experiment was therefore conducted on 6061 aluminum plate, using modified ring type specimens, in three widely different heat-treated conditions (i.e., annealed,

solution treated and fully aged) to determine more precisely just what effect heat treatment has on the rate at which stress-relief takes place. In view of the soft condition of the annealed and solution treated specimens low initial stress (5:55 ksi) were used to avoid plastic yielding. This stress was reversed every 24 hours at temperature (400°F). The results are presented in Figure 51. They are remarkable in that they indicate the rate of residual stress-relief to be the greatest, by a factor of at least 2, in the material least likely to undergo any sort of metallurgical change, i.e., the annealed material and least in the material most likely to undergo metallurgical changes, i.e., the solution treated material. Furthermore, after the initial cycle, the rates of stress-relief remained almost constant in the annealed and fully aged materials, but decreased quite rapidly in the initially solution treated material. The reason for this last observation is not immediately apparent. After the first cycle, both the fully aged and the initially solution treated specimens would be in essentially the same overaged condition. Conceivably, the precipitate formed under cyclic stressing provides a more effective barrier to dislocation movement than precipitates formed under the usual conditions.

A plot of remaining residual stress vs. time at 350°F for 6061 in the same heat-treated conditions is illustrated in Figure 52. The modified split-ring specimen was used in this experiment. Note that once again the annealed specimen relieved at a much faster rate than either the solution treated or the T6 specimen.

3. Creep Back Experiments

When plastic deformation in aluminum alloys results from a time-temperature treatment under stress, some of this deformation is recoverable by removing the stress and maintaining (or raising) the temperature. In fact, for small amounts of plastic deformation, recovery is very close to 100%.

Figures 53 and 54 illustrate the behavior of modified ring type specimens in 6061-T651 and 7075-T651, alternately loaded and unloaded for 24 hour periods at 400°F. The initial stresses were 15 and 53 ksi respectively and the distances between the bench marks on the specimen arms, when in the stressed conditions, were maintained constant. The dashed curves represent specimens in which stresses were maintained during their entire time-temperature treatment. Note that the over-all behavior is essentially unaffected by the interrupted stressing; the plastic deformation occurring at the points of interruption are, presumably, the results of dislocations moving first in one direction and then in the other along the same glide paths, thus having a negligible over-all effect.

The results from another experiment, in which creep back in ring specimens was measured as a function of prior residual stress-relief, are presented in Figure 55. Prior residual stress-relief was obtained at a variety of time and temperature combinations. Creep back was obtained by heating to 800°F in a salt pot for 1 hour. Note that the amount of creep back

decreases with increasing residual stress-relief and would presumably be zero at 100% stress-relief. Note also that there is little or no effect of initial stress on per cent creep back. The data, for initial stresses ranging from 5 to 50 ksi, lie quite close to the curve obtained from specimens stressed initially to 20 ksi.

4. Discussion of Mechanisms of Residual Stress-Relief

Recent studies (1,2) of the relief of residual stresses in plain carbon steels at M.I.T. by Brown, Rack and Cohen have shown that the mechanisms involved are quite complex. They theorize that the production of a carbide structure during tempering, with its associated plastic zones, leads to stress relaxation. In the case of spheriodized steel where the carbides are already present, the coarsening of these carbides is again thought to play the major role in the stress relaxation phenomenon. However, in the latter case, the effect of microyielding of the matrix is also considered necessary to completely explain the experimental results. In contrast, the results obtained in this investigation suggest that in aluminum alloys the effects of precipitation are comparatively small and that the effects of microyielding predominate in the relief of residual stresses during time-temperature treatments. In Rack's work on steel (2) it is shown that the degree of relaxation markedly decreases with increase in the stability of the structure. In aluminum alloys the opposite appears to be the case. Figures 51 and 52 indicate a much higher degree of relaxation in annealed 6061-T6 compared with that of the same material in either the T6 or solution treated conditions. The results obtained from the various experiments performed in the present study can be rationalized by considering the effects of microyielding alone.

Figure 49 illustrates the observed decrease in the rate of residual stress-relief with time at temperature. Assuming that relaxation results from microyielding caused by dislocations released from sources which are activated by stress and temperature, a rapid decrease in the rate of relaxation would be expected to occur from the back stresses set up as these dislocations become arrested at grain boundaries and other obstacles.

The "creep back" phenomena (Figure 55) may also be rationalized by the microyield postulation by assuming that microyield occurs in localized areas within each grain. Thus, the strain in a considerable volume of the matrix is purely elastic. Upon unloading the specimen, the elastically strained portions of the matrix together with the back stresses set up by the arrest of dislocations supply the restoring force necessary to produce creep back. Because in the unloaded specimen a condition of equilibrium exists, these restoring forces are exactly balanced by equal and opposite forces. These balancing forces occur, upon unloading the specimen, within the areas of the matrix where plastic strain occurred during the initial relaxation of the external load applied to the specimen. In these areas, the stress undergoes a reversal of sign upon unloading. If, upon reheating without external load, both sets of forces decay uniformly, equilibrium will be maintained at all times without over-all geometrical change (creep back) in

the specimen taking place. It follows, therefore, that for creep back to occur, plastic relaxation of the elastic strains must occur more readily in the previously deformed areas of the specimen than in the areas which were elastically strained only. In this case, equilibrium can be maintained only by an over-all change in specimen geometry, hence, the occurrence of creep back. A possible explanation of the enhanced rate of relaxation in the microyielded areas is that glide paths for dislocations have already been established. Furthermore, many dislocations, produced and arrested during the initial relaxation when the specimen was loaded, are now available and free to move in the opposite direction. When small amounts of relaxation occur, where recovery by creep back is nearly 100%, it may be that deformation is confined largely to individual grains, unaffected by the effect of plastic deformation in adjoining grains. On the other hand, in cases where slip crosses grain boundaries, recovery is difficult since each grain is dependent for its complete recovery on the recovery of its adjoining grain or grains. Thus, for low values of relaxation, recovery by creep back should be essentially complete as observed in the data in Figure 55. For higher amounts of relaxation, creep back is incomplete.

The results obtained from the stress cycling experiments, Figure 51 and Figures 56 and 57 from the first annual report data are the most difficult to explain. Because of the creep back behavior, stress relaxation during the second half of the first cycle would be expected to be faster and proceed much further than it did during the first half cycle. Although the data in Figures 56 and 57 indicate an increase in the initial rate of relaxation upon reversal of the applied stress, the amount of relaxation in any one half cycle is relatively constant. An explanation for this behavior lies in a consideration of the mechanism by which relaxation is opposed, i.e., the back stresses set up by the arrest of dislocations. Whenever the applied stress is reversed at the end of a half cycle, the same number of dislocations must move back in the opposite direction and become arrested to set up the back stresses necessary to arrest further relaxation. Thus, approximately the same amount of deformation occurs for each half cycle.

The fact that the data show that in subsequent cycles, somewhat less relaxation tends to occur than during the first (or first few) cycles, may be due to dislocation entanglements or cross grain boundary slip occurring before well established glide paths have been established. In subsequent cycles it may be that relaxation results largely from the movement of the same dislocations along the same glide paths, first in one direction and then in the other. Thus, in cyclic experiments, the creep back phenomena has the effect of accelerating the initial rate of relaxation but, not of increasing the total amount of relaxation occurring after a relatively long time at temperature.

The results presented in Figure 51, showing the effect of heat treatment on stress relaxation in cyclically stressed specimens, can also be explained in terms of the postulation that the effects of microstrain predominate in the relaxation of strains in these aluminum alloys. In the

annealed material, precipitated particles have already coalesced and present no real barrier to dislocation movement. Thus, the average distance moved by the dislocations is increased and relaxation is enhanced.

The difference in the behavior of the T6 and the solution treated materials is less easily explained because, after the first cycle, both materials are essentially in the same (overaged) condition. Conceivably, the alternate movement of dislocations due to cyclic stressing, during aging, could form dislocation entanglements at or near the site of nucleating precipitate particles. If these entanglements are unable to free themselves on stress reversals, they might, in fact, grow as additional dislocations become entangled during subsequent stress cycles.

The results presented in Figures 53 and 54 show that, when a specimen is alternately loaded and unloaded during a stress-relief treatment, the total amount of plastic relaxation in a given time at temperature, when under load, is essentially the same as that in a specimen loaded continuously for the same time. This behavior does not conflict with the concept that microstrain plays the predominant role in stress relaxation. The dislocations moving in a reverse direction during the unloaded (creep back) periods can quickly return to their former positions along established glide paths upon reloading.

The results presented in Figures 47 and 50, indicate that an incremental stress added at any time to an existing stress undergoing a time-temperature stress relieving treatment will relieve at a rate that is characteristic for the material; i.e., independently of either the existing stress or its degree of relief. This behavior is in agreement with the microstrain concept if we assume that the back stress set up by arrested dislocations is directly proportional to the number of dislocations arrested. That is, the relaxation resulting from any stress value or increment thereof will become arrested only when a proportionate number of dislocations have moved and become arrested.

Thus, in summation, it appears that a theory for the mechanism of residual stress-relief in aluminum alloys, based on the assumption that microstrain plays the major role, is able to explain the various behaviors observed in this study.

V. WELDING STUDIES (Subcontracted to M.I.T. Welding Laboratory)

A. Introduction

Concurrent with the primary objective of developing stress-relief treatments for cold deformed and forged materials, an investigation has been made to determine the distribution and relief of residual stresses resulting from welding. Stress measurements were made at various locations in the weldments in an effort to determine the reproducibility of stresses in welds to the end that stress-relieving treatments could be developed for these structures.

In the previous year's work, multiple pass butt welds were made exclusively for study. Measurements of residual stresses in these weldments revealed low level stresses which varied greatly from specimen to specimen and even from location to similar location within one specimen in an irregular manner. The reason for this wide variation and the low stress levels, is believed to have resulted from the multipass technique used. Each pass relieved the residual stress in the previous passes in a somewhat irregular manner, being highly dependent on peak temperatures and weld-bead configurations. As a result, useful residual stress-relief studies on these specimens could not be made. During the current year, circular, single bead-on-plate welds were studied. This type of weld is simple to produce, has high restraint, is uniform in contour and the stresses produced are not subject to relief from heat during subsequent passes. As a result much higher stresses were observed and stress values and distributions were uniform and reproducible.

B. Materials

1. 5456-H343 in 1 inch and 3/4 inch thicknesses.
2. 7106-T63 in the 1/2 inch thickness.
3. 7039-T651 in the 1/2 inch thickness.
4. 2219-T651 in the 1/2 inch thickness.

C. Experimental Procedures

Circular, single pass bead or plate welds were deposited symmetrically on square specimens. In the 7106-T63 materials, specimen sizes were 8 inches by 8 inches and 12 inches by 12 inches. Four inch, six inch and eight inch diameter weld circles were deposited. In the 7039-T63 and 2219-T651 materials, plate sizes were maintained at 8 inches by 8 inches throughout with 4 inch diameter welds. In each material and welding condition, some of the plates were stress-relieved for 2 hours at a temperature of 400°F.

Two levels of arc energy input were employed for all but the 5456-4343 material. The effect of arc energy input on residual stress was determined.

Surface residual stresses were measured tangentially and radially in the weld metal, and in the center of the weld circle using SR4 strain gauges cemented to the surfaces. After the cement had set and the gauge resistances measured, all material except for a thin wafer (about .040 inch thick) under each gauge was machined away. The gauge resistances were then remeasured and the change in stress computed from the change in resistance of each gauge.

D. Experimental Results and Discussion

The experimental results are presented in Tables 5, 6 and 7. Note that residual stresses run as high as 25 ksi compared with the very low stresses observed for the butt welded materials tested during the preceding year. Also, where duplicate specimens were prepared (in the 7106 material) reasonable reproducibility of residual stresses were achieved.

From the results of the study the following observations can be made:

a) The stress distribution in each of the weldments was the result of tangential and radial shrinkage of the weld. Purely tangential shrinkage would tend to put the material inside the circle in uniform biaxial compression and material outside the circle in nonuniform biaxial tension. However, there was enough radial shrinkage that all points inside the circle were in a state of biaxial tension. The weld metal exhibited high tangential stresses with the radial stresses being equal to the uniform biaxial tension stresses within the circle.

b) Lower energy input resulted in higher residual stresses both in the weld and within the circle. This means that, although higher thermal strains are introduced with high energy inputs, there is more auto-stress-relief because of the relatively higher post weld temperature of the plates.

c) Geometric factors influenced the magnitudes of the residual stresses in a predictable way. For example, the thicker plate in 5456-H343 exhibited lower stress within the circle simply because there was a greater cross-section of metal available to carry the load. Furthermore, increasing the size of the circle decreased the residual stresses within the circle largely because the radial strains, resulting from weld shrinkage, are distributed over greater areas.

d) The values of per cent remaining residual stress in the weld and central areas of the specimens, after a stress-relief treatment of 400^{o}F for 2 hours show considerable scatter and do not correlate well with the results predicted from the split-ring specimen.

TABLE 5

RESIDUAL STRESSES IN BEAD-ON-PLATE CIRCLE WELDS IN ALUMINUM

Material	Plate Dimensions	Weld Diameter	Arc Energy Input	Stress-Relief	Stresses (psi Tension)	
					Hoop-Weld	Center-Plate
7039	8" x 8" x 1/2"	4"	29,500 J/in.	400°F - 2 hrs.	8,100	4,000; 3,600
7039	8" x 8" x 1/2"	4"	29,400 J/in.	None	10,500	6,100; 6,300
7039	8" x 8" x 1/2"	4"	16,000 J/in.	500°F - 2 hrs.	8,200	7,200; 7,500
7039	8" x 8" x 1/2"	4"	16,000 J/in.	None	13,600	9,200; 8,800
2219	8" x 8" x 1/2"	4"	29,500 J/in.	400°F - 2 hrs.	7,600	6,900; 4,900
2219	8" x 8" x 1/2"	4"	29,500 J/in.	None	9,000	9,600; 8,900
2219	8" x 8" x 1/2"	4"	16,000 J/in.	400°F - 2 hrs.	10,500	3,700; 4,700
2219	8" x 8" x 1/2"	4"	16,000 J/in.	None	21,900	12,700; 10,300

TABLE 6

RESIDUAL STRESSES IN BEAD-ON-PLATE CIRCLE WELDS IN ALUMINUM

Material	Plate Dimensions	Weld Diameter in.	Arc Energy Input	Stress-Relief	Stresses (psi Tensions) Hoop-Weld	Center-Plate	
5456	10" x 10" x 1"	6"	31,400 J/in.	None	20,000	1,900;	1,300
5456	15" x 12" x 3/4"	6"	31,900 J/in.	None	24,000	11,500;	11,500
5456	15" x 12" x 3/4"	6"	31,900 J/in.	400°F - 2 hrs.	4,350	500;	360
7106	8" x 8" x 1/2"	4"	27,000 J/in.	None	18,000	9,000;	7,000
7106	8" x 8" x 1/2"	4"	30,000 J/in.	400°F - 2 hrs.	4,700	1,450;	1,250
7106	8" x 8" x 1/2"	4"	29,900 J/in.	None	17,000	10,000;	8,000
7106	8" x 8" x 1/2"	4"	16,900 J/in.	None	21,000	13,000;	11,000
7106	8" x 8" x 1/2"	4"	15,900 J/in.	None	25,000	12,500;	11,000
7106	8" x 8" x 1/2"	4"	15,900 J/in.	400°F - 2 hrs.	8,200	3,000;	2,200
7106	12" x 12" x 1/2"	6"	28,000 J/in.	None	25,000	13,000;	12,000
7106	12" x 12" x 1/2"	6"	28,000 J/in.	400°F - 2 hrs.	8,700	4,300;	4,200
7106	12" x 12" x 1/2"	8"	29,000 J/in.	None	24,000	3,800;	3,200
7106	12" x 12" x 1/2"	8"	28,000 J/in.	400°F - 2 hrs.	6,700	2,100;	1,550

TABLE 7

AVERAGE REMAINING RESIDUAL STRESS %
AFTER A STRESS-RELIEF OF 400°F FOR 2 HOURS

Material	Predicted From Ring Specimens %	Low Arc Energy Input		High Arc Energy Input	
		Hoop Weld %	Center Plate %	Hoop Weld %	Center Plate %
5456	5	18	4		
7106	52	33	22	30	33
7039	35	67	69	77	62
2219	72	48	45	84	64

VI. SUMMARY AND CONCLUSIONS

A. Summary

In accordance with the principle objectives of this study, the response of residual stresses to time-temperature treatments was determined for several high strength aluminum alloys. The effect of these treatments on the strength and toughness properties was also determined.

In addition, a variety of experiments were run with the object of shedding some light on the mechanisms involved in the residual stress-relieving of aluminum by time-temperature treatments. A relatively simple theory is presented which appears to be able to satisfactorily explain the various behaviors observed.

B. Conclusions

1. The time-temperature residual stress-relieving behavior of all of the 7xxx series (Zinc) aluminum alloys are very similar. Except for the major alloying elements, composition variables appear to have little effect on residual stress-relief.

2. The quench induced residual stresses in the 7075-T6 forged material tested were shown to be consistantly lower than those in 7075-T6 plate material. While the reason for this behavior was not determined, it is suggested that variations in grain size and/or texture may be responsible.

3. As with the previous alloys tested, the effect of time-temperature treatments on the physical properties of high strength aluminum alloys is to increase fracture toughness and decrease strength. In general the decrease in strength bears a close relationship to the amount of residual stress-relief obtained, regardless of the particular time-temperature treatment employed to effect the stress-relief. Very large amounts of stress-relief can be obtained in the heat treatable alloys only at considerable loss of tensile strength properties. On the other hand, significant amounts of stress-relief can be obtained in most of the alloys with only small losses in tensile strength properties.

4. The fracture toughness of these alloys, as determined by pre-cracked Charpy tests, was found to be relatively temperature insensitive over the range of ambient temperature to -423 ^{o}F.

5. The rate at which residual stress-relief takes place in aluminum alloys is highly dependent on the previous relief history of the particular stress under consideration. As stress-relief progresses, the rate at which it occurs decreases rapidly. However, any stress increment added to an existing stress undergoing a time-temperature stress-relieving treatment will relieve at a rate that is characteristic for the material and independent of the existing stress and the amount of relief the existing stress has already sustained.

6. Residual stress-relief results obtained from the modified split-ring specimen can be used to predict with fair agreement the amount of stress-relief of actual quench induced residual stresses in plate materials.

7. Welding studies using circular bead-on-plate configurations have shown that high residual stresses are produced, particularly in the weld metal. The relief of these stresses by time-temperature treatments were not accurately predicted by the modified split-ring specimen results. The reason for this apparent anomaly is not clear, but is presumably due to the effects of previous strain history during solidification and cooling of the weld metal and/or other variables.

8. The predominant mechanism by which residual stresses are relieved during time-temperature treatments appears to be one of microstrain. The behaviors observed in the various experiments can be explained by use of this theory.

References

1. Brown, R. L. and Cohen, Morris, "Stress Relaxation of Hardened Steel," Metal Progress, Feb. 1962, p. 66-71.

2. Rack, H. S., "Stress Relaxation in Plain Carbon Steel."

3. Oding, I. A., "Relaxation and Creep of Metals," Vestnik Mashinostroeniga, Vol. 26, 1946, No. 5/6, p. 1-10; No. 7/8, p. 1-10; No. 9/10, p. 1-10.

4. Orner, G. M. and Kulin, S. A., "Development of Stress Relief Treatments For High Strength Aluminum Alloys," Annual Report No. 1, Contract No. NAS8-11091, DEN-1-4-85-00008(IF) CPB-02-1177-63, October, 1964.

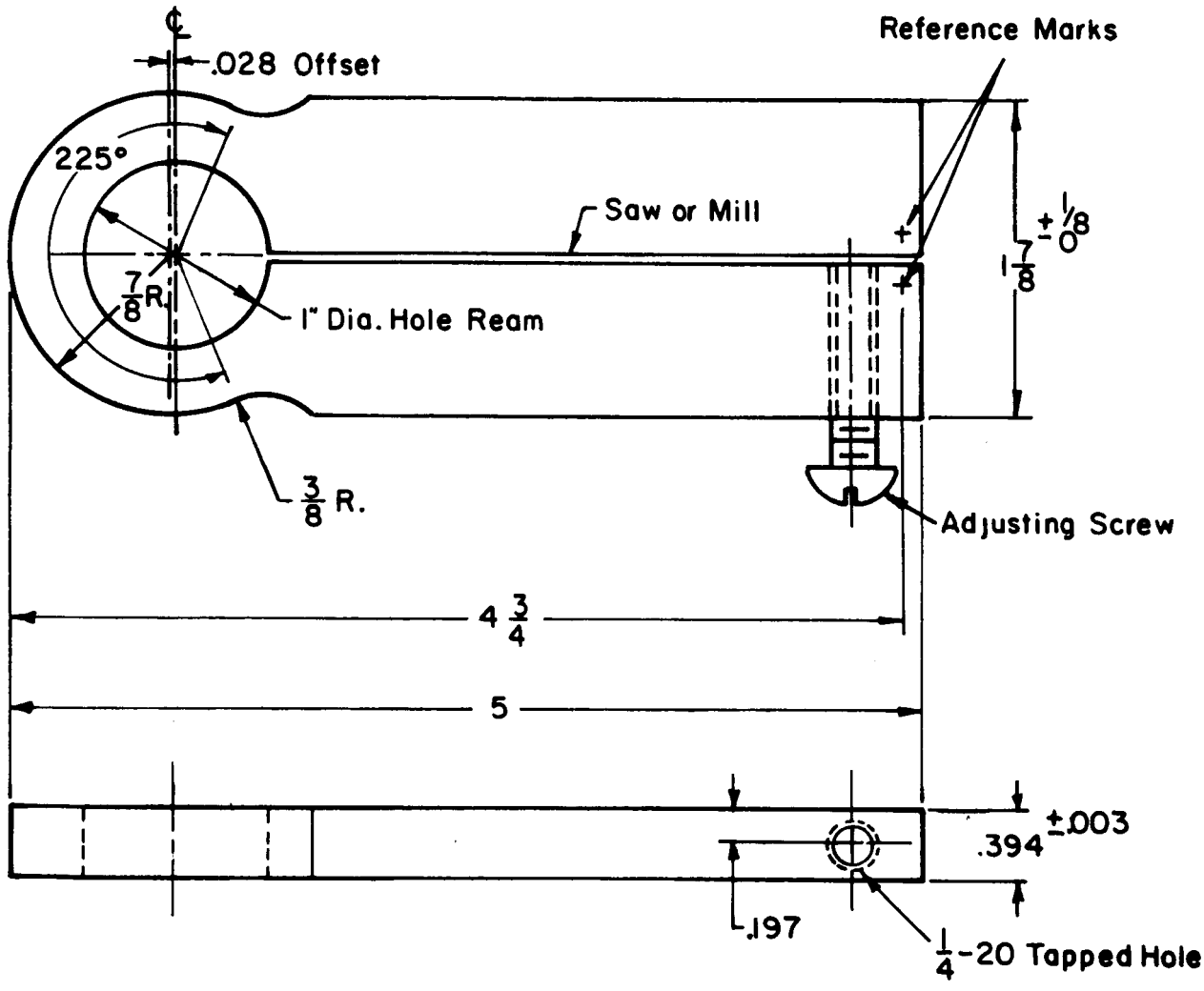

Figure 1. Modified Split Ring Specimen for Measurement of Relief of Residual Stress.

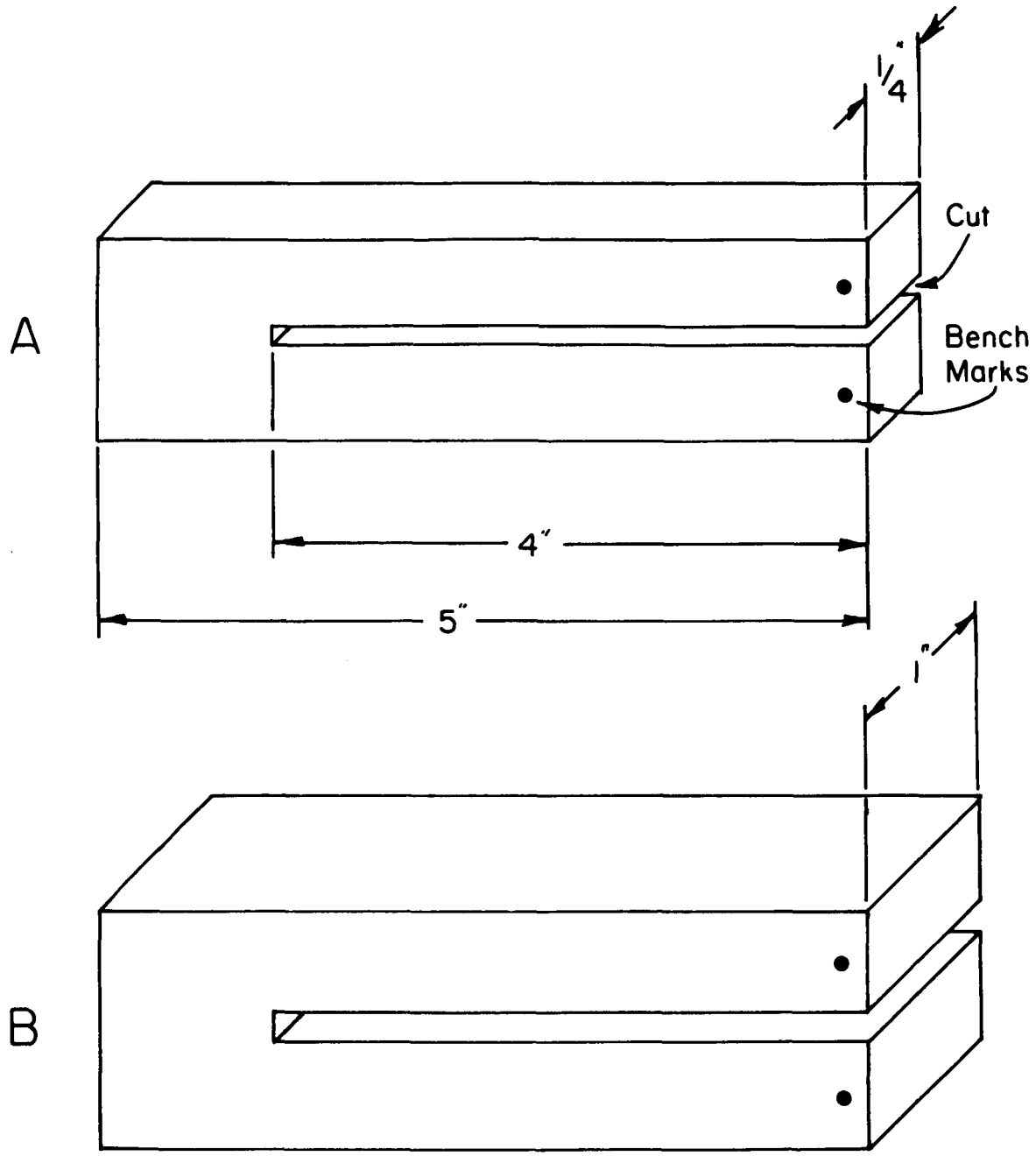

Figure 2. Specimen for Measuring Residual Stress Relief in 1 inch Thick Plate. Configuration B is Used When Specimen Heat Treatment Involves Solution Treating and Quenching.

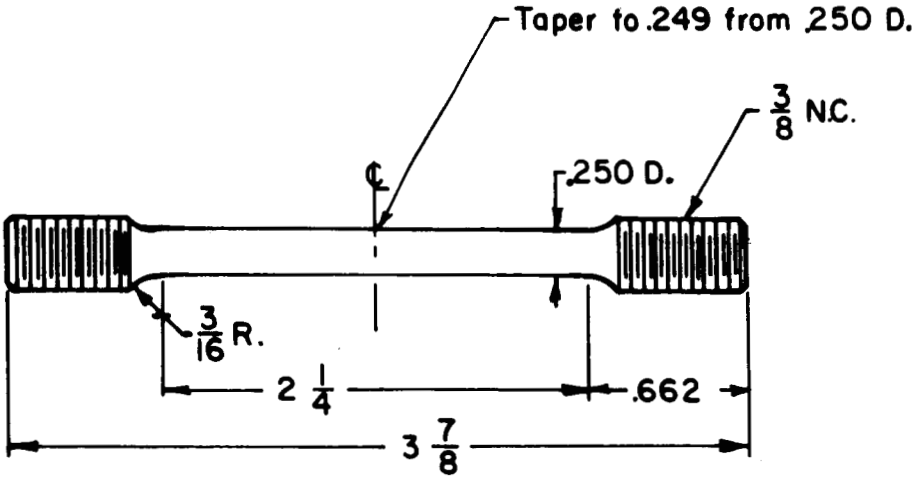

Figure 3. **Tensile Specimen.**

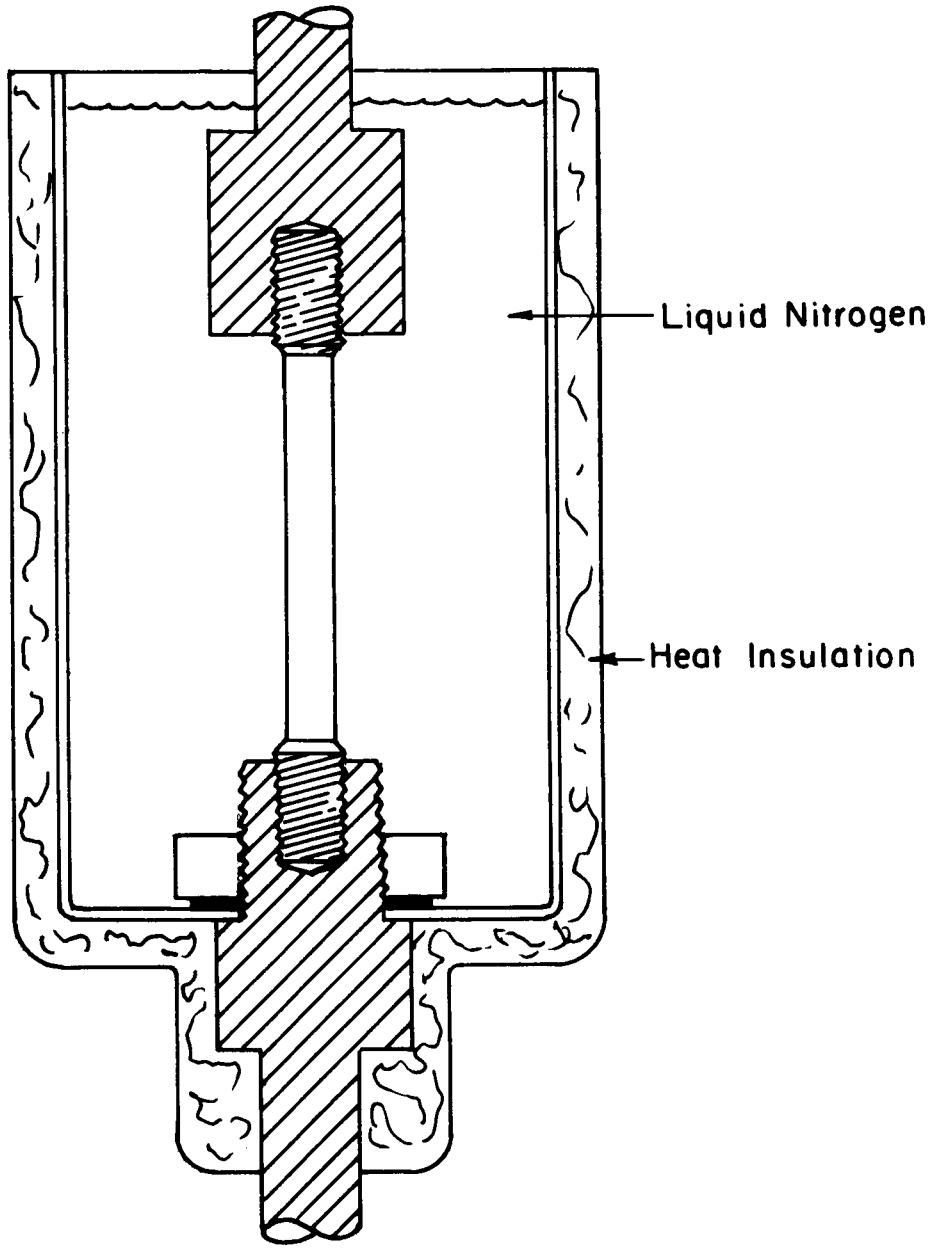

Figure 4. Apparatus Used to Cool Tensile Specimens to -320°F During Testing.

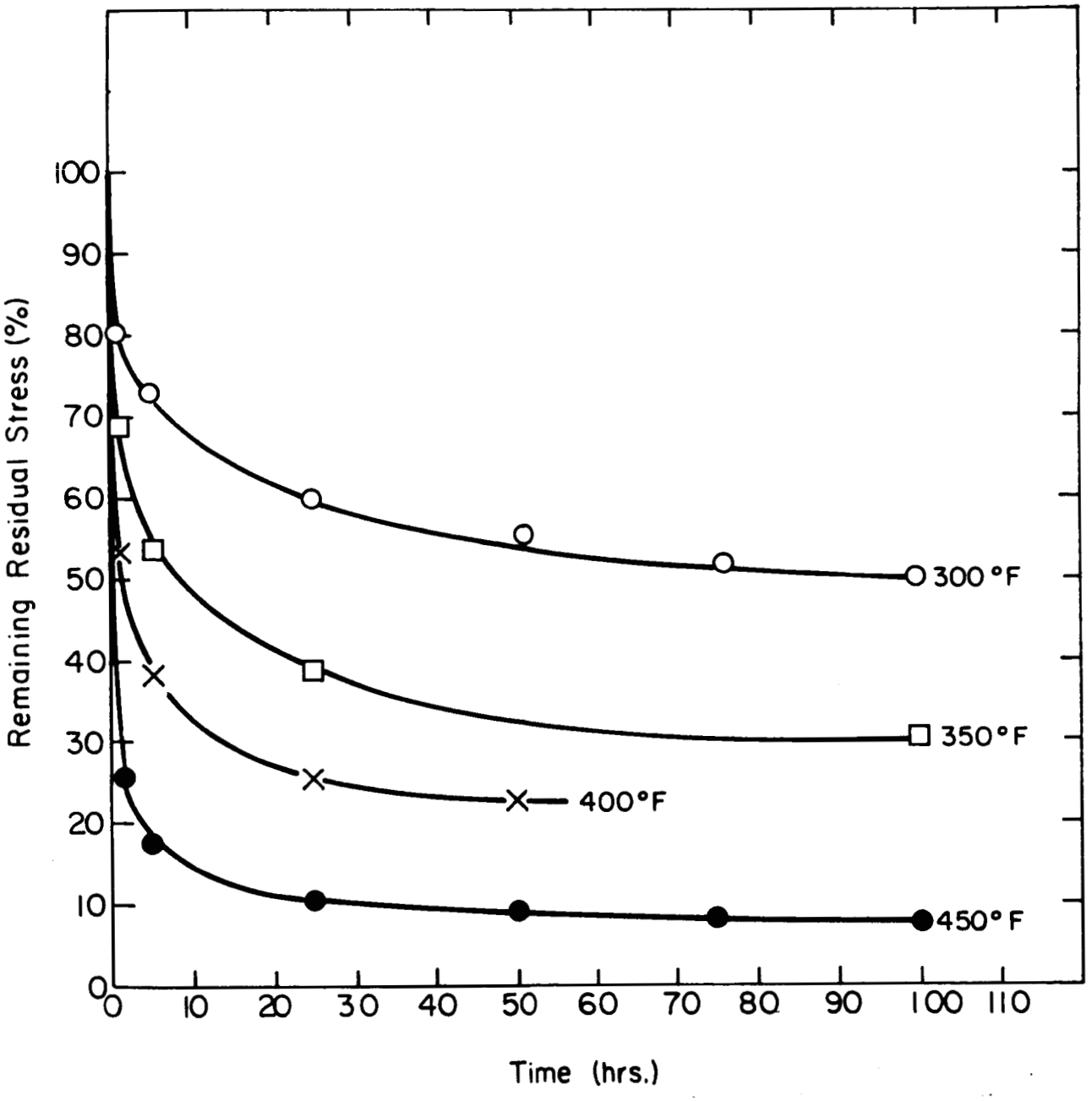

Figure 5. Residual Stress Relief Characteristics of Forged 7178-T6 Aluminum. Stressed Initially to 40 ksi.

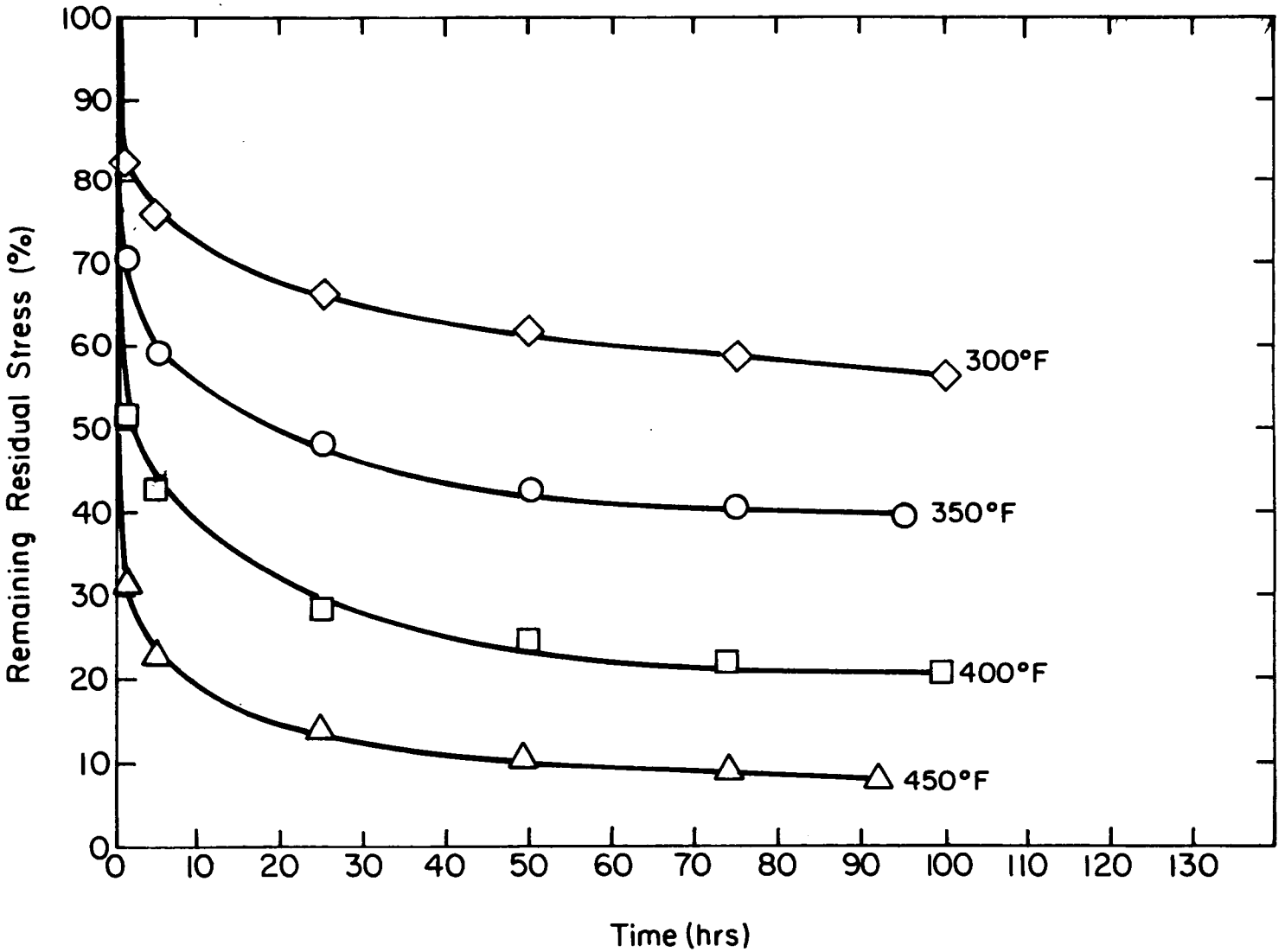

Figure 6. Effect of Time and Temperature on Remaining Residual Stress for 7106-T63 Plate Stressed Initially to 40 ksi.

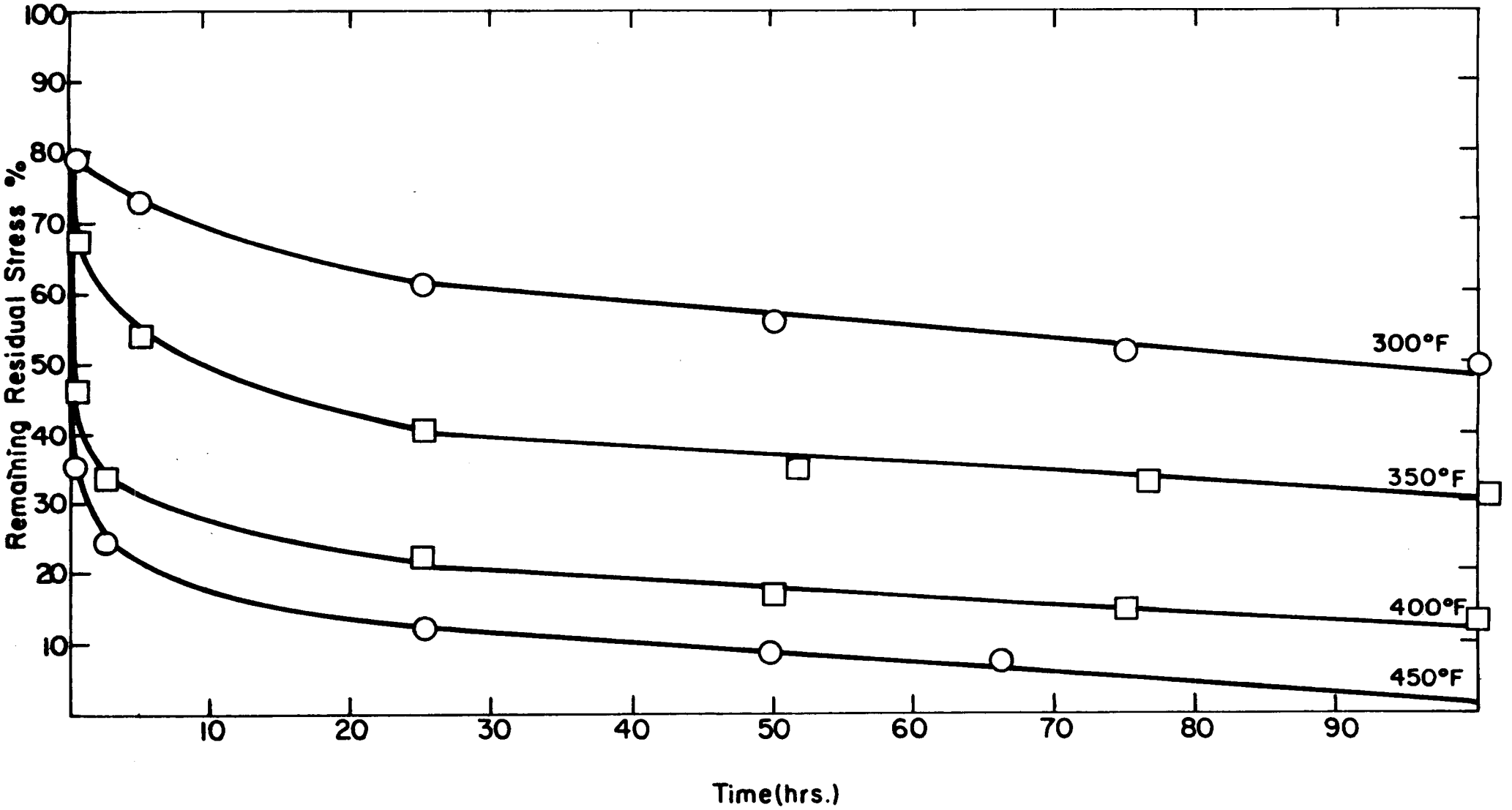

Figure 7. Effect of Time and Temperature on Remaining Residual Stress for 7039-T651 Plate Stressed Initially to 40 ksi.

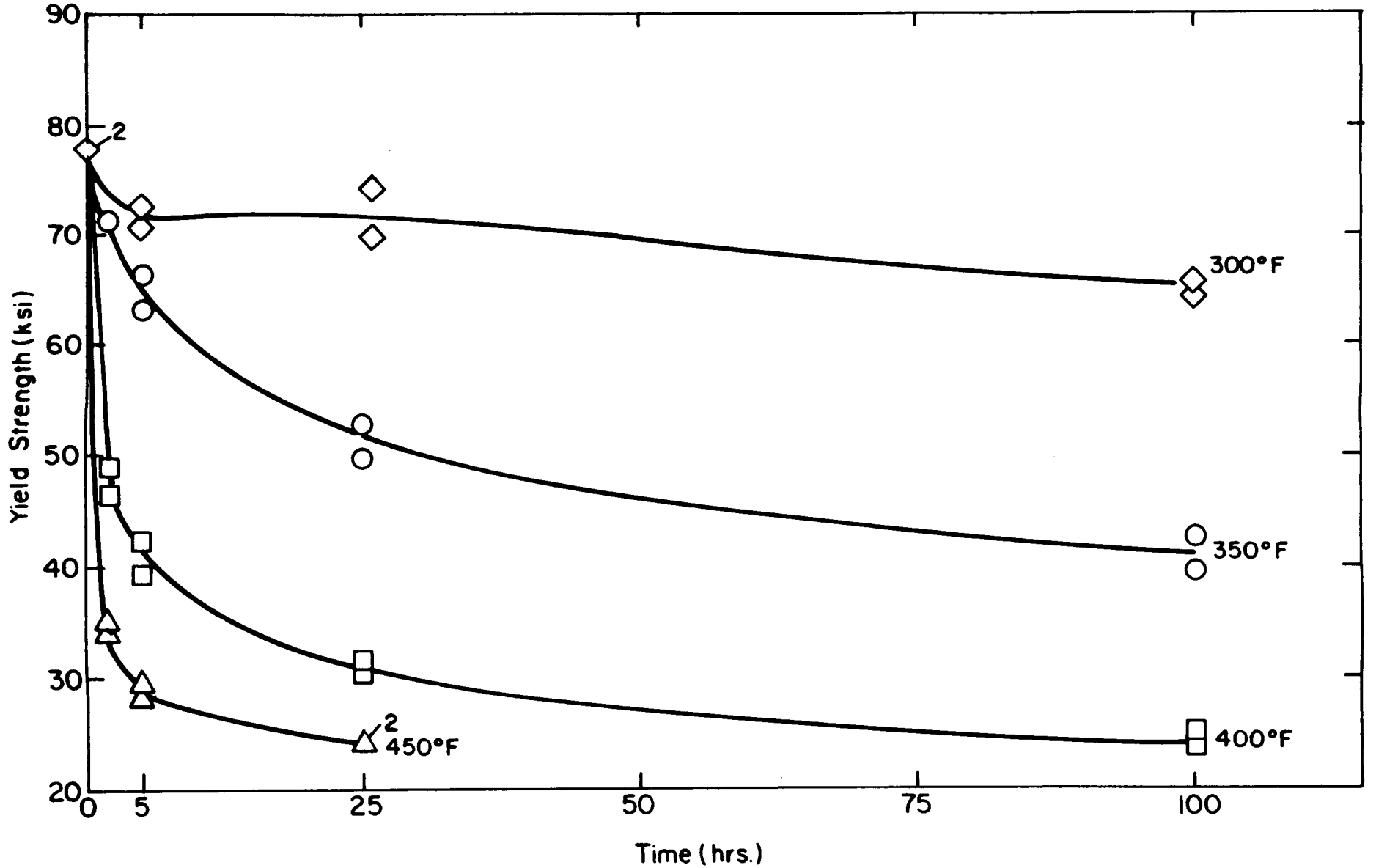

Figure 8. Effect of Time and Temperature on the Yield Strength of Forged 7178-T6 at Room Temperature.

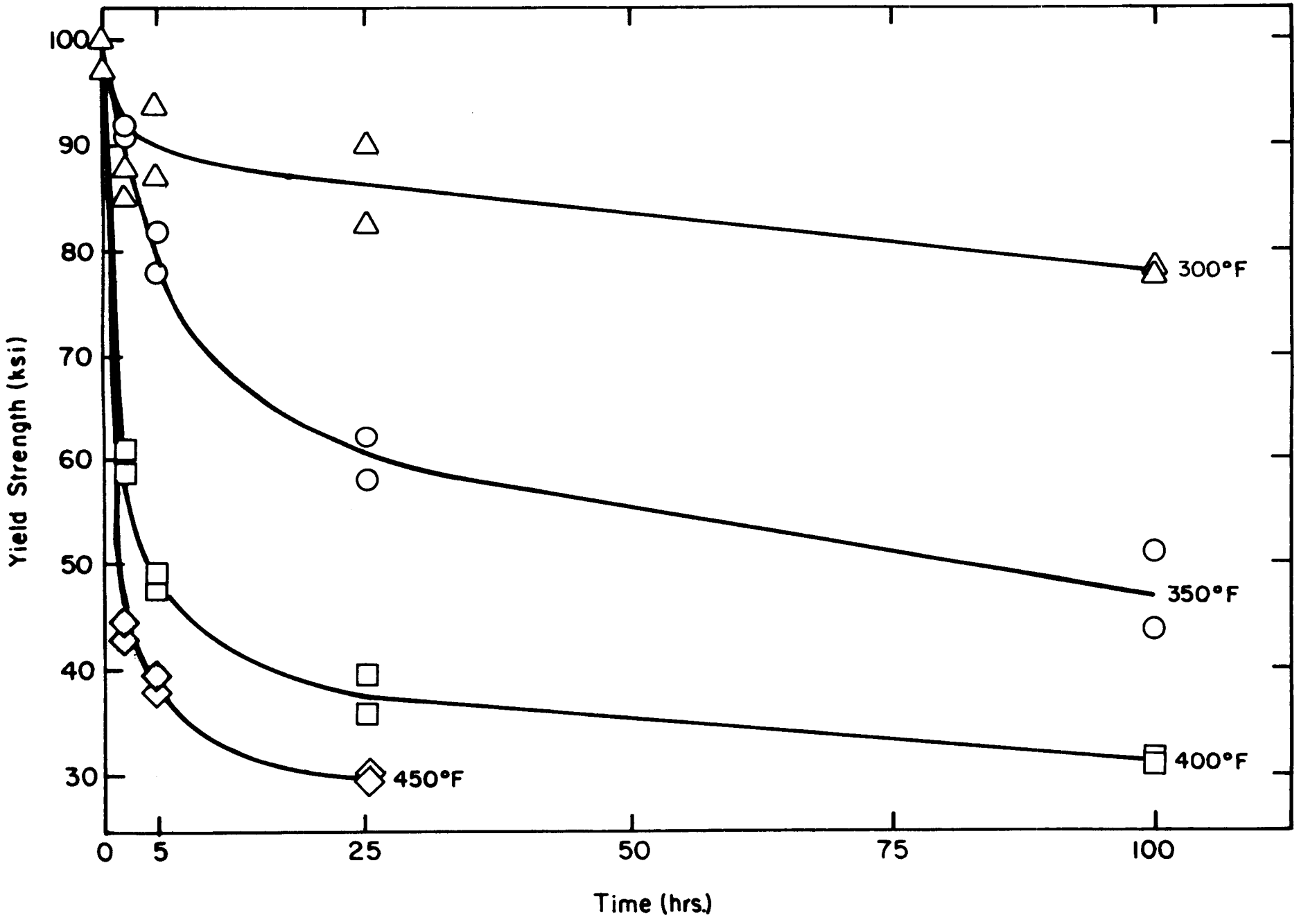

Figure 9. Effect of Time and Temperature on the Yield Strength of Forged 7178-T6 at -320°F.

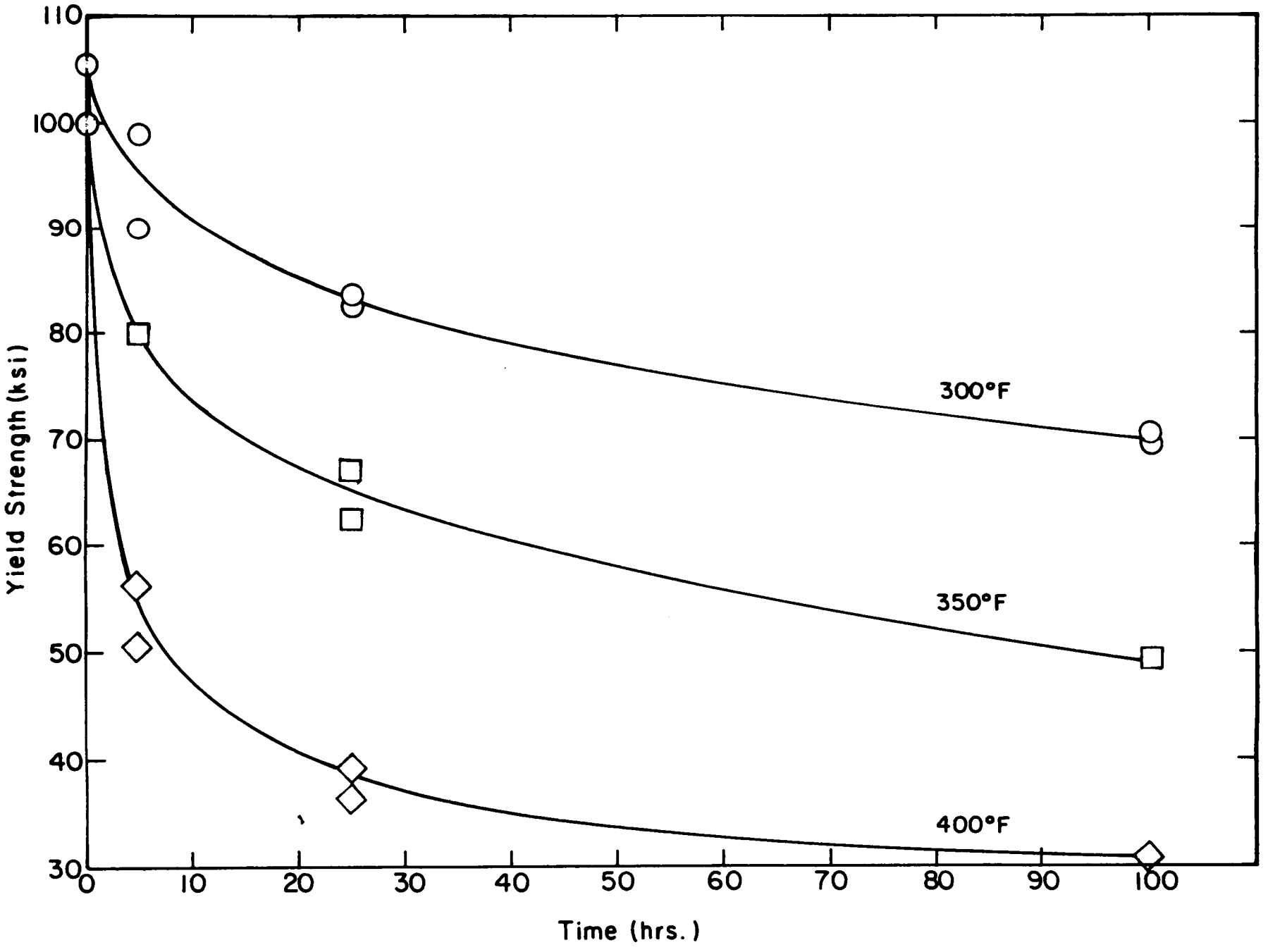

Figure 10. Effect of Time and Temperature on the Yield Strength of Forged 7178-T6 at -423°F.

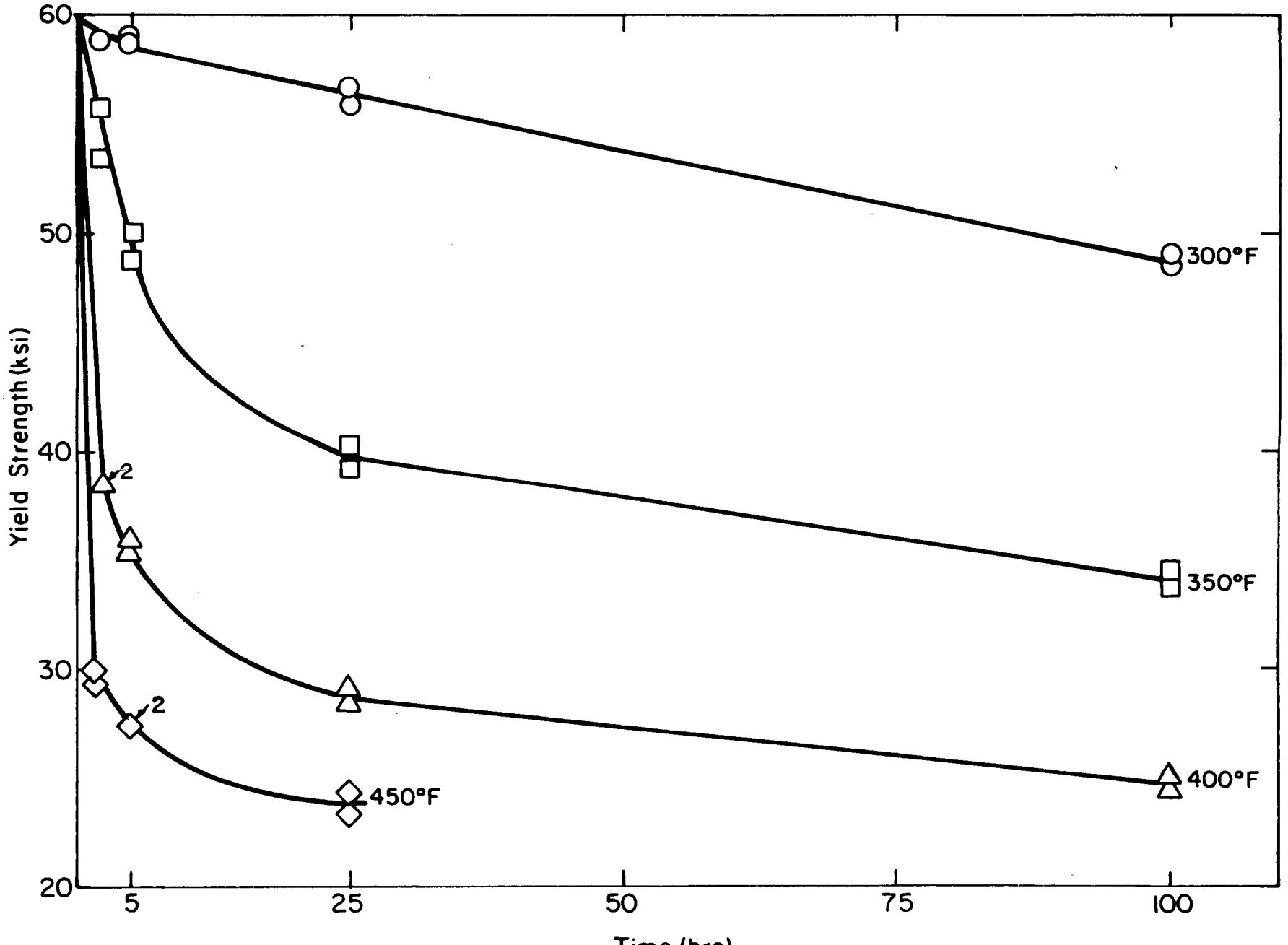

Figure 11. Effect of Time and Temperature on the Yield Strength of 7106-T63 Plate at Room Temperature.

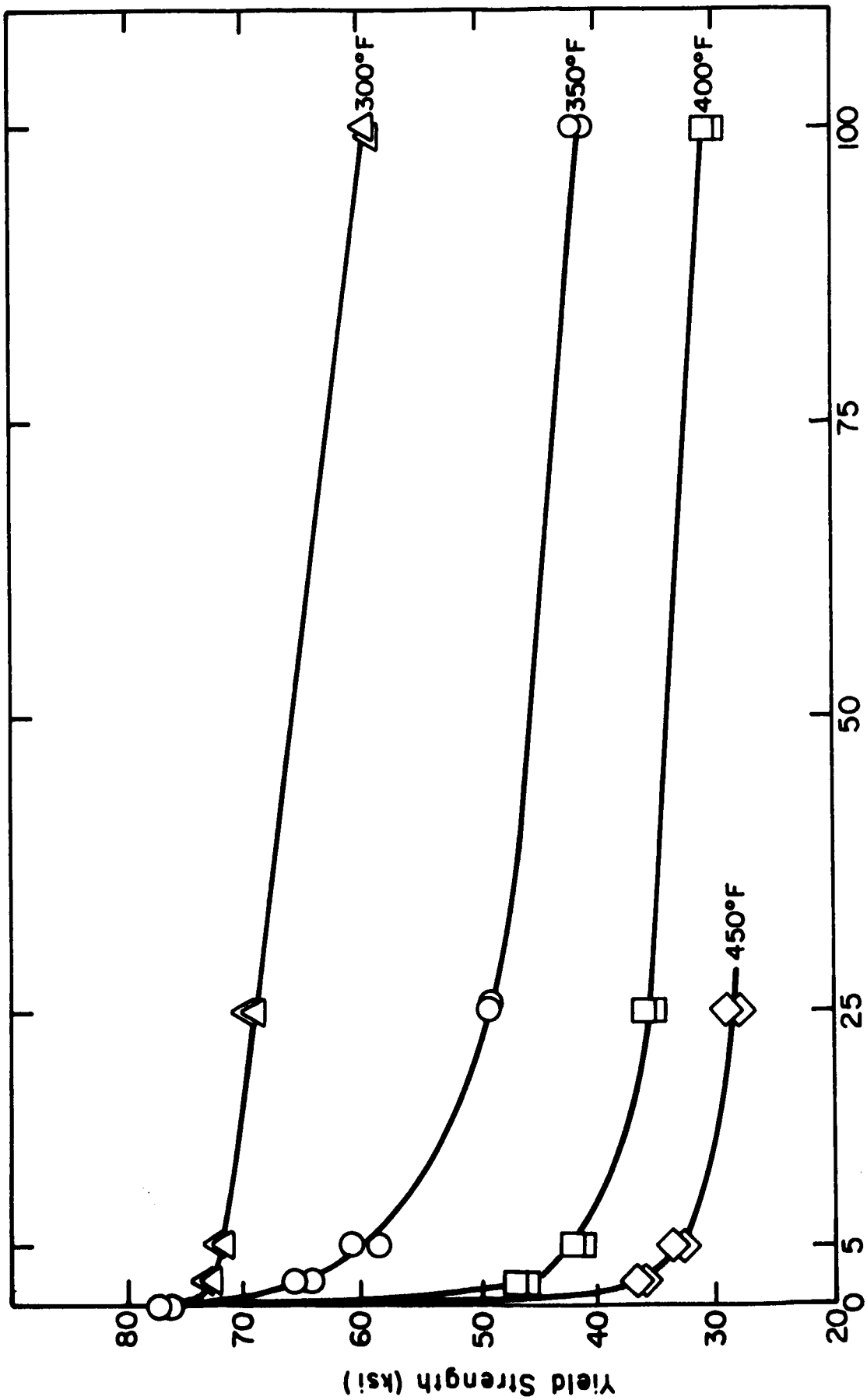

Figure 12. Effect of Time and Temperature on the Yield Strength of 7106-T63 at -320°F.

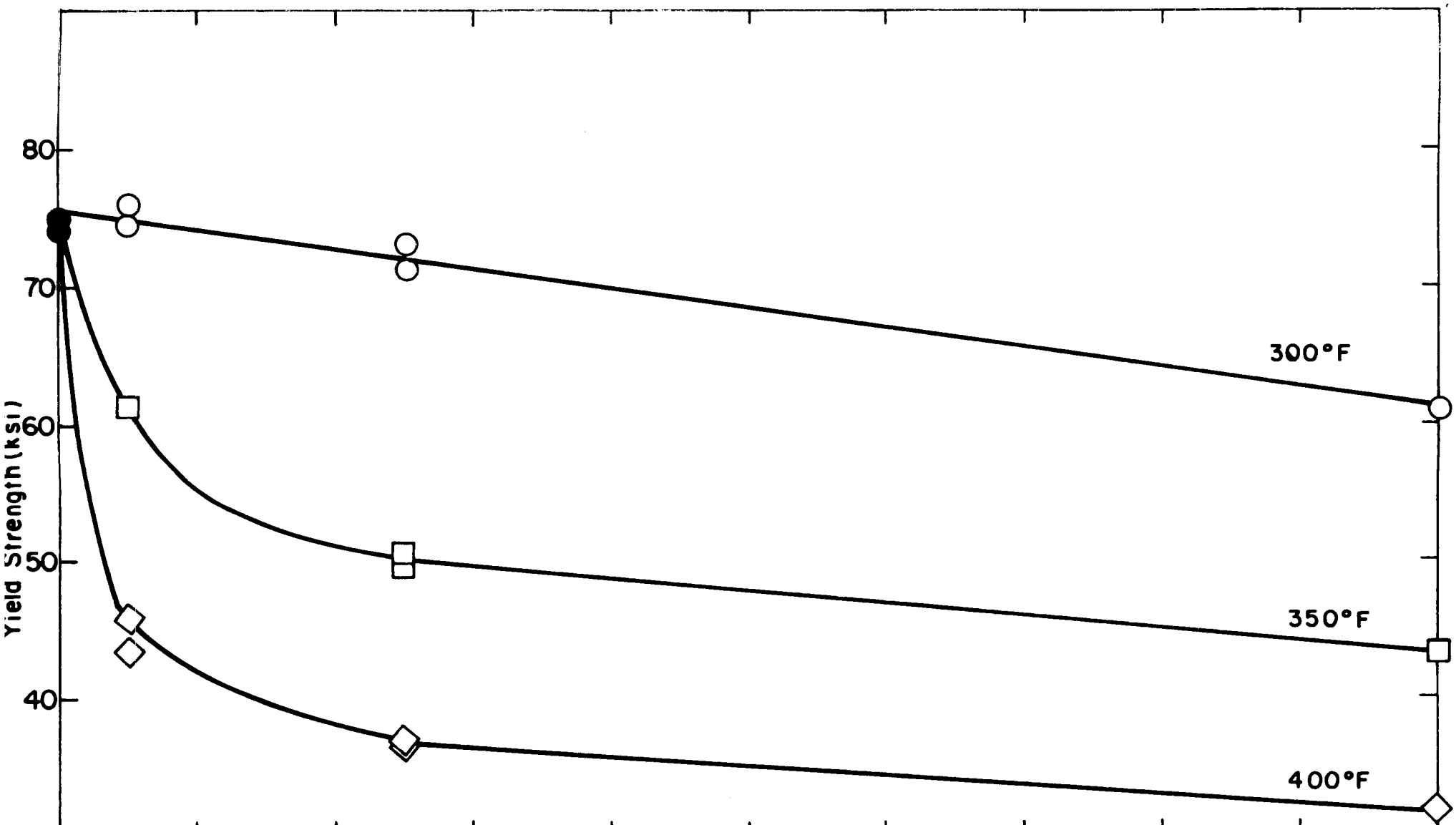

Figure 13. Effect of Time and Temperature on the Yield Strength of 7106-T63 at -423°F.

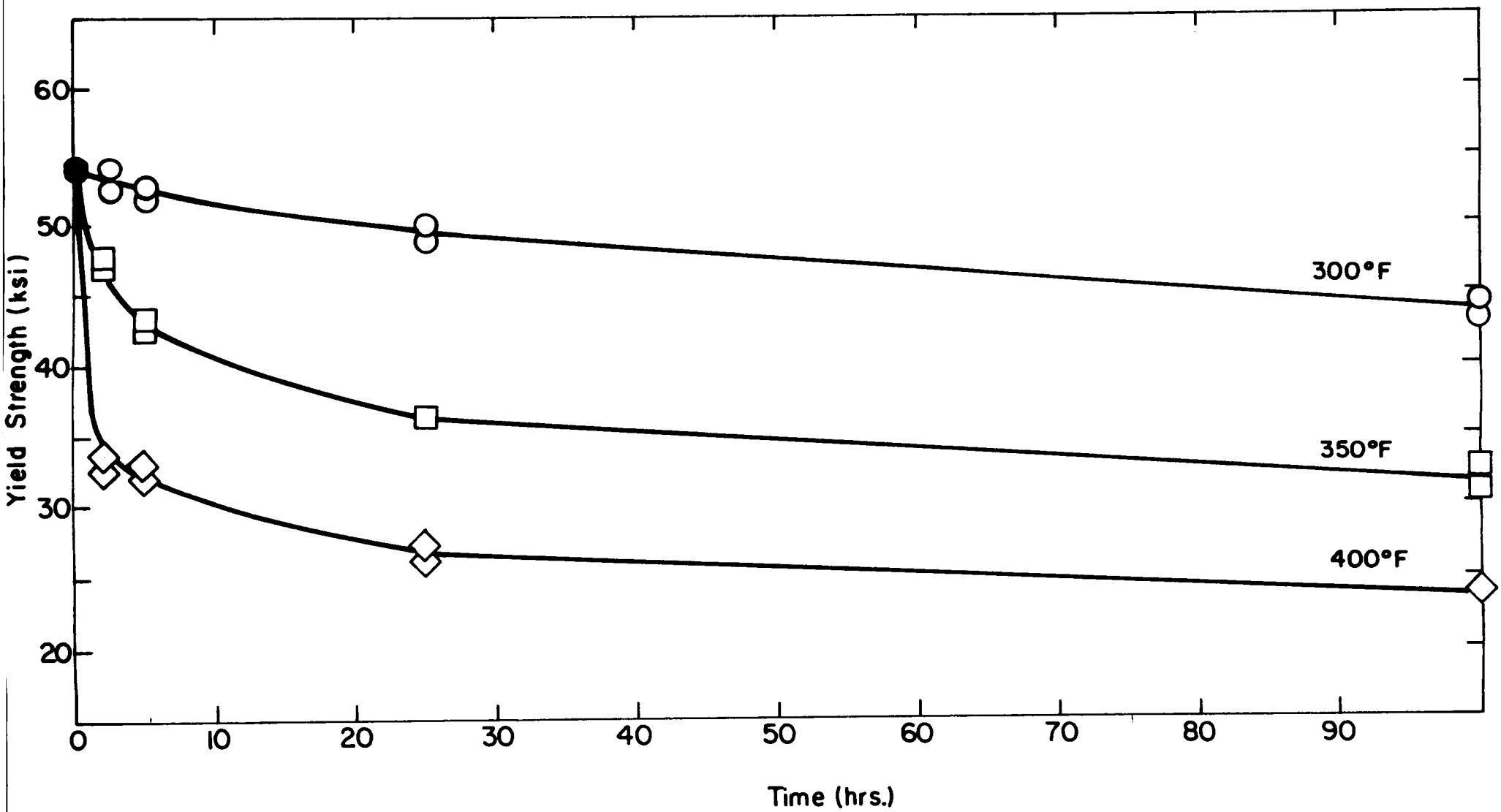

Figure 14. Effect of Time and Temperature on the Yield Strength of 7039-T651 at Room Temperature.

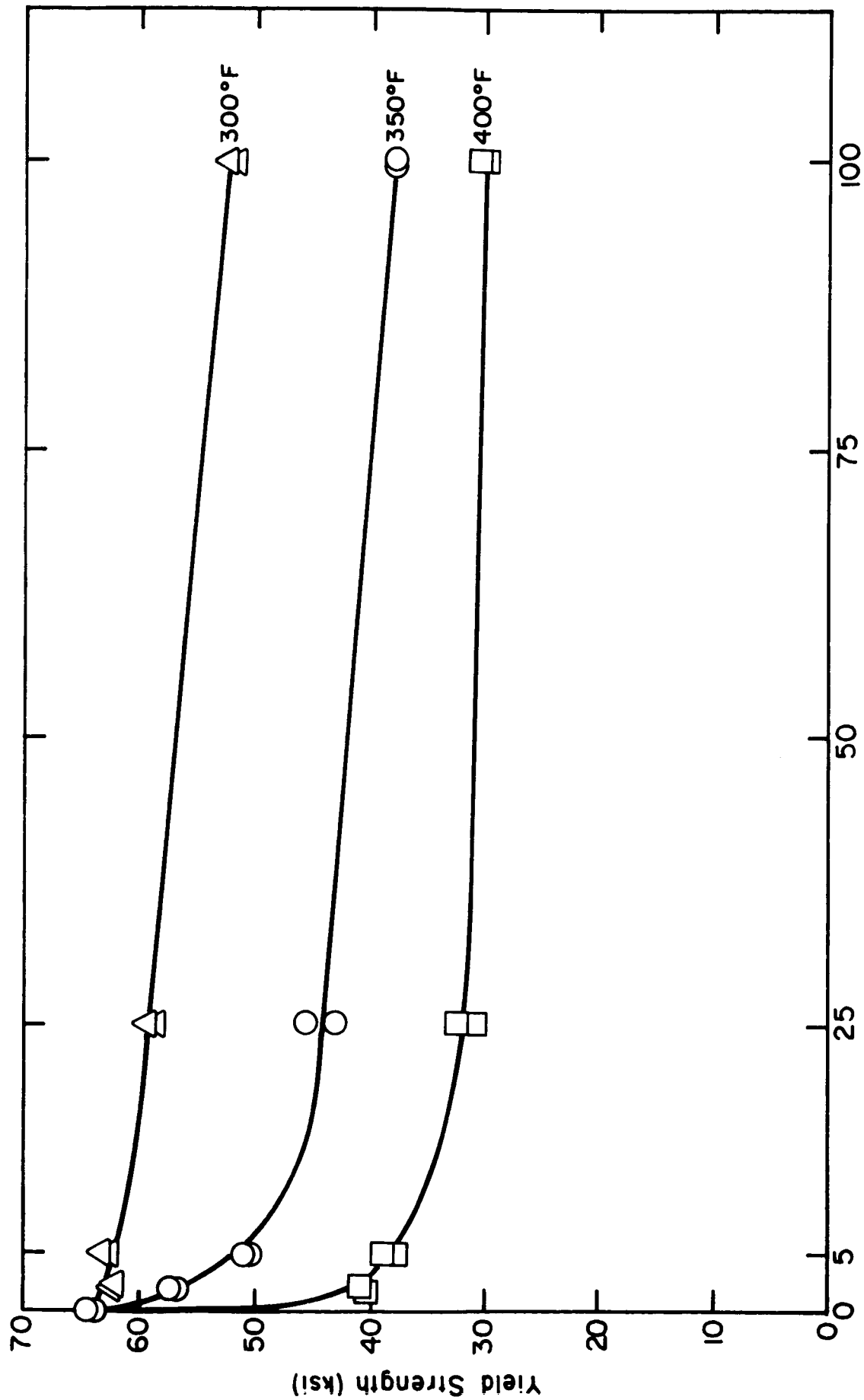

Figure 15. Effect of Time and Temperature on the Yield Strength of 7039-T651 at -320°F.

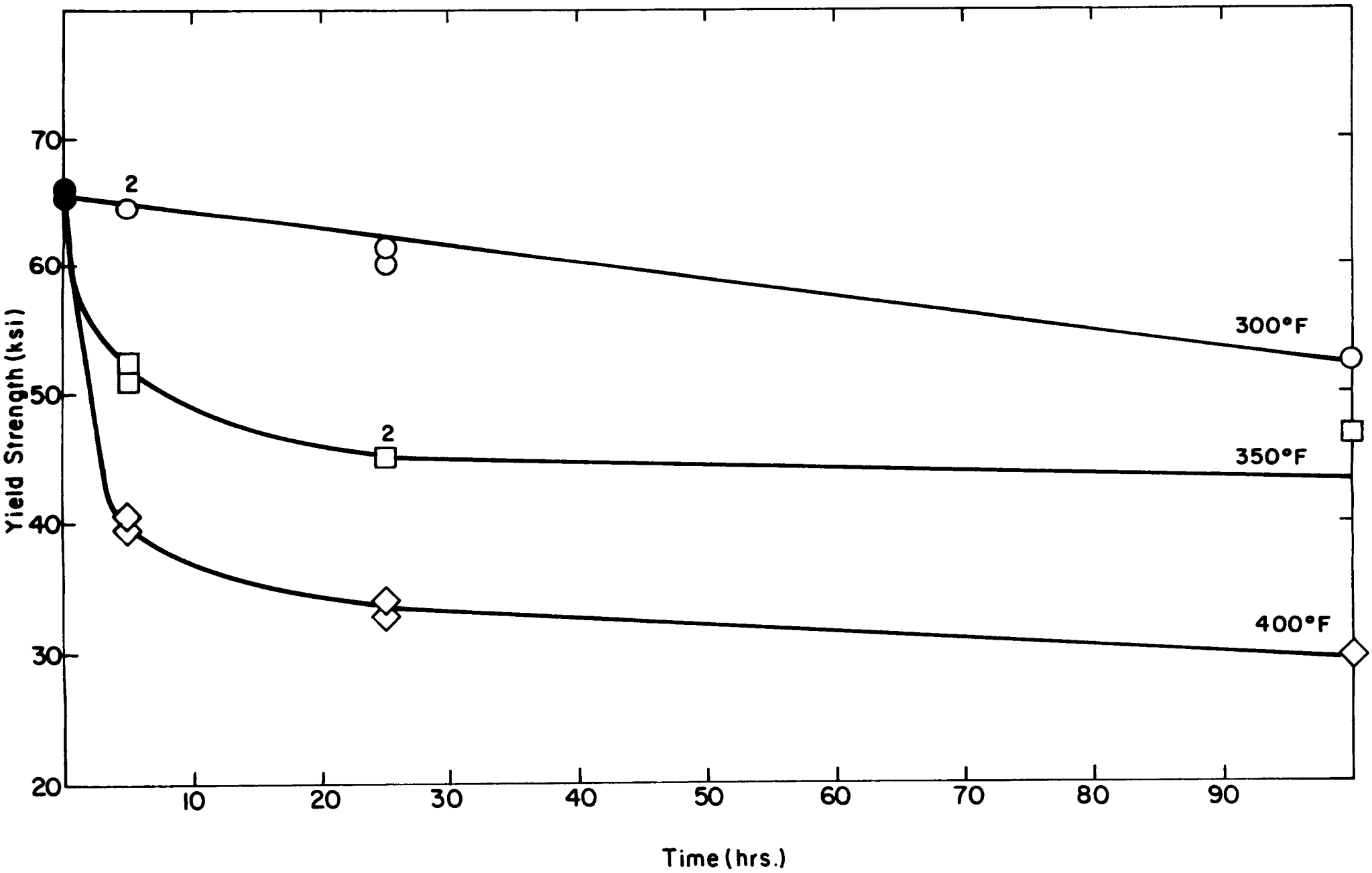

Figure 16. Effect of Time and Temperature on the Yield Strength of 7039-T651 at -423°F.

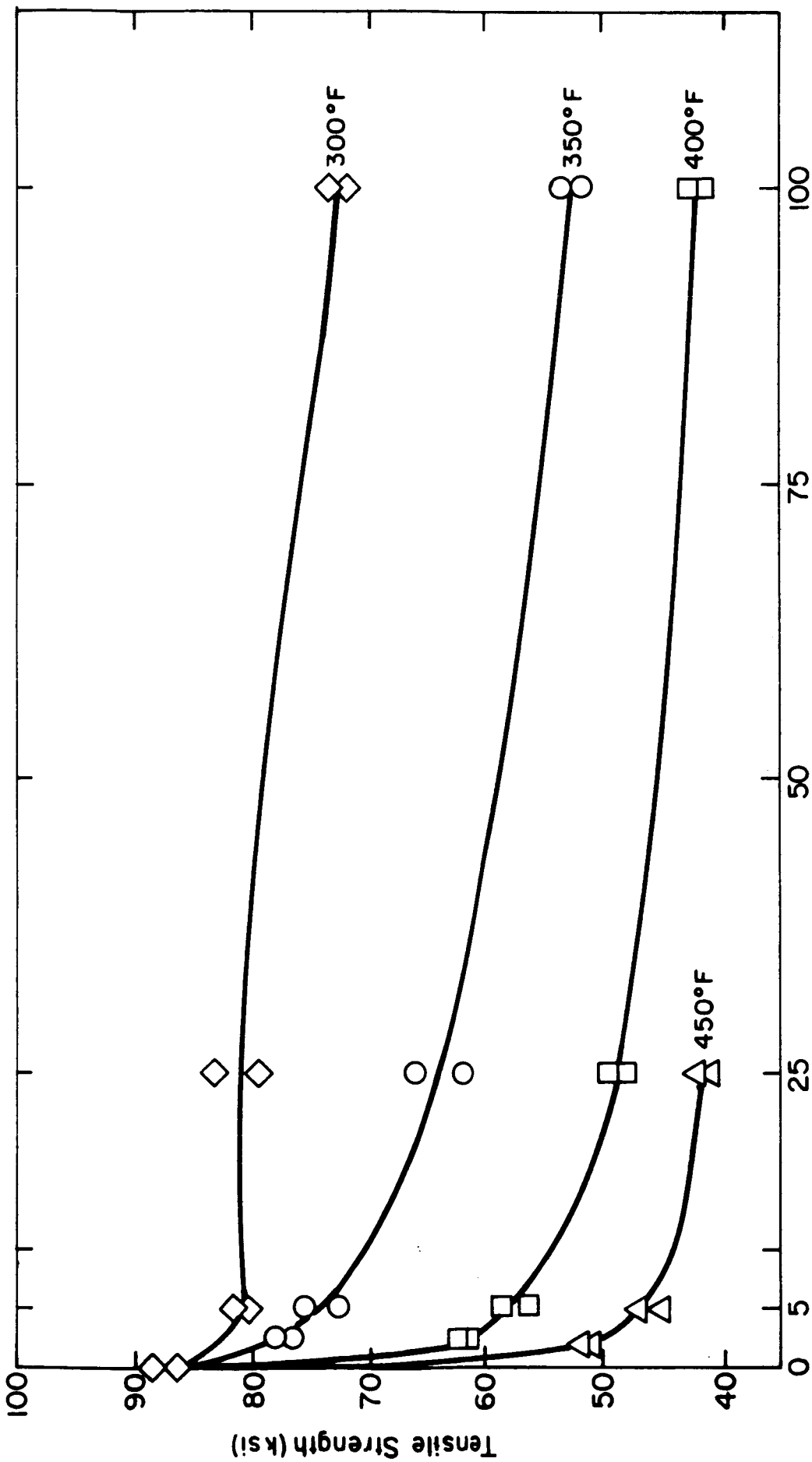

Figure 17. Effect of Time and Temperature on the Tensile Strength of Forged 7178-T6 at Room Temperature.

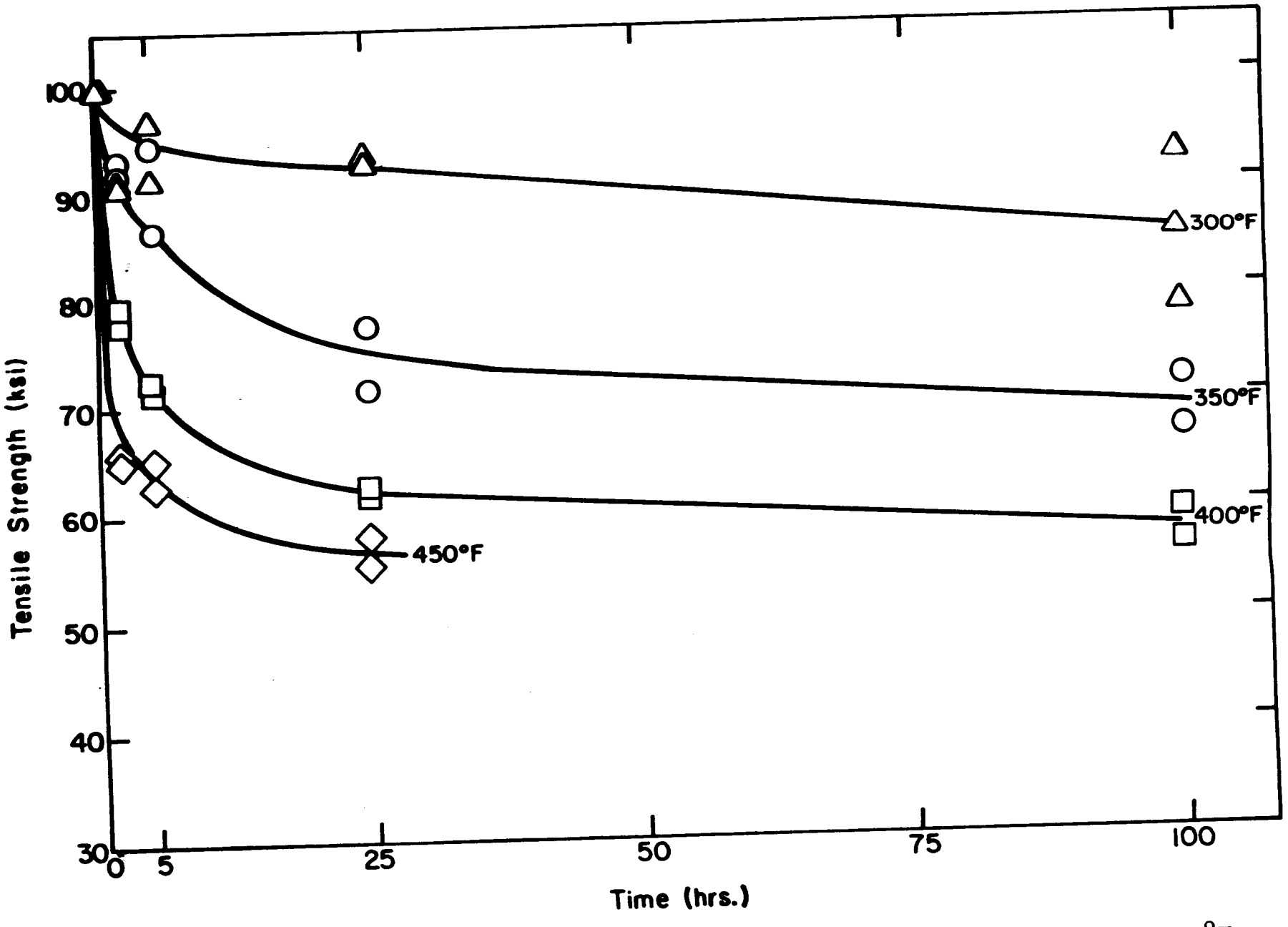

Figure 18. Effect of Time and Temperature on the Tensile Strength of Forged 7178-T6 at -320°F.

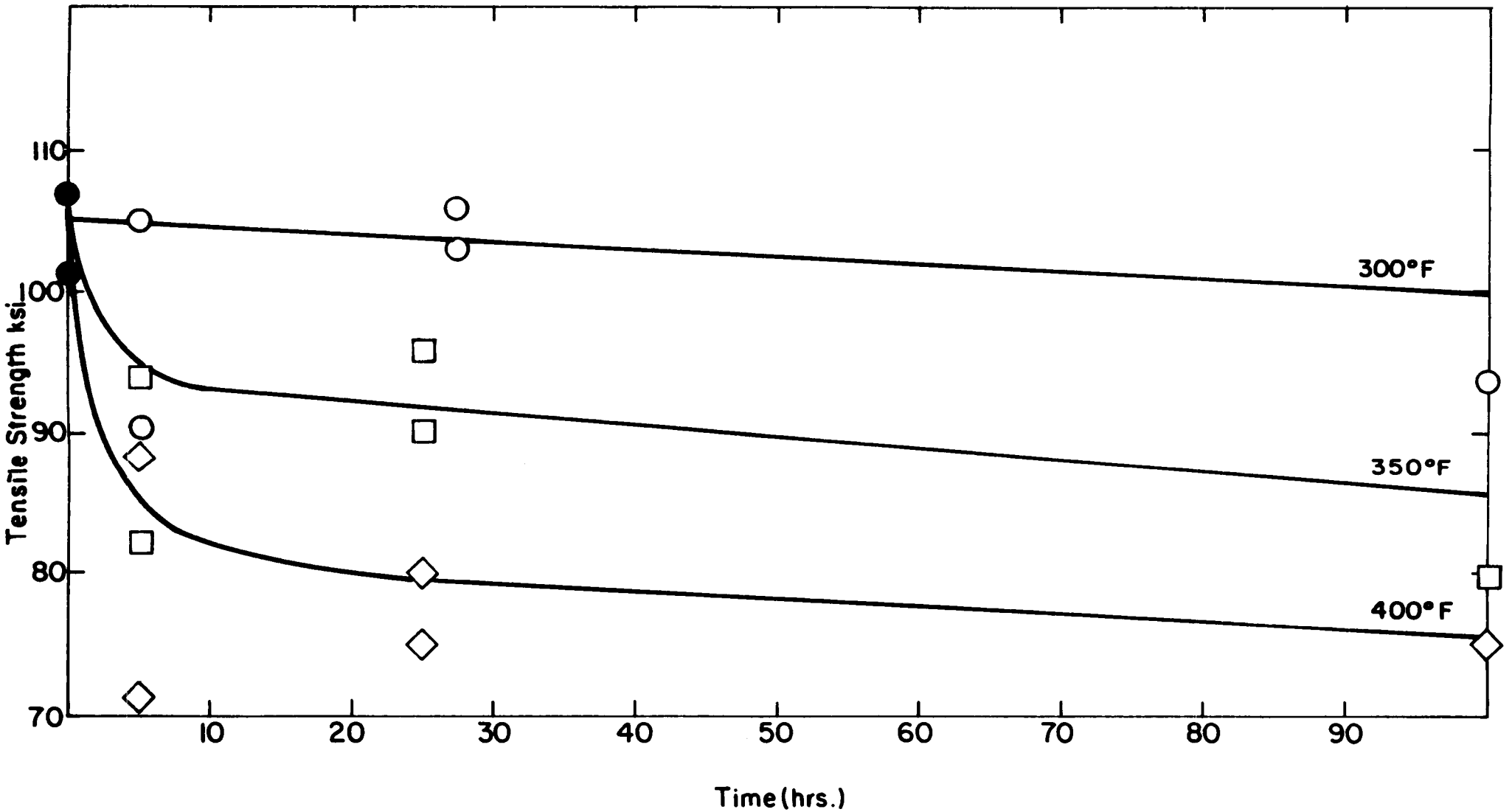

Figure 19. Effect of Time and Temperature on the Tensile Strength of Forged 7178-T6 at -423°F.

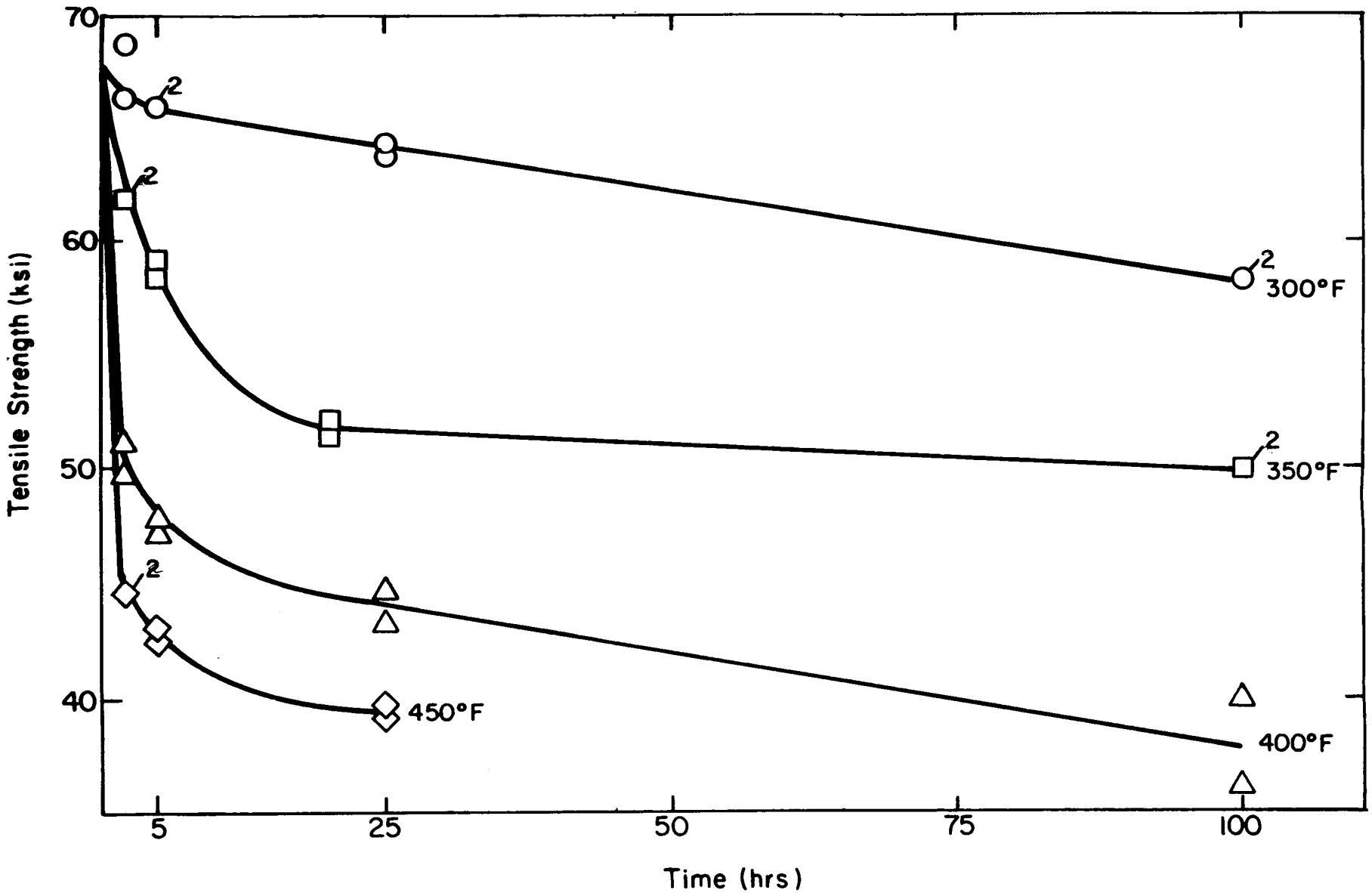

Figure 20. Effect of Time and Temperature on the Tensile Strength of 7106-T63 Plate at Room Temperature.

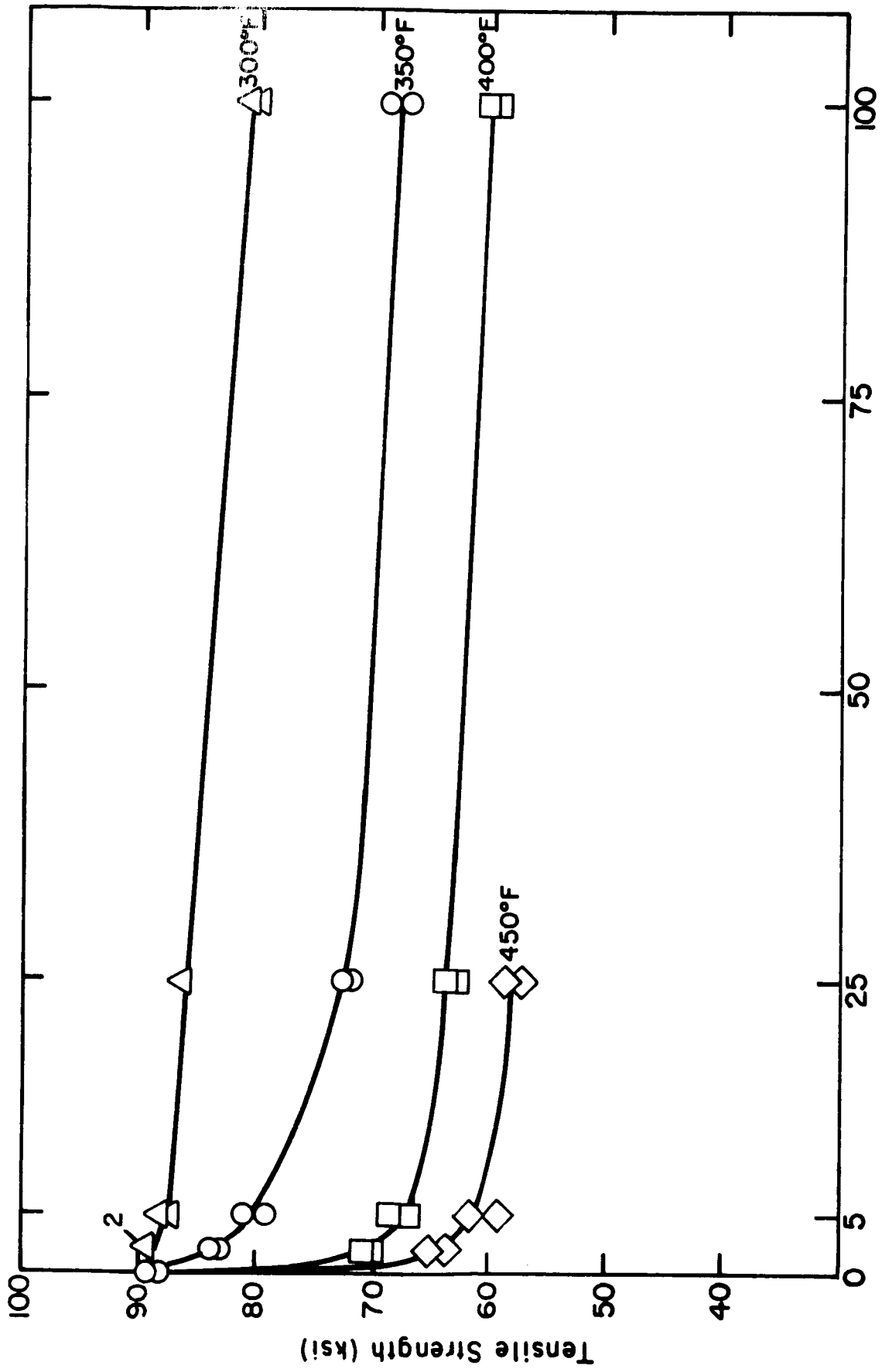

Figure 21. Effect of Time and Temperature on the Tensile Strength of 7106-T63 at -320°F.

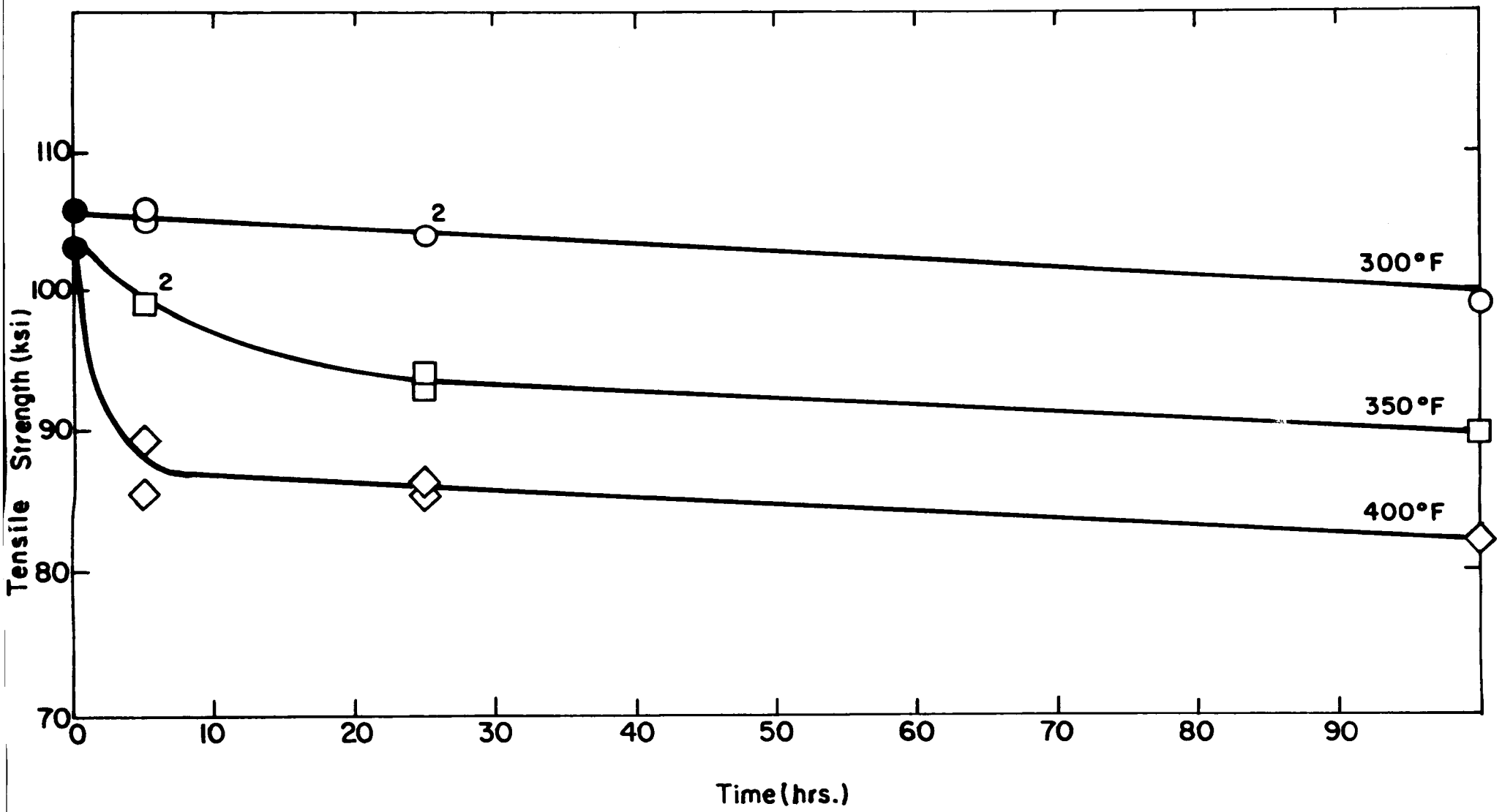

Figure 22. Effect of Time and Temperature on the Tensile Strength of 7106-T63 at -423°F.

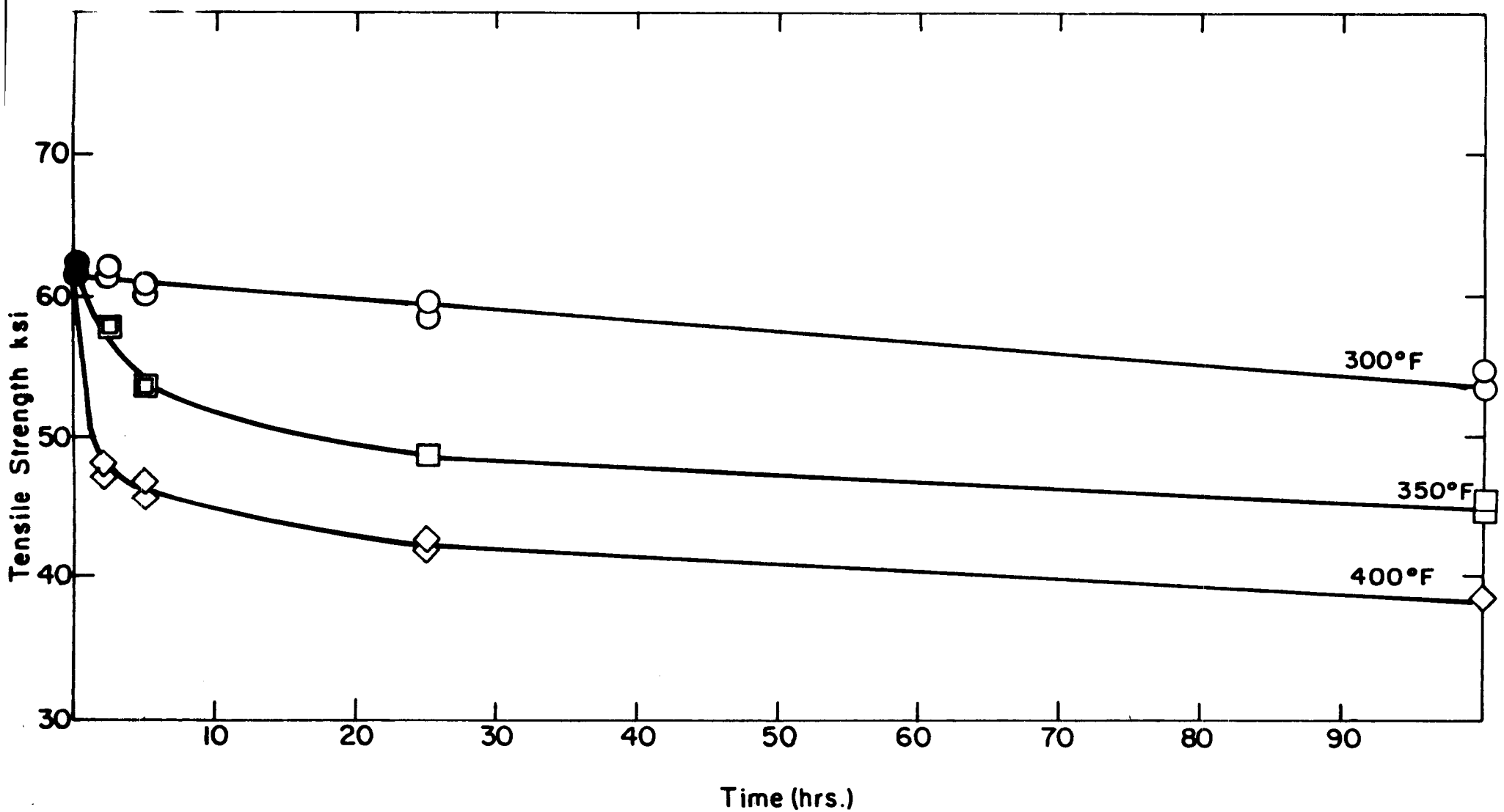

Figure 23. Effect of Time and Temperature on the Tensile Strength of 7039-T651 at Room Temperature.

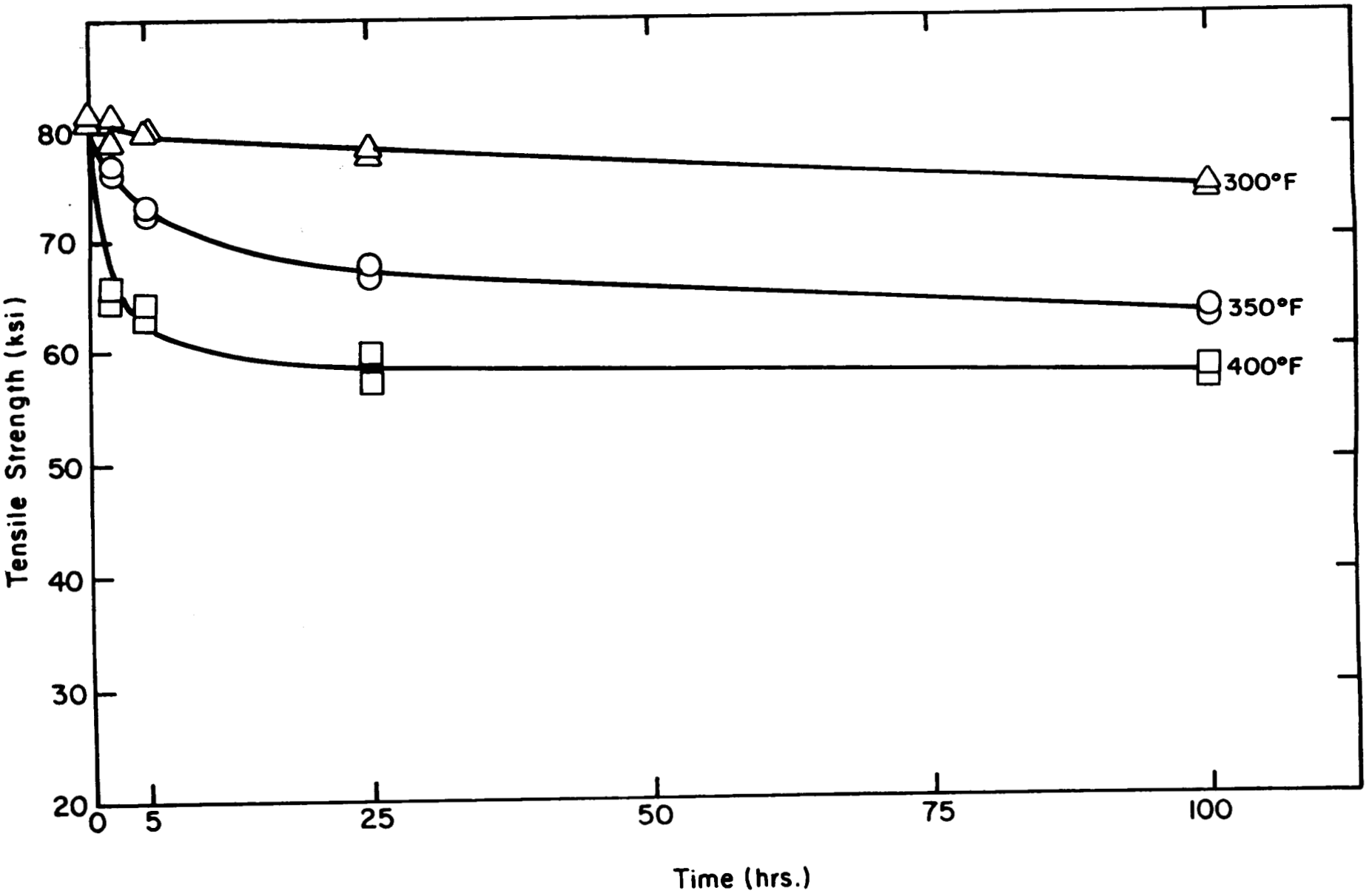

Figure 24. Effect of Time and Temperature on the Tensile Strength of 7039-T651 at -320°F.

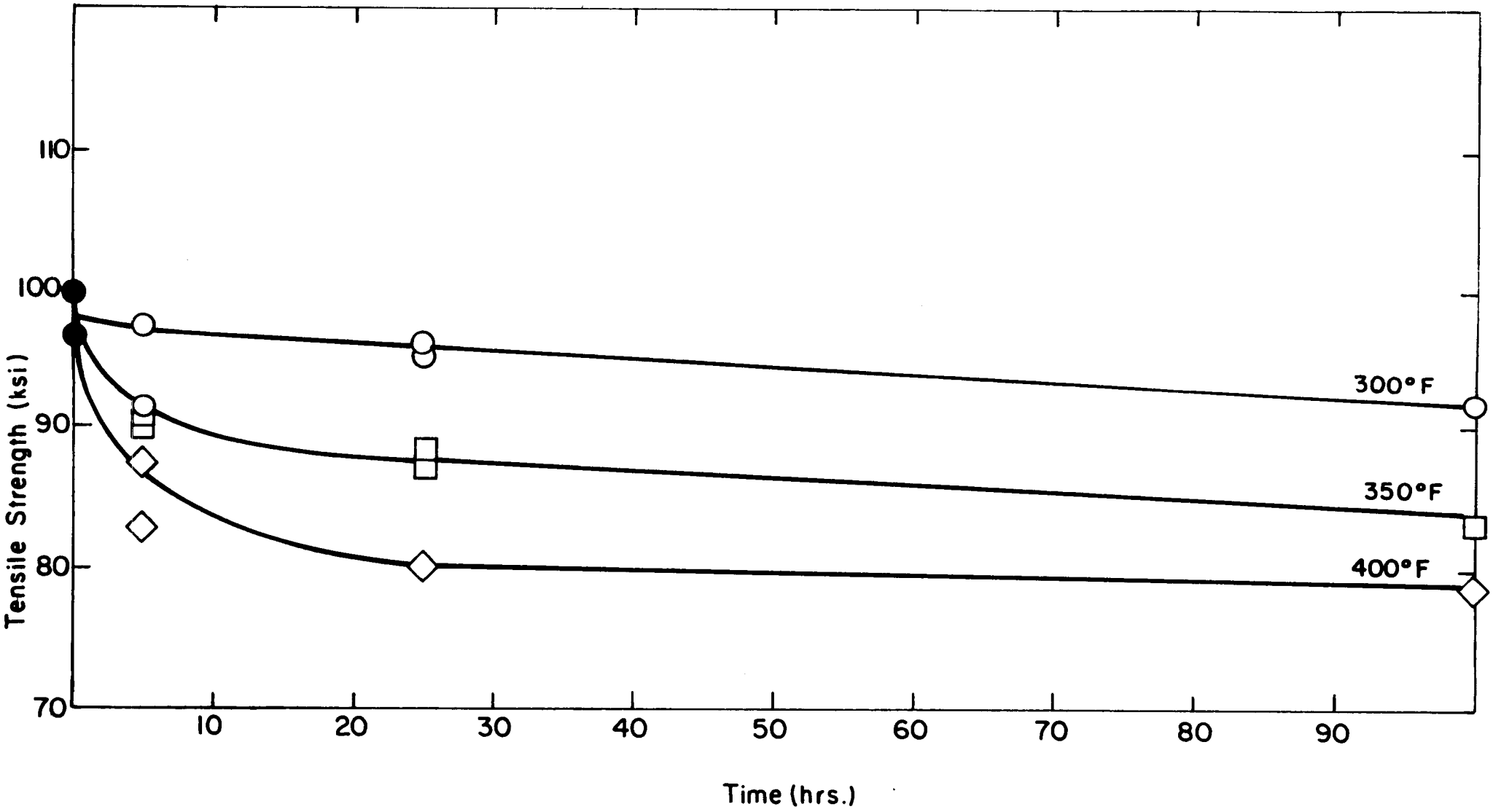

Figure 25. Effect of Time and Temperature on the Tensile Strength of 7039-T651 at -423°F.

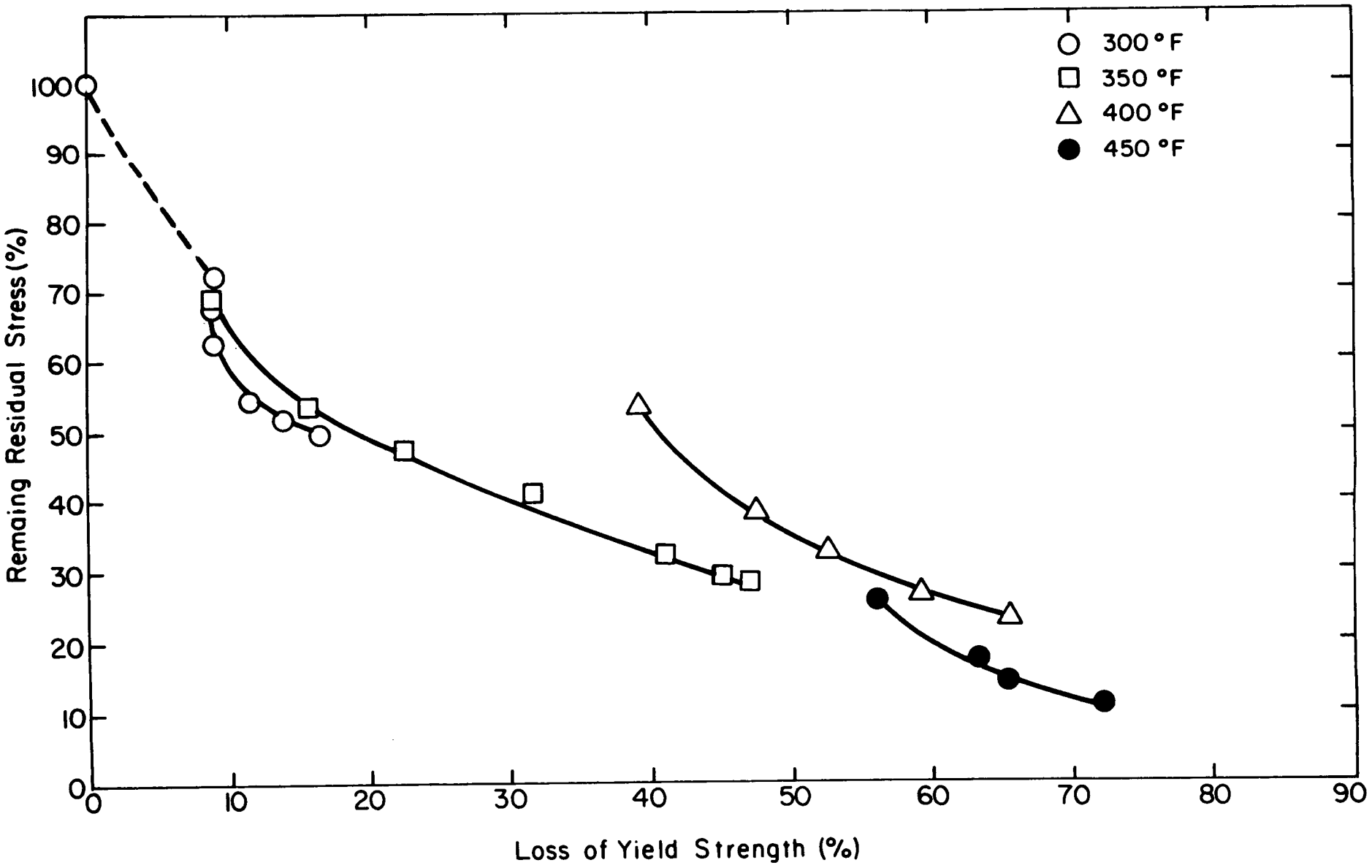

Figure 26. Relationship Between Remaining Residual Stress and Loss of Tensile Yield Strength at Room Temperature for Various Time-Temperature Treatments for Forged 7178-T6.

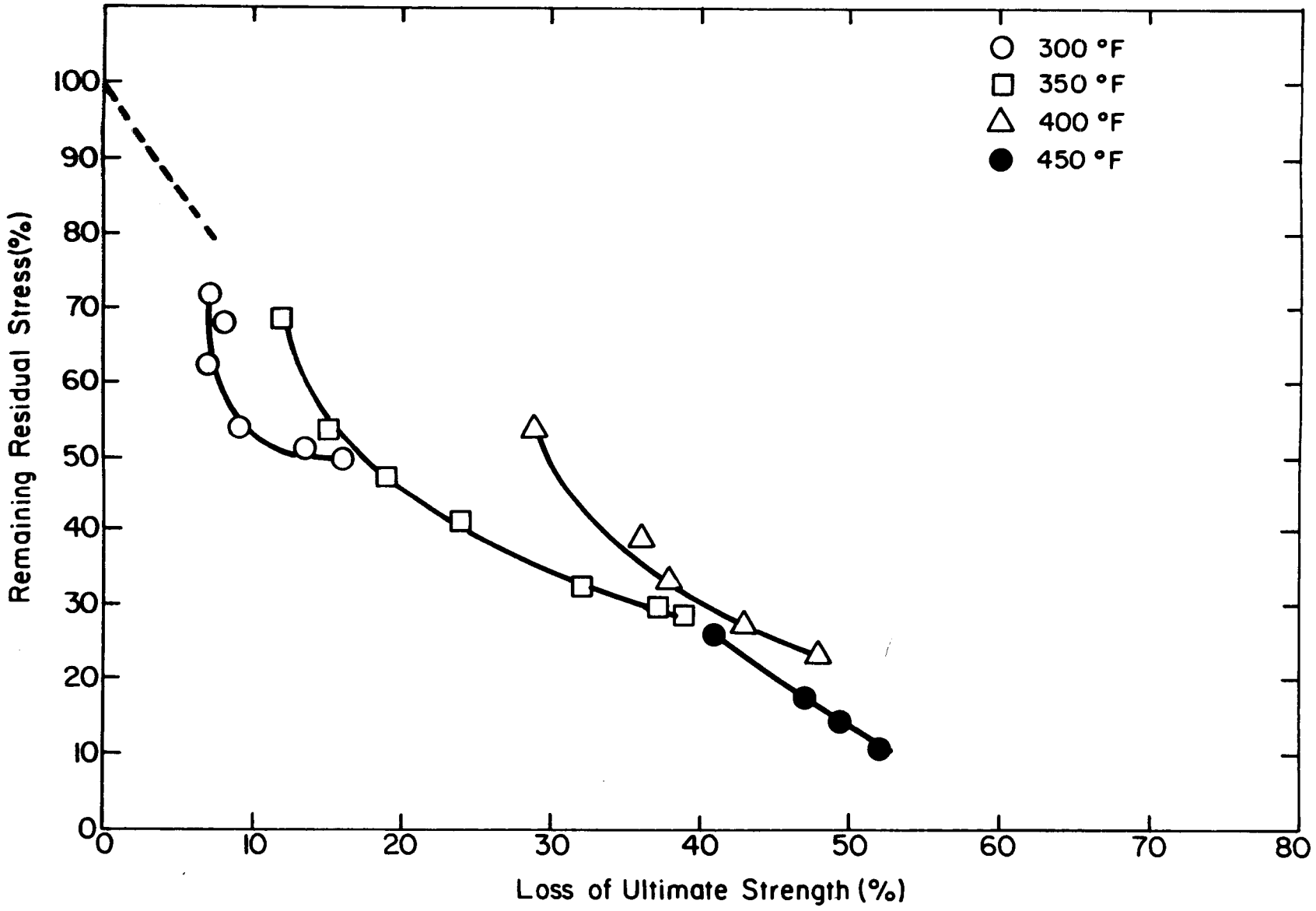

Figure 27. Relationship Between Remaining Residual Stress and Loss of Ultimate Tensile Strength at Room Temperature for Various Time-Temperature Treatments for Forged 7178-T6.

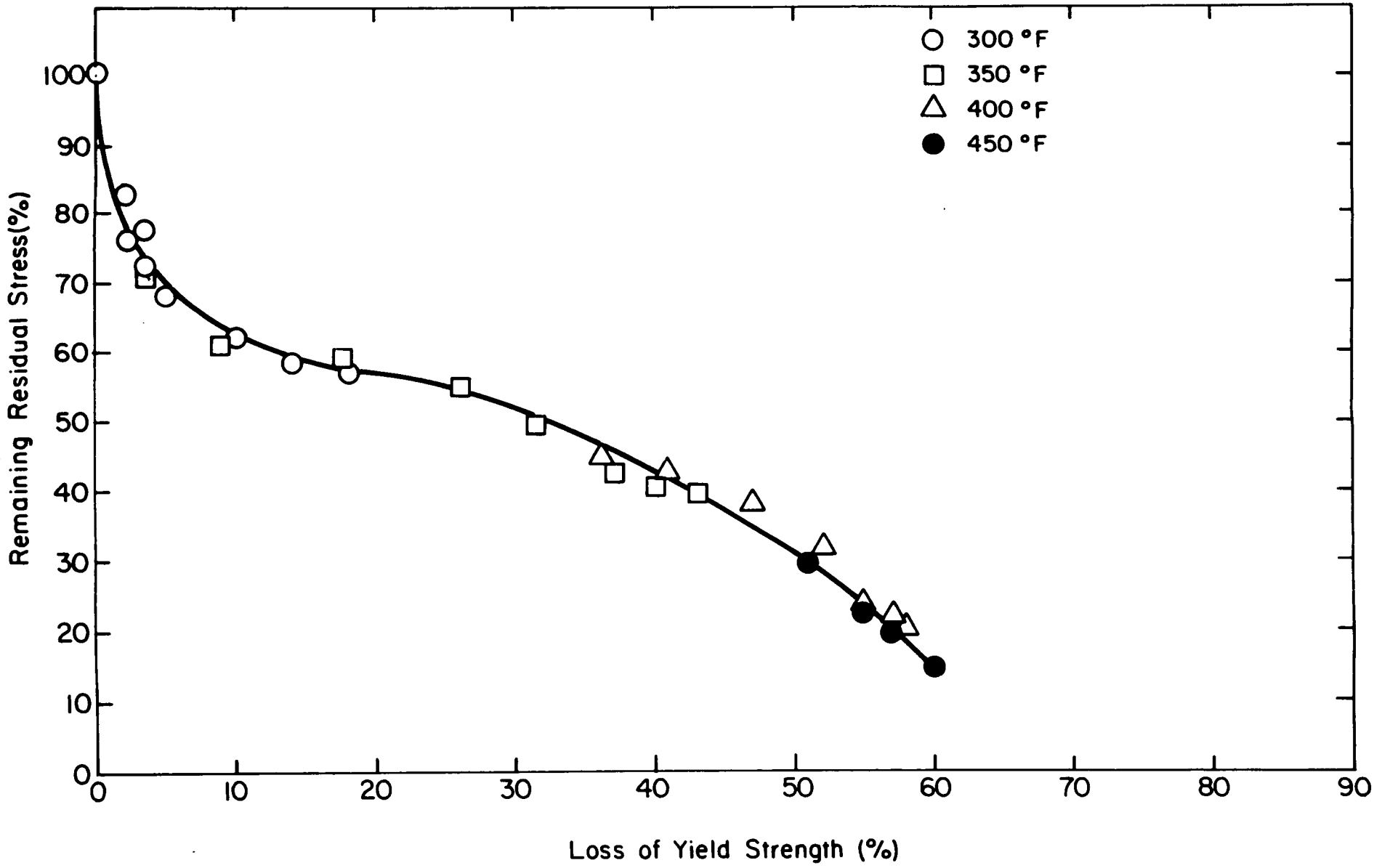

Figure 28. Relationship Between Remaining Residual Stress and Loss of Tensile Yield Strength at Room Temperature for Various Time-Temperature Treatments for 7106-T63 Plate.

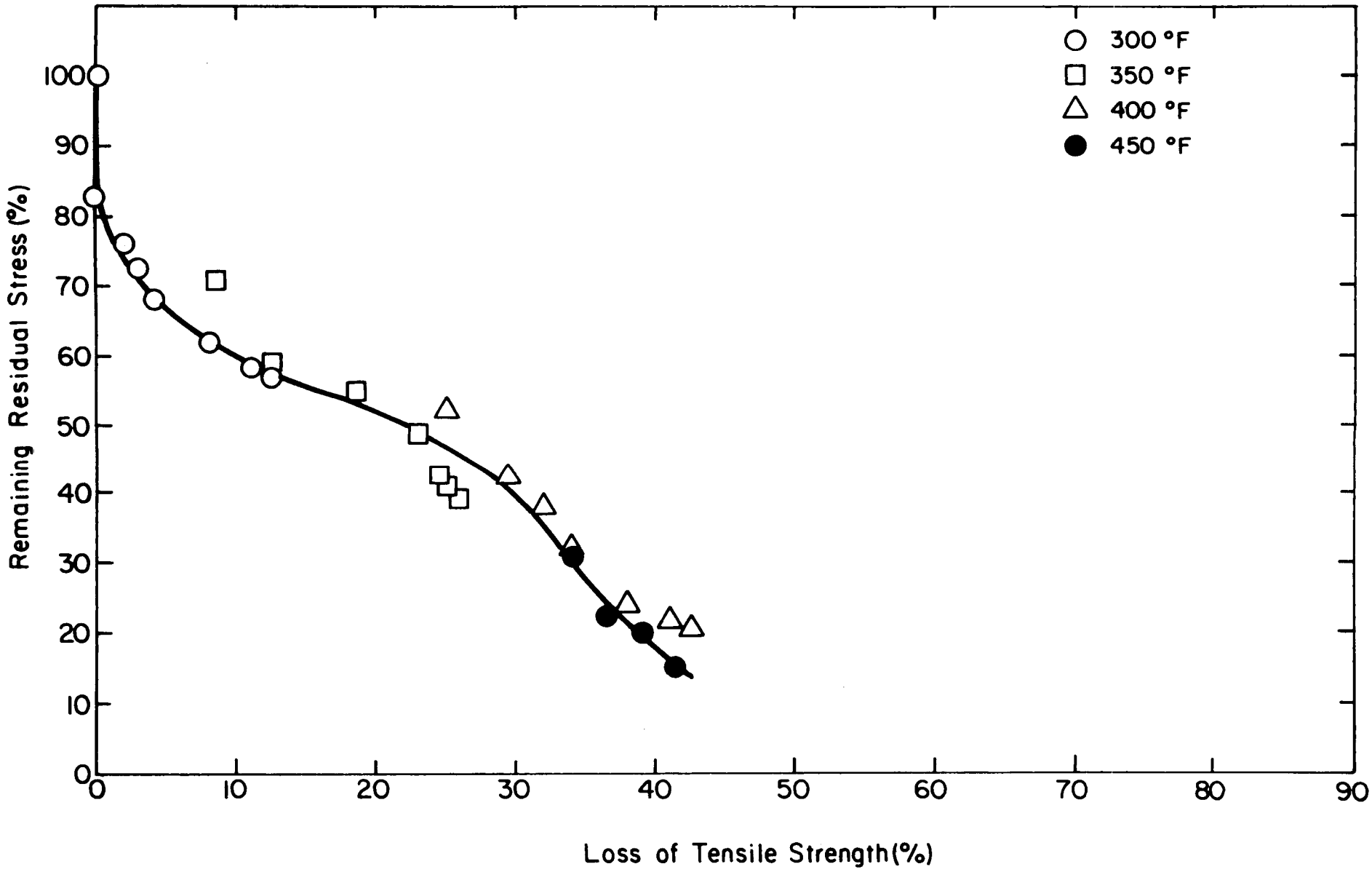

Figure 29. Relationship Between Remaining Residual Stress and Loss of Ultimate Tensile Strength at Room Temperature for Various Time-Temperature Treatments for 7106-T63 Plate.

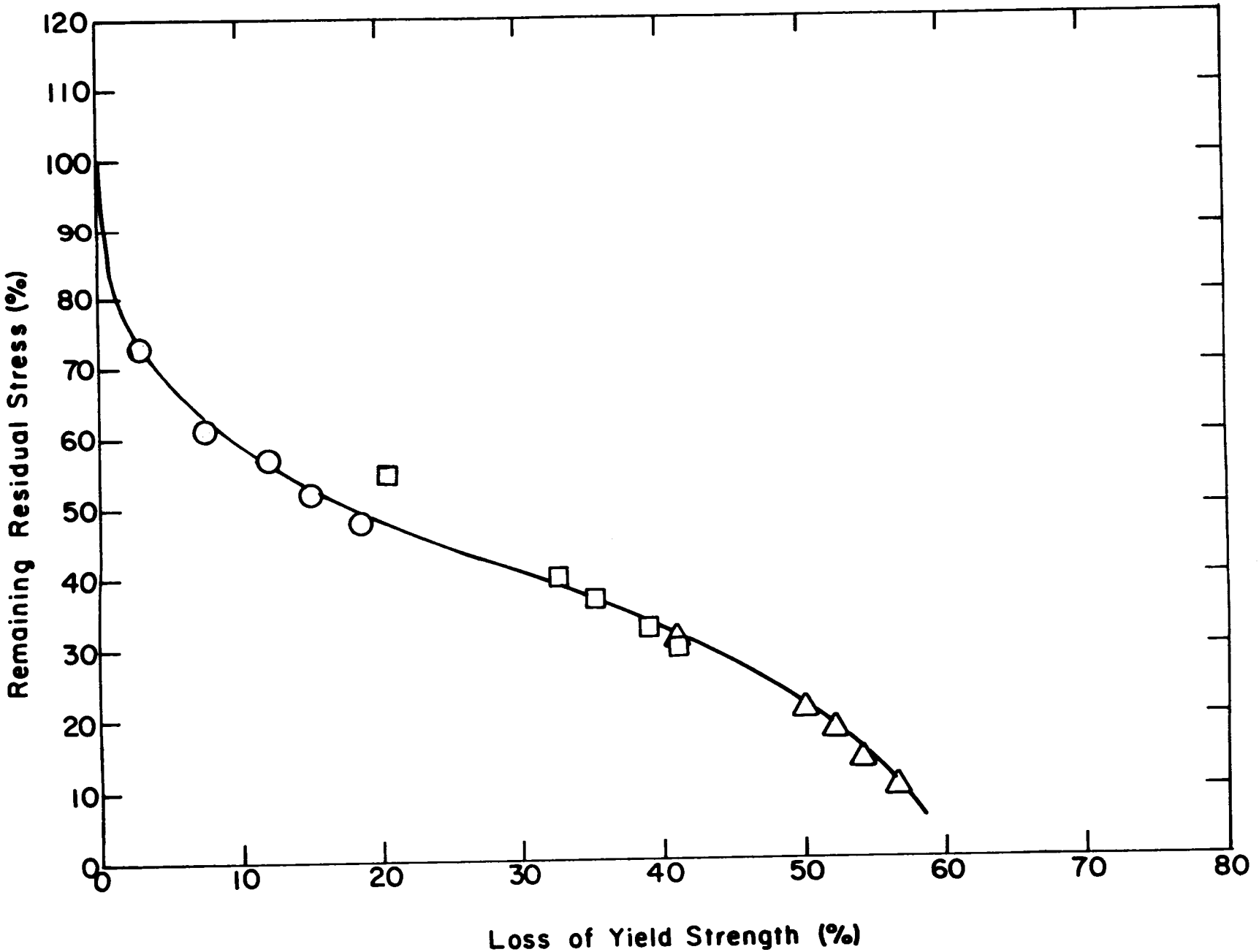

Figure 30. Relationship Between Remaining Residual Stress and Loss of Yield Strength at Room Temperature for Various Time-Temperature Treatments for 7039-T651 Plate.

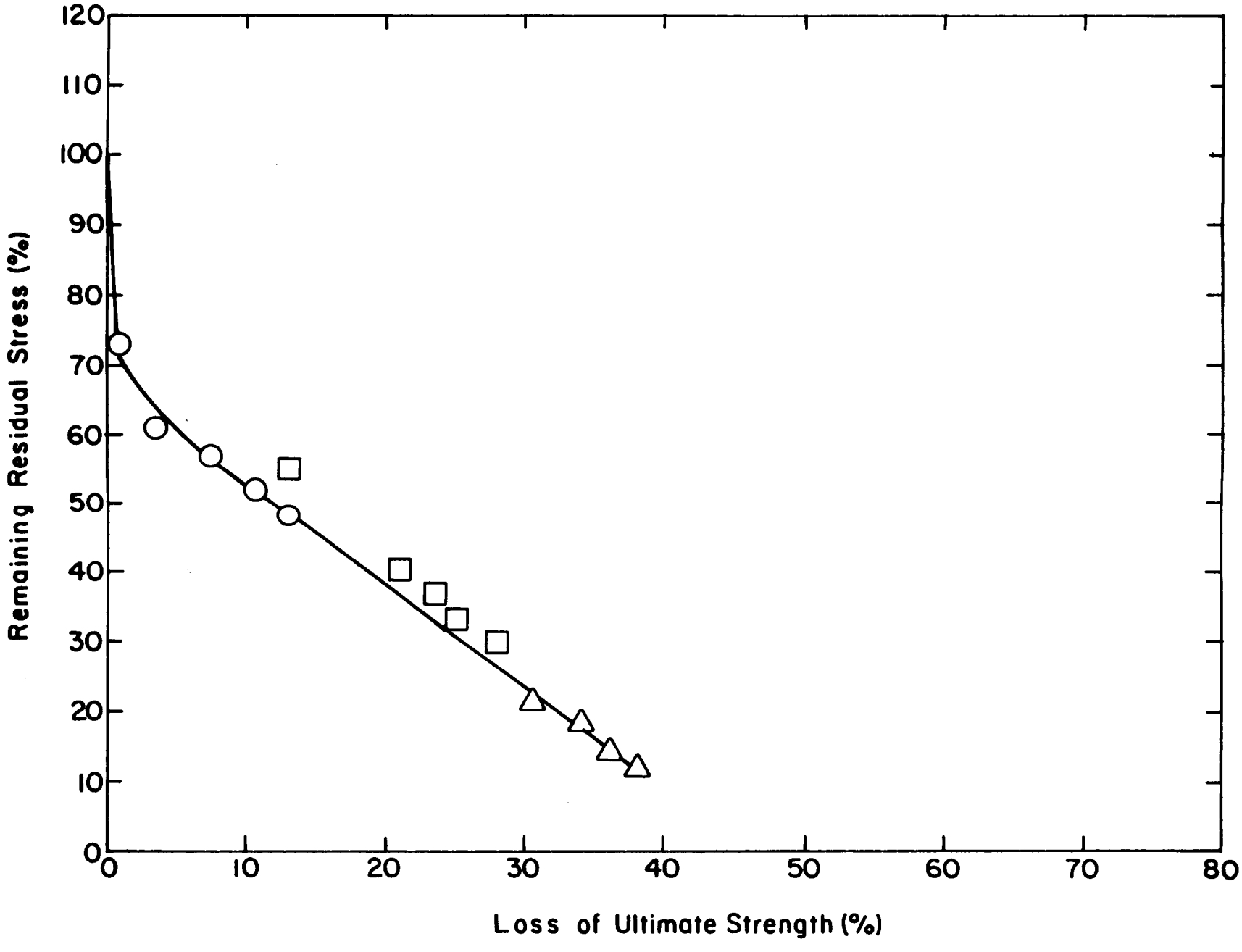

Figure 31. Relationship Between Remaining Residual Stress and Loss of Ultimate Tensile Strength at Room Temperature for Various Time-Temperature Treatments for 7039-T651 Plate.

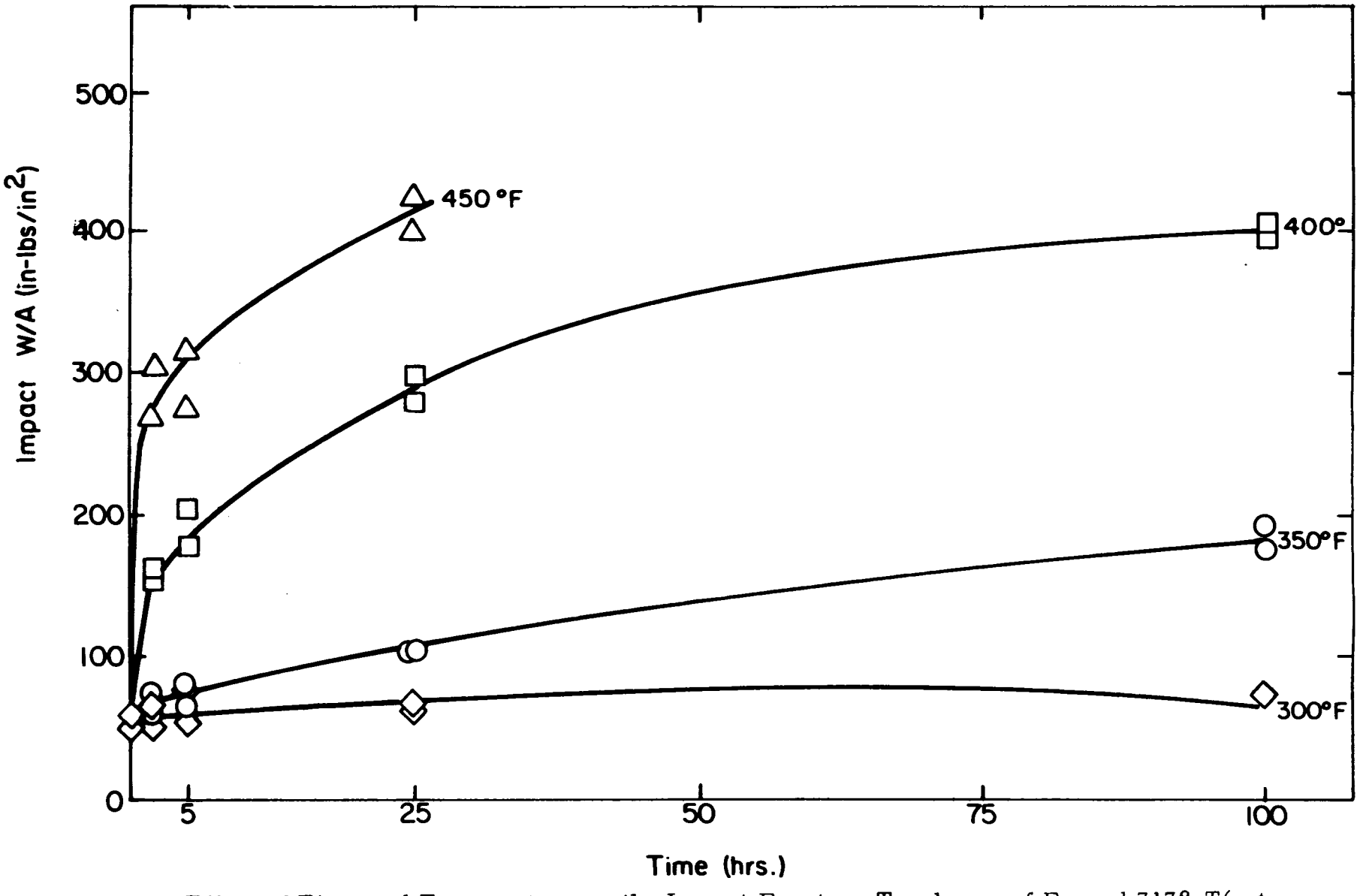

Figure 32. Effect of Time and Temperature on the Impact Fracture Toughness of Forged 7178-T6 at Room Temperature.

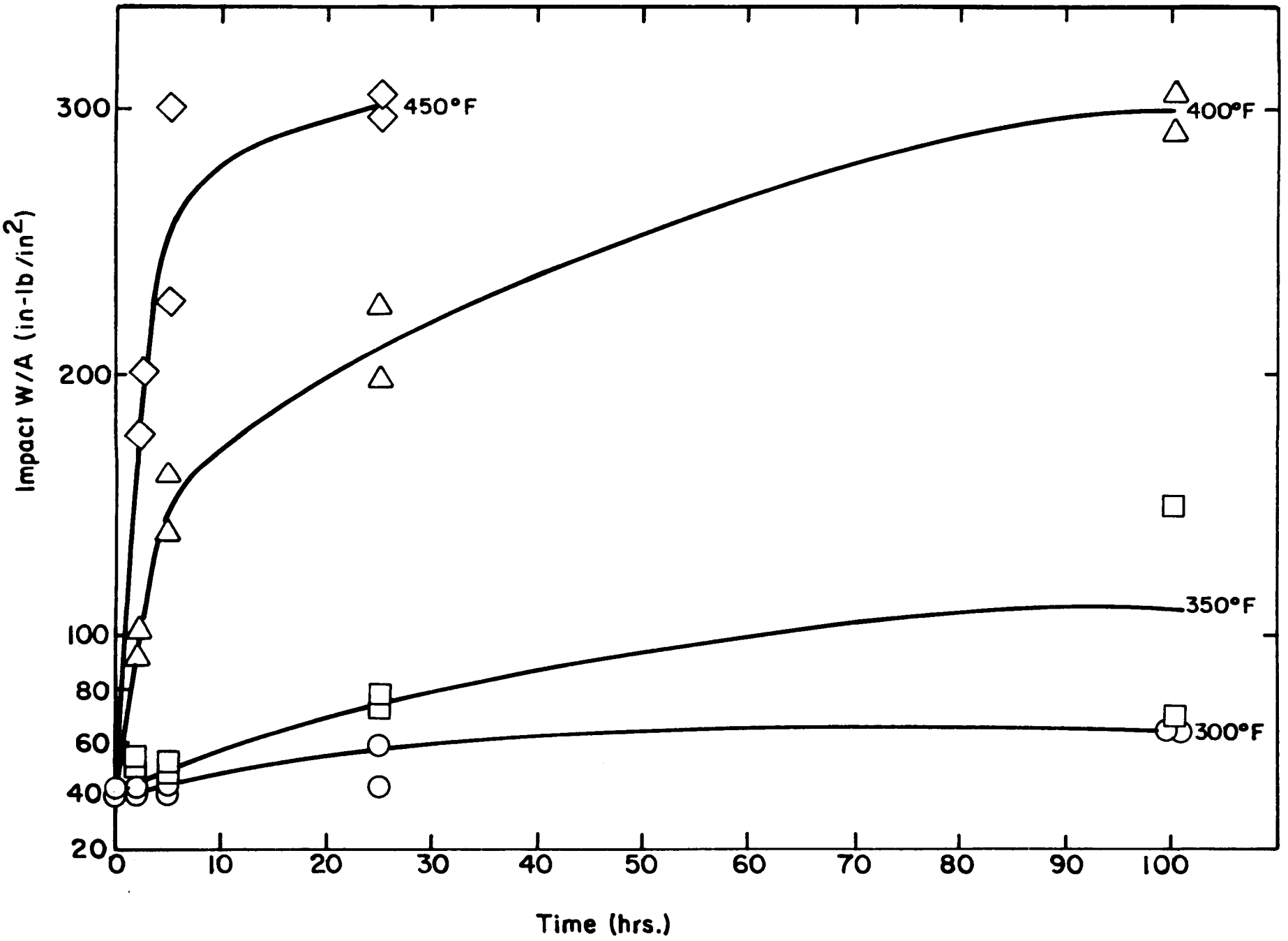

Figure 33. Effect of Time and Temperature on the Impact Fracture Toughness of 7178-T6 at -320°F.

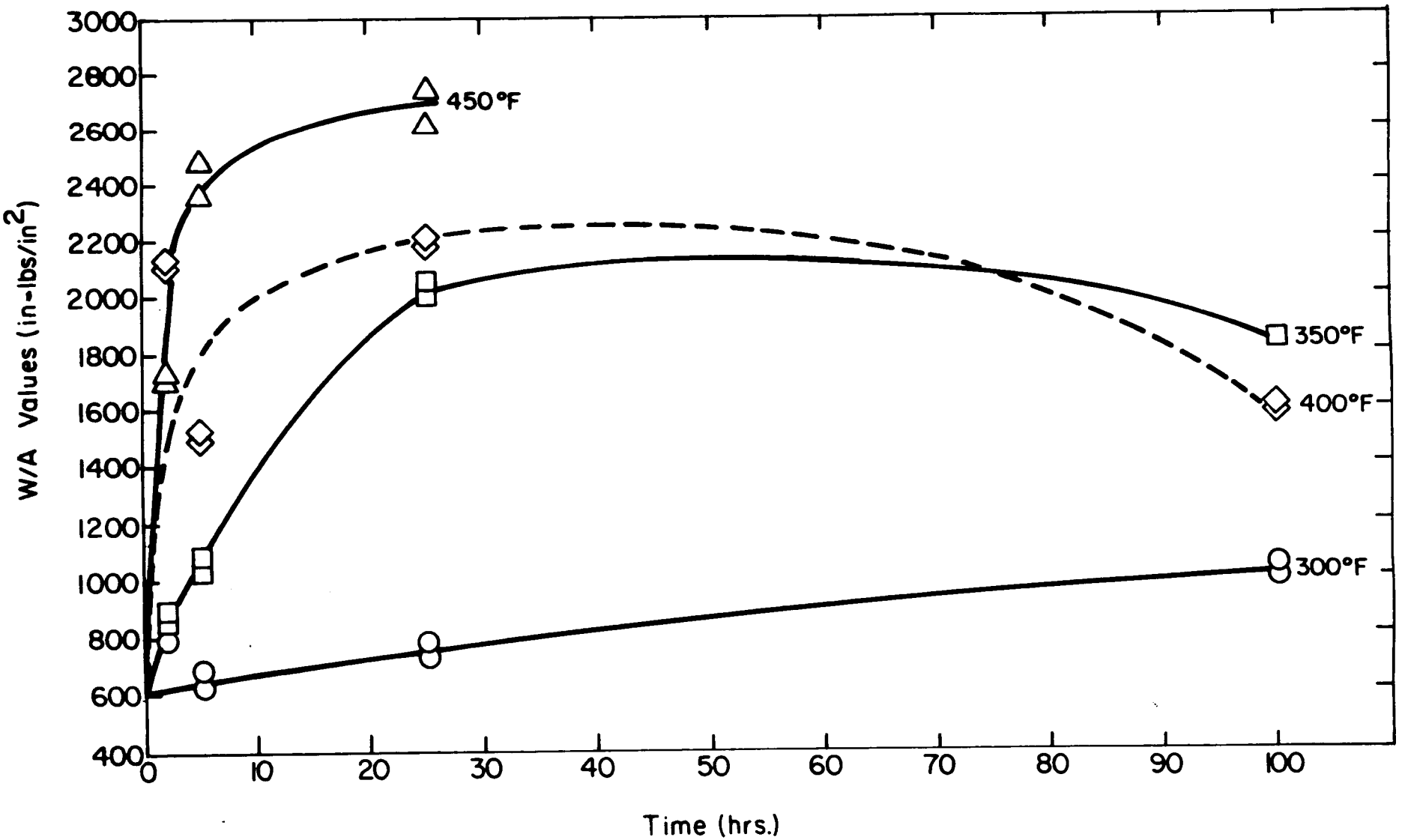

Figure 34. Effect of Time and Temperature on the Impact Fracture Toughness of 7106-T63 Plate at Room Temperature.

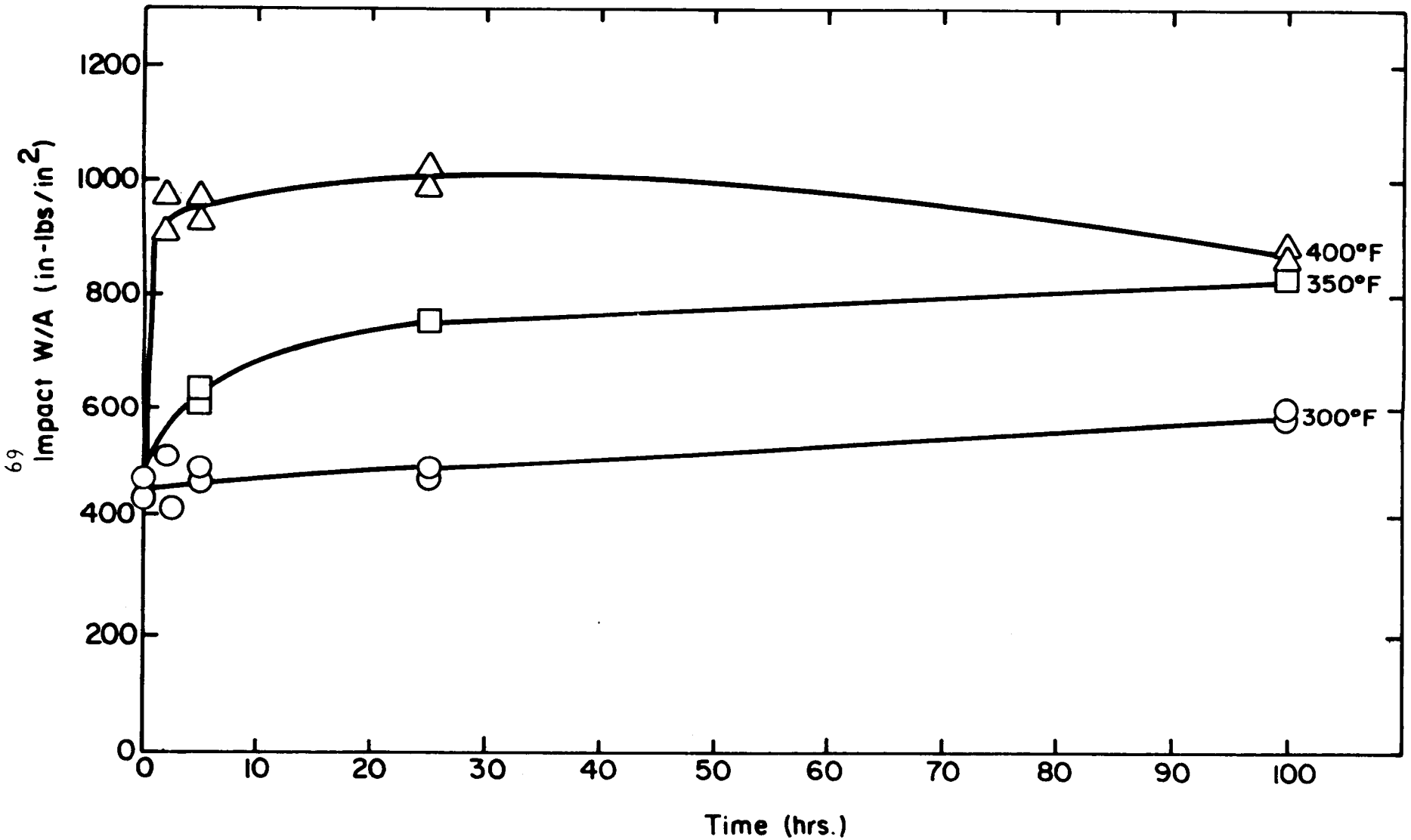

Figure 35. Effect of Time and Temperature on the Impact Fracture Toughness of 7106-T63 at -320°F.

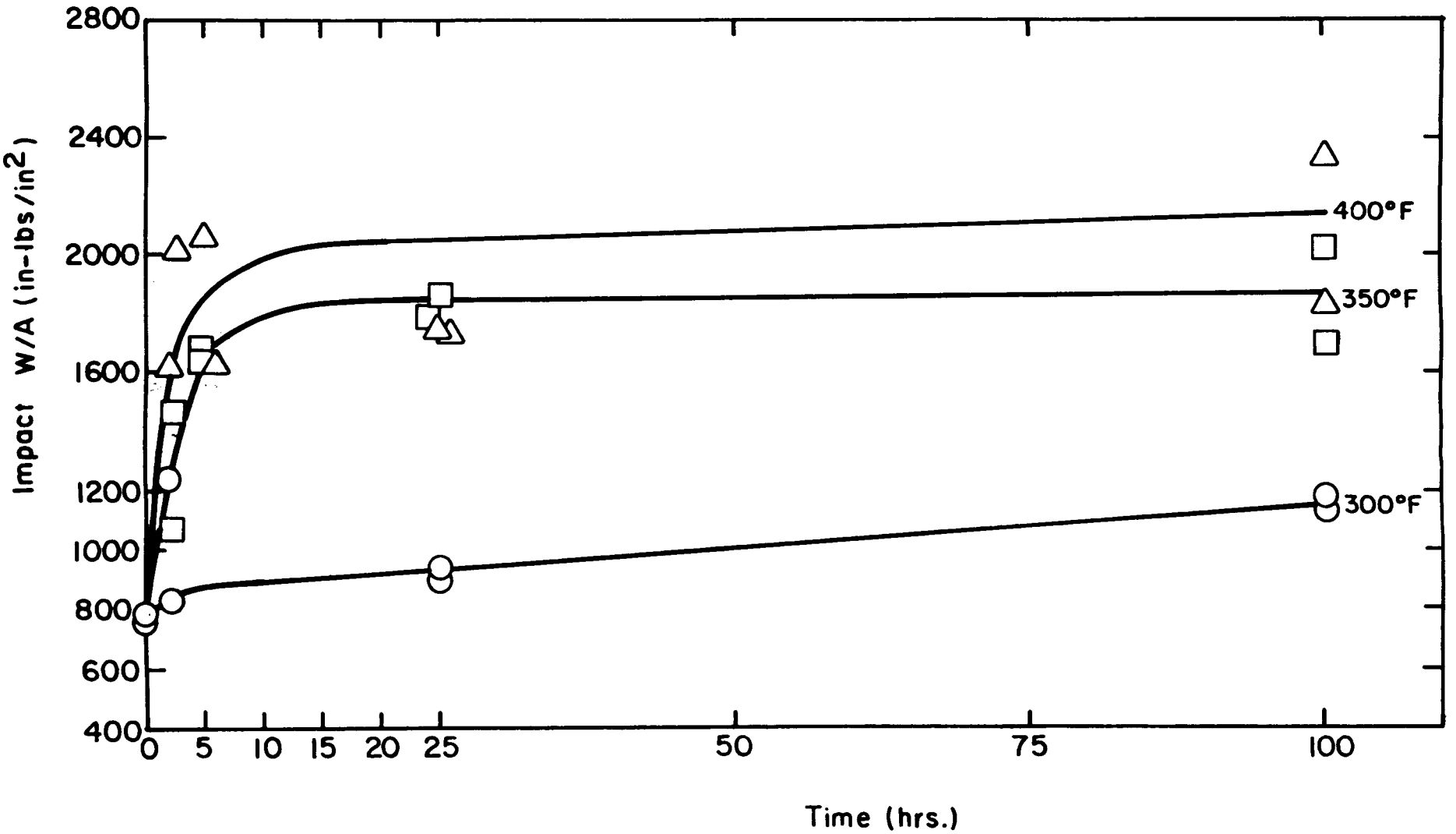

Figure 36. Effect of Time and Temperature on the Impact Fracture Toughness of 7039-T651 at Room Temperature.

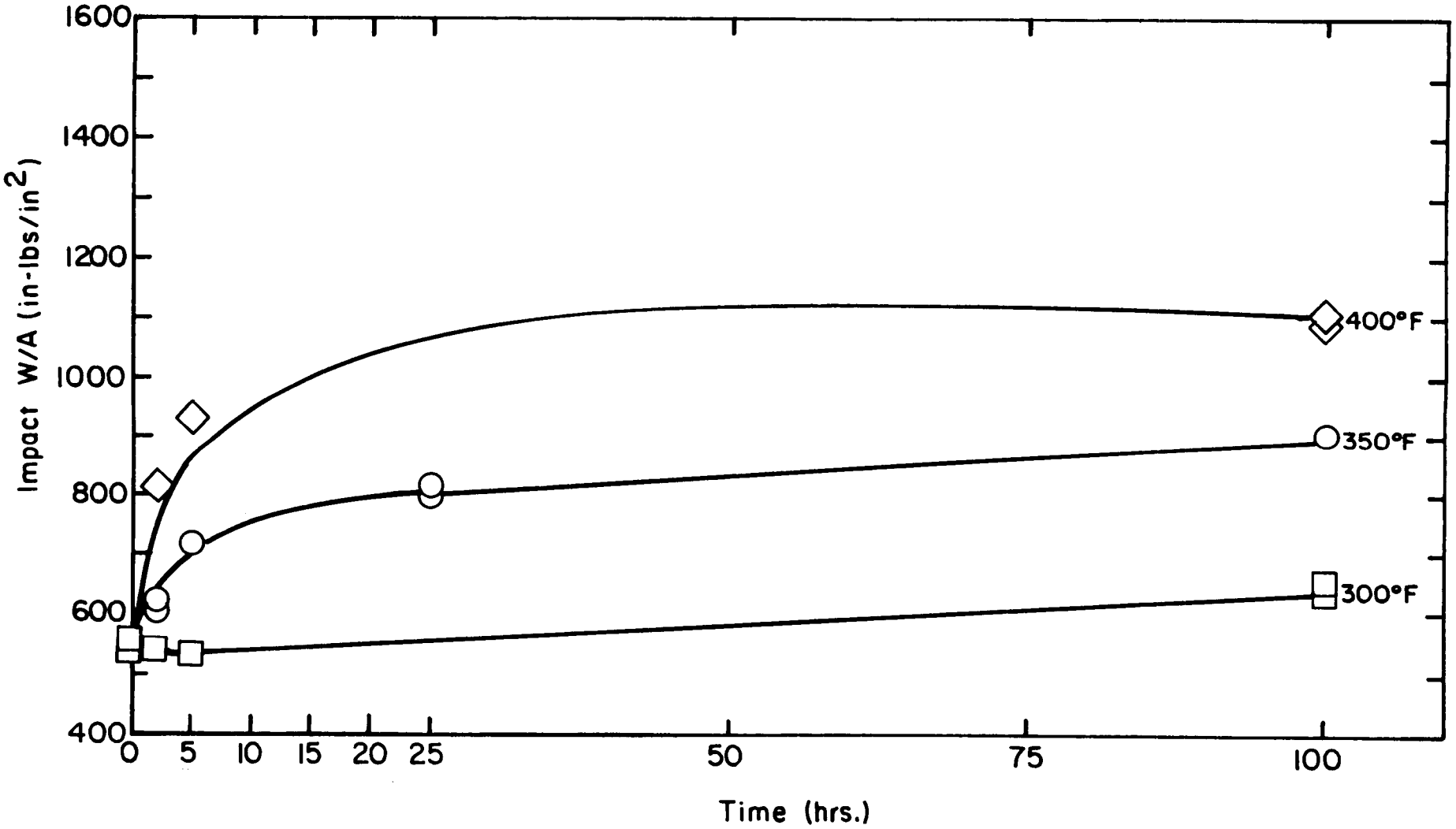

Figure 37. Effect of Time and Temperature on the Impact Fracture Toughness of 7039-T651 at -320°F.

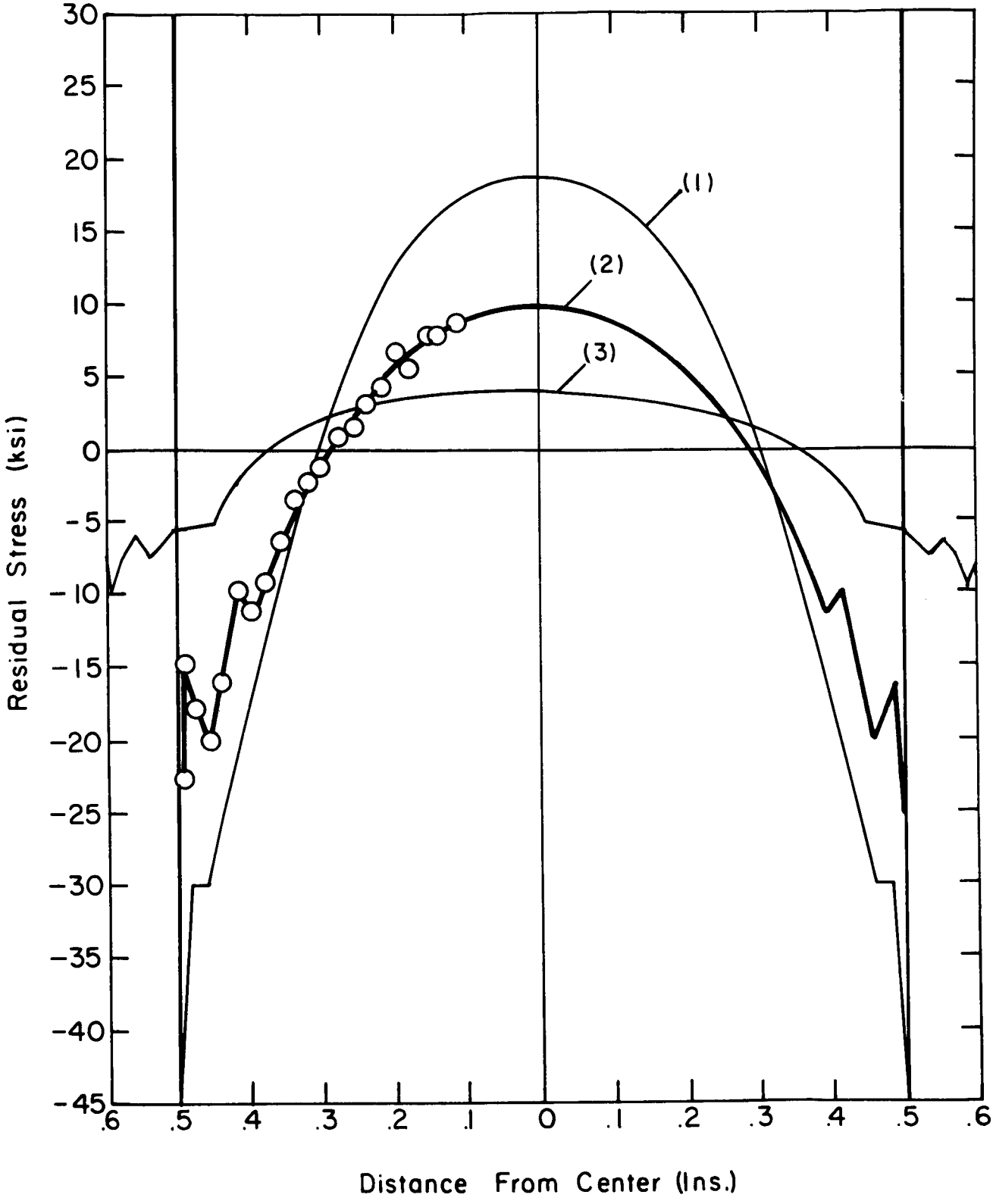

Figure 38. Residual Stress Distributions Through the Thickness in 1 inch Thick 7075-T6 Rolled Plate (1), Reheat Treated Forged Plate (2) and As-Received Forged Plate (3).

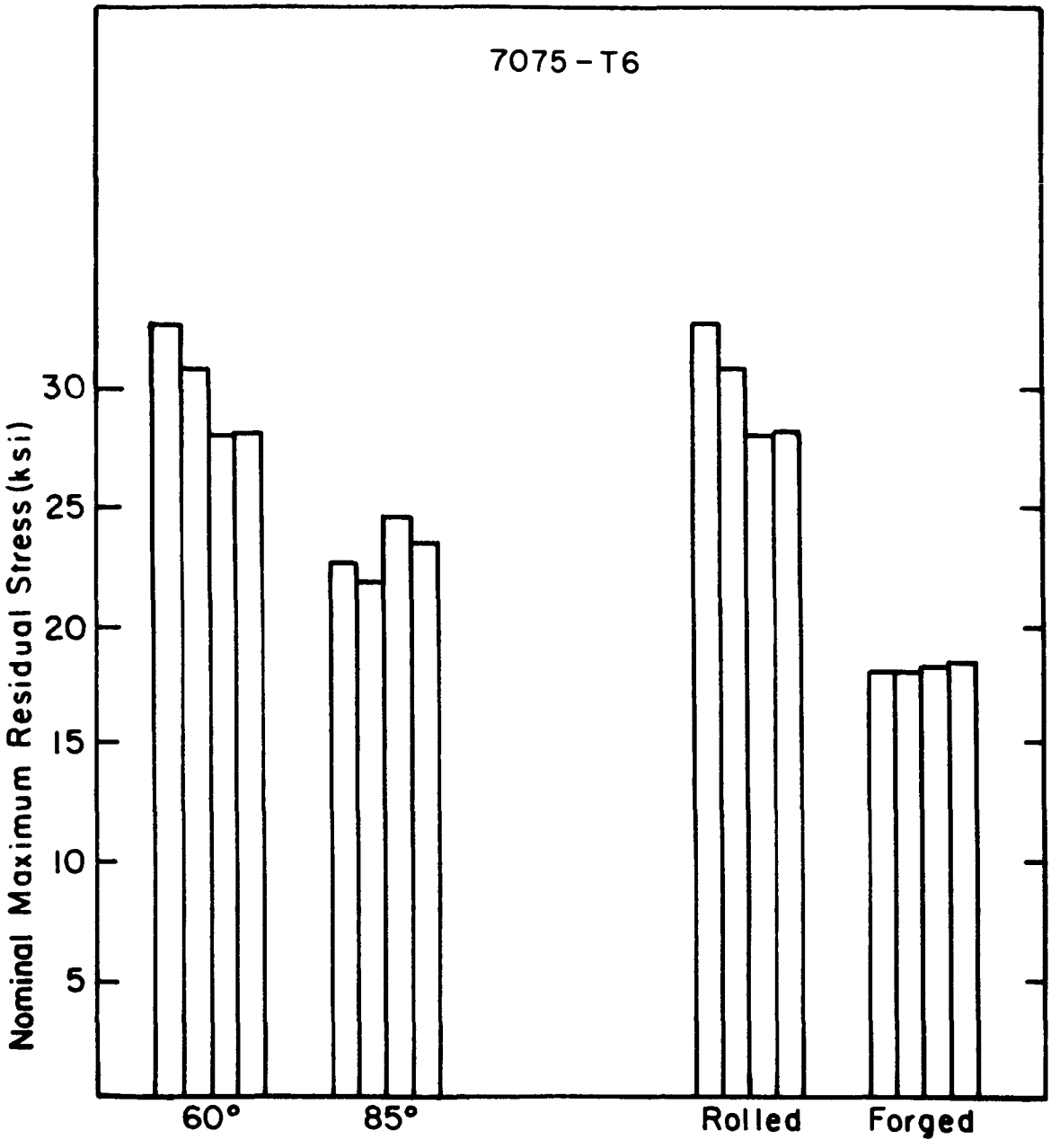

Figure 39. Effect of Quench Bath Temperature on Residual Stress. Effect of Fabrication Variables on Residual Stress.

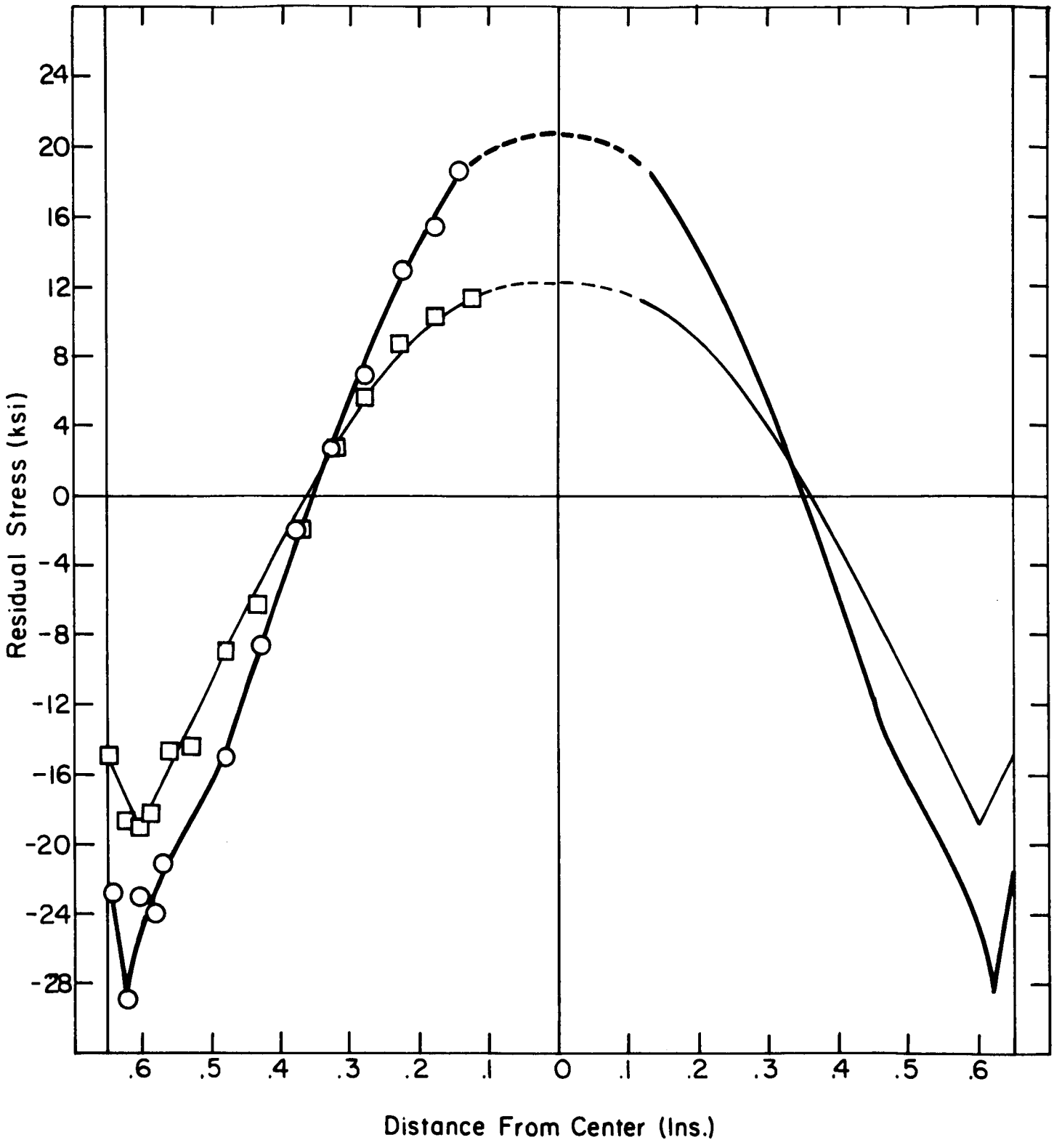

Figure 40. Residual Stress Distribution Through the Thickness of 1.3 Thick 7178 Forging, As-Received (O) and After Stress Relieving at 350°F for 100 Hours (□).

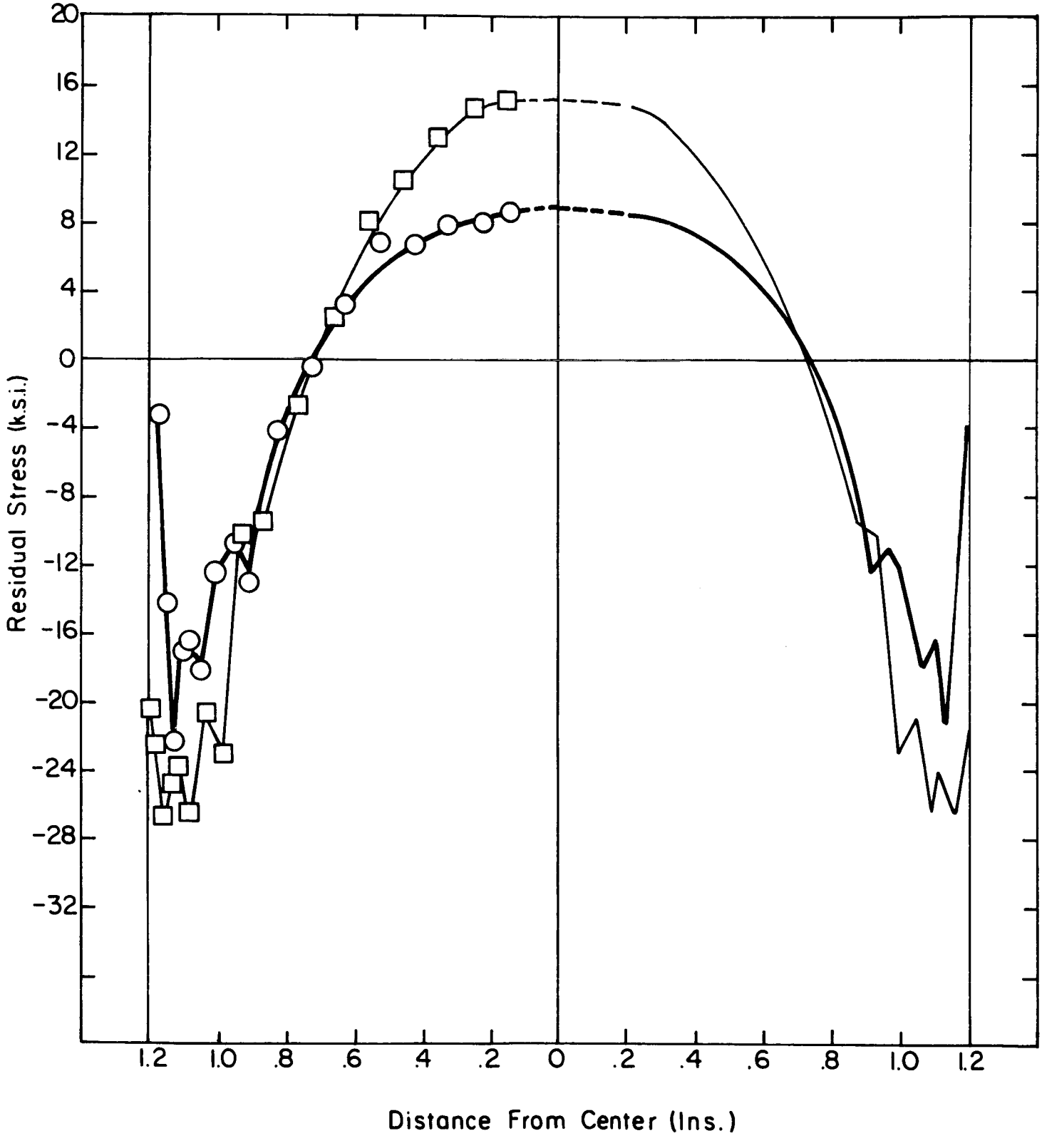

Figure 41. Residual Stress Distribution Through the Thickness of 2.4 Thick 7178 Forging, As-Received (O) and After Stress Relieving at 350°F for 100 Hours (□).

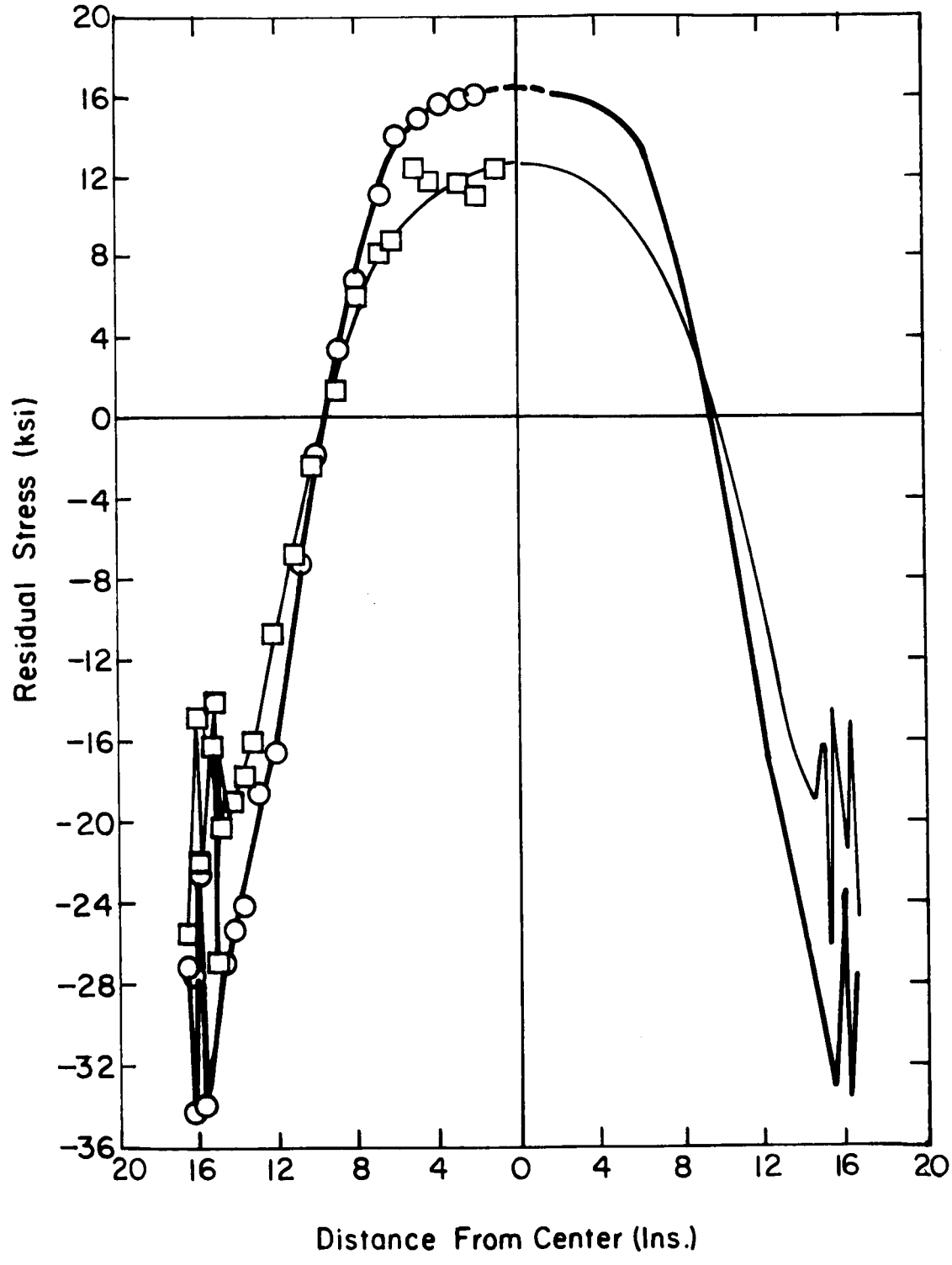

Figure 42. Residual Stress Distribution Through the Thickness of 3.3 Thick 7178 Forging, As-Received (O) and After Stress Relieving at 350°F for 100 Hours (□).

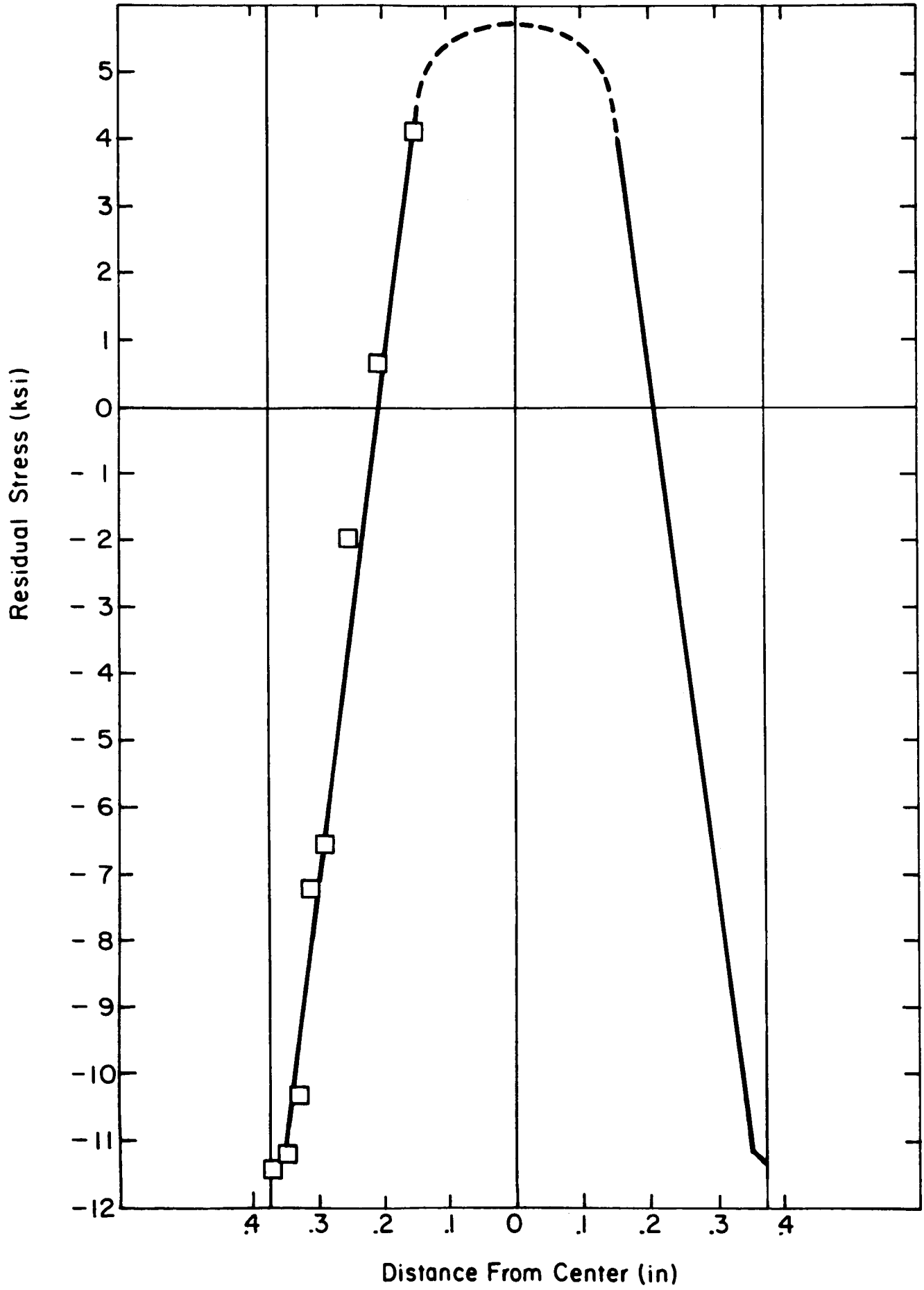

Figure 43. Residual Stress Distribution Through the Thickness in 3/4 inch Thick 2219-T6 as Heat Treated.

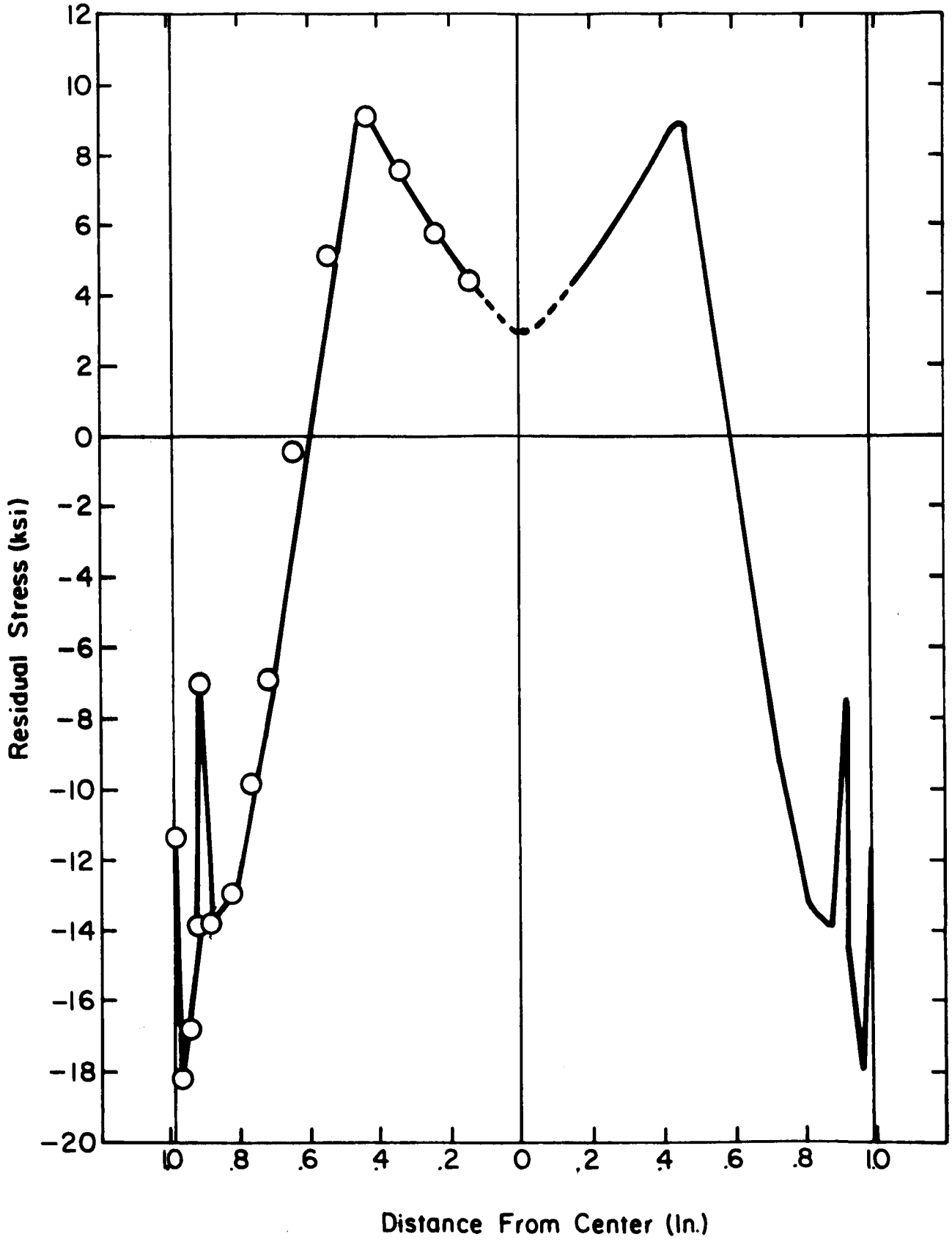

Figure 44. Residual Stress Distribution Through the Thickness in 2 inch Thick 2219-T6 Plate as Heat Treated.

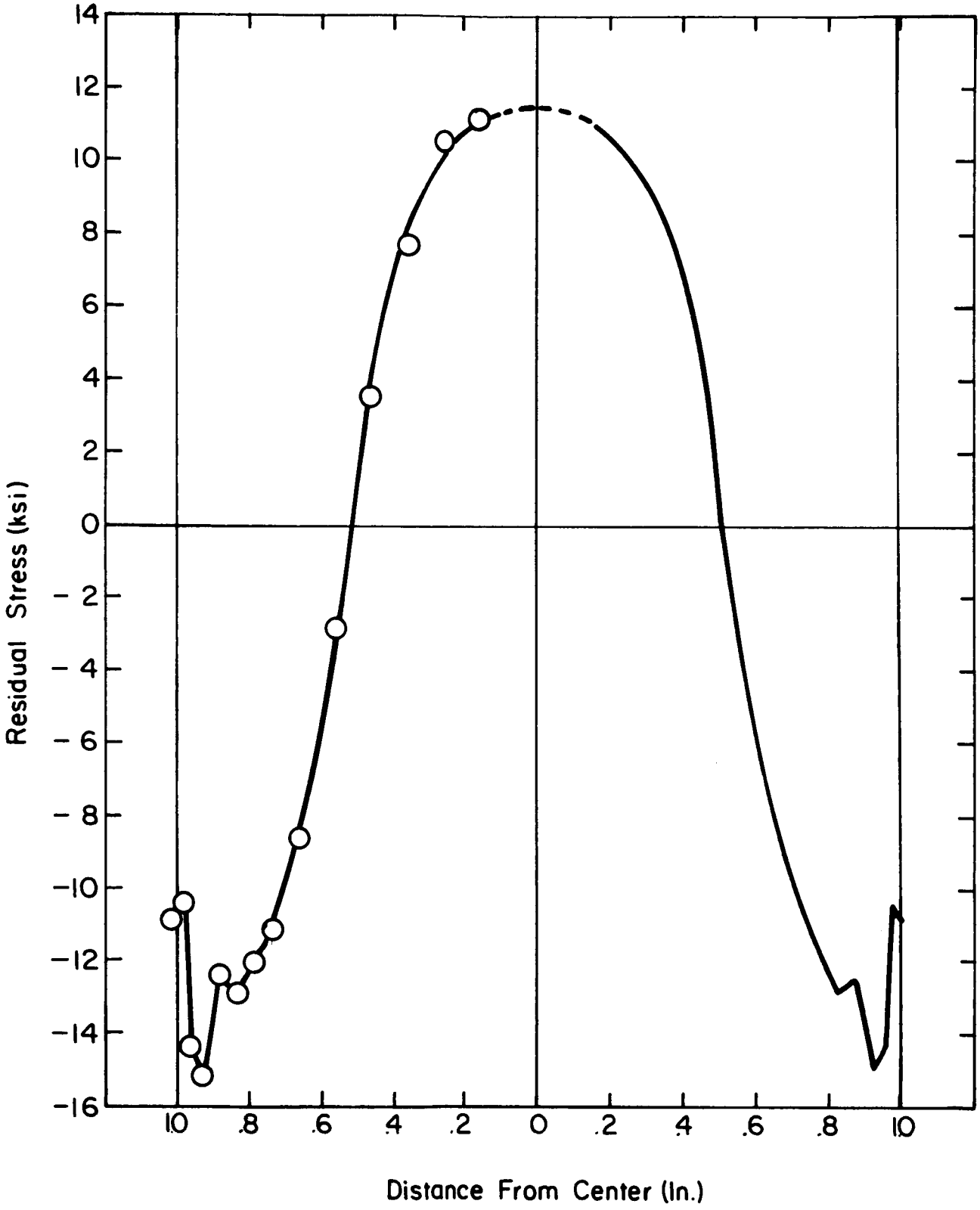

Figure 45. Residual Stress Distribution Through the Thickness in 2 inch Thick 7039-T6 as Heat Treated.

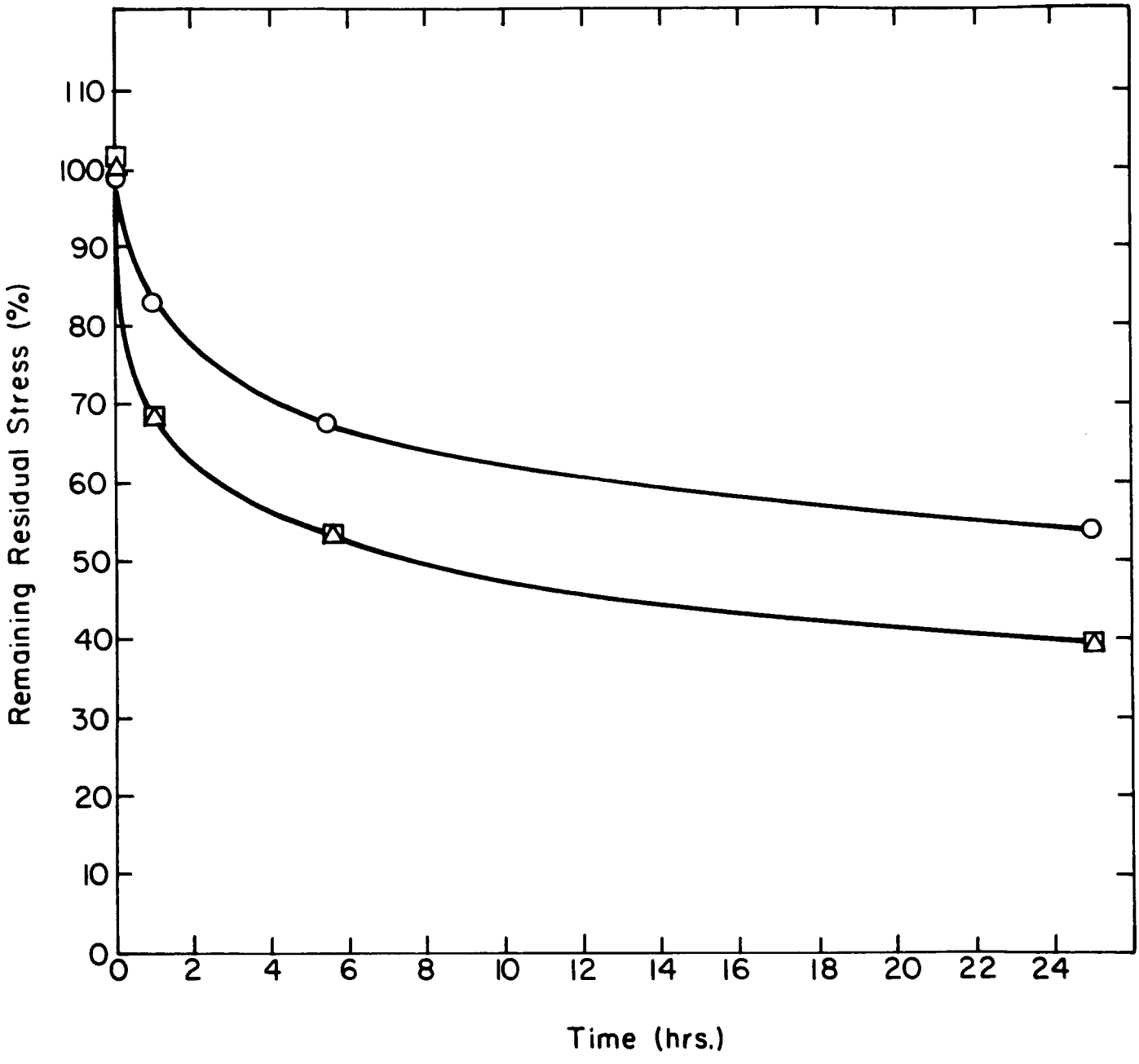

Figure 46. Effect of Time and Temperature on Residual Stresses in Forged 7178, As-Received (□), Re-solution Treated, Quenched and Aged in Unstressed Condition (□) and Re-solution Treated, Quenched and Aged Under Simulated Residual Quench Stresses (O).

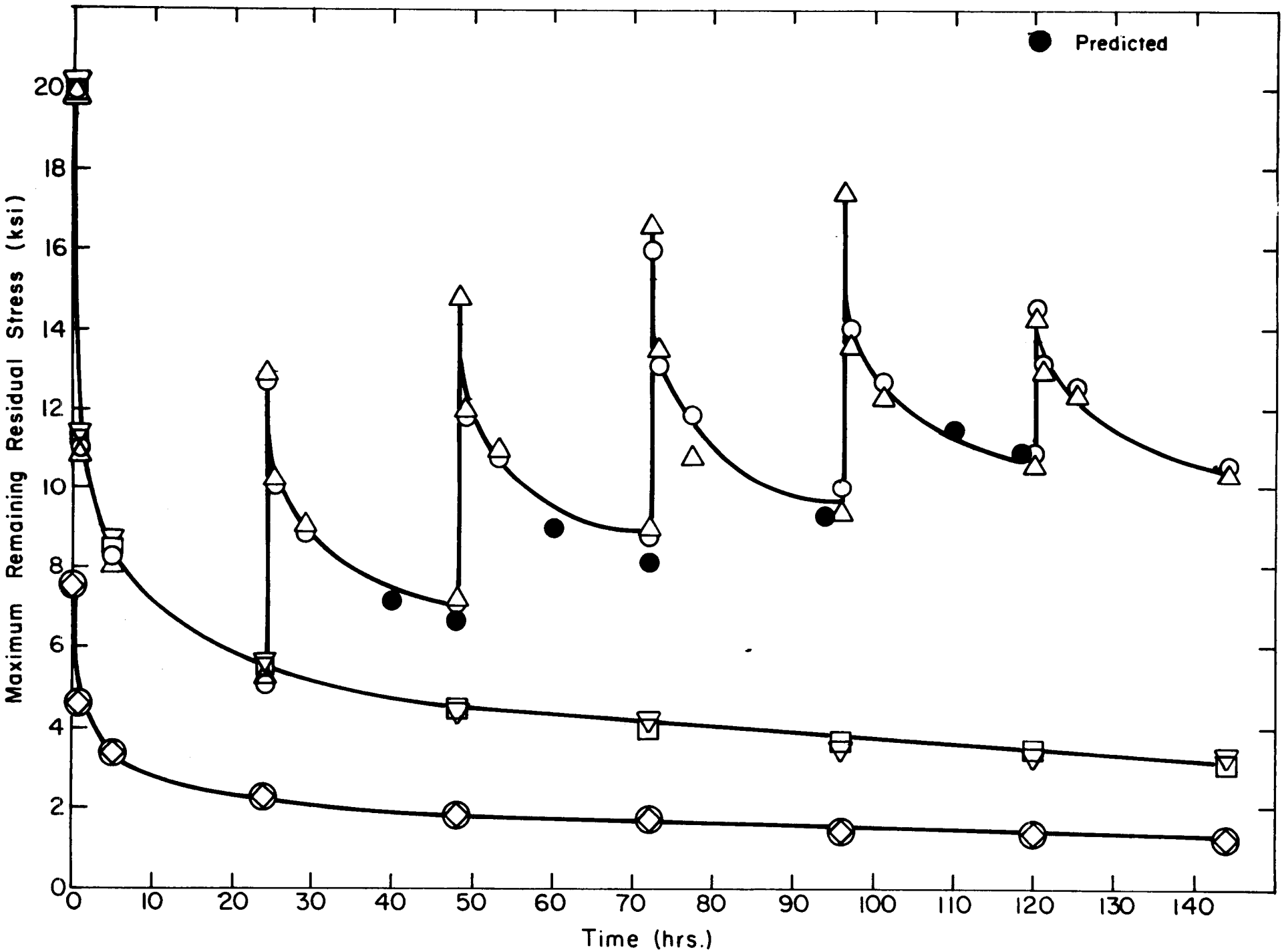

Figure 47. Effect of Time and Temperature (400°F) on Stress in 7075-T651 Stressed to Two Initial Stress Levels and With Additional Stress Increments Added During the Time-Temperature Treatment.

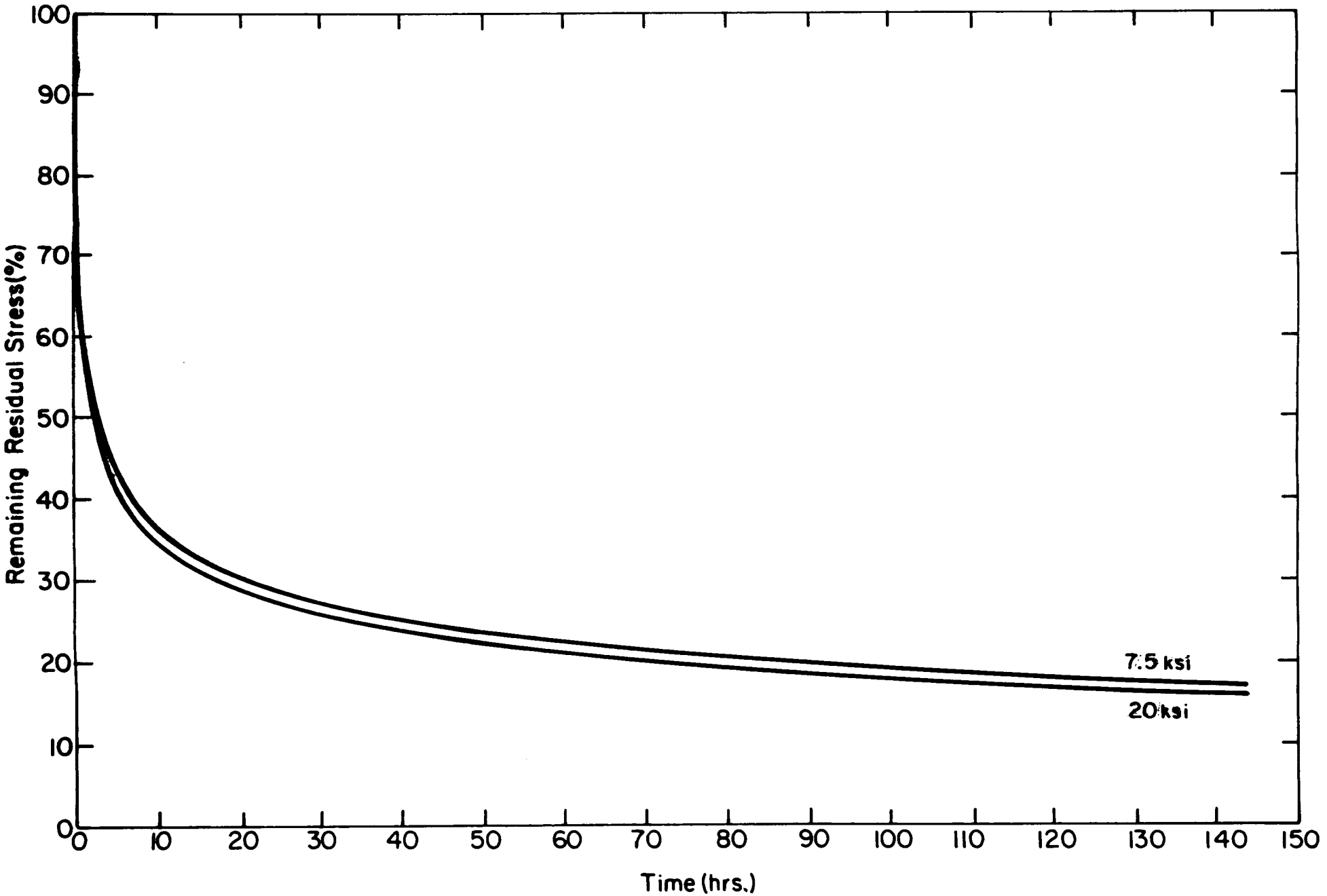

Figure 48. Effect of Initial Maximum Stress Level on Remaining Residual Stress in 7075-T6 Stressed to 7.5 and 20 ksi.

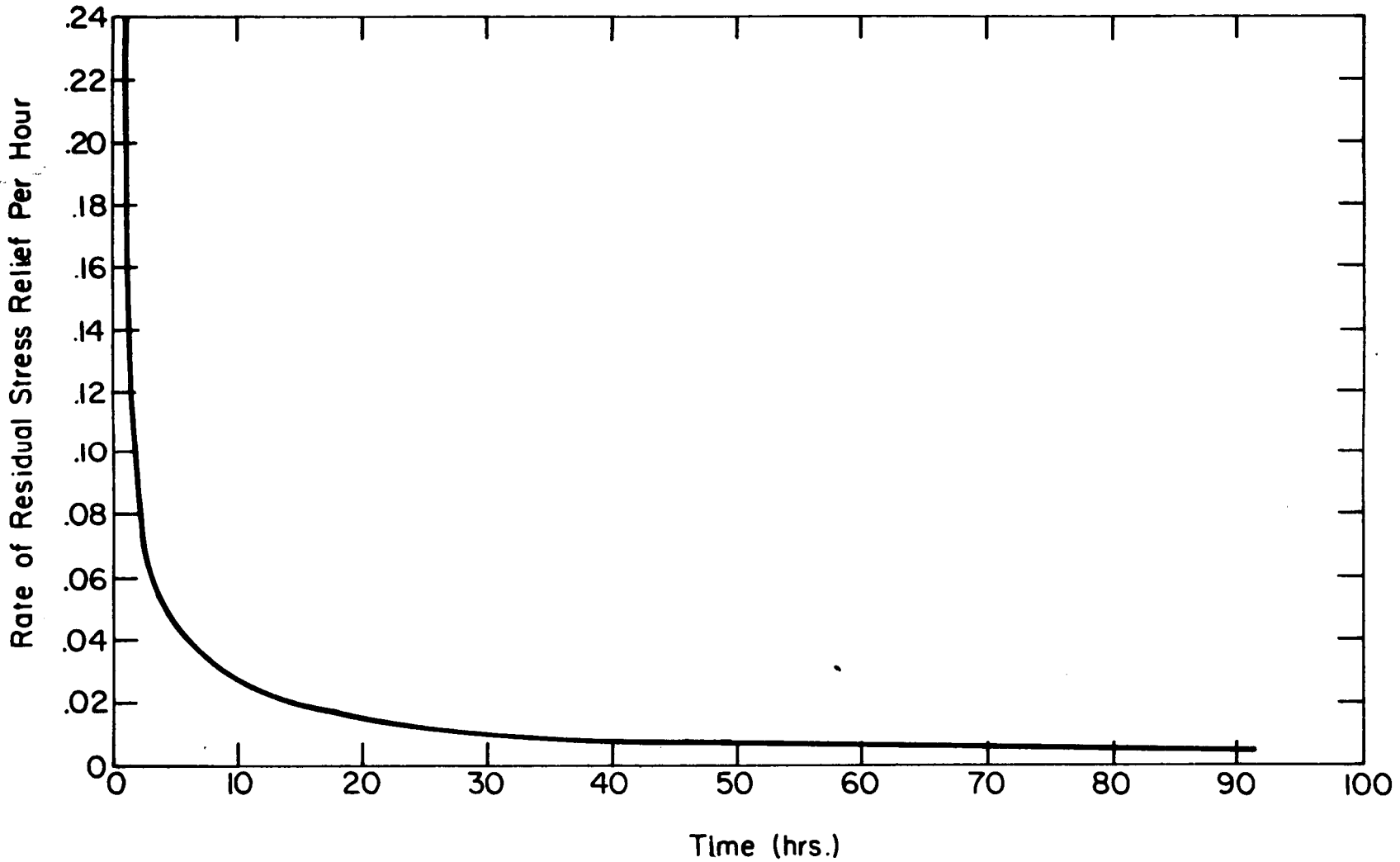

Figure 49. Effect of Time at Temperature on the Rate of Residual Stress Relief in 7075-T651 at 400° F. Initial Maximum Stress 20 ksi.

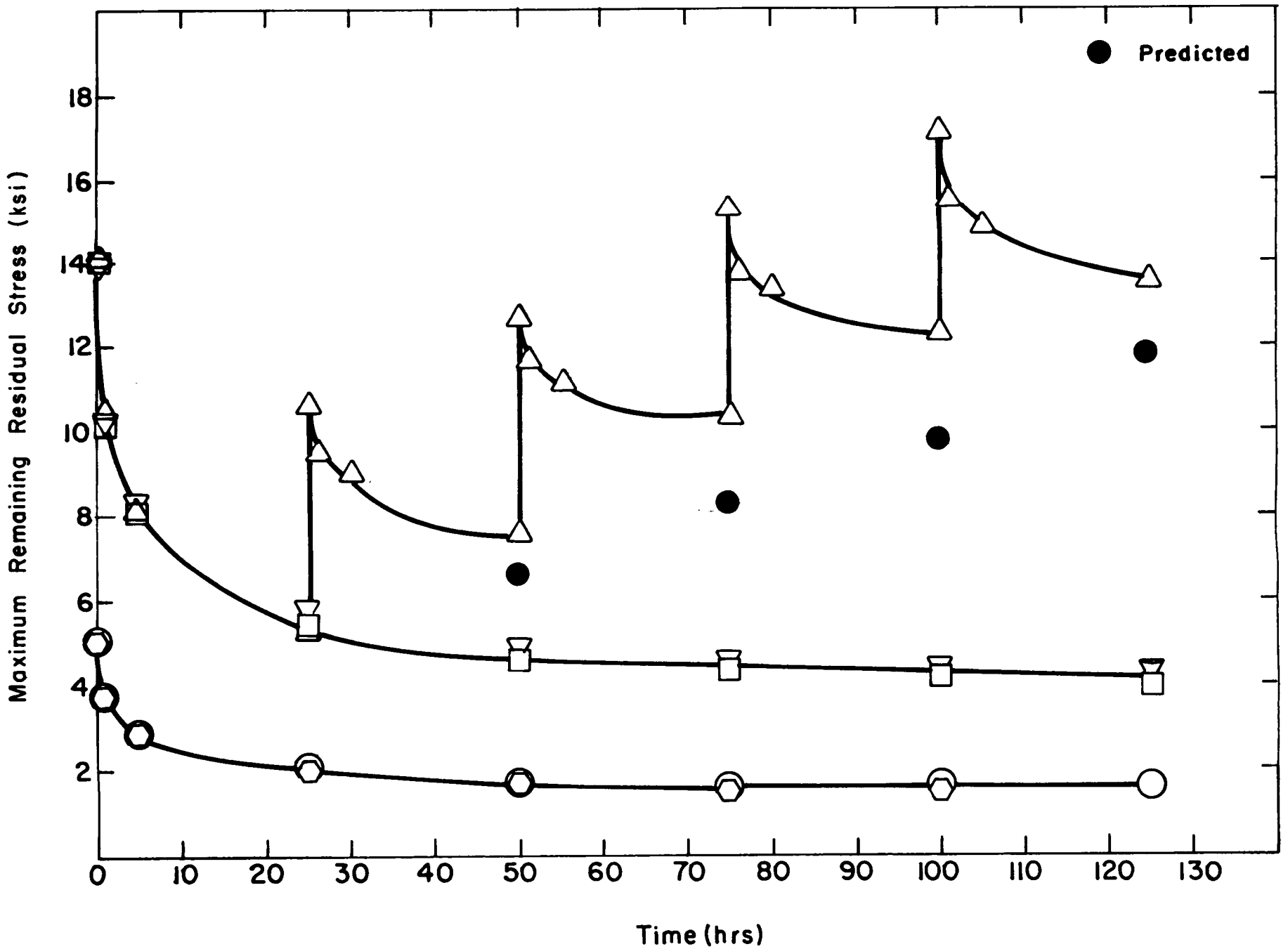

Figure 50. Effect of Time and Temperature (500°F) on Stress in 6061-T651 Stressed to Two Initial Stress Levels and with Additional Stress Increments Added During the Time-Temperature Treatment.

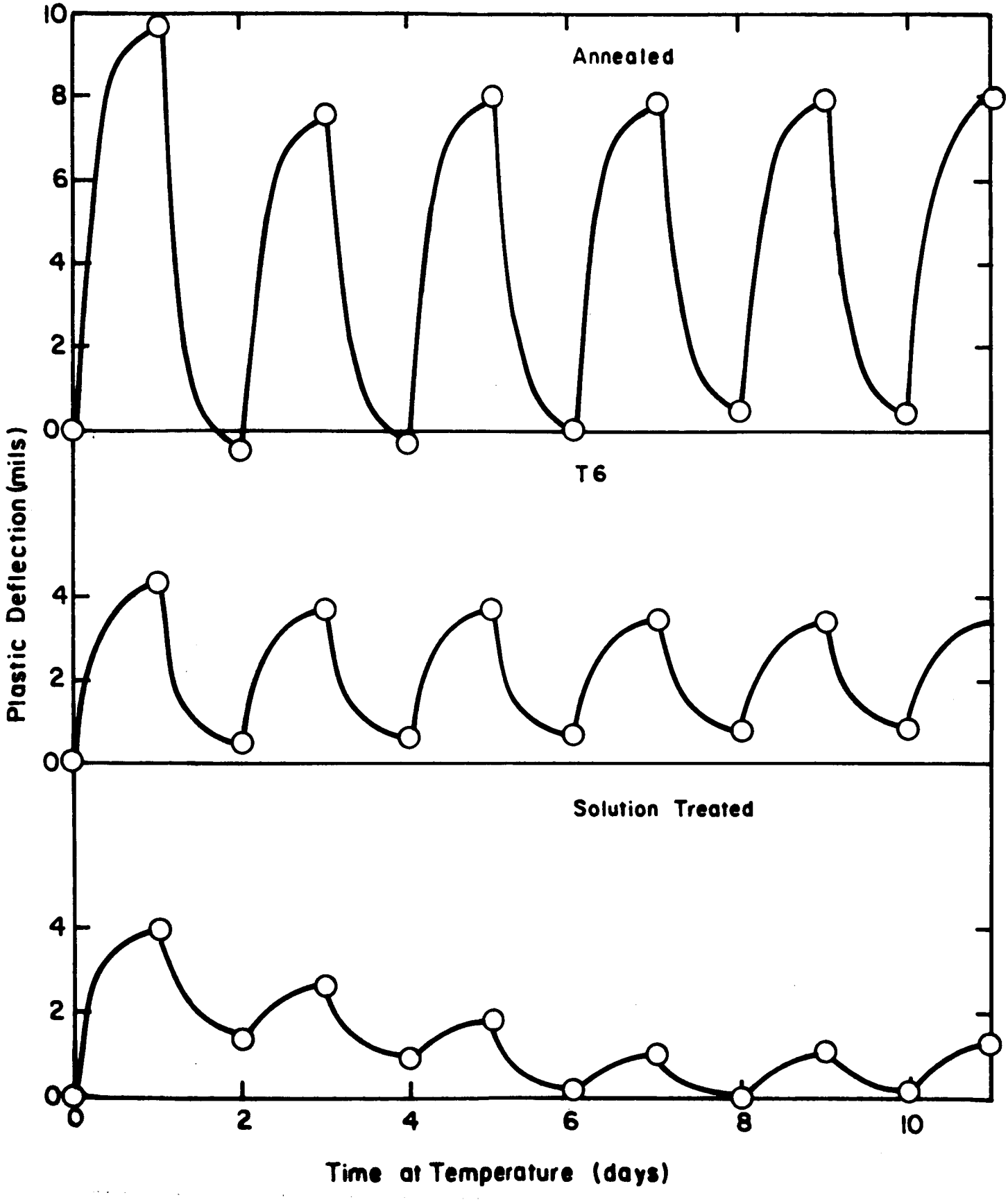

Figure 51. Effect of Heat Treatment on the Rate of Residual Stress Relief at 400° F in 6061-T6 Subjected to Reversed Stress Cycling (Modified Ring Type Specimens).

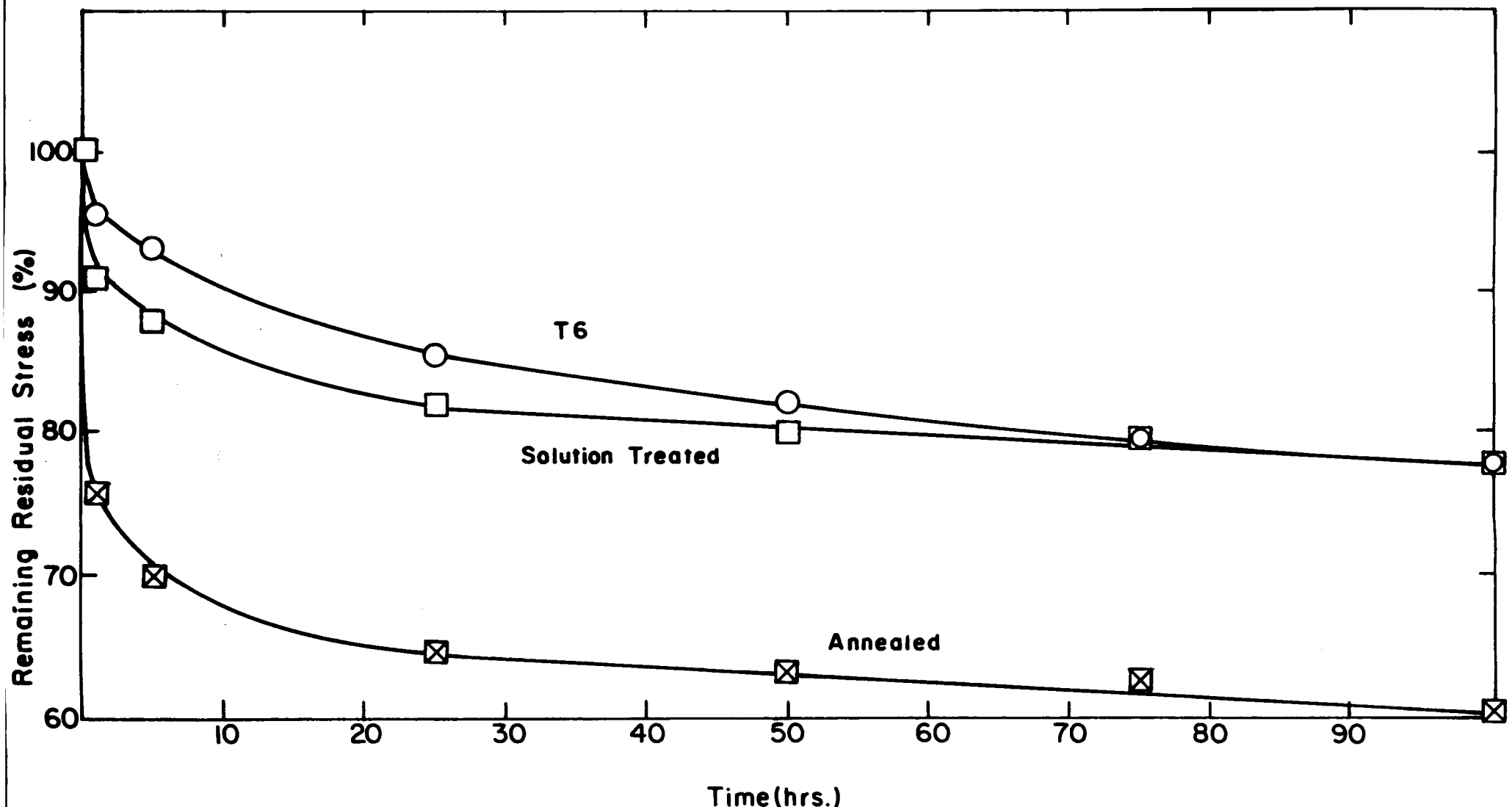

Figure 52. Effect of Heat Treatment on the Rate of Residual Stress Relief at 400°F in 6061-T6. (Modified Ring Type Specimens.)

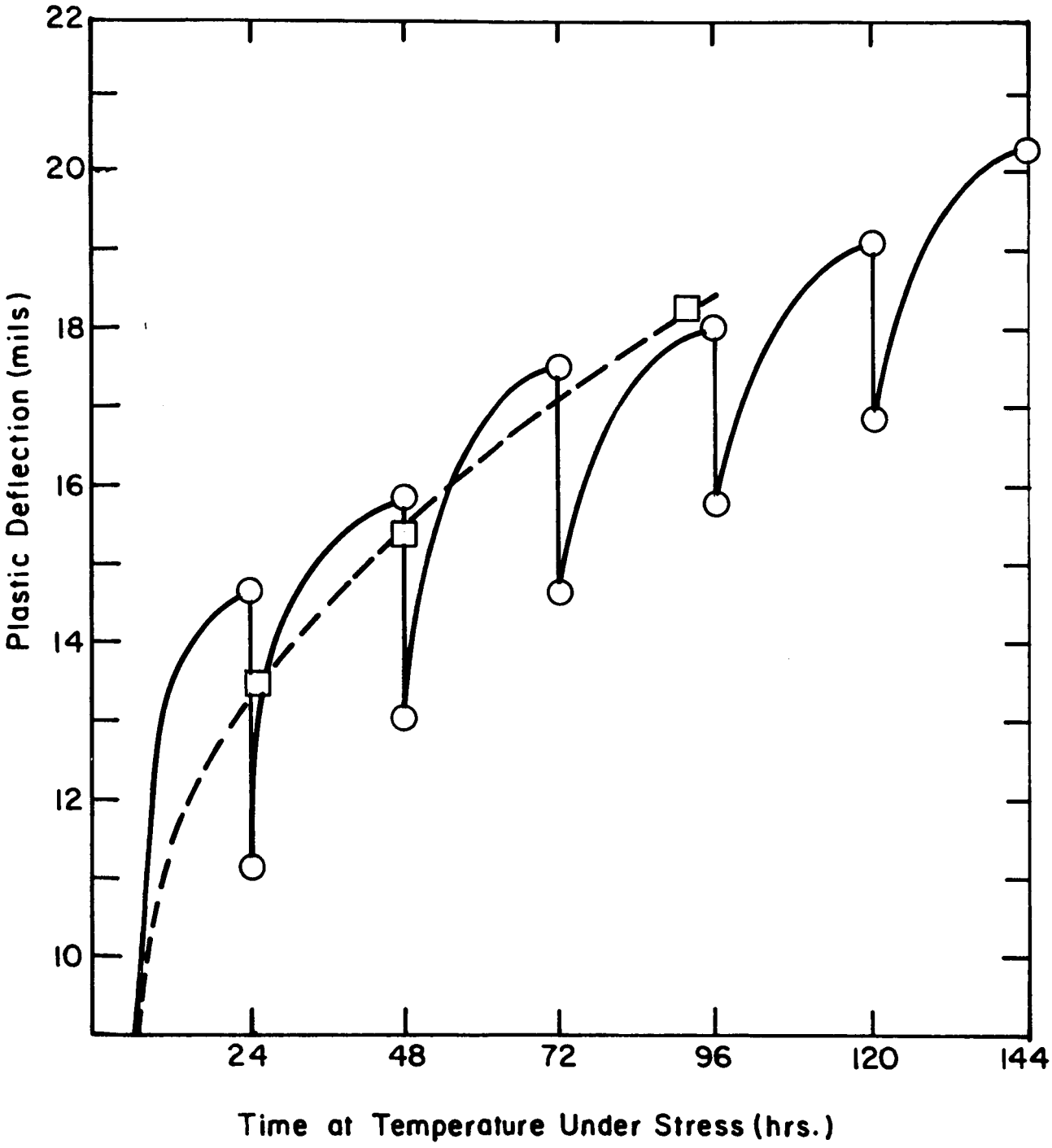

Figure 53. Effect of Alternate Loading and Unloading at 400°F for 24 Hour Periods on Residual Stress Relief in 6061-T6. The Dashed Curve Represents Data From a Similar Specimen, Loaded Continuously.

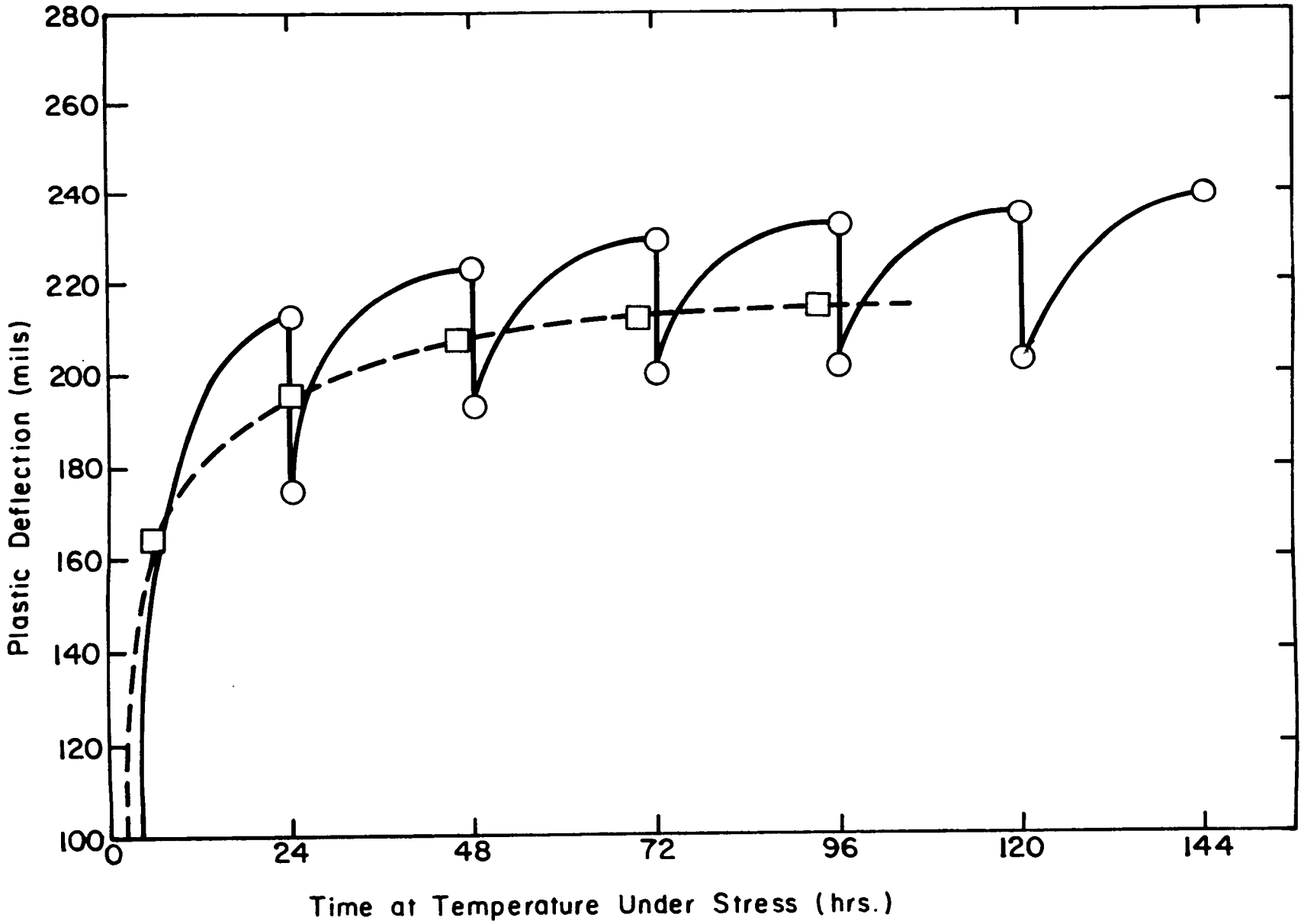

Figure 54. Effect of Alternate Loading and Unloading at 400°F for 24 Hour Periods on Residual Stress Relief in 7075-T6. The Dashed Curve Represents Data From a Similar Specimen Loaded Continuously.

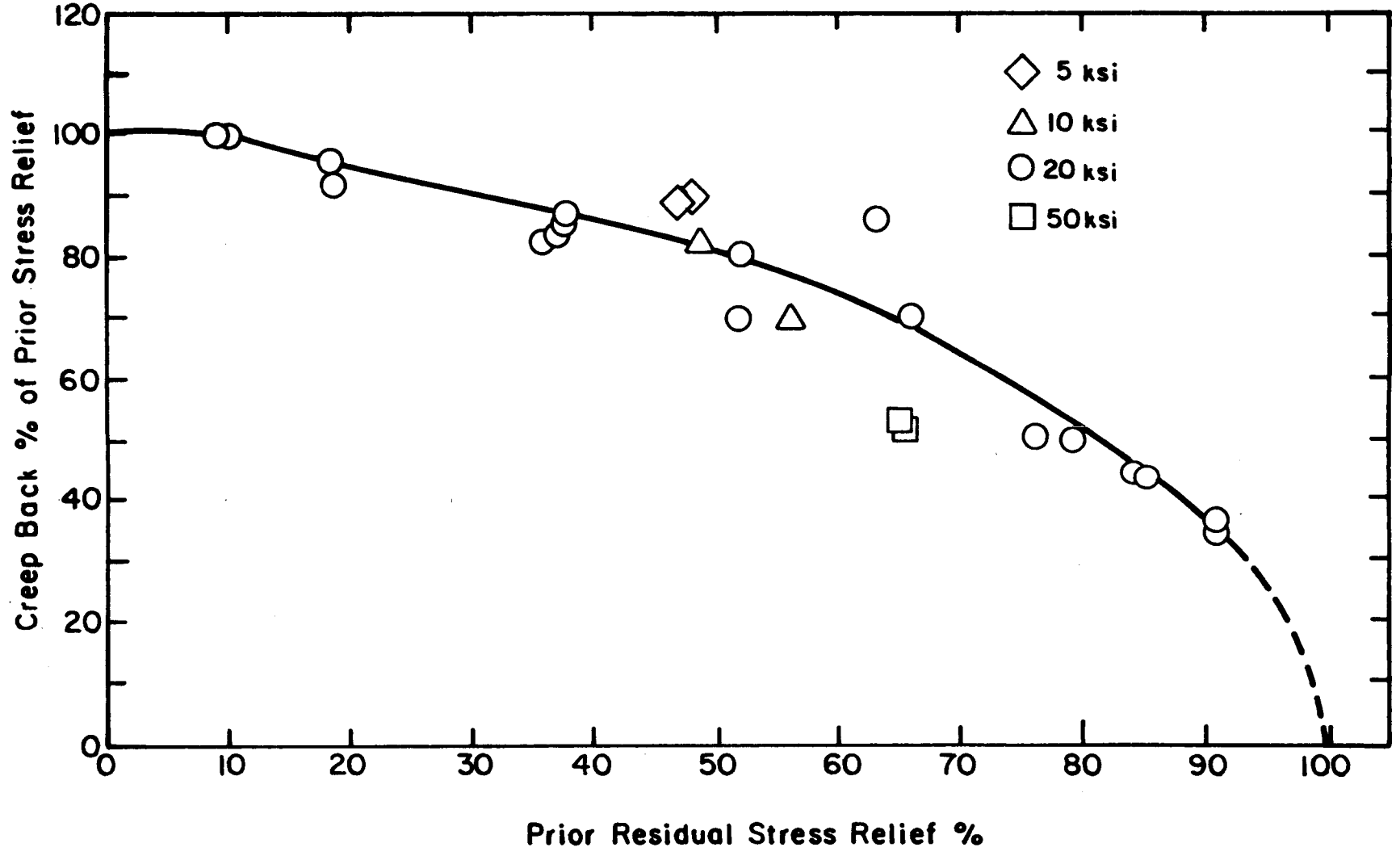

Figure 55. Per Cent "Creep Back" as a Function of Prior Residual Stress in 7075-T6.

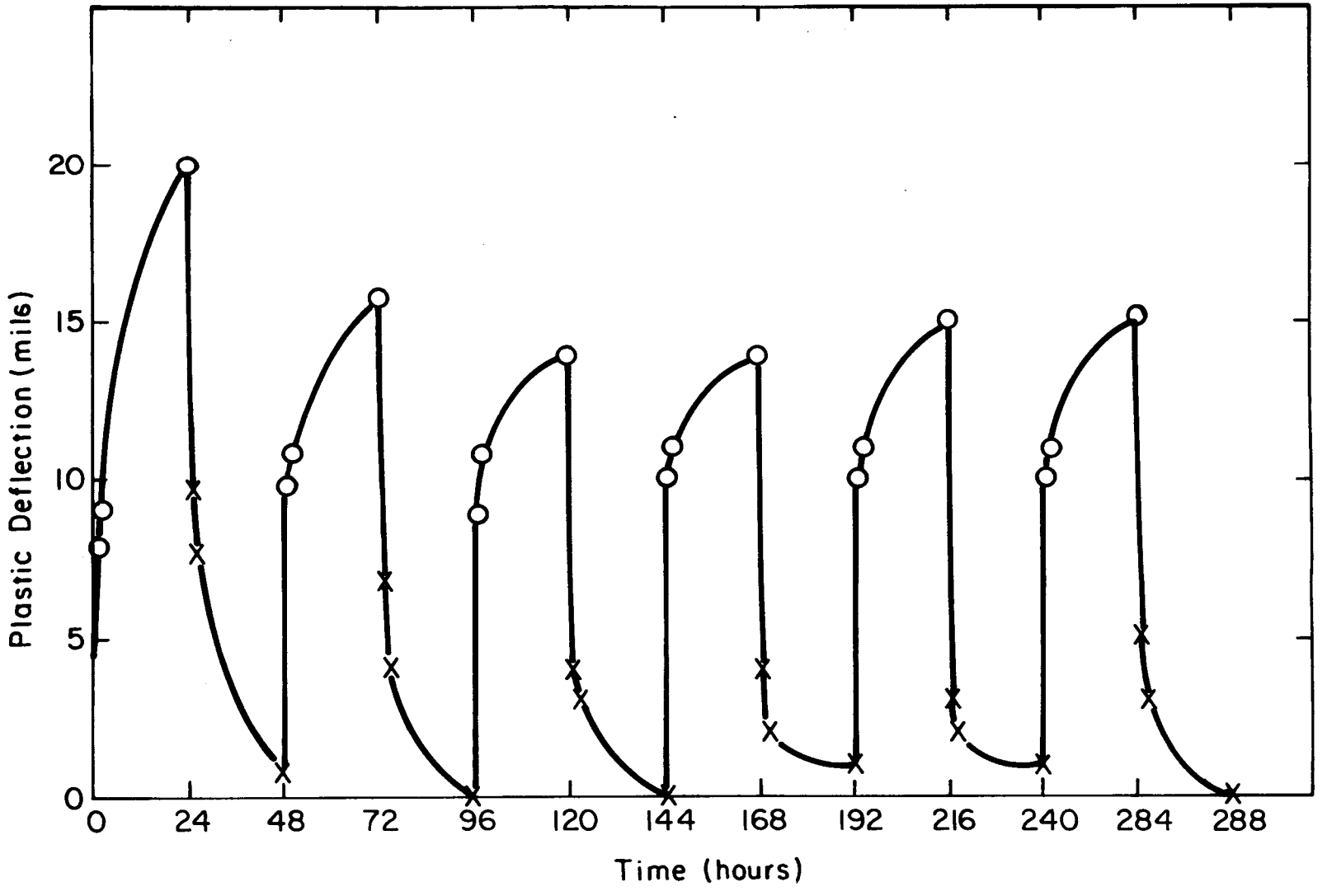

Figure 56. Plastic Deflection of a 6061-T651 Stress Relief Specimen Subjected to Time-Temperature (400°F) Treatments with a Reversal of Stress (15 ksi max.) Every 24 Hours.

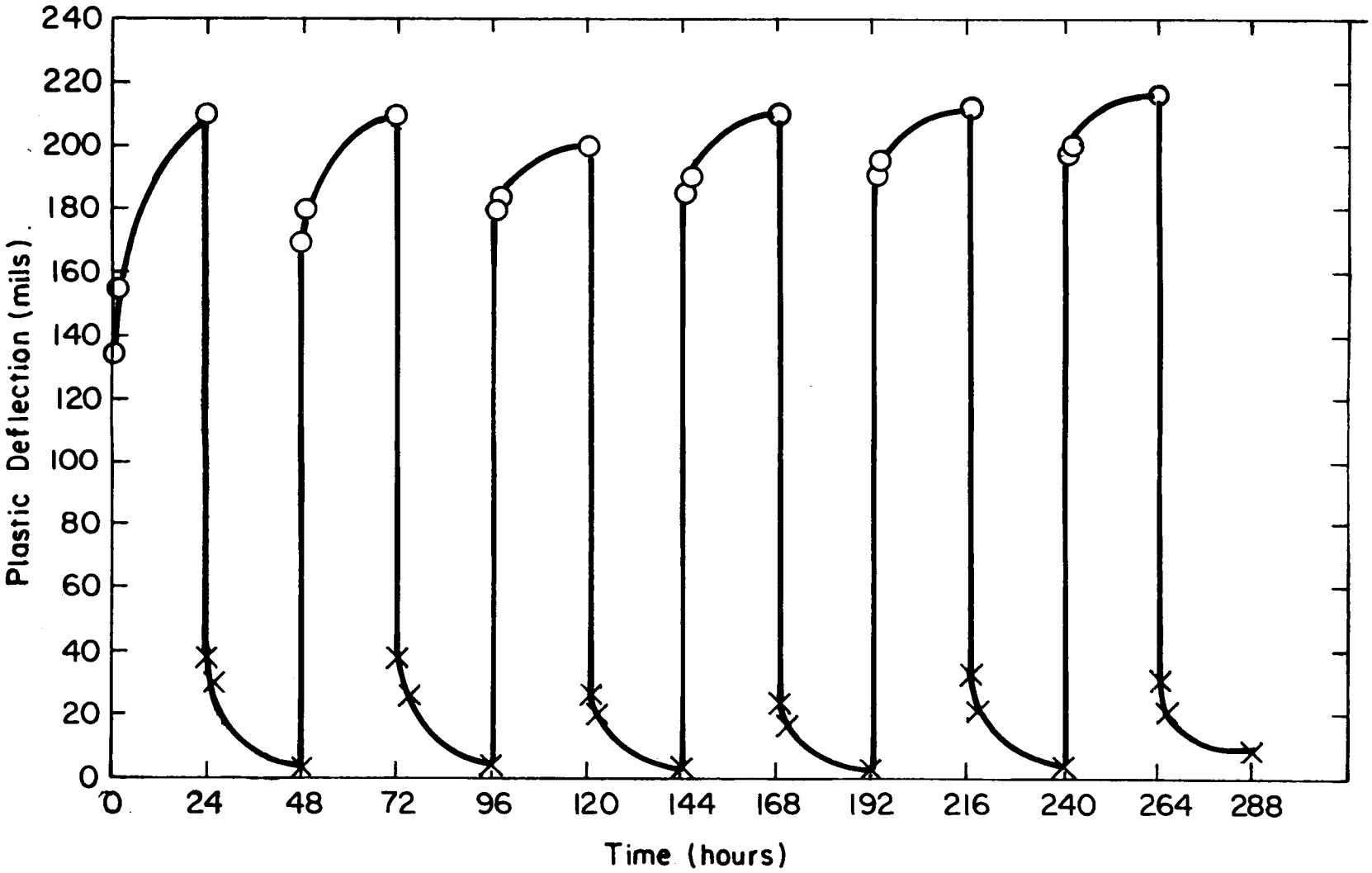

Figure 57. Plastic Deflection of a 7075-T651 Stress Relief Specimen Subjected to Time-Temperature (400°F) Treatments with a Reversal of Stress (37.5 ksi max.) Every 24 Hours.

Defense Metals Information Center
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201
Attention: Mr. Runck

Douglas Aircraft Company
MSSD, MRPH, Department A-260
3000 Ocean Park Boulevard
Santa Monica, California 90405
Attention: Mr. G. V. Bennett

Kaiser Aluminum and Chemical Corporation
Department of Metallurgical Research
Spokane, Washington 99210
Attention: Mr. F. W. DeMoney, Head
Mechanical Metallurgy Branch

Northrop Norair
3901 West Broadway
Hawthorn, California 90250
Attention: Mr. H. W. Jones, Supervisor
Technical Information

Southwest Research Institute
8500 Culebro Road
San Antonio, Texas 78206
Attention: Mr. R. D. Wylie

National Aeronautics and Space Administration
Langley Research Center
Langley Station
Hampton, Virginia 23365
Attention: Mr. Herbert F. Hardrath

National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: Mr. Samuel S. Manson

Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201
Attention: Dr. Horace J. Grover

The Boeing Company
Airplane Division
Box 707
Renton, Washington 98056
Attention: Mr. Howard W. Smith
Assistant Director of Engineering

Boeing Scientific Research Labs
Solid State Physics Laboratory
P.O. Box 3981
Seattle, Washington 98124
Attention: Professor Egon Orowan

Professor Norman C. Dahl
Dept. of Mechanical Eng. (3-360)
Mass. Institute of Technology
77 Massachusetts Avenue
Cambridge, Massachusetts 02139

National Aeronautics and Space Adm
Manned Spacecraft Center
Houston, Texas 77001
Attention: Mr. Robert E. Johnson

Martin Company
P.O. Box 179
Denver, Colorado 80201
Attn: Mr. F. R. Schwartzberg (L-