RESIDUAL STRESSES IN WELDMENTS IN HIGH-STRENGTH STEELS

by

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ABSTRACT

The systematic results of series experimental studies on thermal strain changes, temperature histories, deflection changes during welding and residual stresses existed in weldments after cooling were presented. Investigations were conducted on simple weldments made with several types of materials including mild steel, 308 stainless steel, T-1 steel, HY-80 steel and a Ti-6Al-2Cb-1Ta-0.8Mo alloy. Comparisons on experimental data were made with the results of one-dimensional computer program that have been developed in Department of Ocean Engineering, M.I.T..

The one-dimensional analysis appear to be sufficiently accurate for temperature predictions. Better agreements were obtained in strain changes and deflection changes in GTA welded plates than that in GMA welded plates.

Residual stresses are about 50 % yield strength of the material in high-strength steels such as HY-80, T-1 steel and Ti-6211 alloy.

The accuracy of the analysis is limited due to lack of knowledge of the variation of the material properties with temperature and that of the heat losses during welding.

THESIS SUPERVISOR : Koichi Masubuchi

TITLE : Professor of Ocean Engineering & Materials Science

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I. INTRODUCTION

A. GENERAL

Residual stresses due to welding are thermal stresses remaining when the material has cooled to ambient temperature. Thermal stresses have been investigated both by analytically and experimentally for many yesrs. In 1936, Boulton and Lance Martin[1] first presented analytical and experimental results and shown that welding induced plastic deformation of material in and near the weld and that the residual stresses resulting after cooling were due to these plastic deformations. Fujita[2] studied the thermal and residual stresses arising in a center welded plate by both experimental and theoretical means. His tests indicated that the temperature distribution of a plate can be assumed to be that of an infinite plate if the width of the plate is wider than about ten inches. After that a number of research programs have been carried out on residual stresses and distortion in weldments, several reviews and books have been written on various subjects related to residual stresses and distortion in weldments.[3,4] Until recently, however, almost all studies were on residual stresses and distribution after welding is completely and only limited studies were made on transient thermal stresses and metal movement.[5] This is due to the complexity of the problem characterized by large temperature changes in small areas near the welding arc with its resulting non-elastic deformation, temperature dependency of the material properties and/or phase transformations, and complex boundary conditions resulting from conditions of geometry and multipass welding. With the advancement of the computer technology, it is possible to analyze thermal stresses and metal movement with reasonable cost and time. Hence, investigators at M.I.T. and some other laboratories in the world are currently developing computer programs on thermal stresses during welding.

B. DEVELOPMENT OF ANALYTICAL STUDIES

Based upon the earlier work by Prof. Masubuchi et al.[6] of Battelle Memorial Institute, researchers of M.I.T. first developed a one-dimensional program of thermal stresses during welding.[7] In the one-dimensional program, it was assumed that: (1) The longitudinal stress σ_x is a function of the lateral distance from the weld line, y, only and (2) σ_y and τ_{xy} are zero. Then, two-dimensional programs were developed.[8-10] Recently, efforts were made to improve the two-dimensional analysis to cover butt joints as well as bead-on-plate welds. Complex boundary conditions must be considered in calculating transient thermal stresses during welding a butt joint. The portion of the joint ahead of the welding arc is separated, while the portion of the joint behind the arc is connected. The complicated boundary conditions keep changing as the welding arc travels.

In order to analyze thermal stresses with an reasonable accuracy, it is essential to conduct an accurate analysis of heat flow. Hence, an elementary three-dimensional finite element method program has been developed on heat flow during welding at M.I.T. A limited effort has been made to analyze transient heat flow during multipass welding of heavy plates, it has been found that a general three-dimensional analysis of transient heat flow is expremely costly.[13] From the results of recently studies at M.I.T. and other laboratories, an approximate analysis of thermal stresses and residual stresses in heavy weldments is possible by using current 2D plane stress programs properly.

C. EFFECTS OF METALLURGICAL TRANSFORMATION ON THERMAL STRESSES AND RESIDUAL STRESSES

It has been well established that in a weldment in low-carbon steel, longitudinal residual stresses in regions in the weld are tensile and almost as high as the yield strength , several investigators have also found that residual stresses in weldments in some high-strength steels are considerably lower than the yield strength of the base metal. Several investigators thought that metallurgical transformation during cooling could have important effects on these stresses.

Recently a study was made at M.I.T. by Toshioka, results of the analysis are shown in figure 4,5,6 of Reference 11. The results clearly indicate that metallurgical transformation has significant influence on the distribution of residual stresses in weldments in high-strength alloy steels. It must be mentioned that the analysis by Tosioka is somewhat incomplete in handling welding situations and he used the exxisting two-dimensional plane-stress program. A further study is needed to assess the effects of metallurgical transformation in residual stresses in weldments.

D. PREVIOUS EXPERIMENTAL STUDIES

Several investigations have studied experimentally on residual stresses in weldments in high-strength steels. Masubuchi and Martin[14] investigated residual stresses in butt welds 5/8 inches by 38 inches made in low-carbon steel and in SAE 4340 steel oil quenched and tempered at 500 F. Figure 1 shows distributions of longitudinal and residual stresses along the transverse line. Residual stresses were tensile in areas near the weld and compressive in areas away from the weld. The important finding obtained in this investigation is that residual stresses in the low-carbon steel and SAE 4340 steel weldments were similiar despite the considerable difference in the yield strengths of the base metals and the weld metals used. The differences were as follows:

Low-carbon steel base metal ---------------	35-40 ksi
E 6010 weld metal -------------------------	60 ksi
SAE 4340 Q & T steel ----------------------	224 ksi
E 15016 weld metal ------------------------	150 ksi

the maximum residual stress to mean yield strength ratio in low-carbon steel is significant higher than that in SAE 4340.

Similar results were made by Kikuchi and his research group[15] on welded plates of 80 kg/mm^2 high tensile steels (HT80) and 50 kg/mm^2 high tensile steels (SM50), i.e. small ratio of tensile residual stress to yield stress of HT80. See figure 2 .

Figure 3 summarizes experimental results by Kihara, et al[16] and Yada, et al.[17] The ratio of the maximum residual stresses to the yield strength decreases as the yield strength of steel increases.

In a recent study conducted by Klein[18,19], measurements were made of transient thermal strains during welding butt joints in several high-strength steels. Results are summarized in Figure 4 which shows the relationship between the yield strength of the material and residual strains(measured after welds cooled to room temperature) at locations one inch from the weld center line. Strain decreased as the yield strength increased.

Experimental results obtained so far indicate that residual stresses in weldments in high-strength steels appear to be not as high as the yield strength of othe material.

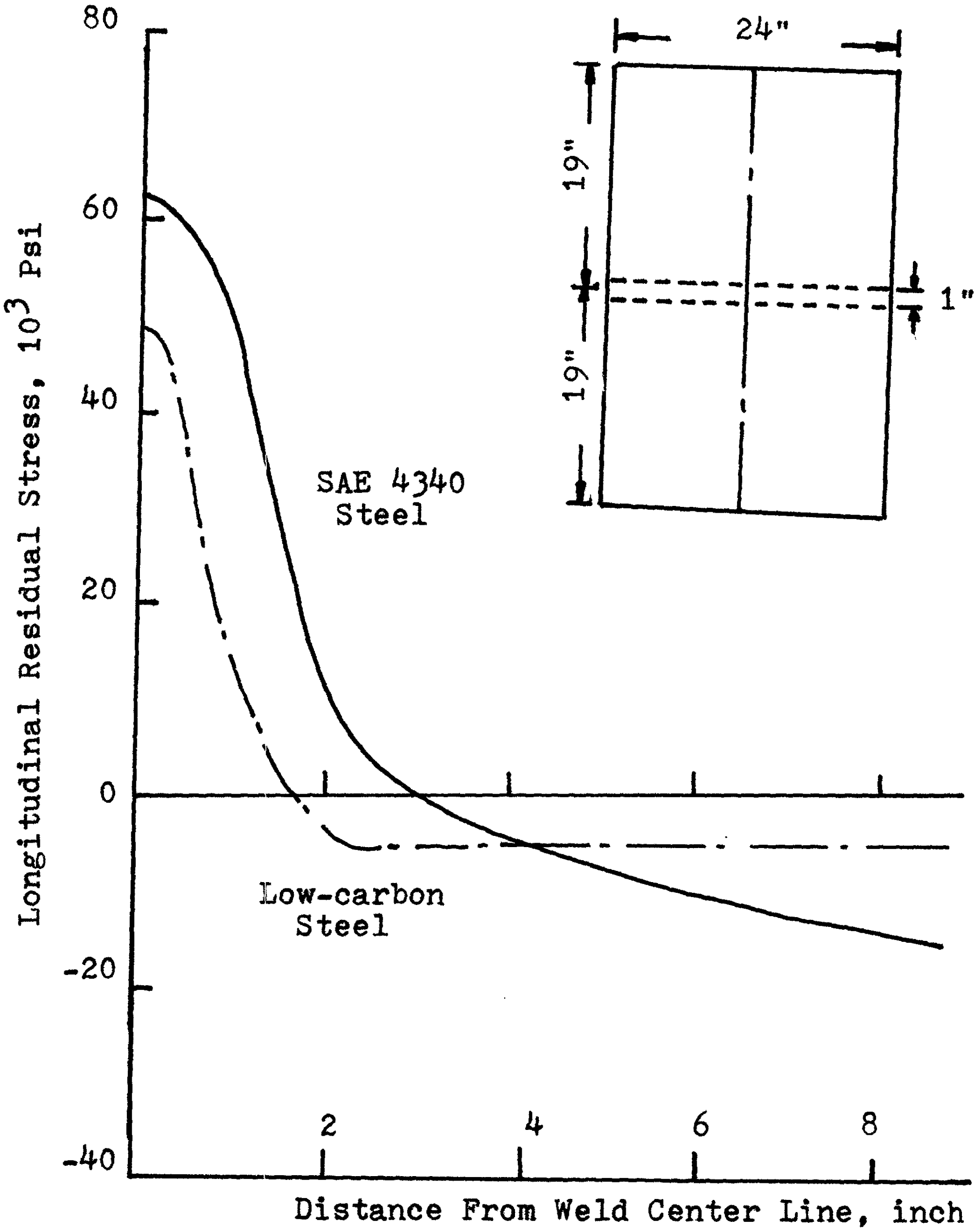
E. THE PURPOSE OF PRESENT STUDY

In studying thermal stresses during welding, it is important to maintain a good balance between analysis and experiments. A series of experiments were conducted at M.I.T. during the last several years on weldments in various materials and thicknesses, and experimental data were compared with analytical predictions. Although a number of studies have been made of the residual stresses on weldments in high-strength steels, there has been not even a single study which covers three subjects: (a) experiments on transient strains. (b) experiments on residual stresses. (c) comparison of experimental data with analytical predictions. Hence, a comprehensive study will be made of thermal stresses and residual stresses in simple welds in low-carbon steels and in high-strength steels in present work.

The study in this paper covers the following two tasks:

Task 1: Experiments on transient thermal strains in simple welds and analysis.

Task 2: Experiments on residual stresses and analysis.



Distribution of Longitudinal stresses along the Transverse Line Passing the Weld Center

Figure 1 RESIDUAL STRESSES IN 38-INCH-LONG BUTT WELD IN LOW CARBON STEEL AND 4340 STEEL. (REFERENCE 14)

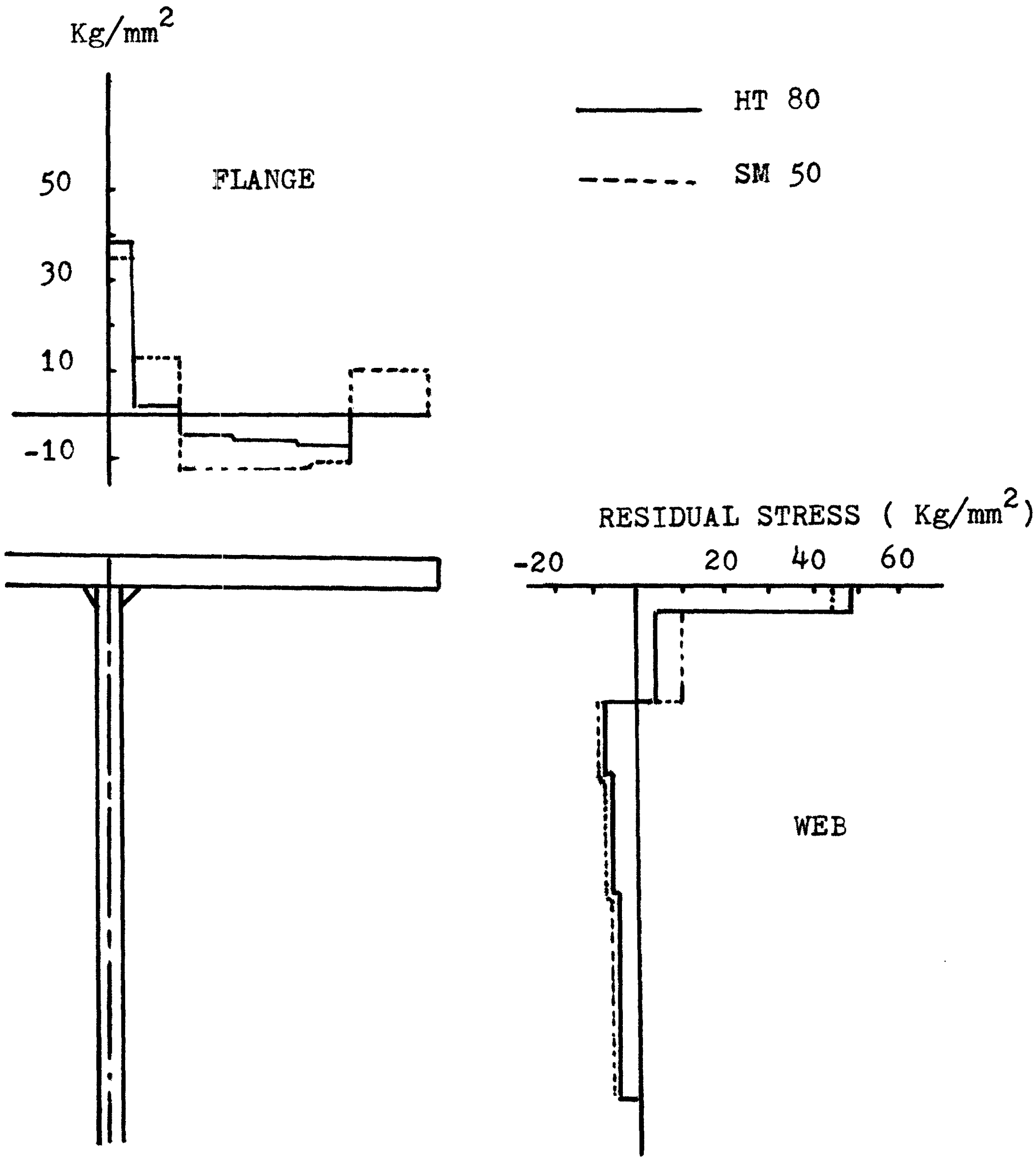


Figure 2 Residual Stress Distribution (REFERENCE 15)
(I Section Member)

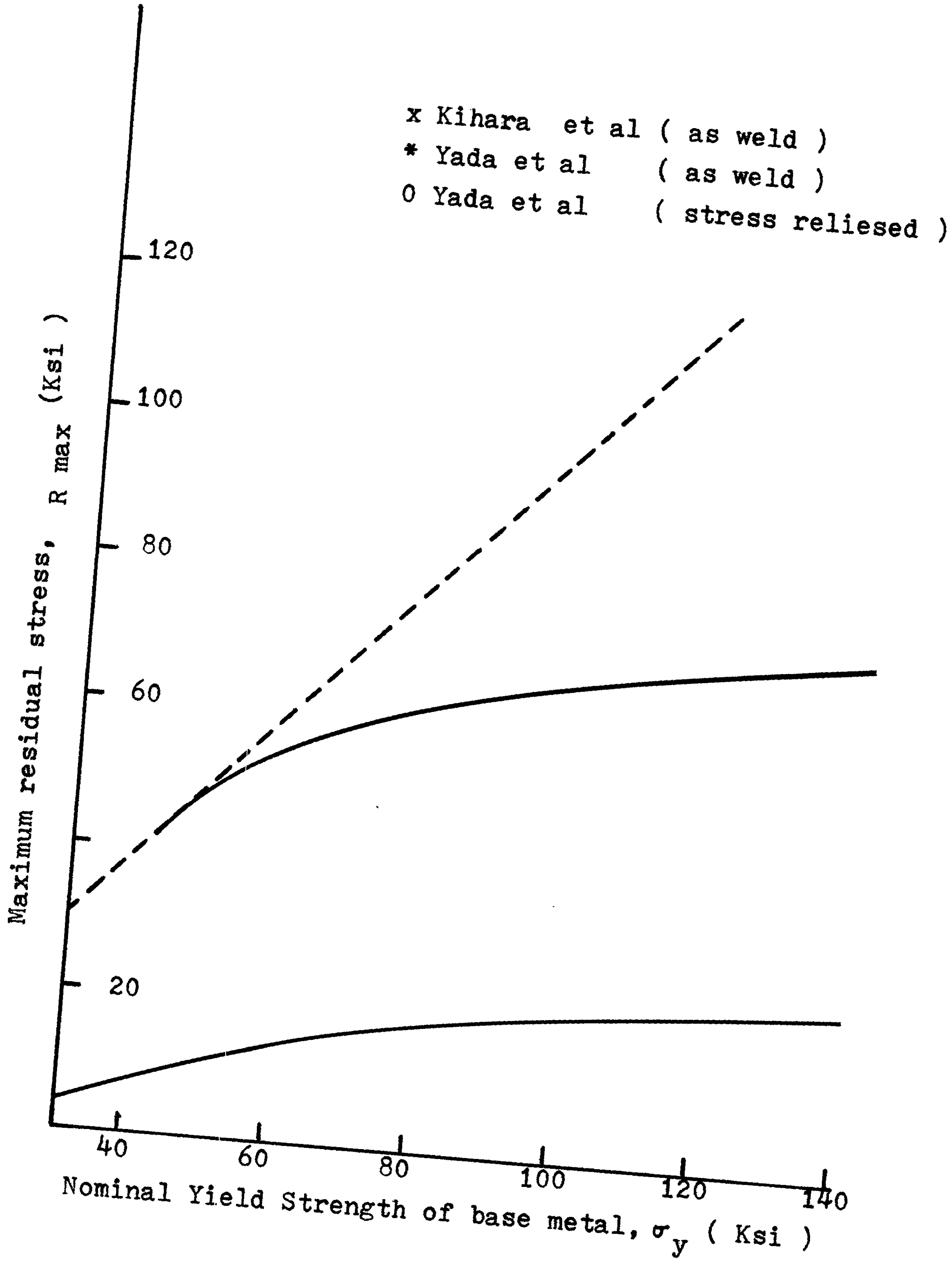


Figure 3 Welding Residual Stresses in High Strength Steel

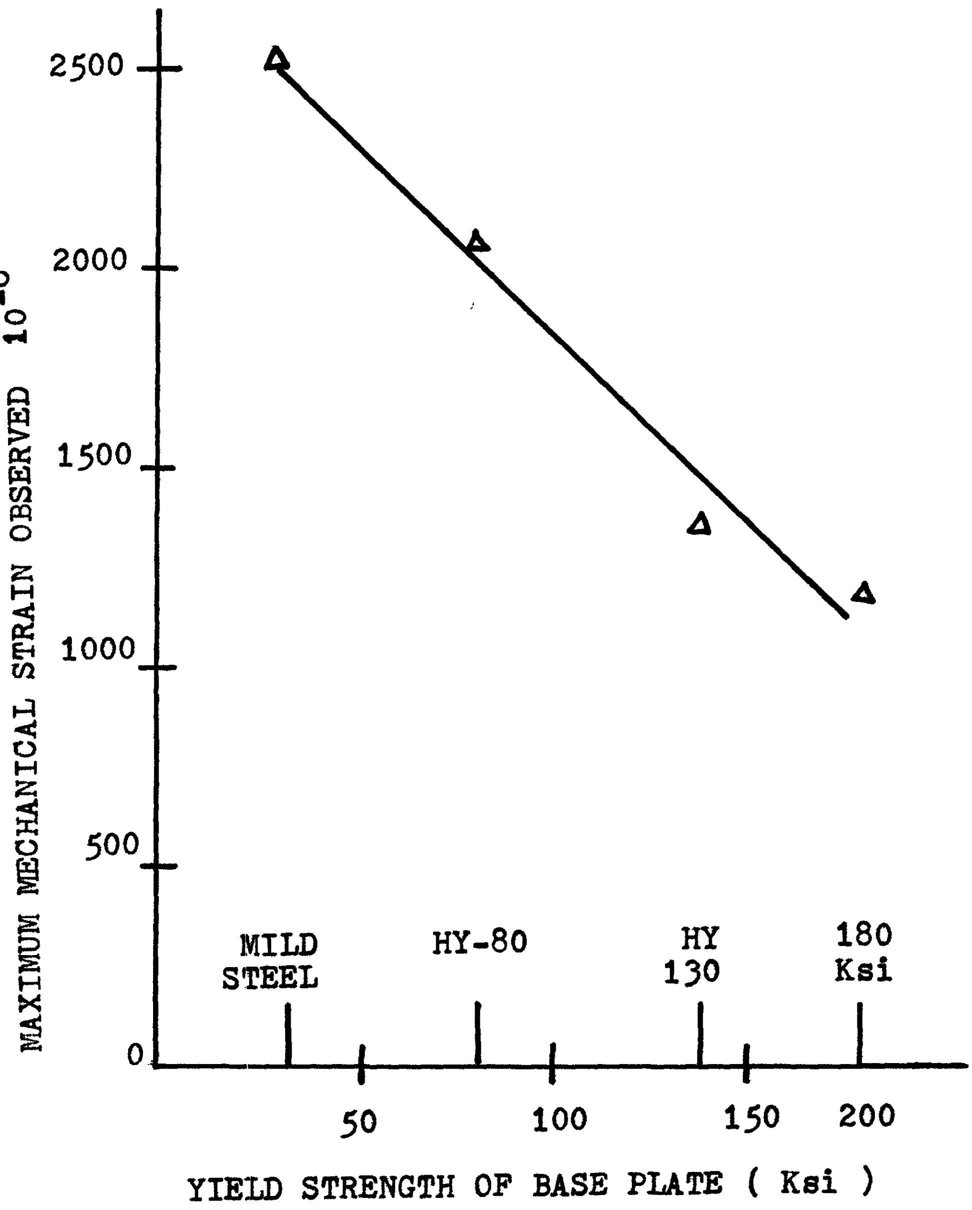


Fig. 4 Maximum mechanical strains observed at locations one inch from weld line (Reference 18)

II. MATERIAL CHARACTERISTICS

A. MATERIALS SELECTION

In order to obtain conclusive evidence for current study on the transformation effects, experiments should be made on several materials with different metallurgical characteristics. The following is a combination of material used in present study:

1. Low-carbon steel.
2. T-1 Quenched & Tempered high-strength steel.
3. HY-80 Quenched & Tempered high-strength steel.
4. 18-8 Stainless steel.
5. Titanium alloy Ti-6Al-2Cb-1Ta-0.8Mo.

Since the results of the temperature calculation are affected both by the thermal properties of the materials and by the welding conditions, while the results of the stress calculation are determined by the temperature distribution and by the mechanical properties of the materials, the mechanical properties which govern both heat flow and stress analysis may vary considerably between room temperature and melting point of particular material. Hence, both the physical and mechanical temperature dependency properties of the material should be considered for experimental data analysis.

B. TEMPERATURE ANALYSIS

In order to calculate thermal stresses during welding, it is first necessary to calculate temperature changes. The temperature distribution is calculate from the two-dimensional solution for a line source in an infinite plate. This solutions:

$$T = T_0 + \frac{q}{2\,s}\, e^{-\frac{v}{2K} w} K_0\left(\frac{v}{2K}\, r \right) \qquad \ldots\ldots(1)$$

where $r = (w^2 + y^2)^{1/2}$

$K_o(z)$ = the zero order modified Bessel function of the second kind.

$w = x - vt$ = moving coordinate.

T = temperature.

T_0 = initial temperature of the plate.

s = thermal conductivity.

$K = \frac{s}{cg}$ = thermal diffusivity.

c = specific heat.

g = density of the material.

q = eff x V x I/ h = heat source intensity.

eff = arc efficiency.

h = plate thickness in inches.

V = arc Voltage in Volts.

I = welding current in ampares.

From the equation shown above, the temperature distribution is of course controlled by the welding conditions and thermal properties. While the problem of thermal stress analysis is more complicated than the calculation of temperature distributions. There are two important ways in which the temperature distribution affects the plastic deformation, The first of these is obvious as a result of the increased temperature, the material near the weld expands. The second effect involves

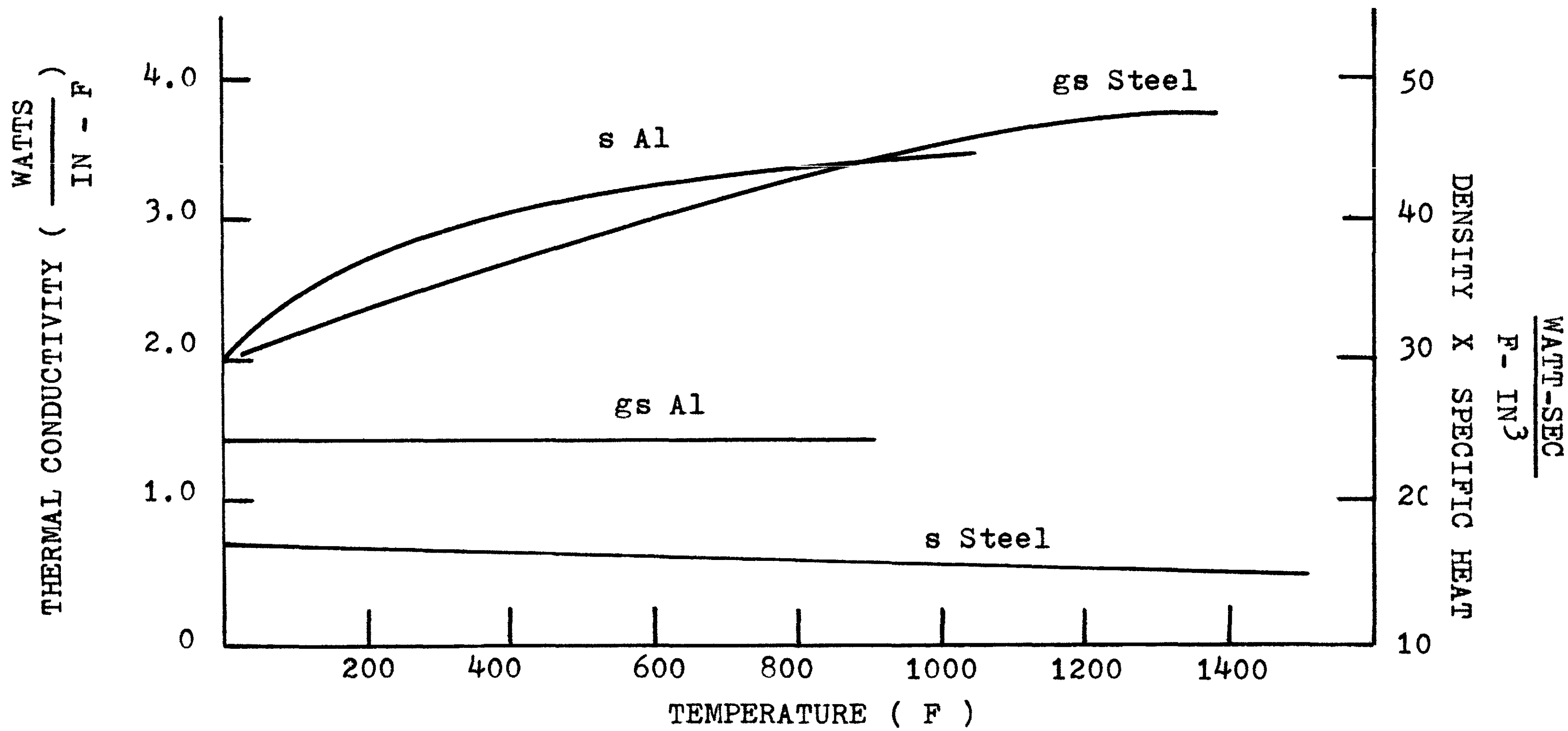


Figure 5 Thermal properties for Steel and Aluminum
(Reference 20)

the variation of yield strength with temperature. At elevated temperatures the yield strength of the material is considerably reduced and large plastic deformations occur for the same total strains.

C. EFFECTS OF MATERIAL PROPERTIES :

Comparing temperature distributions for different materials is much more complicated, since the variations in properties with temperature may be difference for different materials. Figure 5 shows the thermal conductivity and the product of density and specific heat for steel and aluminum (Reference 20), these properties will affect the accuracy of analysis like welding conditions do. The problem we have have is lack of sufficient data of material properties at elevated temperature that used for analytical calculations.

D. MATERIAL PROPERTIES USED FOR THIS STUDY :

1. Mild steel: Mild steel is an ABS class B type steel, most of the material properties were taken from Reference 20.

2. T-1 alloy steel: T-1 steel, an ASTM/A517 steel produced by the US steel corporation, is a low carbon, Q & T alloy steel which exhibits a combination of high yield strength, excellent tougness, high resistance to impact abration and good weldable. T-1 steel is commonly used for commercial applications including pressure vessels, storage tanks and merchant ships. Compared with HY-80, T-1 steel contains less nickel and is less costly, The chemical compositions and the heat treatment mechanical properties were shown in Table 2-1, 2-2 and 2-3, these data were taken from Ref. 21.

TABLE 2-1 Chemical Composition of T-1 alloy Steel

C	Mn	P	S	Si	
0.10/0.20	0.60/1.0	0.035 max	0.040 max	0.15/0.35	
Ni	Cr	Mo	V	Cu	B
0.70/1.00	0.45/0.65	0.40/0.60	0.03/0.08	0.15/0.50	0.002/0.006

TABLE 2-2 Mechanical and Physical Properties of T-1 Steel

Mechanical Properties	
Yield strength min. Psi	100,000
Tensile strength Psi	115,000/135,000
Elongation in 2 in min %	18
Reduction of Area %	45
Physical Properties	
Density, Pci	0.2833
Electrical Resistivity, microhm-cm	24.0
Modulus of elasticity	
Tension, Psi	28 to 30 x 10^6
Compression, Psi	28 to 30 x 10^6
Coefficient of Expension	6.5 x 10^{-6}(-50 to +150 F)
	7.74 * 10^{-6}(70- 1300 F)

TABLE 2-3 The effect of elevated temperature on modulus of elasticity

Temperature F	Modulus of elasticity Psi
80	30,300,000
200	28,600,000
400	27,400,000
600	27,400,000
800	25,600,000
1000	22,700,000
1200	14,600,000

Figure 6 shows the short-time Tensile properties of T-1 at elevated temperatures. Which took from USS United State Steel.[21]

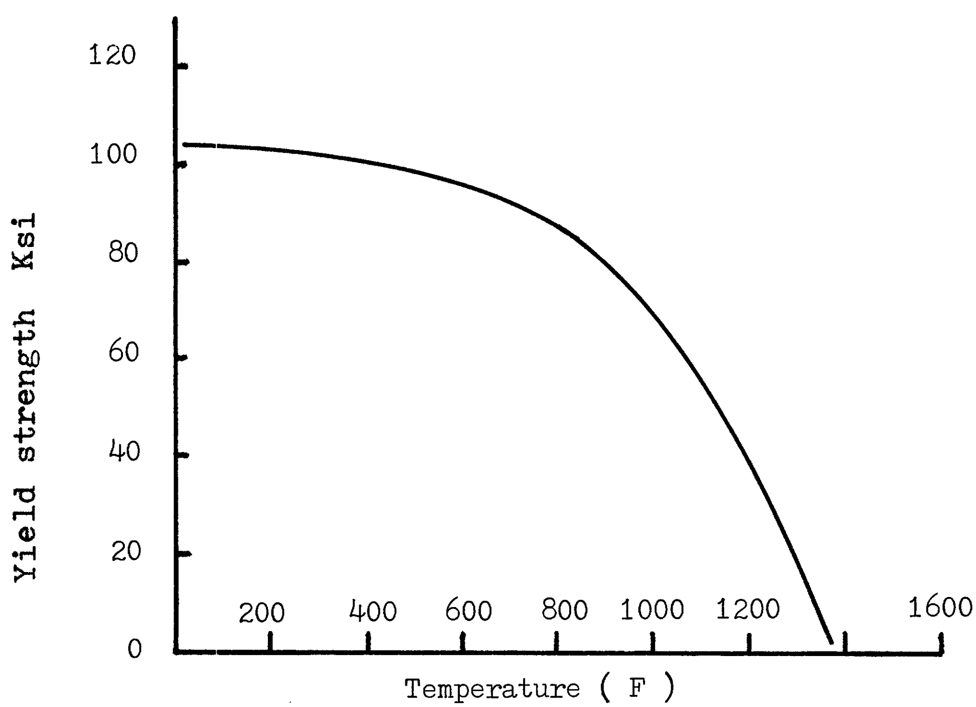


FIG. 6 Yield Strength of T-1 steel Vs. Temperature.

3. HY-80 Steel:

HY-80 is a low carbon alloy steel which acquires strength and toughness through quenching and tempering. It is a material suitable for submarine pressure hulls which have modest resistance to corrosion and relatively stable physical properties in the range of temperature from -30 F to 120 F, its modulus of elasticity is fixed at about 30×10^6 psi and density at about 0.283 lb/cu.in.[22] The chemical composition of HY-80 is shown in Table 2-4.

TABLE 2-4 Specification Limited of HY-80 Chemical Composition

C	Mn	P*	S*	Si	Cu
.18 max	0.10/0.40	.025 max	.025 max	0.15/0.35	0.25 max
Ti	Mo	Va	Ni	Cr	
.02 max	0.20/0.60	0.03 max	2.00/3.25	1.00/1.80	

* On both Ladle and Check Analysis the per cent of P and S together shall not be more than 0.045.

The material properties for HY-80 at elevated temperature were obtained by either from the data of T-1 steel or that of HY-130 in J. Schrodt's thesis.[23]

Table 2-5 shows the temperature dependent properties of HY-80 used for analysis.

Table 2-5 Material Properties Vs. Temperature
(HY-80)

Temperature	70.00	200.00	300.00	400.00	500.00	600.00	700.00	1000.00
Young's modulus	30.30	29.6	29.0	28.8	28.0	27.7	27.0	22.7
Initial Y.S.	82.	81.2	80.4	79.6	78.0	75.6	74	52
Coefficient of expansion	6.5	6.65	6.8	6.95	7.10	7.25	7.40	8.05
Strain-Hardening parameter	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Thermal conductivity	0.473	0.498	0.511	0.525	0.528	0.532	0.525	0.476
Heat capacity	112.78	115.94	120.16	124.37	128.59	132.8	138.07	156.0

4. Titanium alloy:

Titanium metal is finding many uses. It's alloys are of great significance in strength/weight ratio, corrosion, marine and aerospace applications. Ti-6Al-2Cb-1Ta-1Mo is a near alloy type having intermediate ultimate strengths from 125-150 Ksi, strengthed principlally by Al and small amounts of carefully formulated beta phase. It's chemical composition is shown as followed:

Table 2-6 Chemical Composition of Ti 6211 alloy

N	C	Fe	Al	Cb	Ta	Mo
.05	0.1	0.05	5.9	2.2	1.0	0.8

Figure 7 shows the thermal expansions of Ti-6Al-4V and Ti-6211[25] which is used for strain compensation of strain gages that mounted in Ti-6211 specimen during experimental study.

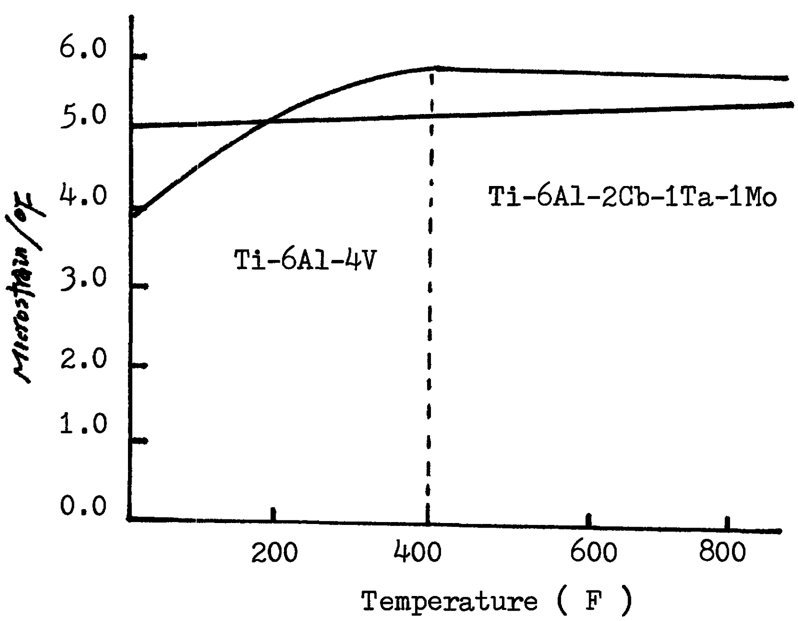


Fig 7 Expansion coff. vs Temperature

Temperature	70.00	200.00	400.00	600.00	800.00	1000.00	1200.00	1400.00
Young's modulus	17.5	16.3	15.4	14.4	13.3	12.3	9.50	6.17
Initial Y.S.	100.0	90.5	81.0	71.6	62.1	52.6	43.1	31.7
Thermal conductivity	0.163	--	--	--	--	--	--	--
Heat capacity	128.7	139.3	149.8	160.4	170.9	181.5	192.0	202.6

Table 2-7 Material properties Vs Temperature
(Ti-6Al-2Cb-1Ta-1Mo)

Table 2-7 shows the material properties of Ti-6211 alloy that were prepared for experimental analysis.

5. Stainless steel:

308 Type is one of 18-8 stainless steel which representing chromium contents from 17 to 20 percent and nickel contents from 8 to 13 percent. It is available in the form of sheets, strip, plates, bars and tubing. 308 type stainless steel is a higher alloy steel having higher corrosion resistance and heat resistance, primarily used for welding filler metal to compensate for alloy loss in welding. Table 2-8 shows the chemical composition of 308 type stainless steel.

Cr	Ni	C	Mn	Si	P	S
17/21	10/12	0.08	2.0	1.0	0.045	.030

Table 2-8 Chemical Composition of 308 type Stainless steel.

Table 2-9 shows the physical propertiesof 308 type of stainless steel.[24]

Table 2-9 308 Type physical properties

Melting point, F	2550-2650
Density, lb/cu.in	.287/.29
Specific gravity	7.86/7.94
Coeff. of Expansion in/in/ F	9.2×10^{-6} (68-212) 11.0×10^{-6} (68-1600)
Thermal conductivity	9.4-12.4 (Btu/hr-ft- F)
Specific Heat(Btu/lb/ F)	0.12

Table 2-10 shows the comparaison of steel, aluminum and Titanium in physical properties.

The material properties of each specimen that used for input data of one-dimensional program were shown in appendix B.

Table 2-10 Comparison of some physical properties between steel, aluminum and Titanium.

Materials	Steel	Aluminum	Titanium
Density, ρ lb/in^3	0.234	0.1	0.163
Young's modulus E x 10^6 psi	30	10	17
Yield strength σ_{ys} x 10^3 psi	35-150	30-50	40-150
Strength/Weight σ_{ys}/ρ x 10^3	123-150	300-500	250-920
Thermal conductivity, λ BTU/hr/ft^2/ft/F	26.2	130	9
Coeff. Linear thermal exp. α x 10^{-6}/F	6.8	13	4.7
Electrical resistivity $10^{-6}\Omega$ cm	9.7	2.7	42
Melting point °F	2800	1220	3040
Melting point of oxide °F	FeO 2400	Al_2O_3 3700	

III EXPERIMENTAL INVESTIGATION

A. OBJECTIVES

The objective of the experimental investigation was to obtain a series experimental data of thermal stresses and residual stresses in simple weldments in various strength-level materials. The study covers :

(1) Experiments on transienl strains.

(2) Experiments on residual stresses.

(3) Comparisons of experimental data with analytical predictions.

Experiments were conducted in two phases. The major objective of experiment phase 1 was to measure temperature and strain changes on test specimens during welding. Temperature changes during welding were measured by thermocouples, while strains changes were measured by strain gages mounted on specimen surfaces. The specimens were welded by either bead-on-edge with GMA process or heat-on-edge with GTA process. The major objective of experiment phase 2 was to measure the residual stresses existed near the welded line of the specimens. In order to do that, electric resistance strain gages were used, this is one of stress-relaxation techniques for residual stresses measurements. one or two inches wide piece containing the gages were removed from the specimens and the strains were measured by viscorder and so the residual stresses were obtained by simple calculations.

B. EXPERIMENTAL PROCEDURES

1. PHASE 1 EXPERIMENTS

Specimen Preparation. There are five different materials uesd in this study, among them, two pieces of Mild steel, 308 Stainless steel and T-1 steel were prepared for bead-on-edge and heat-on-edge weld studies. Figure 8 . shows the specimens which were 48 inches long, 6 inches wide and 1/2 inch thick. Three single-strain gages and thermocouples were mounted on the center of the specimens, two more gages were mounted on 12 inches away from the center of the specimen to measure strain changes at different locations along the lengthwise direction. Figure 9 shows the specimen of Ti-6Al-2Cb-1Ta-1Mo Titanium alloy, two rosette strain gages were mounted. HY-80 specimen which was prepared for butt weld was shown in Figure 10.

Types and characteristics of the gages and thermocouples were shown as follows.

STRAIN GAGES :

Materials	Gage type	gage factor
T-1 steel Mild steel	BLH TYPE FAE-25-12S6	2.06 ± 1 %
308 Stain- less steel	BLH TYPE FAE-25-12S9	2.02 ± 1 %
HY-80 steel	BLH TYPE FAER-18B-12S6	2.00 ± 1 %
Titanium alloy	BLH TYPE FAER-18B-12S5	2.02 ± 1 %

THERMOCOUPLE : BLH TYPE GTM-CA (Chromel/alumel)

They were manufactured by BLH Electronics, Inc., Waltham, Massachusetts.

The strain gages were mounted with the BLH EPY-550 cement which is compatible with all phenolic and polyimide SR-4 strain gages.

The specimen area to be gaged must be chemically clean and free of all grease, oil, scale or oxidation. In order to obtain best results, following steps were recommended :

SURFACE PREPATION

1. Remove all foreign matter (oil, paint, oxide, scale, etc.) from surface with disc sander, grinder, or mill file, leaving surface smooth.
2. Clean surface with gauze saturated with Methyl Ethyl Ketone.
3. Dip one-inch strip of Silicon carbide paper into metal conditioner, lap surface, and remove residue with clean tissue.
4. Indicate gage locations by using blade or 4-H pencil.
5. Apply metal Conditioner to surface with cotton swab and remove with one stroke of clean tissue.
6. Clean fingers with Neutralizer and cotton applicator.
7. Apply Neutralizer to surface with cotton swab and remove with one stroke of clean tissue.

GAGE PREPARATION

Clean the bonding side of the gage with a clean MEK saturated cotton swab. Avoid recontamination by handling the gage with tweezers following this operation. As gages were installing on the specimens, a liberal coating of the cement was applied to the gage bonding surface and smooth to a uniform thickness. Position the gage and press out any trapped air bubbles. Thin Teflon film of .oo1" to .003" should be placed between the gage and neuprene rubber pressure pad for easy removal after curing. A bond pressure of 15 psi will insure intimate contact between the gage and the specimen during the curing cycle.

Instrumentation and Recording : Figure 11 shows the outline of the experimental set-up used. Change of temperature and strains during welding, a subsequent cooling were recorded on an oscillographic paper. Figure 12 shows the thermocouple circuit, and Figure 13 shows the strain gage circuit.

Welding Procedures And Conditions : Table 3-1 shows welding procedures and conditions used in phase 1 experiments.

Experiments were conducted on three specimens first, on these specimens three strain gages were mounted at different positions along the edge to be welded with the same distance (1 inch) from the edge, to see if the one-dimensional program is available for analysis.

Two pieces of mild steel, stainless steel and T-1 steel were welded, one was heat-on-edge (i.e. the three specimens just been mentioned) by using GTA welding process and the other was bead-on-edge weld by using GMA welding process. Butt weld was made of HY-80 by GMA process.

Table 3-1 Welding Procedures and Conditions

Material	Voltage	Ampere	Speed	Type of weld	Process	Filler metal
Mild Steel	25	380	.322	Bead on edge	GMA	A 675
Mild Steel	12	295	.268	Heat on edge	GTA	None
T-1 steel	25	420	.333	Bead on edge	GMA	A 675
T-1 steel	12	295	.255	Heat on edge	GTA	None
308 Stainless steel	27	250	.470	Bead on edge	GMA	A675
308 Stainless steel	12	324	.258	Heat on edge	GTA	None
HY-80	25	300	.483	Butt weld	GMA	A675
Ti-6Al-2Cb-1Ta-1Mo	28	300	.358	Bead on edge	GMA	6-2-1-0.8 Ti

It is important to note that the wire used for bead-on-edge weld and butt weld of HY-80 was one that used for ordinary steel and not for high strength steel. This is due to the lack of appropriated wire, but is it thought that it will not have a big effect on the resulting residual stresses.

For Ti-6Al-2Cb-1Ta-0.8Mo alloy specimen, bead-on-edge weld was made by GMA process with matching wire of Ti-6Al-2Cb-1Ta-0.8Mo alloy.

2. PHASE 2 EXPERIMENT

In order to measure the residual stresses of the weldments that had been made in previous experiments, we used electric resistance strain gages. This is one of stress relaxation techniques for measuring residual stresses. It is saed on the fact that strains take place during unloading are elastic, even when the material has undergone plastic deformation.

Principle of Stress-Relaxation Technique Electric-strain gages are mounted on the surface of the test specimens, a small picec of metal containing the gages is removed from weldments. As the specimen is strained, the resistance of the gages changes, the magnitude of strain is then determined by measuring the resistance changes, the strain changes ε_x, ε_y, γ_{xy} that take place during the removal of the piece are then measured., The residual stresses are then calculated by using following expressions :

$$\sigma_x = -\frac{E}{1-v^2}(\varepsilon_x + v\varepsilon_y) \qquad \text{........(2)}$$

$$\sigma_y = -\frac{E}{1-v^2}(\varepsilon_y + v\varepsilon_x) \qquad \text{........(3)}$$

$$\tau_{xy} = -G\gamma_{xy} \qquad \text{........(4)}$$

Specimen Preparations There are six specimens that are available in this study :

Specimens	Type of weld	Size of specimens
Mild steel	Bead-on-edge	48" x 6" x 1/2"
Mild steel	Heat-on-edge	48" x 6" x 1/2"
T-1 steel	Bead-on-edge	48" x 6" x 1/2"
T-1 steel	Heat-on-edge	48" x 6" x 1/2"
Titanium alloy	Bead-on-edge	56" x 7.5" x 1/2"
HY-80	Butt weld	29" x 15" x 1/2"

308 Stainless steel specimens weren't used in this this study owing to their smaller width (4inches) that higher residual stresses could not be obtained.

Types and characteristics of the gages were shown as follows :

Specimens	Gage type	Gage factor	width of piece removed
Mild steels T-1 steels Titanium	BLH TYPE FAER-18B-12S-6	2.00 ± 1 %	2"

	BLH TYPE		
HY-80 steel	FAET-18D-12S-6	1.98 $\pm$ 1 %	1"

The strain gages were mounted with EASTMAN 910 ADHESIVE. Curing process is not necessary for this type of cement, following procedures are useful for gage installation :

GAGE INSTALLATION

1. Prepare surface (Same as that descript in last section)
2. Place gage face up on clean surface anf position terminal strip at end of gage.
3. Apply cellophane tape over top of gage and terminal strip.
4. Carefully lift assembly from working surface and clean back of gage and terminal with cotton applicator slightly moistened with neutralizer.
5. Place gage in position on specimen.
6. Starting at one end of cellophane tape lift gage assembly, leaving other end of tape attached to specimen.
7. Apply thin film of blue 910 catalyst to back of gage and terminal strip and allow to dry.
8. Apply EASTMAN 910 ADHESIVE to gage area of specimen.
9. Feed gage tape onto surface, holding free end of tape above surface with one hand and using ball of tissue in other hand to quickly force gage assembly into place with one stroke.
10. Within one second press gage firmly into contact with surface using thumb or finger. Maintain pressure for approximately 30 seconds.

11. Wait few minutes before removing cellophane tape from top of gage and terminal.
12. Wire gage to terminal with copper jumper wires (No.34) as shown Figure 14.
13. Apply gagekote No. 1 or other suitable protective coatings.

1. Strain gage.
2. Terminal.
3. Connecting wire.

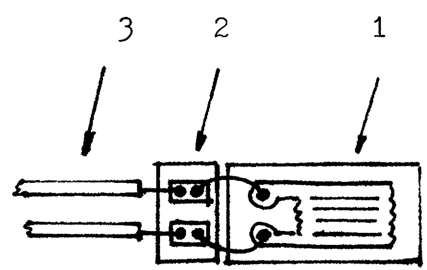


Figure 14. Strain gage installation for experiments.

Residual Stresses Measurement Figure 15, Figure 16 and Figure 17 show the strain gage arrangement on specimens of steels (mild steel, 308 stainless steel and T-1 steel), Titanium alloy and HY-80.

As we contact the strain gages through terminals by connecting wires to the amplifier and the counter, everything is ready for cutting of the small piece of the specimens with the strain gages on it. The procedures in this experiment are recommended as follows :

1. Connecting terminals of the strain gages, and let the specimen free.

2. Taking the readings from the counter for each terminal of the gages before cutting.
3. Putting the specimen on the plateform of the metal cutter well in position to be cut and fixed it tightly.
4. turn on the switch of the metal cutter and start to cut.
5. Let the specimen loose as one side was cut and take the readings from the counter again.
6. Position the specimen by putting the other side of the small piece well on the line for cutting.
7. Fix the specimen and start to cut.
8. After 1 or 2 inches wide specimen has already cut, put this on the working table freely.
9. Take the readings again after the temperature of the small piece was cooled to room temperature.

The results before cutting, after one side cutting and after both sides cutting were recorded and were shown in Table 3-2 to Table 3-7.

C. EXPERIMENTAL DATA ANALYSIS

1. The principle of the strain gages is based on the physical property that a metal strained in tension or in compression will change its resistance. Both mechanical strain and thermal strain changed in specimen may cause the resistance changein strain gages, the mechanical strain may consist of both elastic and plastic strain, hence, the resistance change R is made up of the following :

$$\Delta R = \Delta R(\alpha_T) + \Delta R(\varepsilon_e) + \Delta R(\varepsilon_p) + \Delta R(T)$$

Where

ΔR = Total resistance change

$\Delta R(\alpha_T)$ = Resistance change due to temperature induced thermal strains in specimen.

$\Delta R(\varepsilon_e)$ = Resistance change due to elastic mechanical strain in specimen

$\Delta R(\varepsilon_p)$ = Resistance change due to plastic mechanical strain in specimen

$\Delta R(T)$ = Resistance change due to thermal resistance characteristics of gages.

Since $\Delta R(T)$ and the difference between the based plate α_T and the gage α_T will generate error, a curve of apparent strain versus temperature was made by gage manufacturer to compute this error. Hence the gage readings recorded during the experiment can be corrected by subtracting the apparent strain which corresponding to the temperature measured at gage location. These apparent strains for gages used in present experiments were shown as follows :

Strain gages used on Mild steel, T-1 steel and HY-80 specimens :

Gage :

$$EAP = -107.84 + 2.90\,T - 2.58 \times 10^{-2}T^2 + 6.79 \times 10^{-5}T^3 - 4.90 \times 10^{-8}T^4 \quad .....(5)$$

Rosette :

$$EAP = -77.04 + 2.56T - 2.52 \times 10^{-2}T^2 + 6.72 \times 10^{-5}T^3 - 4.64 \times 10^{-8}T^4 \quad .....(6)$$

The sample specimen used is 1018 steel.

Strain gages used on 308 stainless steels :

Gage : $EAP = -158.79 + 4.13T - 3.20 \times 10^{-2}T^2 + 7.67 \times 10^{-5}T^3 - 5.38 \times 10^{-8}T^4$ .....(7)

The sample specimen used is 316 stainless steel.

Strain gages used on Ti-6Al-2Cb-1Ta-0.8Mo specimen :

Rosette : $EAP = -156.08 + 3.37T - 2.18 \times 10^{-2}T^2 + 3.79 \times 10^{-5}T^3 - 1.26 \times 10^{-8}T^4$ .....(8)

The sample specimen used is Ti-6Al-4V.

Since the difference in α_T between sample specimen and specimens used in study of steels and stainless steels is small, it is neglected for lack of accurate data. For titanium alloy specimen, the difference in $_T$ between Ti-6Al-2Cb-1Ta-0.8Mo and Ti-6Al-4V was shown in Figure 7. hence the apparent strain correction between room temperature and T F for gages should be made as follows :

$$\Delta EAP = \int_{T_1}^{T_2} (\alpha_{Ti-64} - \alpha_{Ti-6211})\, dT \qquad \text{.............} (9)$$

For $T < 400^\circ F$:

$$\Delta EAP = 103.92 - 1.87T + 7.25 \times 10^{-3}T^2 - 6.945\ 10^{-6}T^3$$

For $T > 400^\circ F$

$$\Delta EAP = -60.12 + 0.8T - 2.5 \times 10^{-4}T^2 \qquad \text{.............}(10)$$

The true apparent strain becomes :

$$EAP = EAP - \Delta EAP \qquad \text{.............}(11)$$

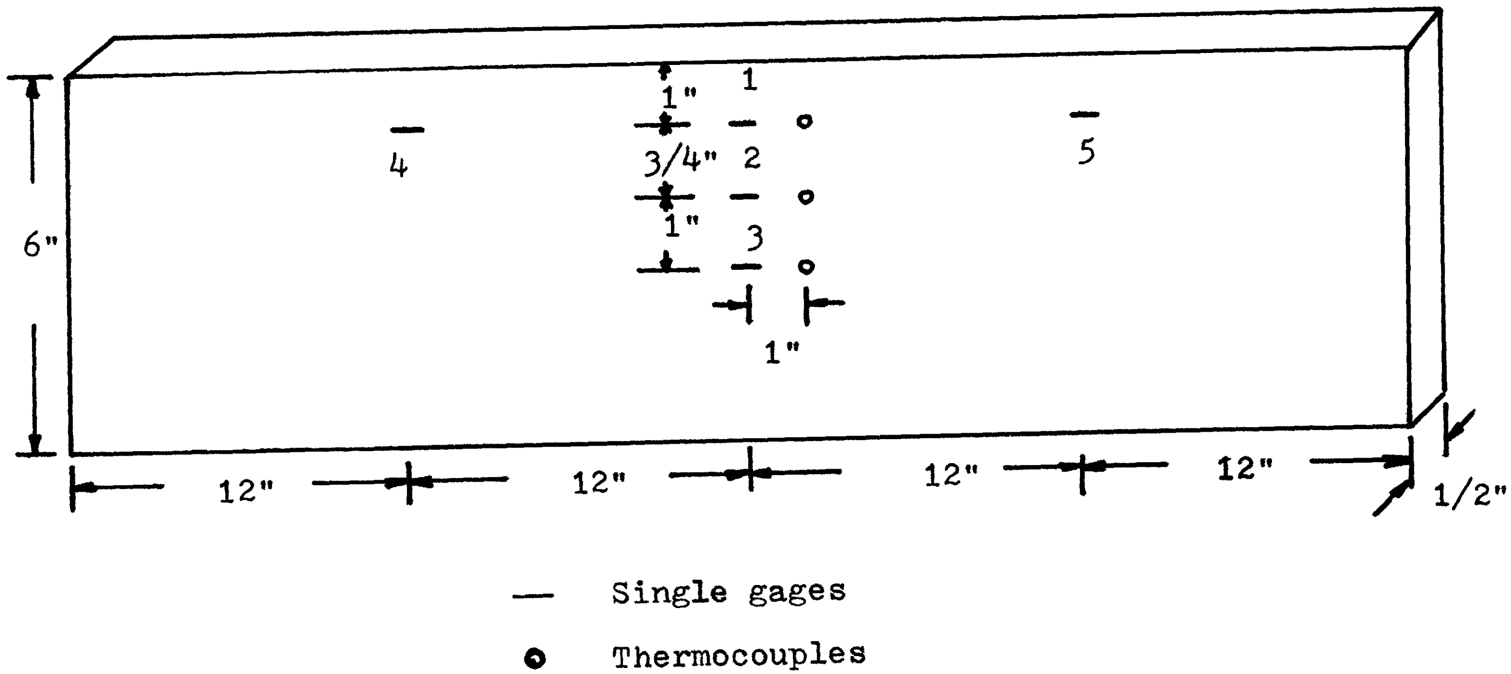


FIG. 8 Specimen Preparations for Mild steel, T-1 steel and 308 Stainless steel.

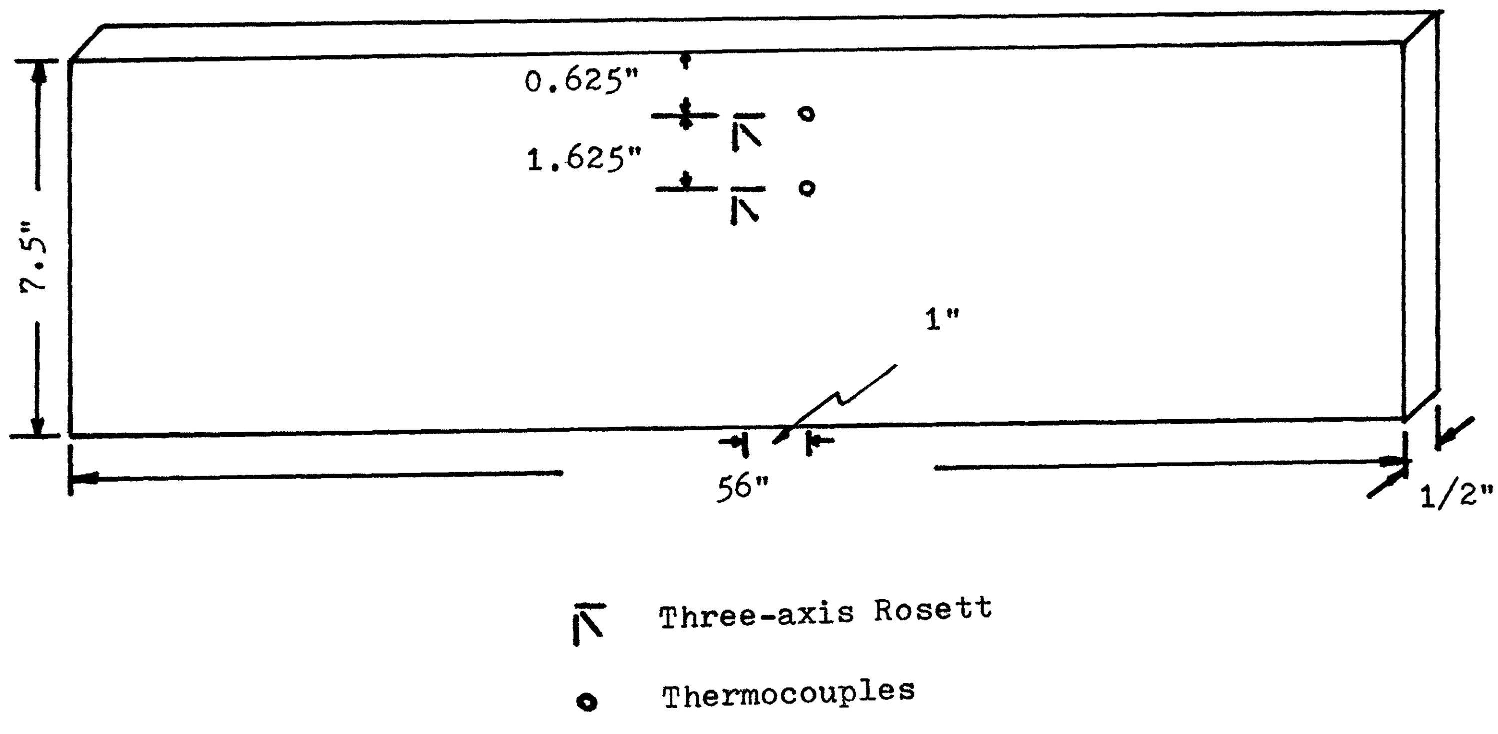


FIG. 9 Specimen Preparations For Ti-6Al-2Cb-1Ta-1Mo alloy

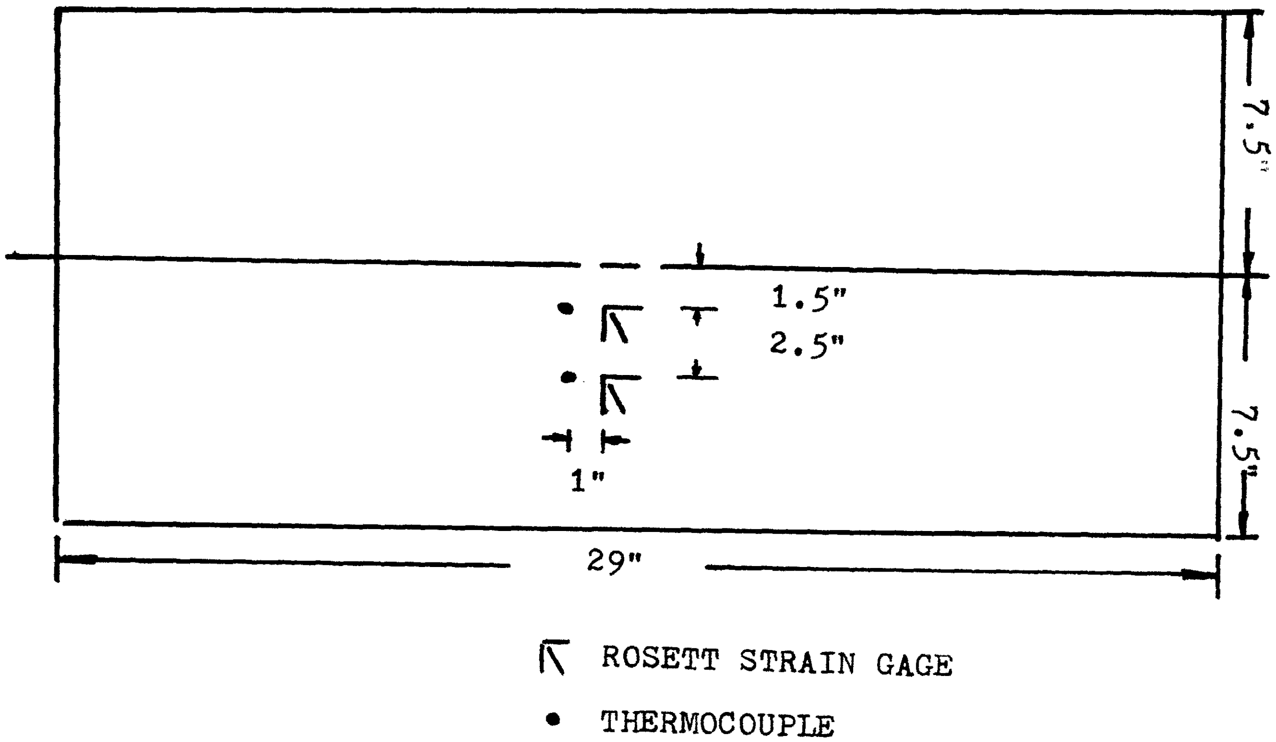


FIG. 10. STRAIN GAGE ARRANGEMENT IN HY-80 SPECIMEN

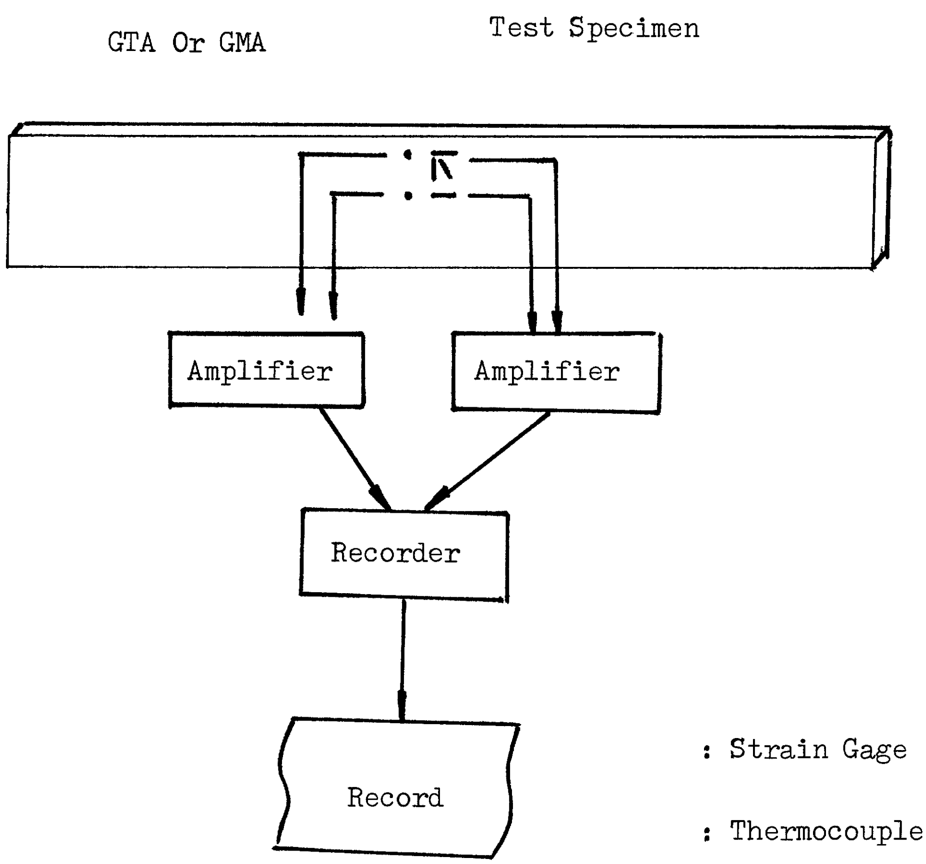


FIG 11. Outline of Experimental Set-up

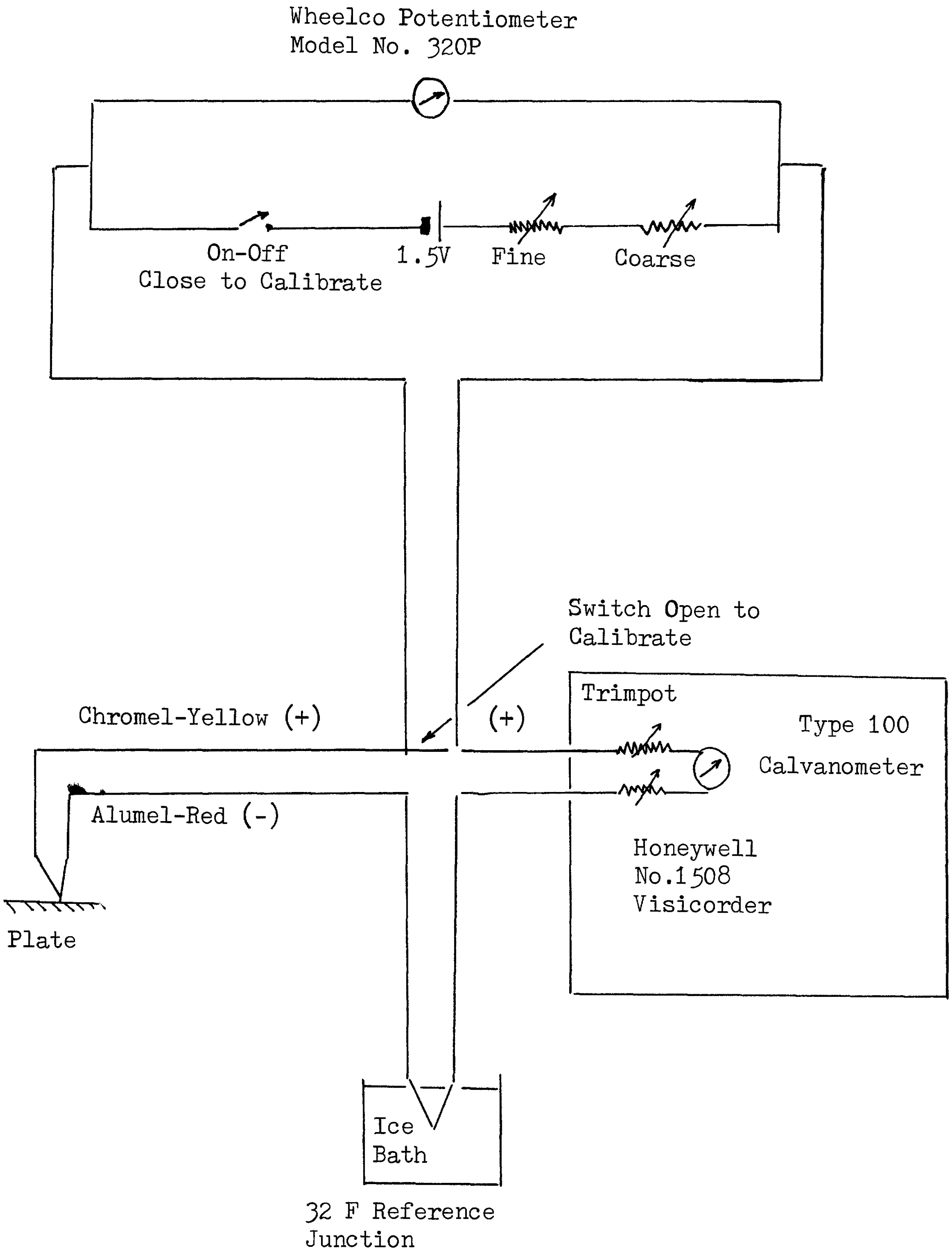


FIG. 12. THERMOCOUPLE INSTRUMENT CIRCUIT

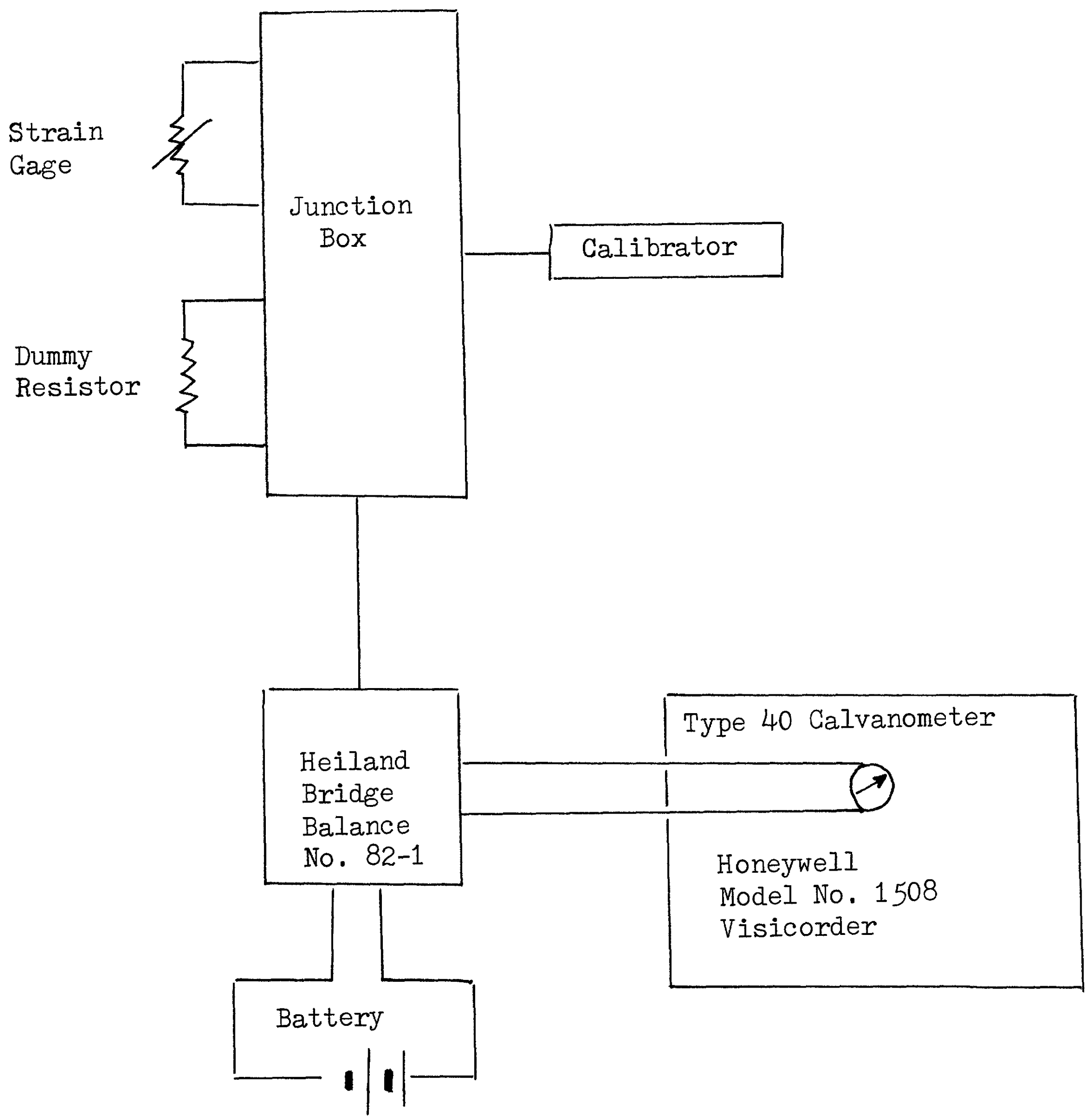


FIG.13. STRAIN GAGE INSTRUMENT CIRCUIT

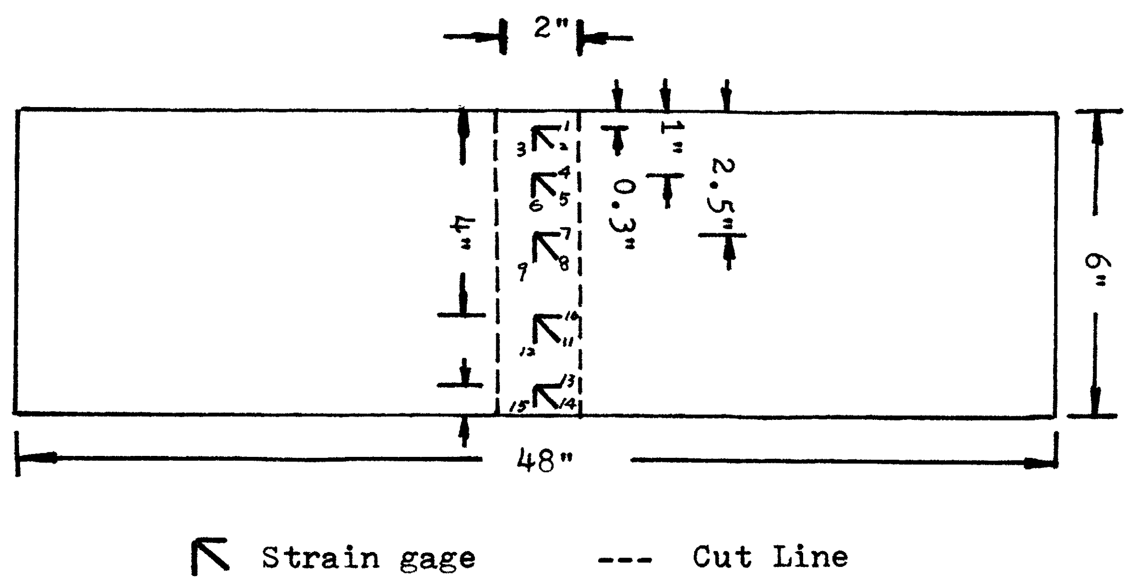


FIG. 15 Strain gages arrangement on specimens of Mild steel and T-1 steel for Phase 2 experiments.

Table 3-2 Residual Stresses Measurements on GMA welded Mild Steel.

Element No.	Readings Before Cutting	One-side Cut Readings	Readings After cutting	Net Readings
1	29898	290297	28901	-997
2	30404	29906	30130	-274
3	30011	30124	30130	147
4	29266	29266	29343	77
5	30890	30565	30859	-31
6	30356	30339	30100	-256
7	30870	31364	31568	698
8	30816	31206	31074	257
9	--	--	--	--
10	31181	31227	31249	62
11	31897	31966	31734	-143
12	30490	30624	30509	19
13	29616	29739	29735	119
14	30580	30522	30426	-154
15	29531	29075	29052	-479

Table 3-3 Residual Stresses Measurement on GTA welded Mild Steel.

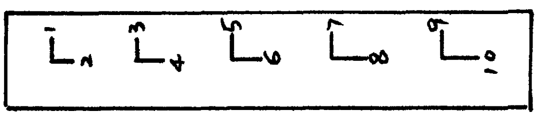
Element No.	Readings before cutting	One side cut Readings	Readings After cutting	Net Readings
1	31750	31000	30878	-872
2	31498	31621	31373	-125
3	30464	30494	30528	64
4	31542	31640	31854	312
5	31500	31336	31566	66
6	31513	31364	31215	-298
7	32545	32721	32827	282
8	30508	30673	30584	26
9	30204	30224	30146	-58
10	30776	30760	30784	8
11	31222	31300	31218	-4
12	30384	30427	30412	28
13	31266	31319	31326	60
14	30397	30389	30357	-40
15	30096	29932	29930	-166

Table 3-4 Residual Stresses Measurement on GMA Welded Specimen of T-1 Steel.

Element No.	Readings Before Cutting	One-side Cut Readings	Readings After Cutting	Net Readings
1	30583	29216	29060	-1523
2	31321	31592	31076	-245
3	31600	31822	31744	144
4	30848	30920	31420	572
5	31030	31448	31411	381
6	29410	29238	29134	-276
7	29623	30070	30158	535
8	29825	30001	30164	339
9	29354	29432	29287	-67
10	32124	32271	32279	155
11	31636	31410	31399	-237
12	32706	32821	32749	43
13	31088	31180	31093	5
14	31759	31296	31440	-319
15	33054	32480	32480	-574

Table 3-5 Residual Stresses Measurement on GTA Welded Specimen of T-1 Steel.

Element No.	Readings Before Cutting	One-side Cut Readings	Readings After Cutting	Net Readings
1	30328	29524	29556	-772
2	29727	29934	29986	259
3	29736	29907	29988	252
4	29851	29813	29941	90
5	29457	29766	29732	275
6	30506	30596	30673	167
7	30324	30335	30362	38
8	31226	31426	31420	194
9	29621	29386	29486	-135
10	30544	30583	30499	-45



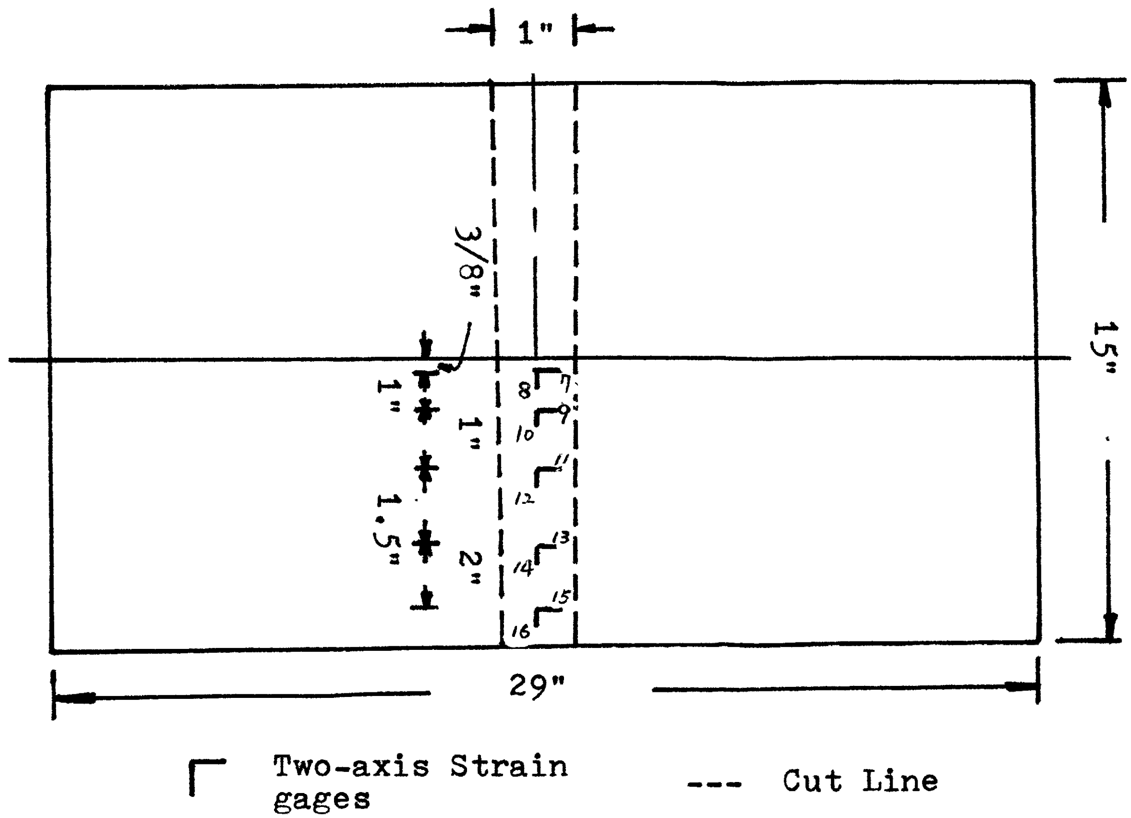


FIG. 16. Strain gages Arrangement on specimen of HY-80 for Phase 2 Experiment.

Table 3-6 Residual Stresses Measurement on Butt-welded specimen of HY-80.

Element No.	Readings Before Cutting	One-side Cut Readings	Readings After cutting	Net Readings
1	30283	30494	30705	422
2	29905	30271	30083	178
3	31105	31022	30889	-216
4	30436	30718	30774	338
5	31540	31849	31745	205
6	31056	31108	30851	-205
7	30333	29207	28994	-1339
8	29142	29244	29476	334
9	30484	30448	30516	32
10	29583	29506	29436	-147
11	29560	29596	29679	119
12	31070	31175	30907	-163
13	29351	29514	29651	300
14	29920	30163	29765	-155
15	29459	29794	29972	513
16	30304	30421	30056	-248

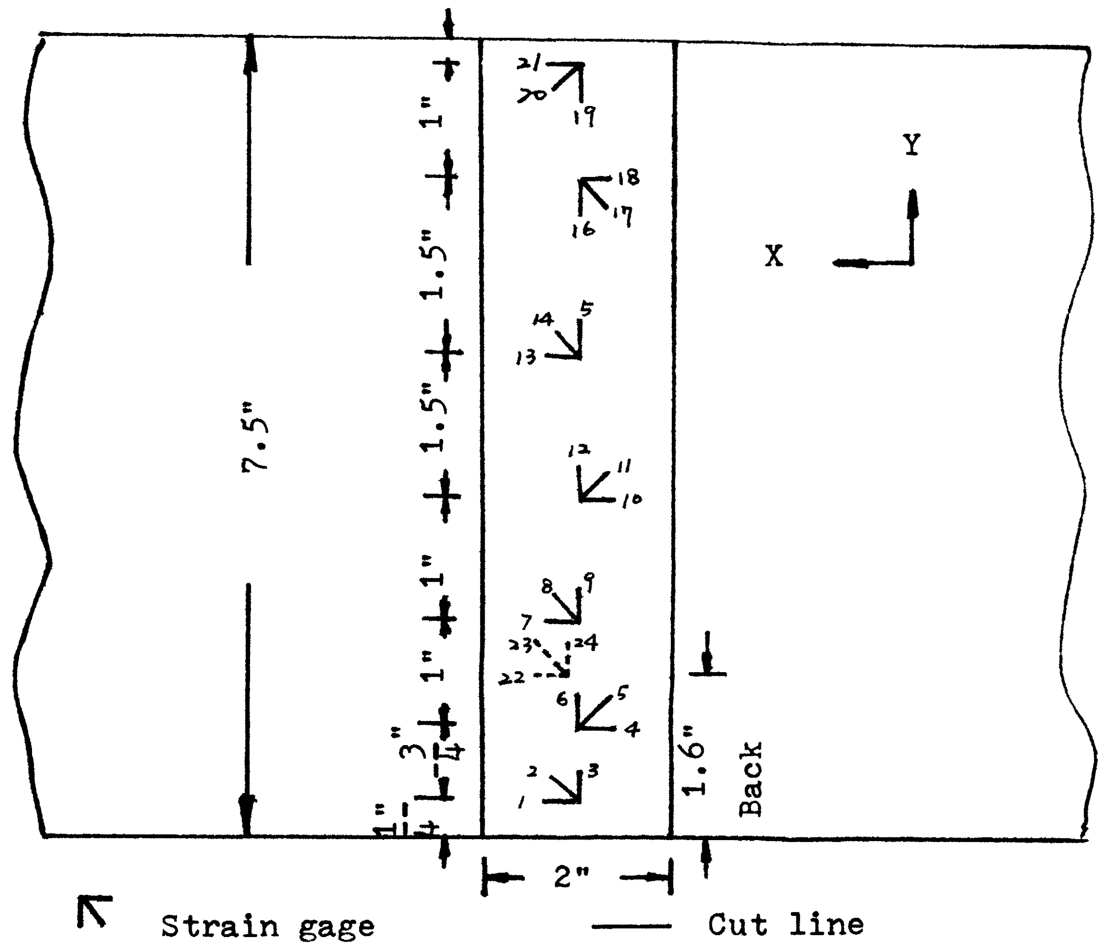


FIG. 17 Strain gages Arrangement on Specimen of Ti-6Al-2Cb-1Ta-1Mo Alloy.

Table 3-7 Reasidual Stresses Measurement on GMA Welded Specimen of Ti-6Al-2Cb-1Ta-0.8Mo Alloy.

Element No.	Readings Before Cutting	One-side Cut Readings	Readings After Cutting	Net Readings
1	30495	29495	28626	-1833
2	31671	30810	31299	372
3	34100	34236	32224	-1876
4	30958	30945	31184	226
5	31824	32255	31436	-388
6	30725	30589	30376	-349
7	32930	33249	33450	520
8	34916	34874	34952	36
9	37414	37320	37272	-142
10	29574	29873	29934	360
11	29644	29783	29809	165
12	29493	29475	29426	-67
13	31764	31964	31976	212
14	31412	31459	31514	101
15	30019	30005	29924	-95
16	30134	30076	29974	193
17	30486	30581	30511	25
18	29471	29536	29664	-160
19	29368	29404	29353	-450
20	29326	29038	29211	-115
21	26993	26626	26568	-15
22	26993	27331	27789	796
23	27788	27749	27884	96
24	27900	27704	27668	-232

2. Residual Stresses were obtained by using equation (2) and equation (3) and were summarized in Table 3-8.

Strain Gage No.	1	2	3	4	5	6	7	σ / σ_{ys}
Mild Steel (GMA) σ_x (Ksi)	31.18	-0.13	-2.27	-2.2	0.57			0.89
Mild Steel (GTA) σ_x (Ksi)	27.87	-7.41	-8.67	-0.5	-0.41			0.80
T-1 Steel (GMA) σ_x (Ksi)	49.2	-16.0	-17.0	-6.2	19.0			0.492
T-1 Steel (GTA) σ_x (Ksi)	23.1	-9.3	-10.8	-3.2	4.94			0.231
HY-80 (Butt)	40.84	0.4	-2.31	-8.36	14.46			0.50
Ti-6211 (GMA)	47.4	-2.23	-9.25	-6.6	-3.54	-2.76	8.87	0.474

Table 3-8 Summary of Residual Stresses in This Study

IV. RESULTS AND CONCLUSIONS

A. RESULTS REPRESENTATIONS

In order to check if one-dimensional computer program is available for analysis in present study, strain gages were mounted along the welding edge to measure the strain changes in each specimen at different positions along the welded edge. Figure 18,19 and 20 shown these strain changes at each points during welding for mild steel, stainless steel and T-1 steel. It is obvious that the history of strain changes at each point are similiar, that is, the results predicted by 1-D program may be used for analysis.

In order to compare experimental results with that predicted by 1-D program, exact heat input should be determined first. Figure 21 to Figure 28 show the maximum reached temperature at different distances from the welded edge for various specimens, and the efficiency of heat input were determined as follows :

Materials	Welding Method	Efficiency
Mild Steel	GMA	0.55
Mild Steel	GTA	0.55
Stainless Steel	GMA	0.43
Stainless Steel	GTA	0.51
T-1 Steel	GMA	0.55
T-1 Steel	GTA	0.48
Ti-6211	GMA	0.35
HY-80	Butt Weld	0.69

As thermal effeciency have been determined, we compared the history of temperature changes and strain changes during welding for both experimental results and that of one-dimensional computer program. Figure 29 to Figure 45 show the comparisons for both longitudinal strain and temperature changes. Deflection changes were also measured by extensiometer at the center bottom of the specimens, and were shown in Figure 46 to 52. Since 1-D computer program is developed by assuming the plates were heated during welding with no deposit metal, hence the comparisons for GTA process plates are similiar but that are poor for GMA process plates.

Residual stress distribution predicted by 1-D computer program based on the assumptions that the aera bounded by tension stresses and that by compression stress are equal, and the melting point was reached during welding so that maximum residual stresses equal to yield strength of the plates could be obtained in the welded line. Residual stresses measured for GTA plates are less than that for GMA plates due to less heat input during welding. From Table 3-8, the residual stresses measured in lower strength materials nearest the welded edge were higher percentage, while the residual stresses measured in high strength steels were about 50 % Of yield strength. Residual stress distributions were shown in Figure 53 to Figure 58.

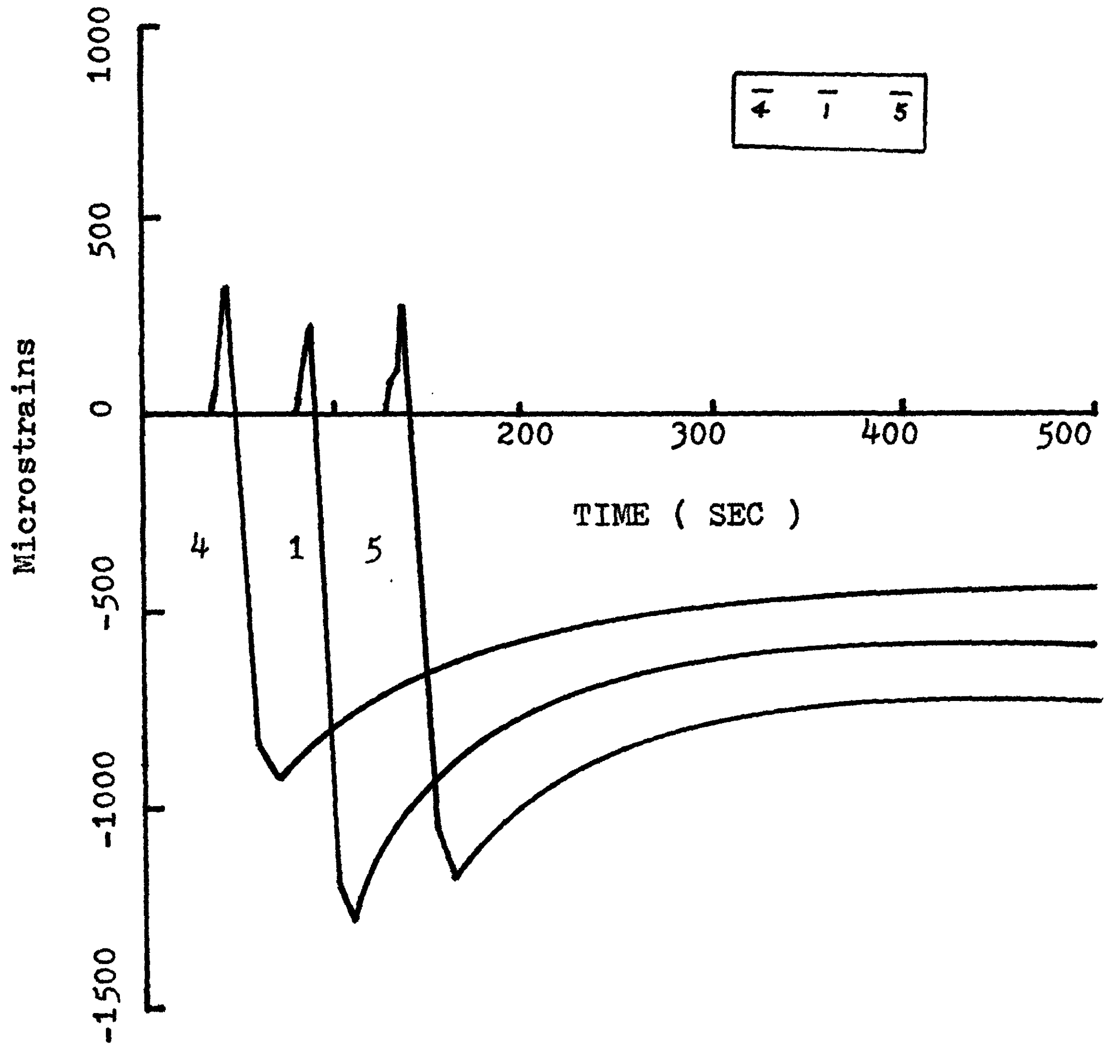


FIG. 18 Strain Changes for Mild Steel (GTA) at Different Points Along the Welded Edge.

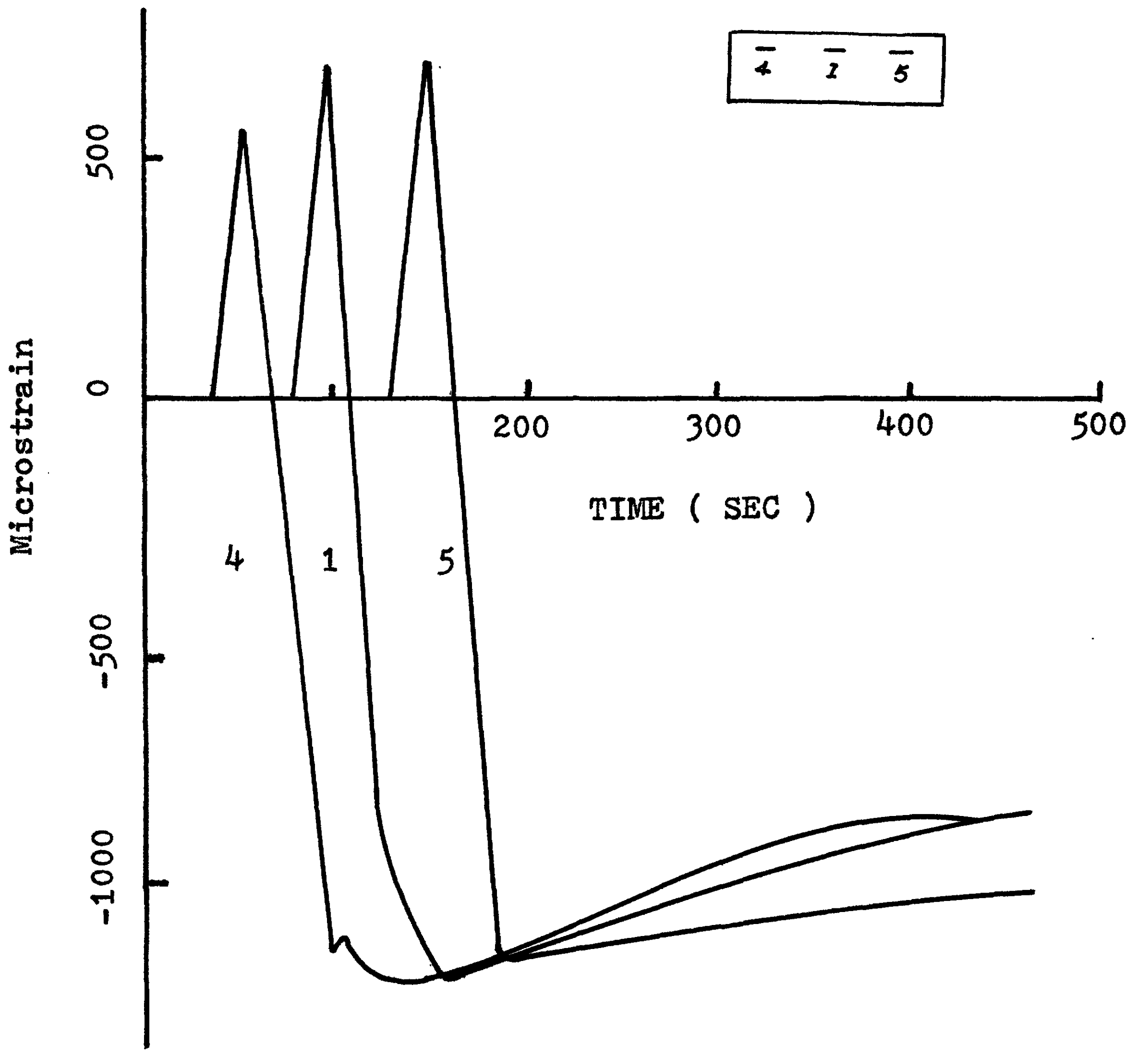


FIG. 19 Strain Changes for 308 Stainless Steel (GTA) at Different Points along the Welded Edge.

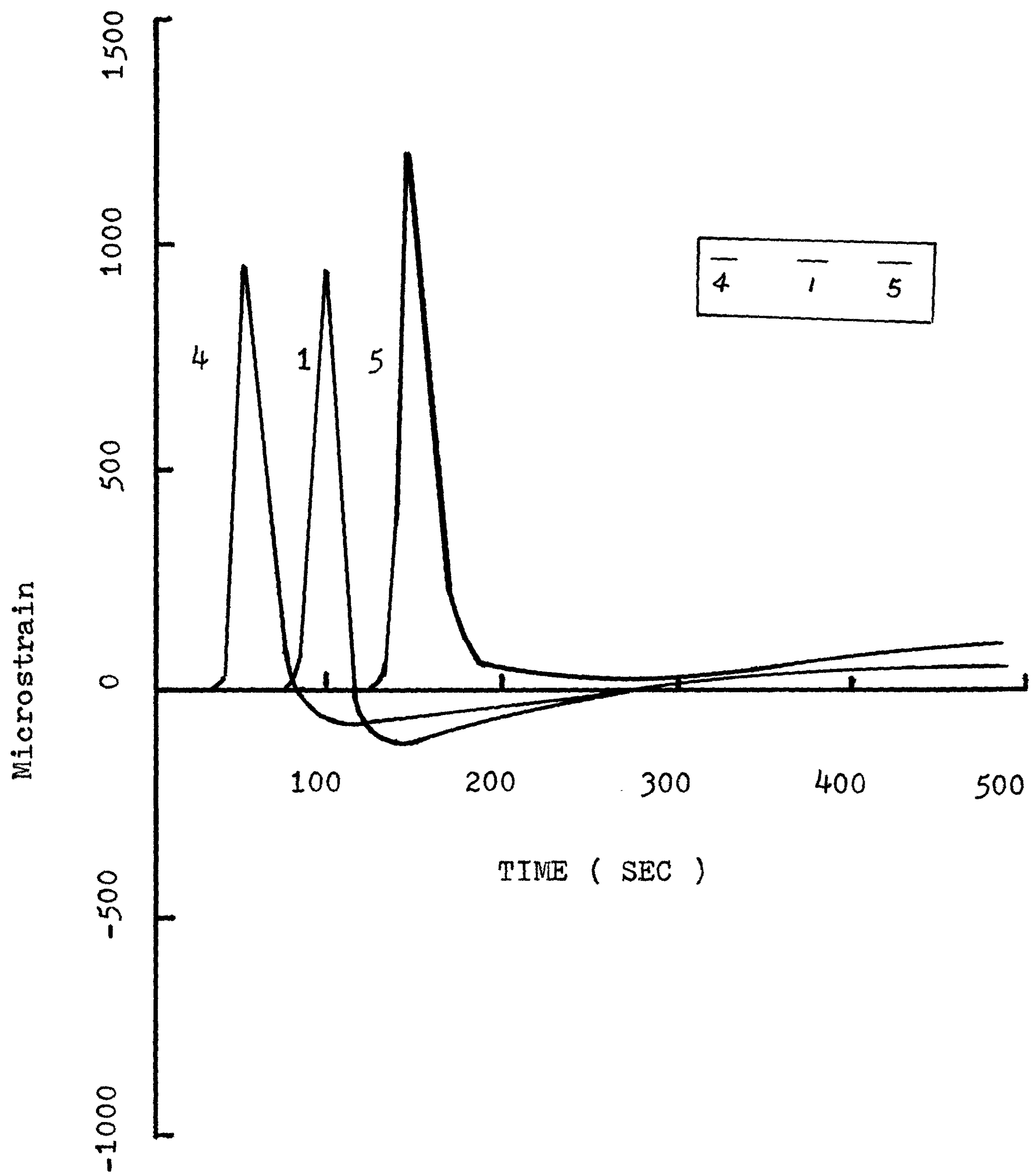


FIG. 20 Strain Changes for T-1 Steel (GTA) at Different Points Along the Welded Edge.

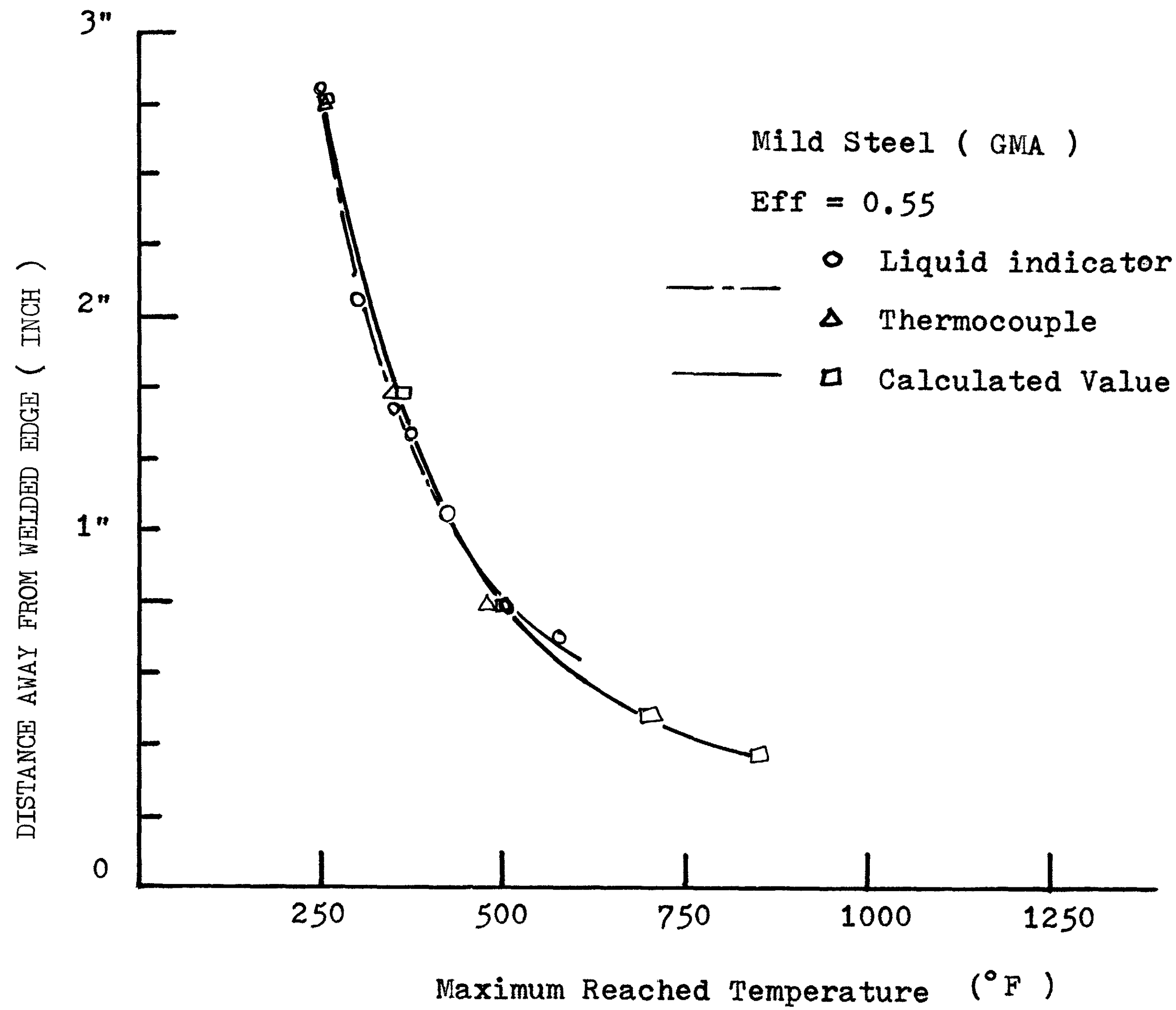


FIG. 21 Maximum Reached Temperature Distribution

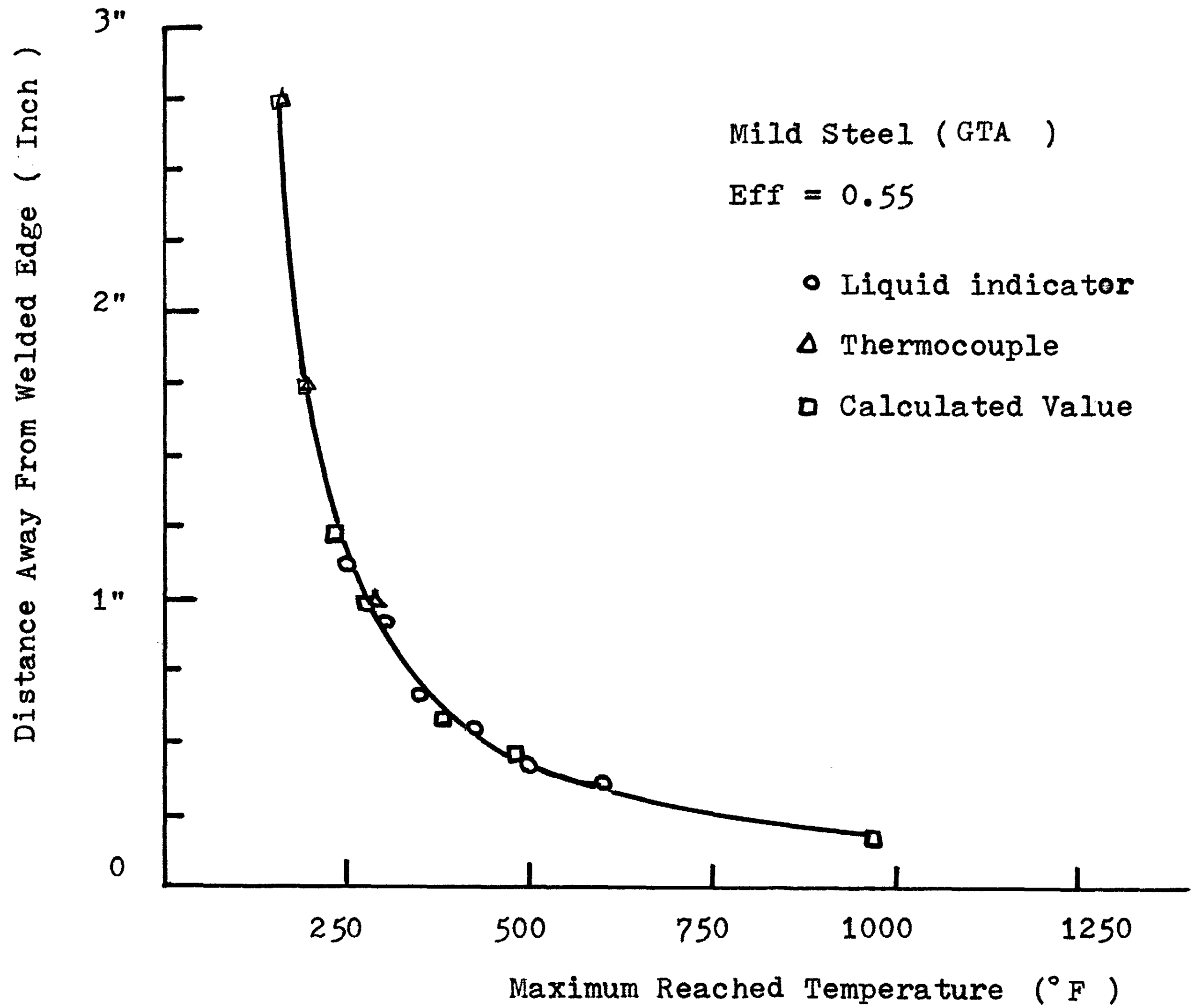


FIG. 22 Maximum Reached Temperature Distribution

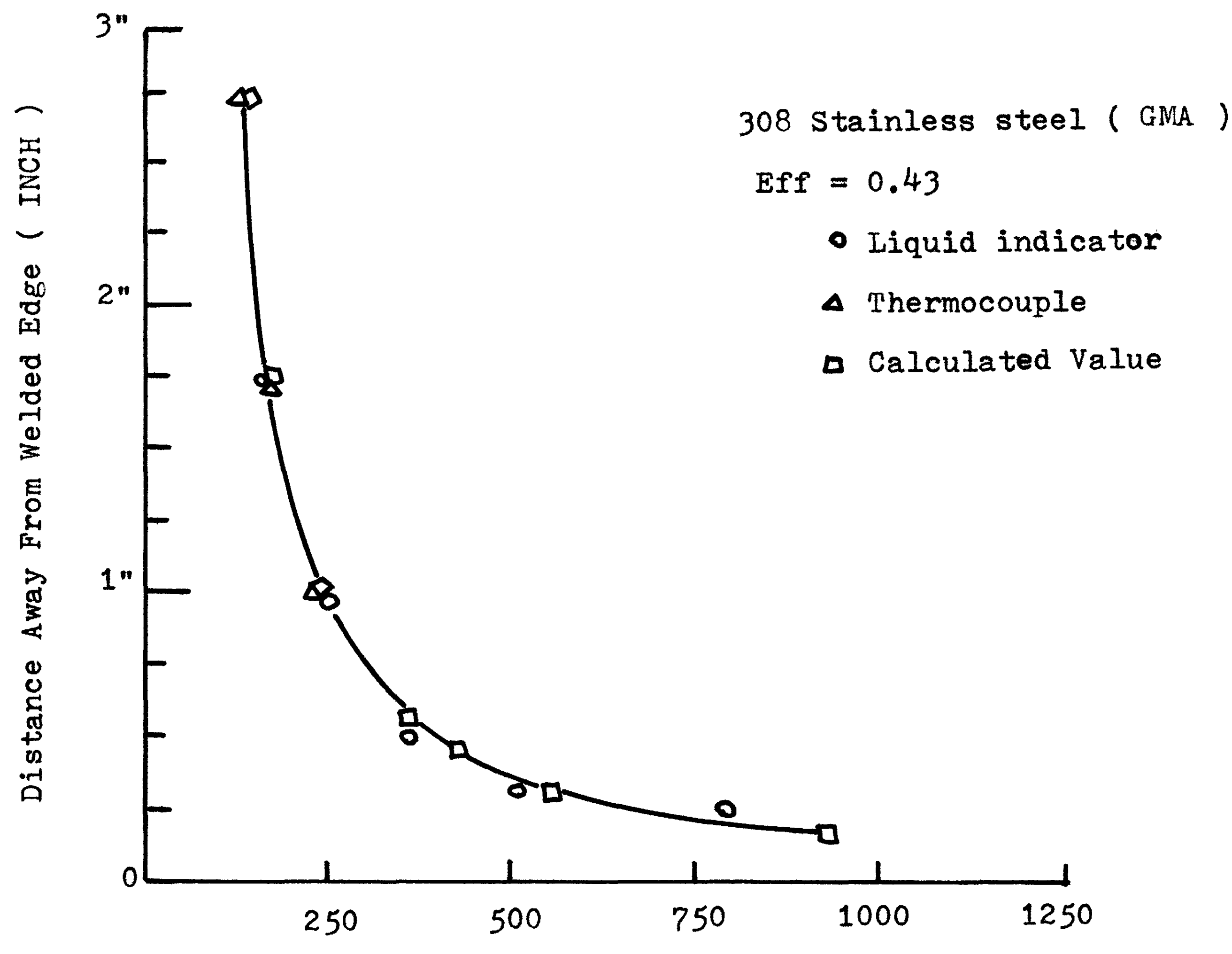


FIG. 23 Maximum Reached Temperature Distribution

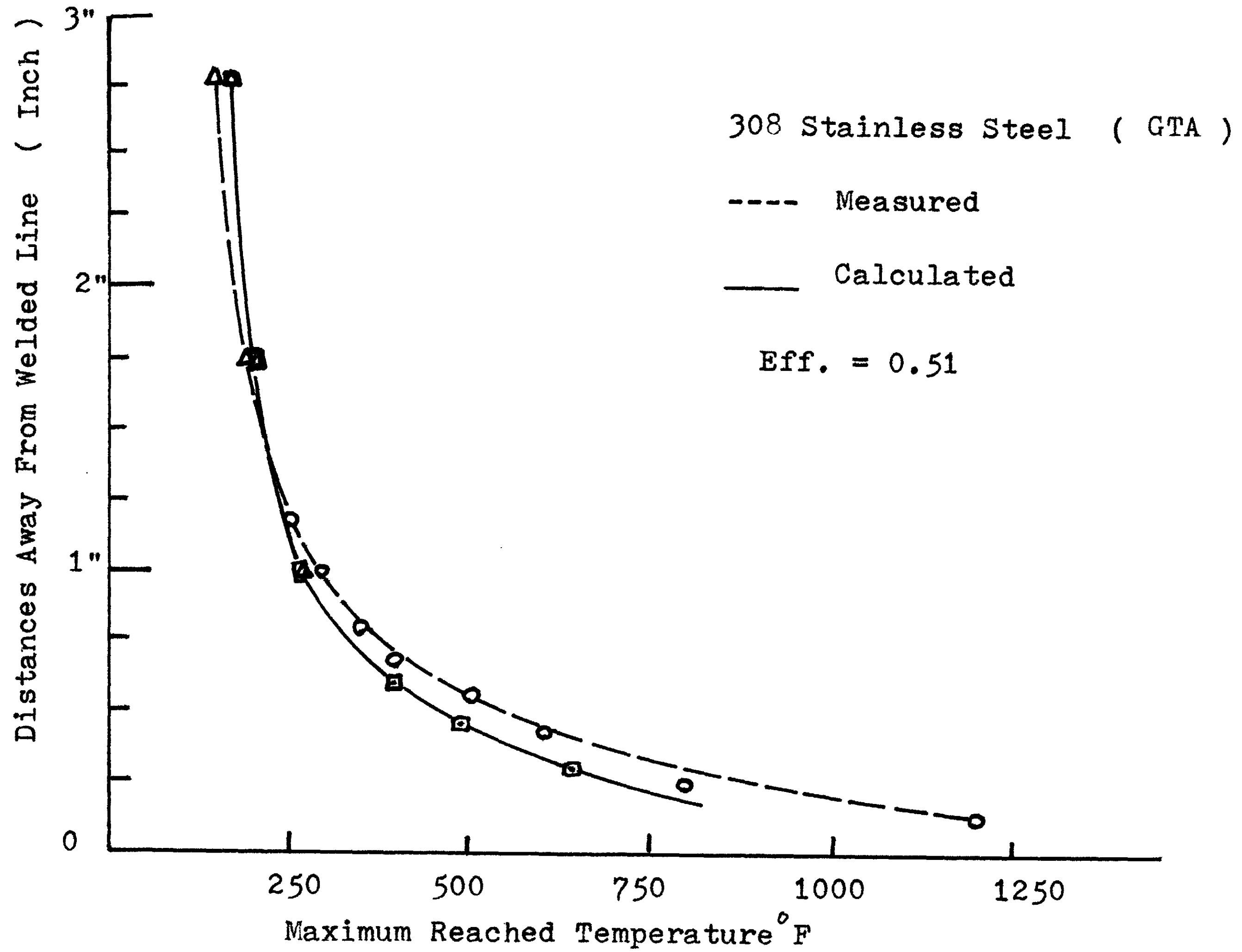


FIG. 24 Maximum Reached Temperature Distribution

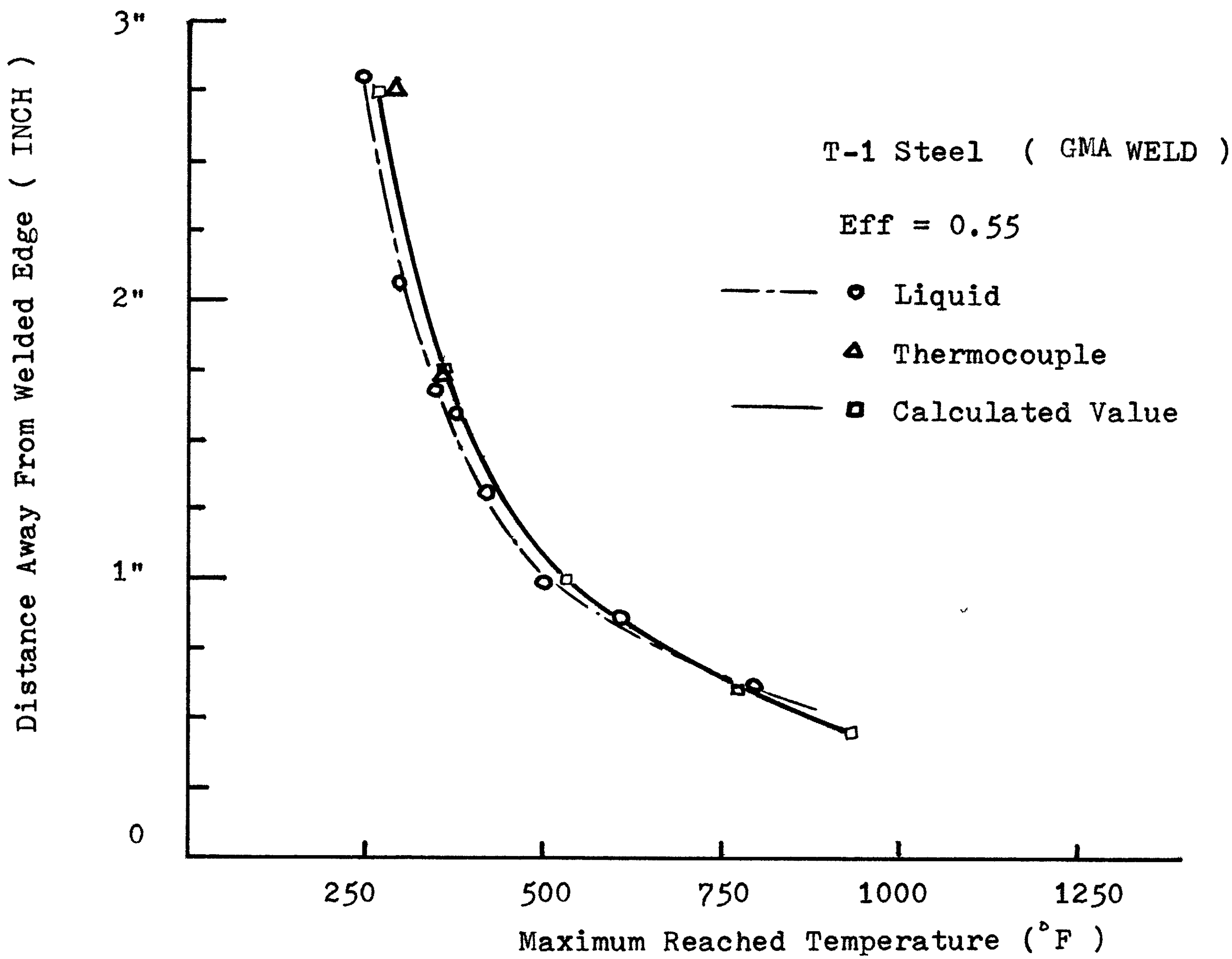


FIG. 25 Maximum Reached Temperature Distribution

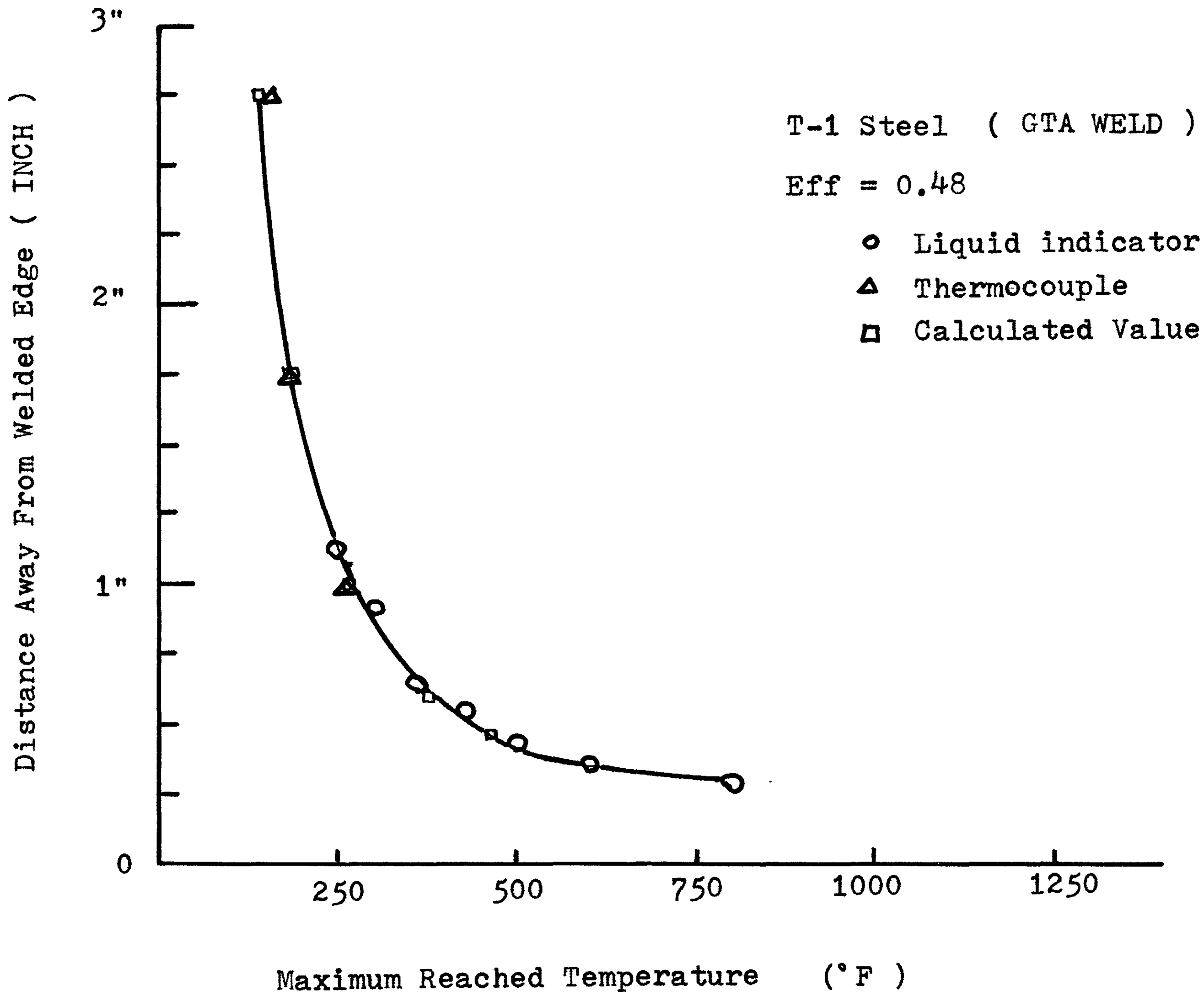


FIG. 26 Maximum Reached Temperature Distribution

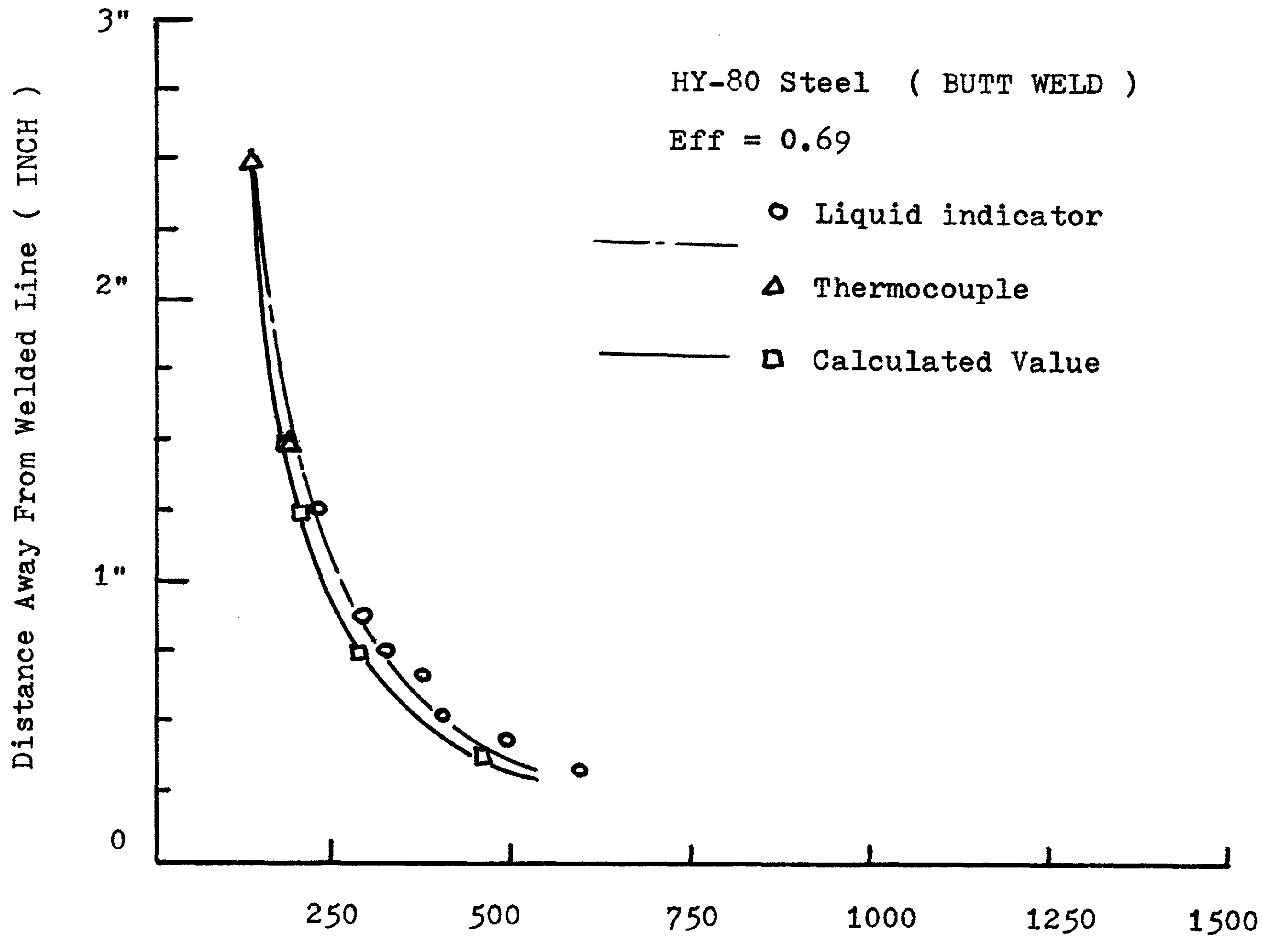


FIG. 27 Maximum Reached Temperature Distribution

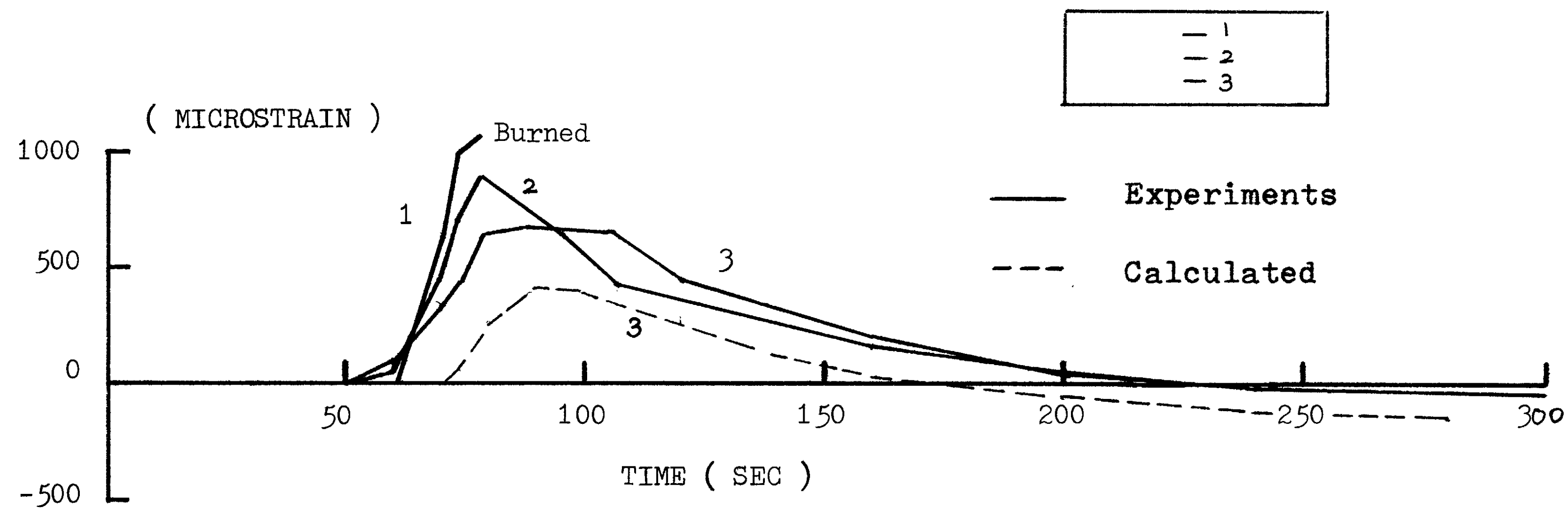


FIG. 29 Strain Changes for Mild Steel (GMA) at Different Depth.

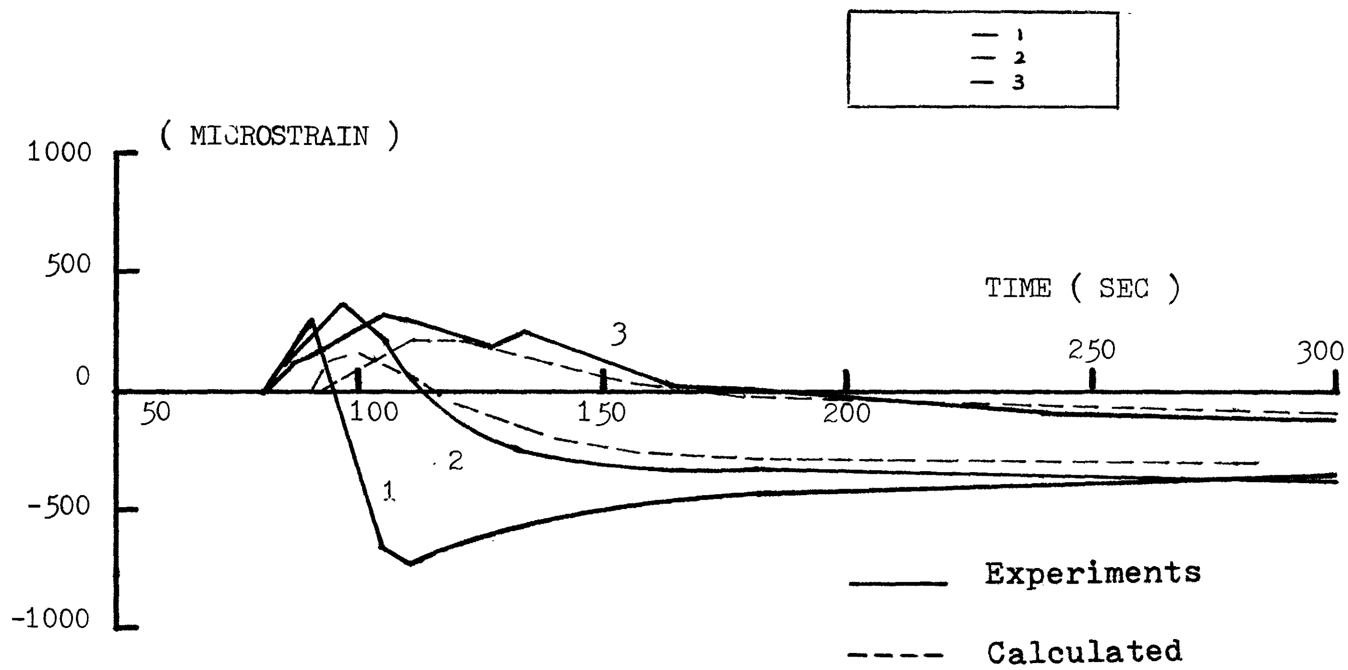


FIG. 30 Strain Changes for Mild Steel (GTA) at Different Depth.

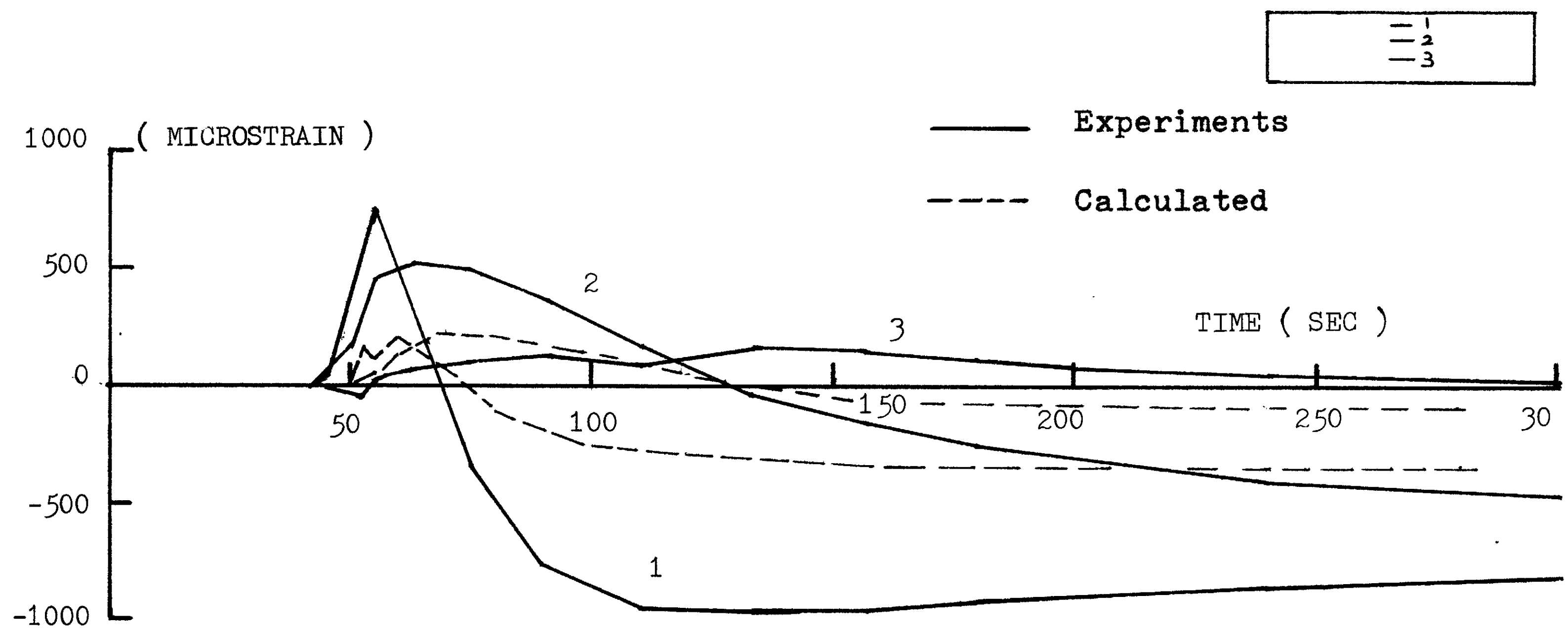


FIG. 31 Strain Changes for 308 Stainless Steel (GMA) at Different Depth.

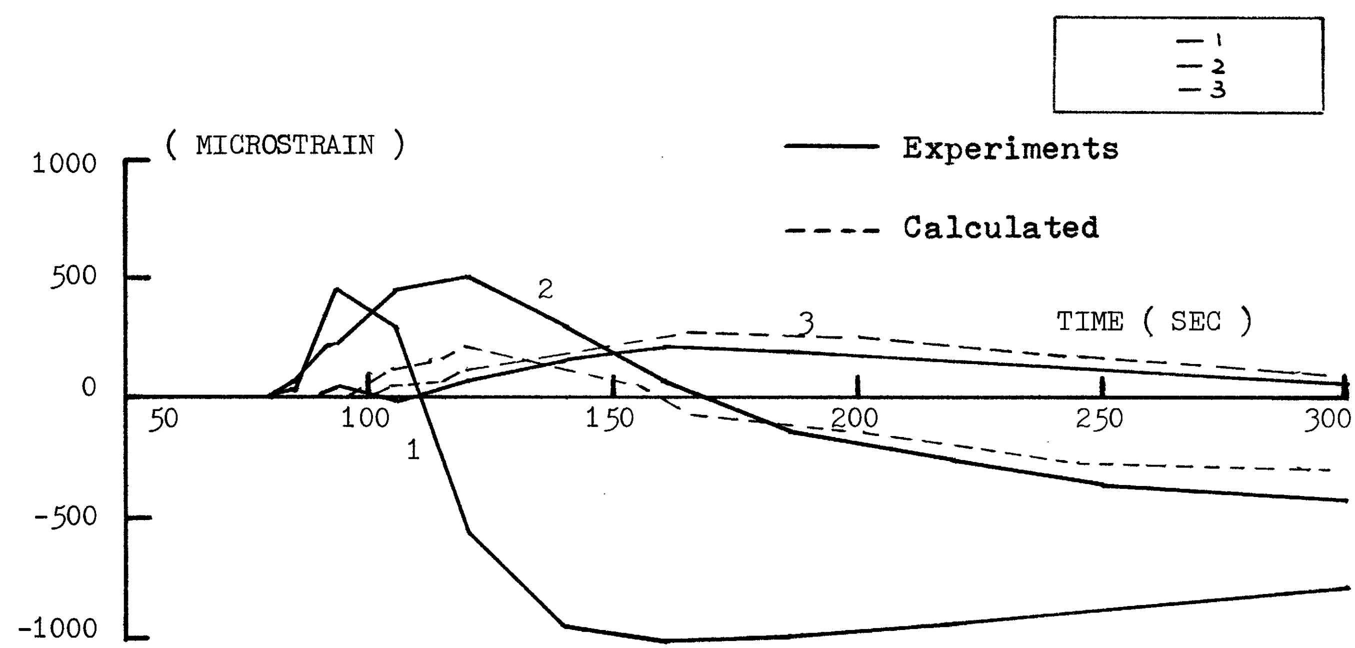


FIG. 32 Strain Changes for 308 Stainless Steel (GTA) at Different Depth.

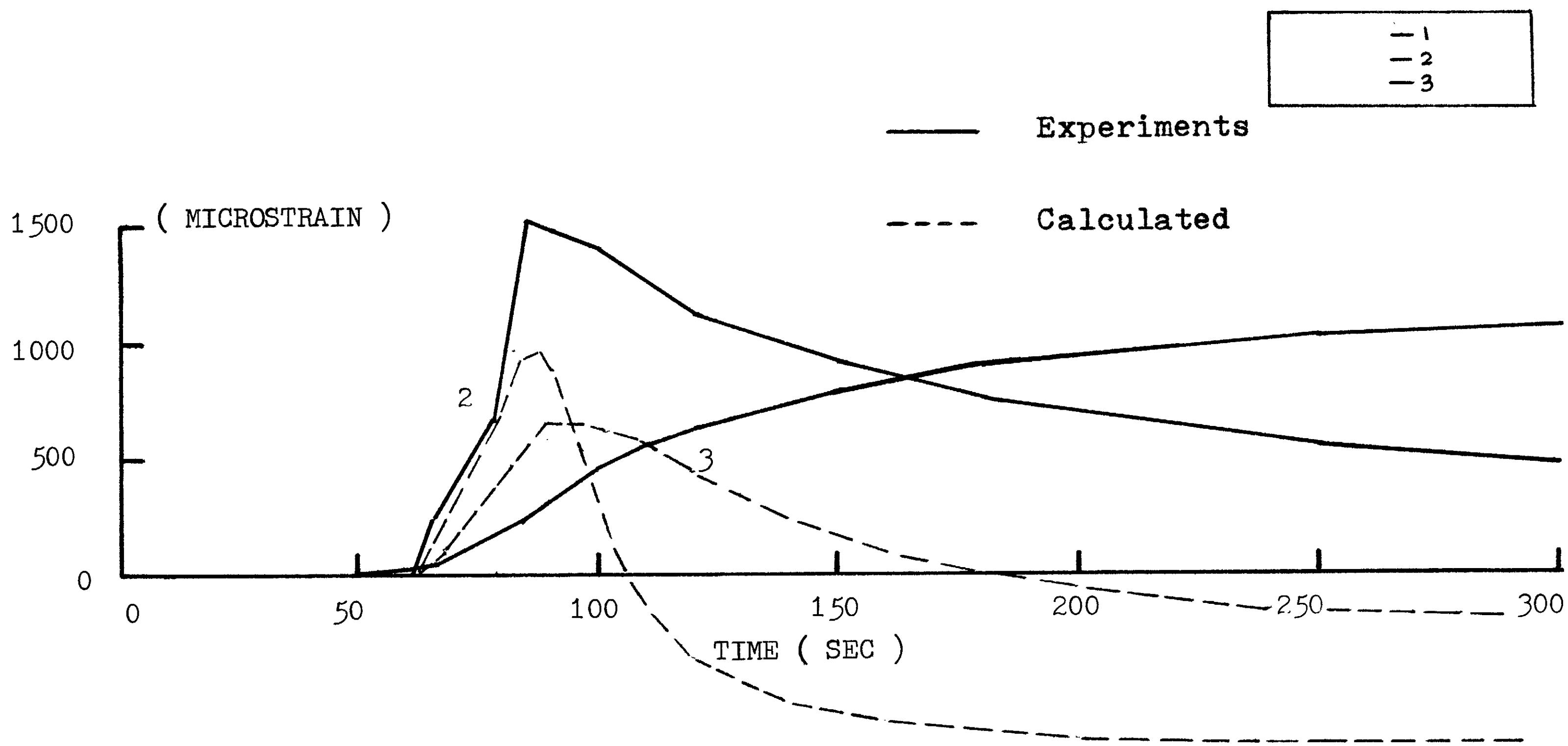


FIG. 33 Strain Changes for T-1 Steel (GMA) at Different Depth.

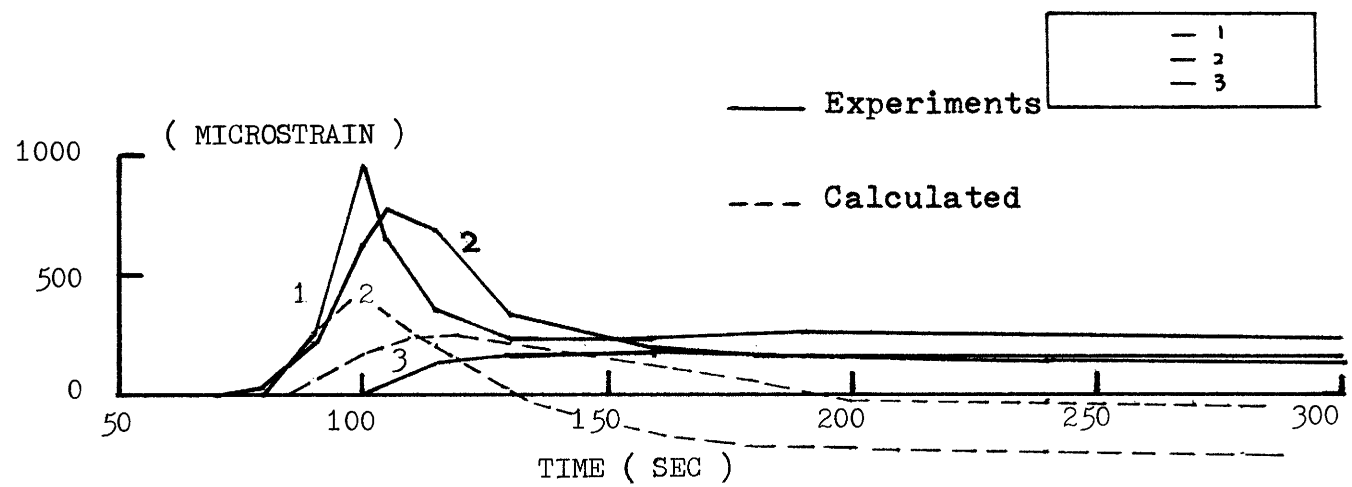


FIG. 34 Strain Changes for T-1 Steel (GTA) at Different Depth.

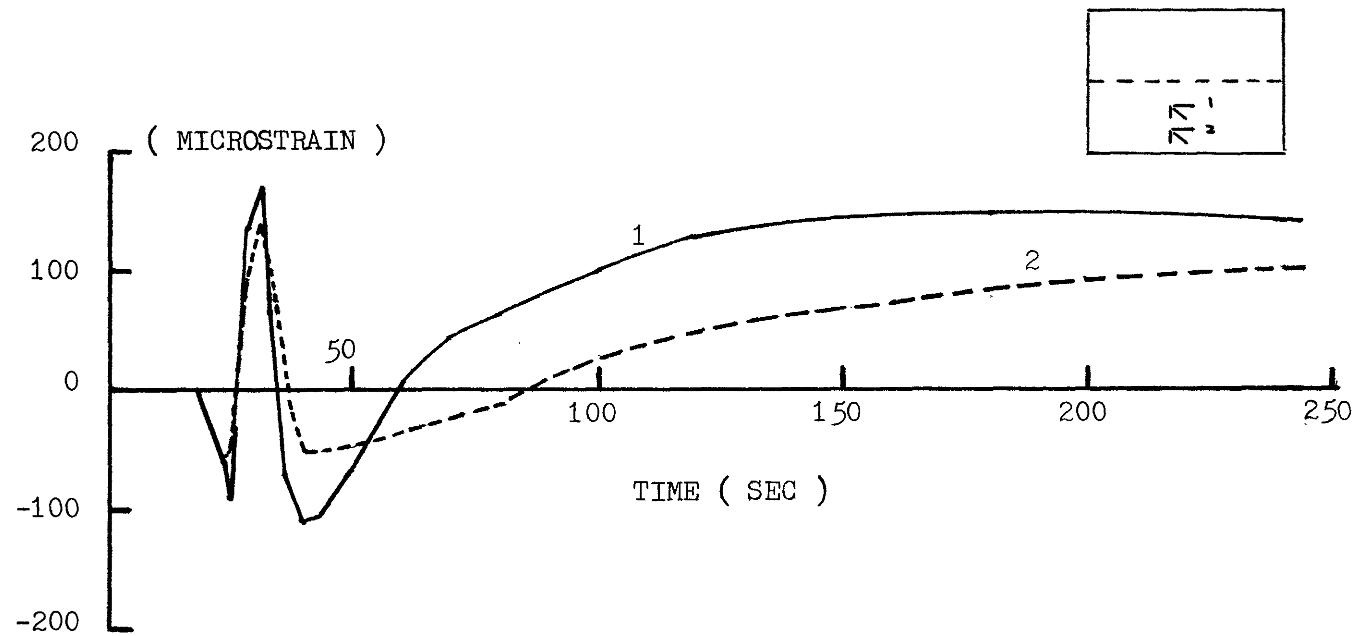


FIG. 35 Strain Changes for HY-80 (BUTT WELD) at Different Locations.

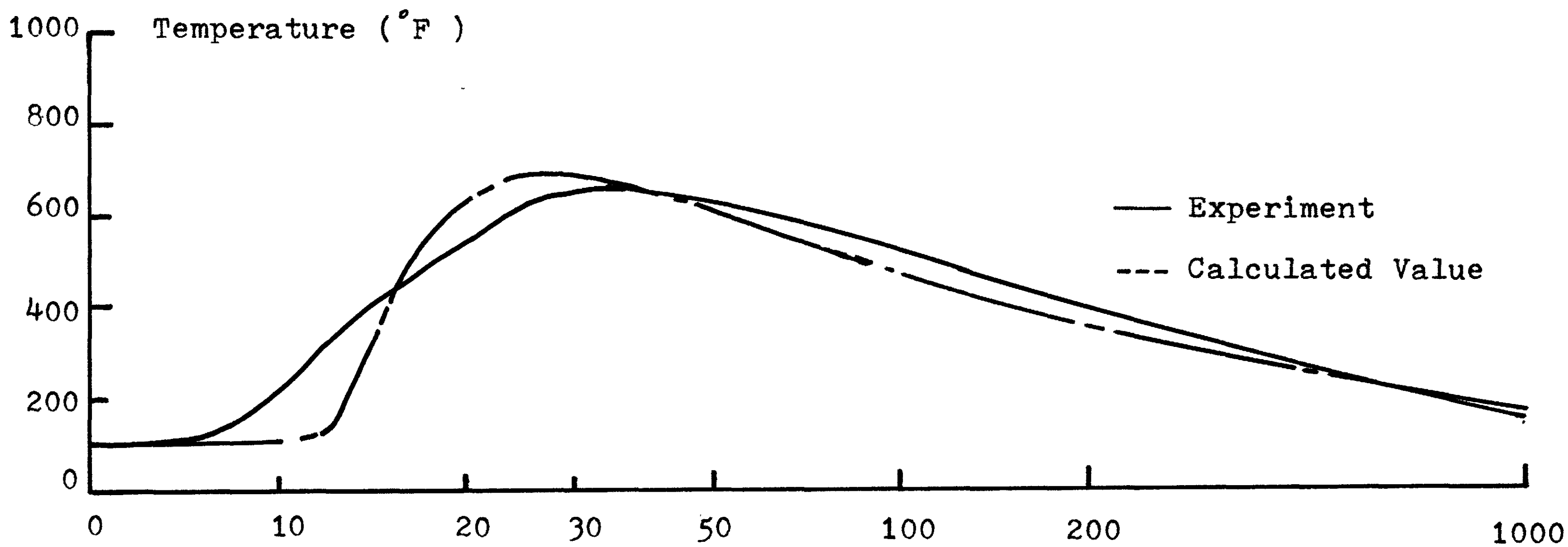


FIG. 36 Temperature Histry at 0.625 Inches From Welded Edge of Ti-6Al-2Cb-1Ta-0.8Mo

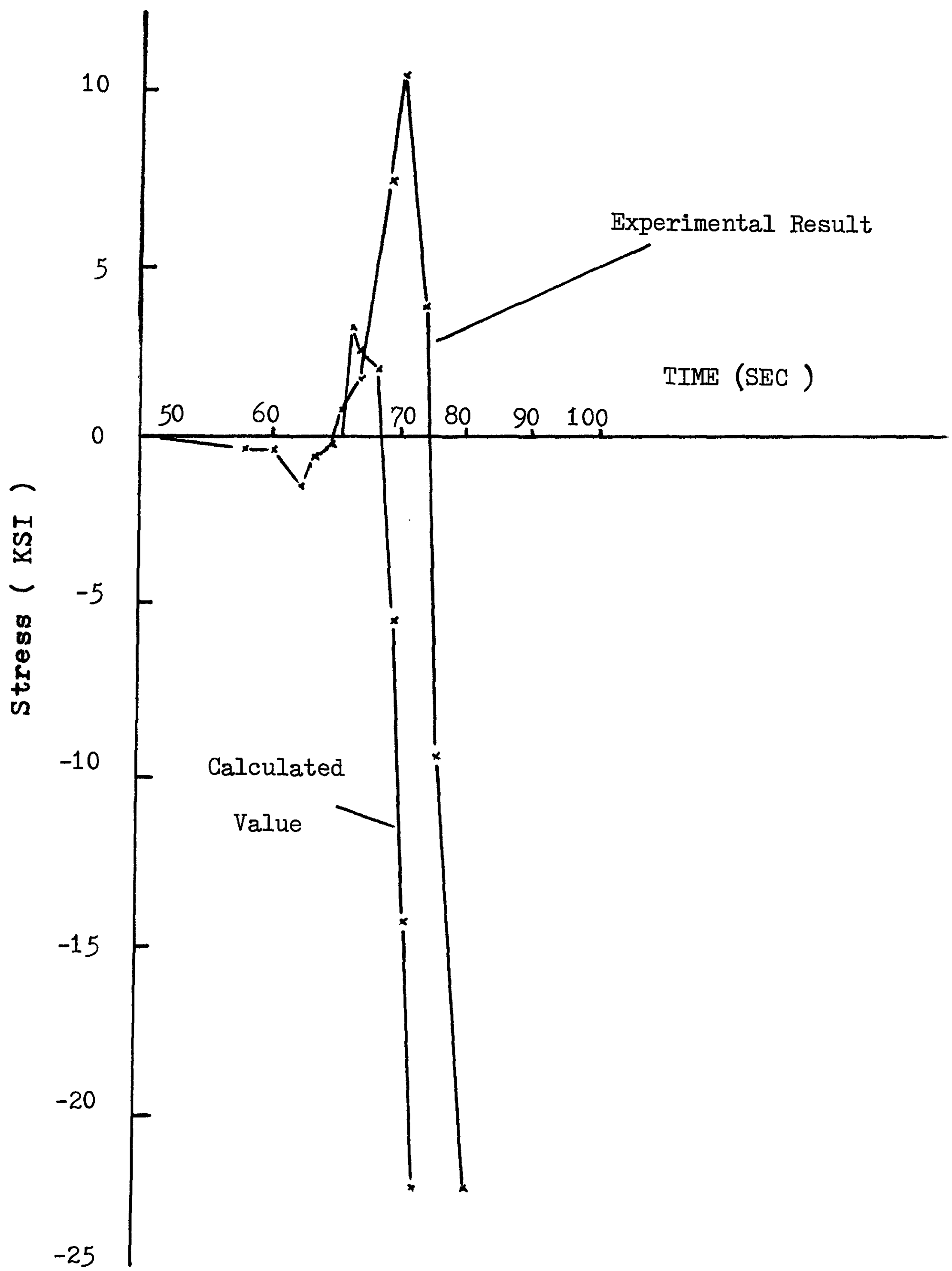


FIG. 37 Stress Changes For Titanium Alloy-6211 Observed on the Gage at 0.625" Away From The Weld Line.

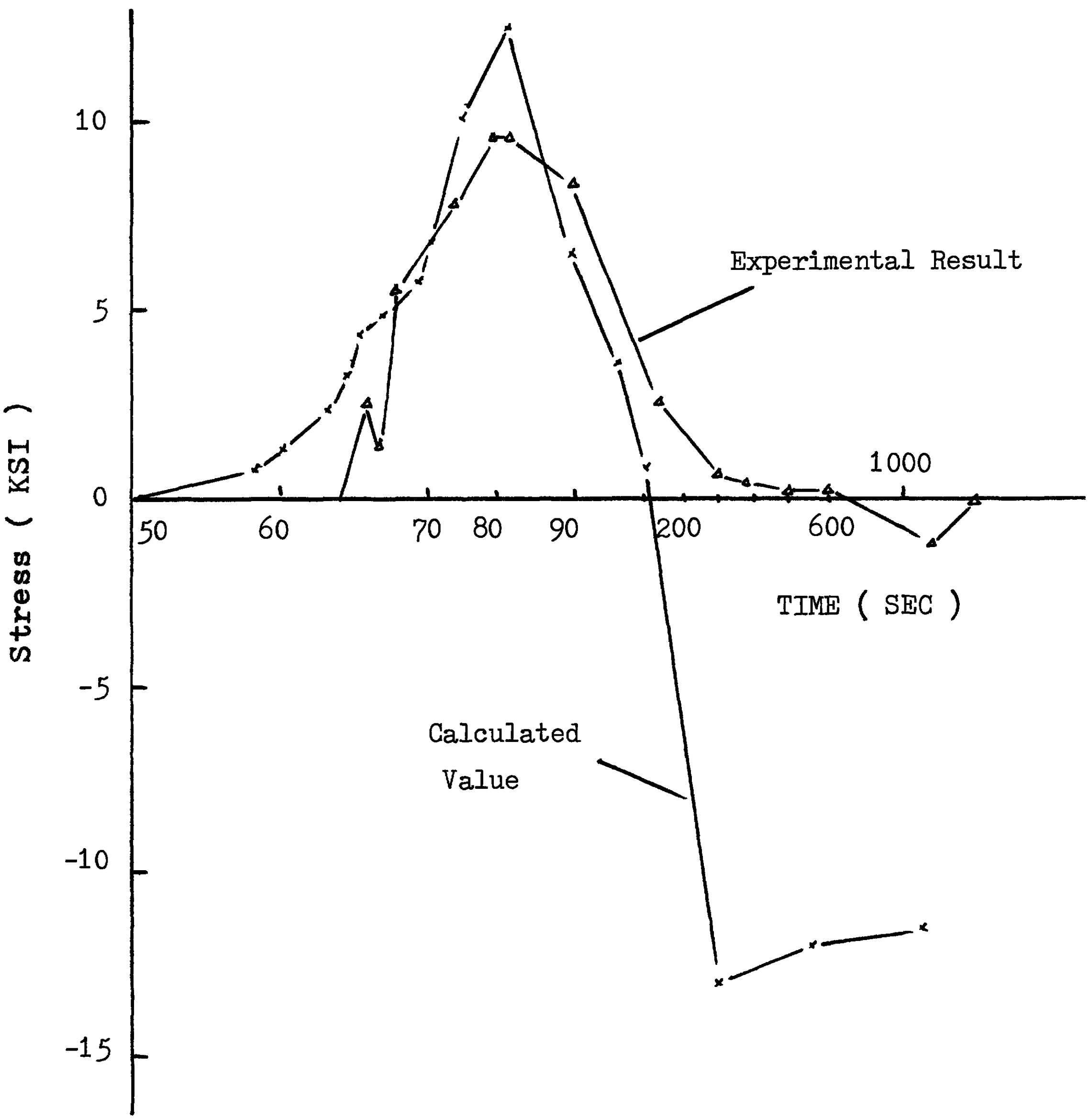


FIG. 38 Stress Changes For Titanium Alloy-6211 Observed on The Gage at 1.625" Away From The Welded Line.

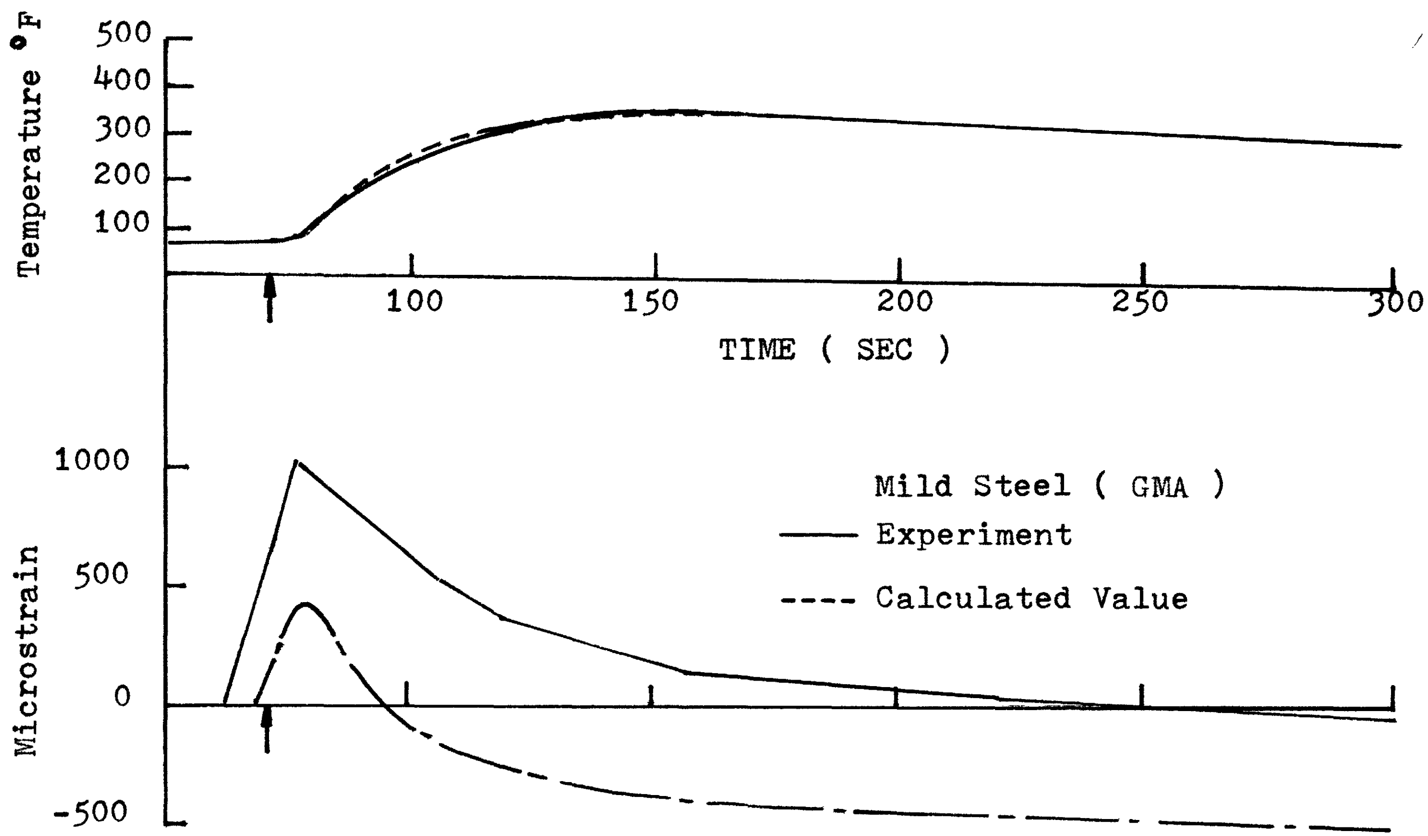


FIG. 39 LONGITUDINAL STRAIN AND TEMPERATURE AT 1.0" FROM WELDING EDGE (GMA WELD)

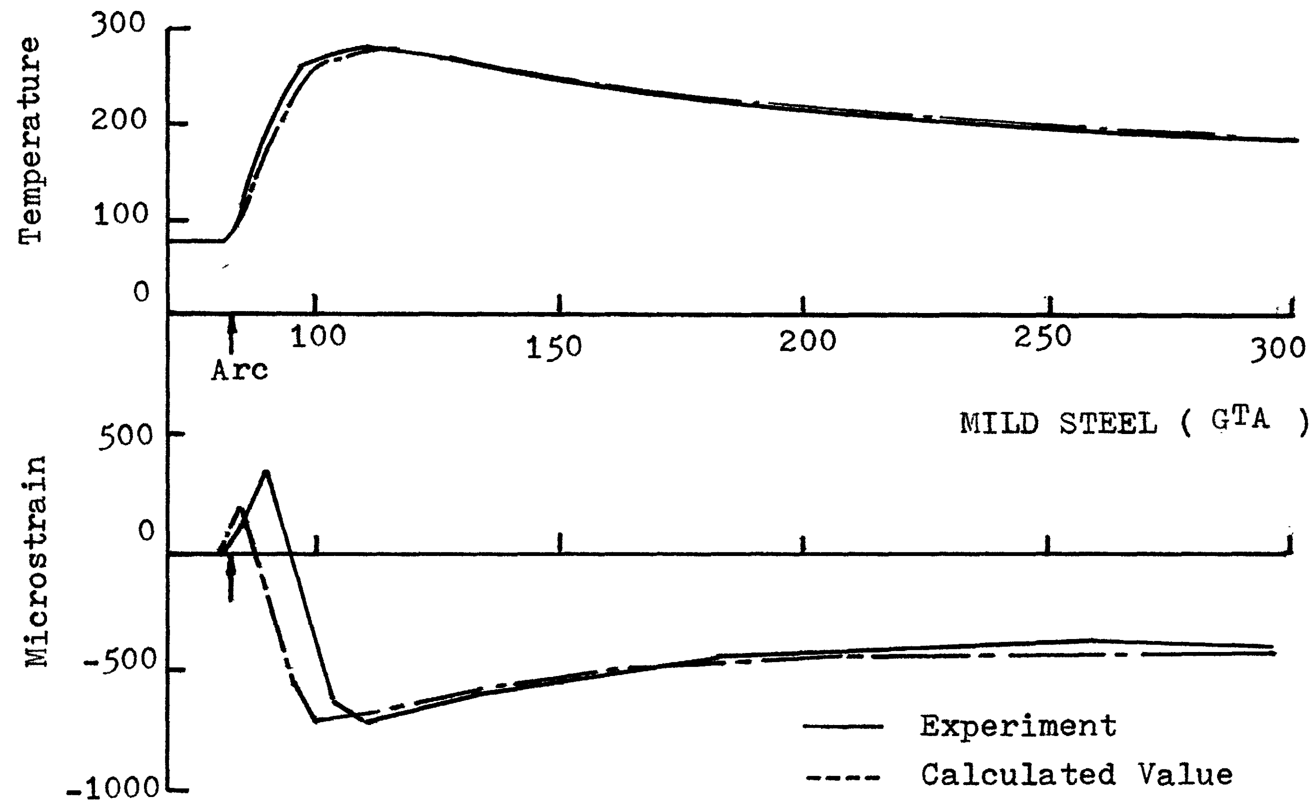


FIG. 40 LONGITUDINAL STRAIN AND TEMPERATURE AT 1.0" FROM WELDING EDGE (GTA)

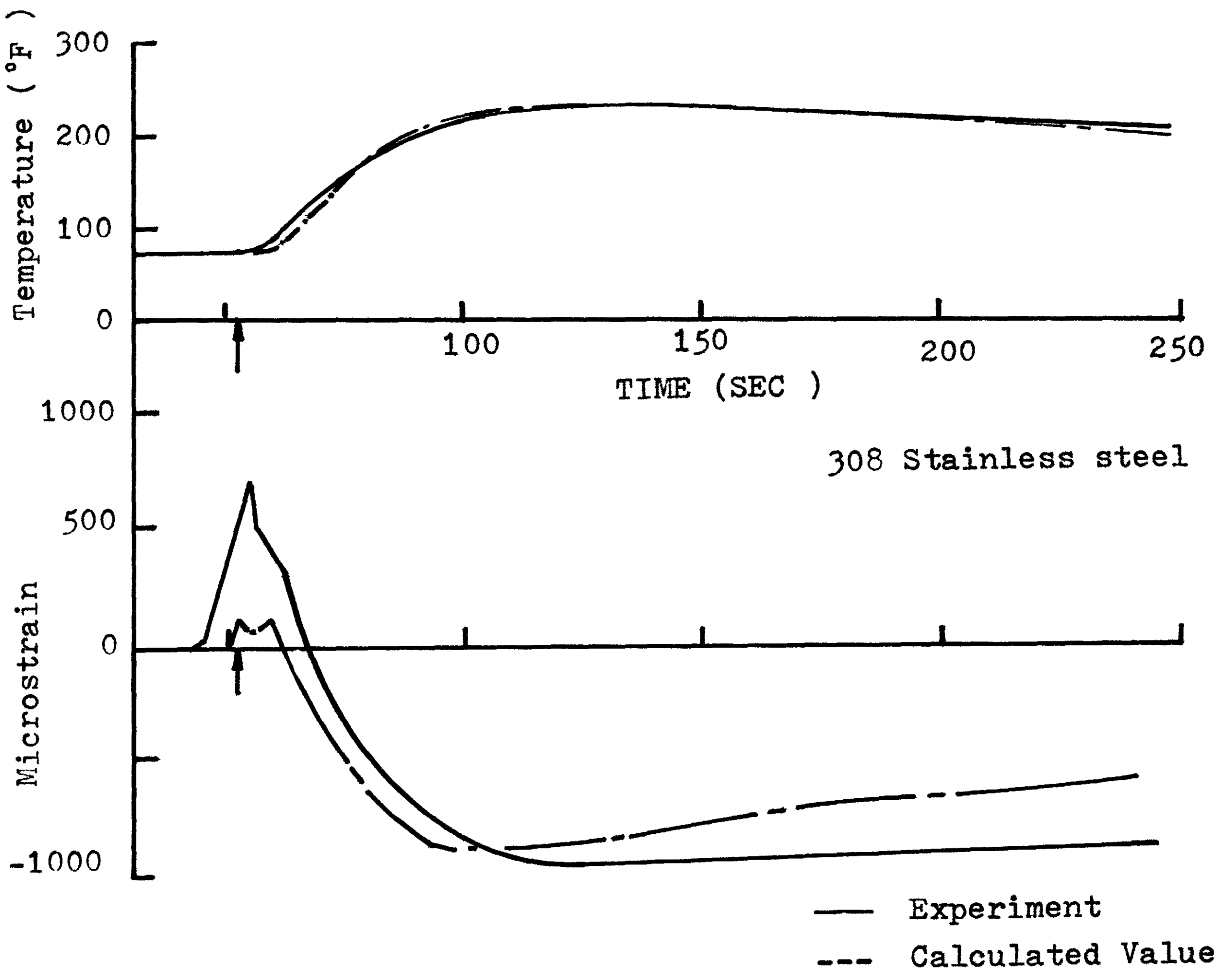


FIG. 41 LONGITUDINAL STRAIN AND TEMPERATURE AT 1.0" FROM WELDING EDGE For Stainless Steel (GMA)

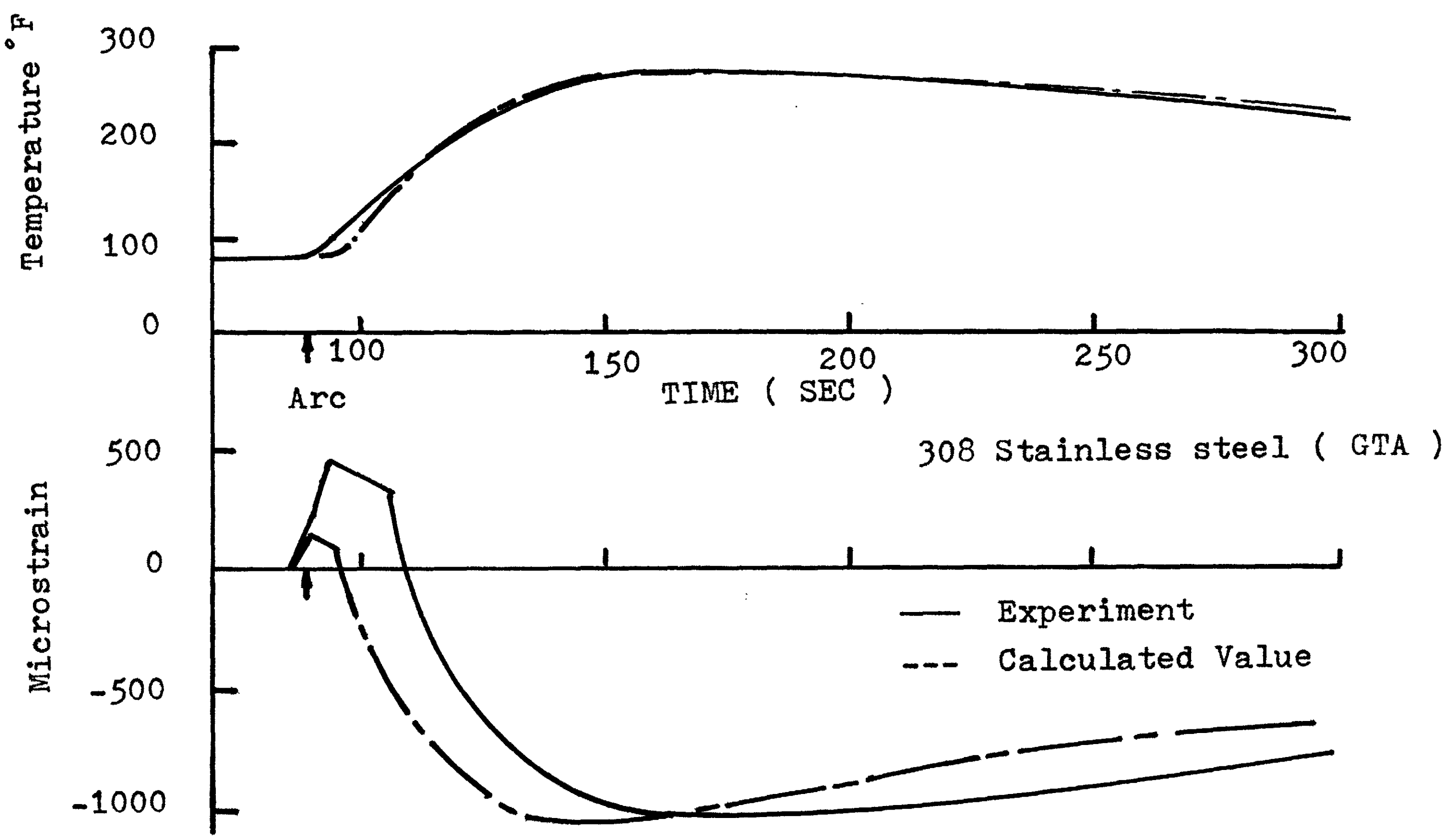


FIG. 42 LONGITUDINAL STRAIN AND TEMPERATURE AT 1.0" FROM WELDING EDGE (Stainless Steel GTA)

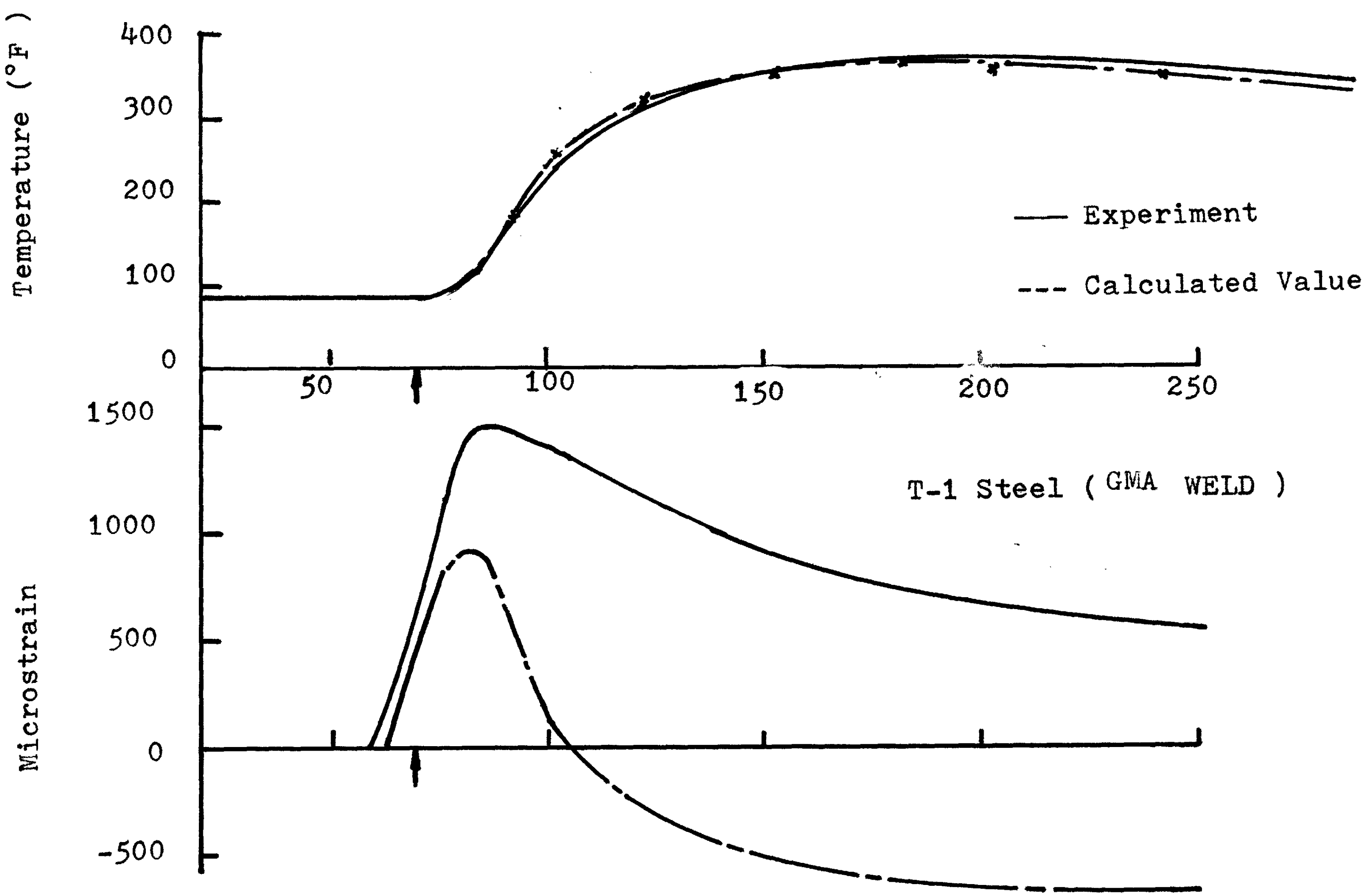


FIG.43 LONGITUDINAL STRAIN AND TEMPERATURE AT 1.75" FROM WELDING EDGE (T-1 Steel GMA)

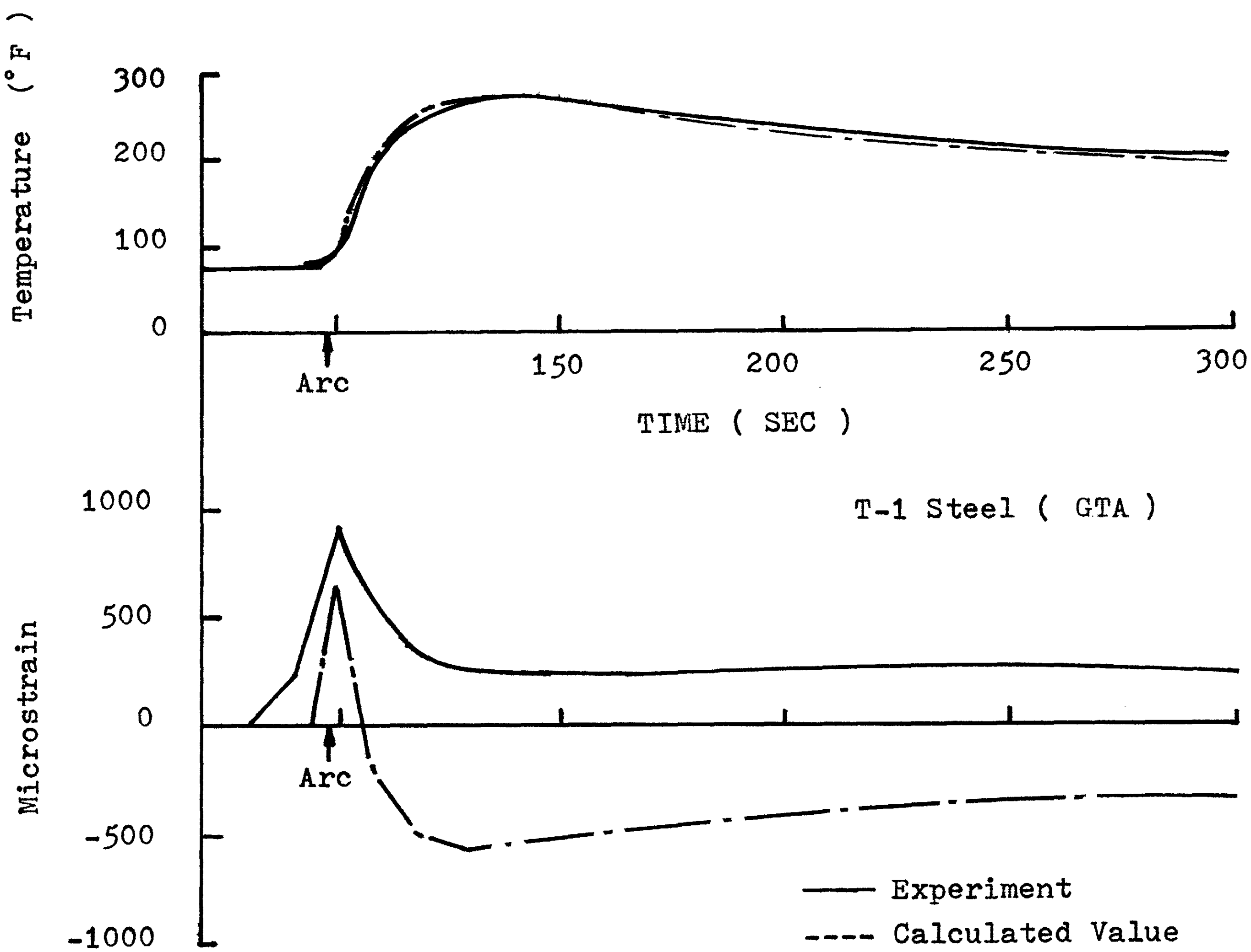


FIG. 44 LONGITUDINAL STRAIN AND TEMPERATURE AT 1.0" FROM WELDING Edge (GTA WELD) for T-1 Steel

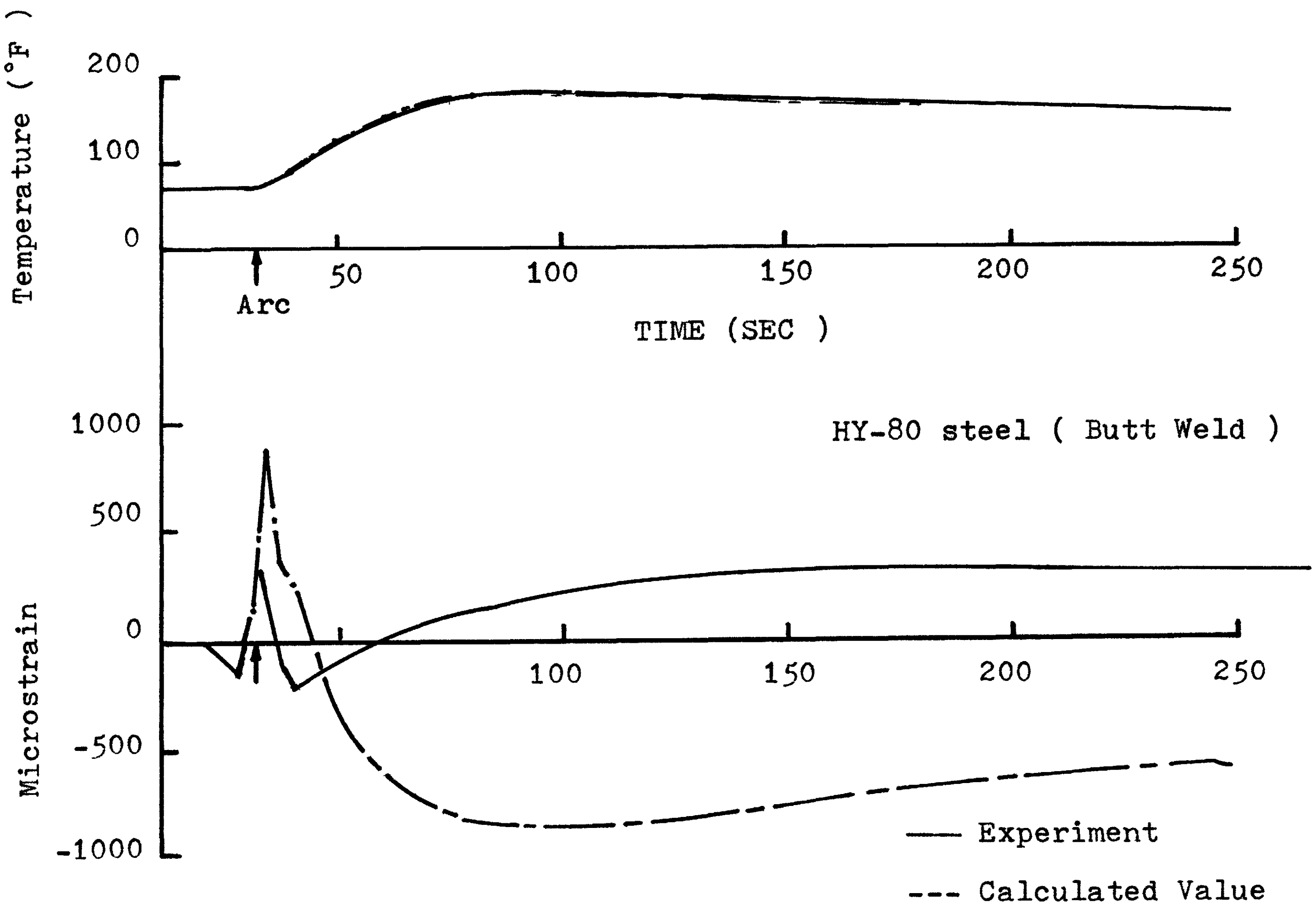


FIG 45 LONGITUDINAL STRAIN AND TEMPERATURE AT 1.5" FROM WELDING LINE (HY-80 BUTT WELD)

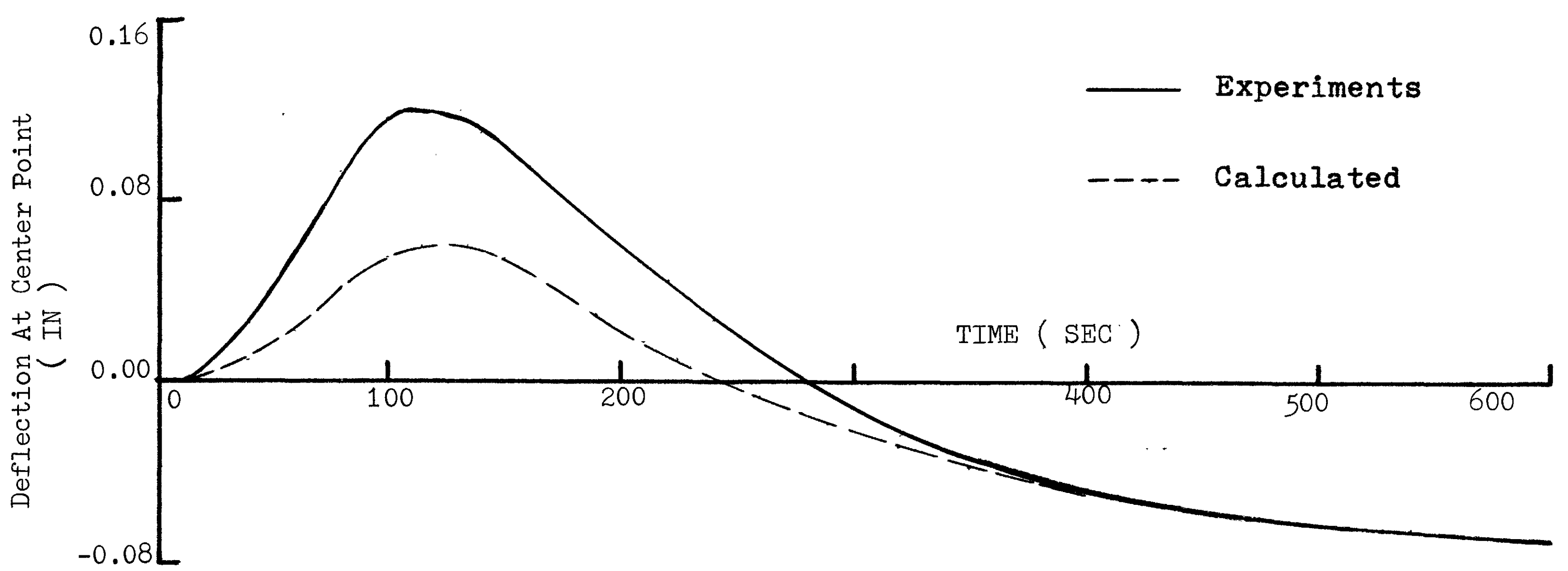


FIG.46 Deflection Changes at The Center of Mild Steel (GMA)

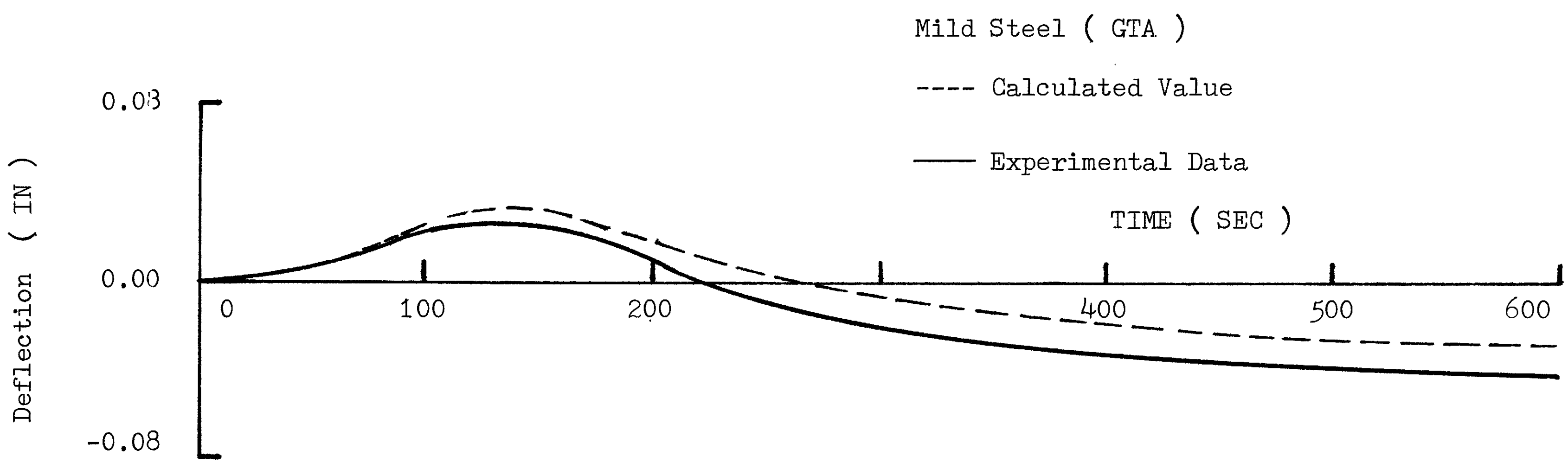


FIG. 47 Deflection Changes at The Center of Mild Steel (GTA)

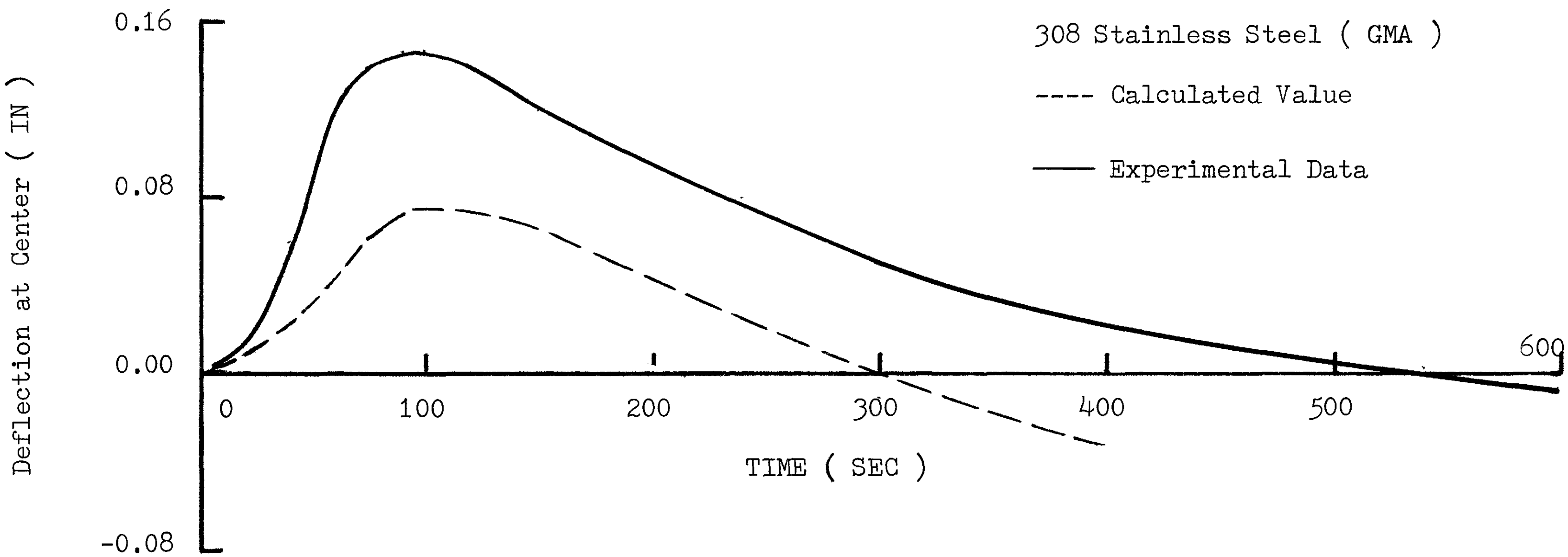


FIG. 48 Deflection Changes at The Center of 308 Stainless Steel (GMA)

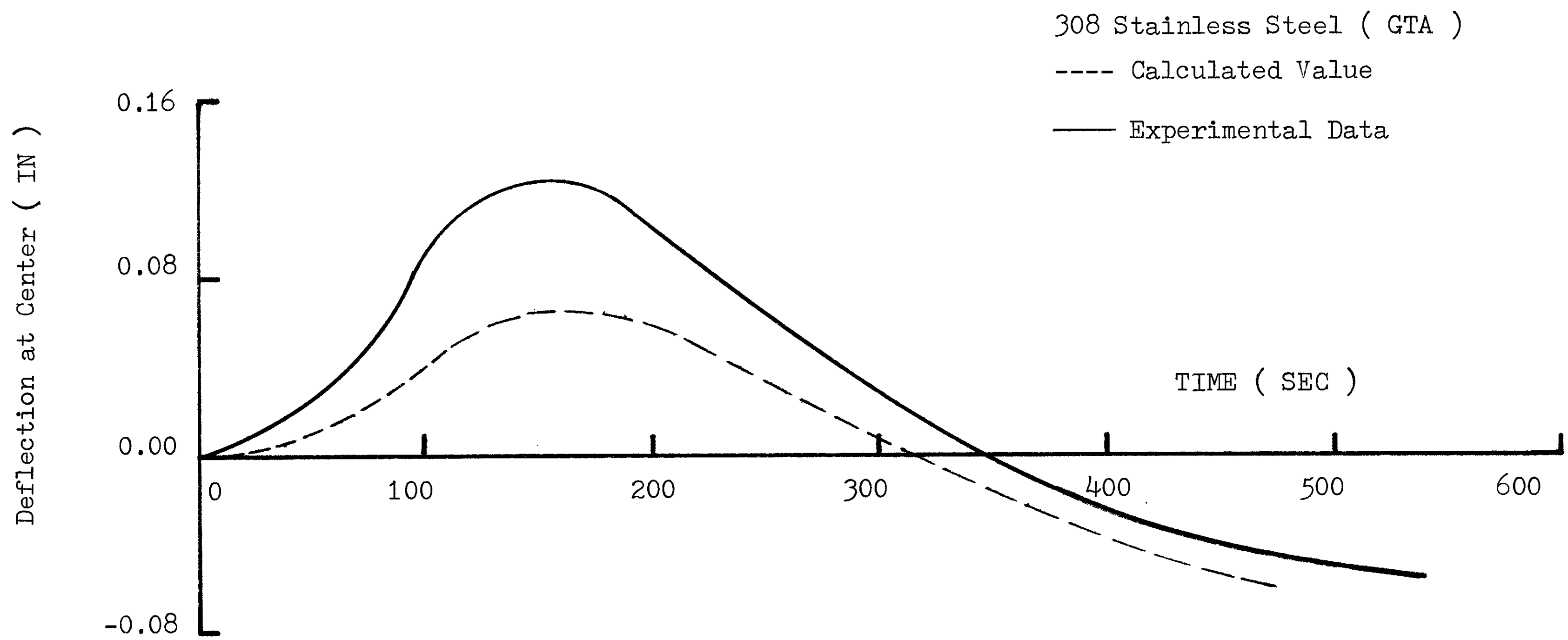


FIG. 49 Deflection Changes at The Center of 308 Stainless Steel Plate (GTA)

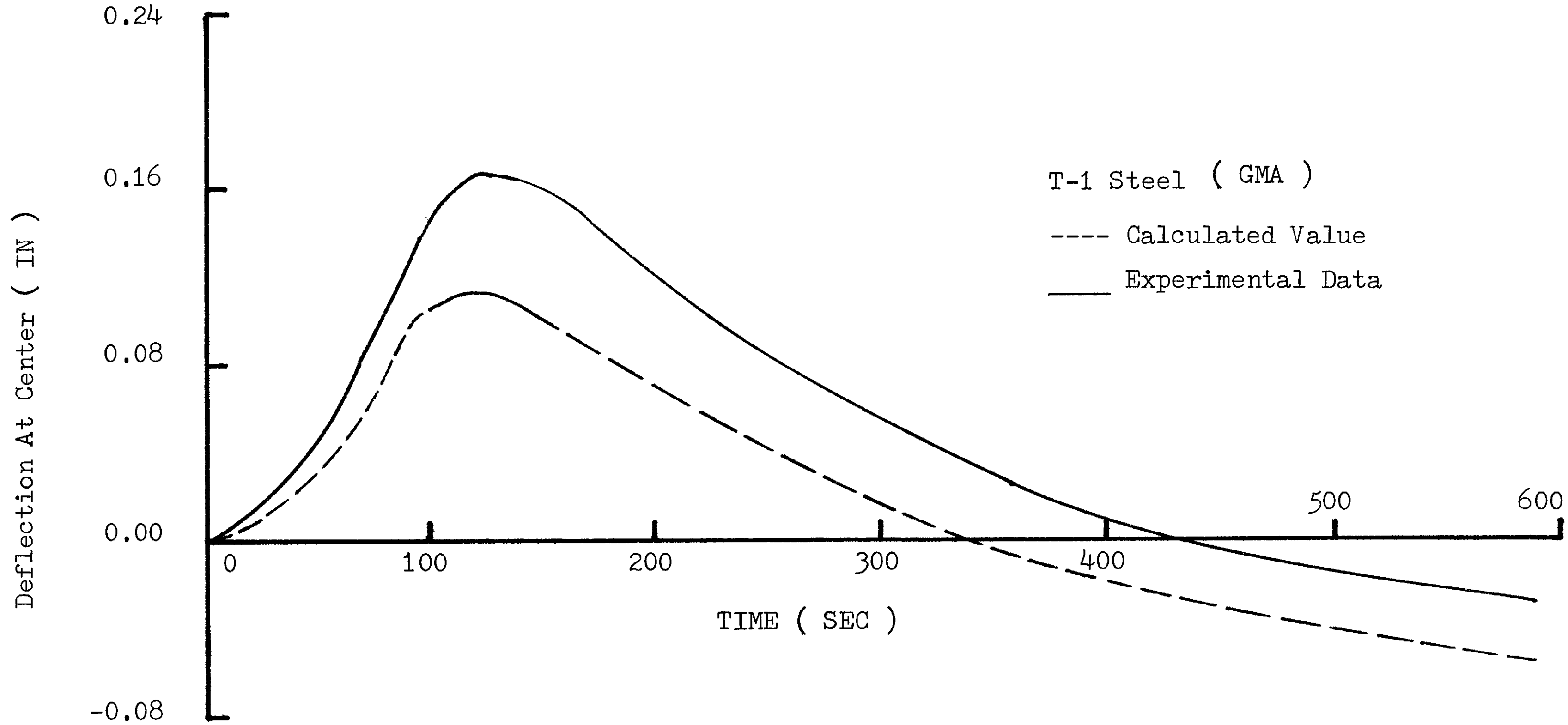


FIG. 50 Deflection Changes at The Center of T-1 Steel Plate (GMA)

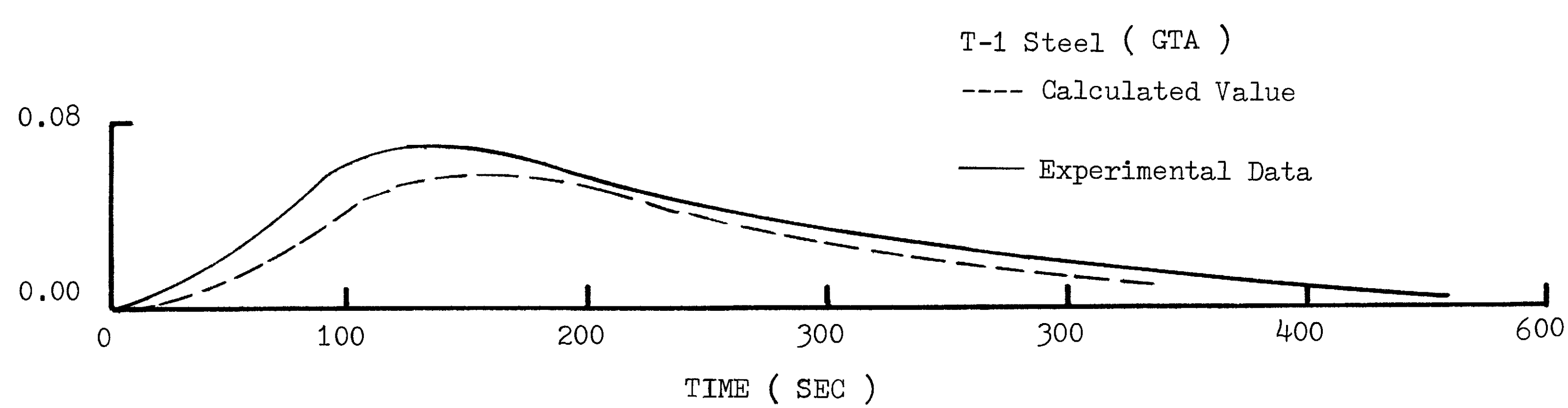


FIG. 51 Deflection Changes at The Center of T-1 Steel Plate (GTA)

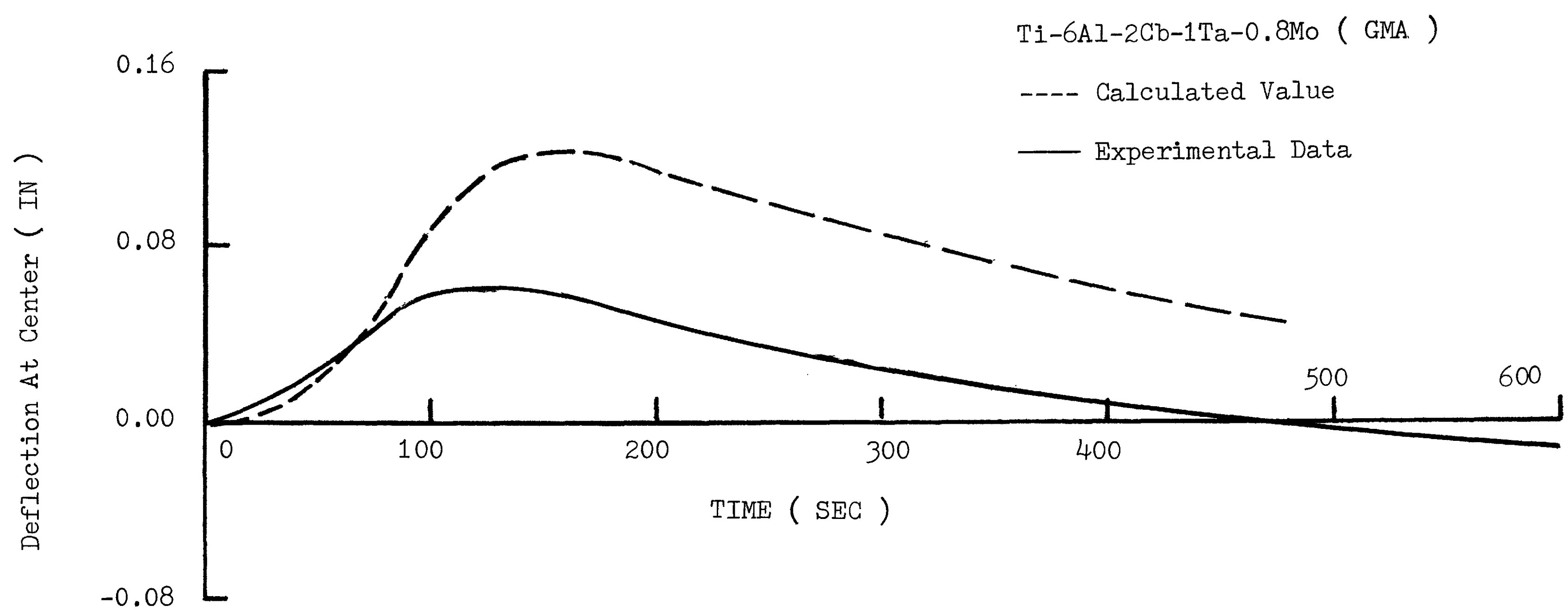


FIG. 52 Deflection Changes at The Center of Ti-6Al-2Cb-1Ta-0.8Mo Plate (GMA)

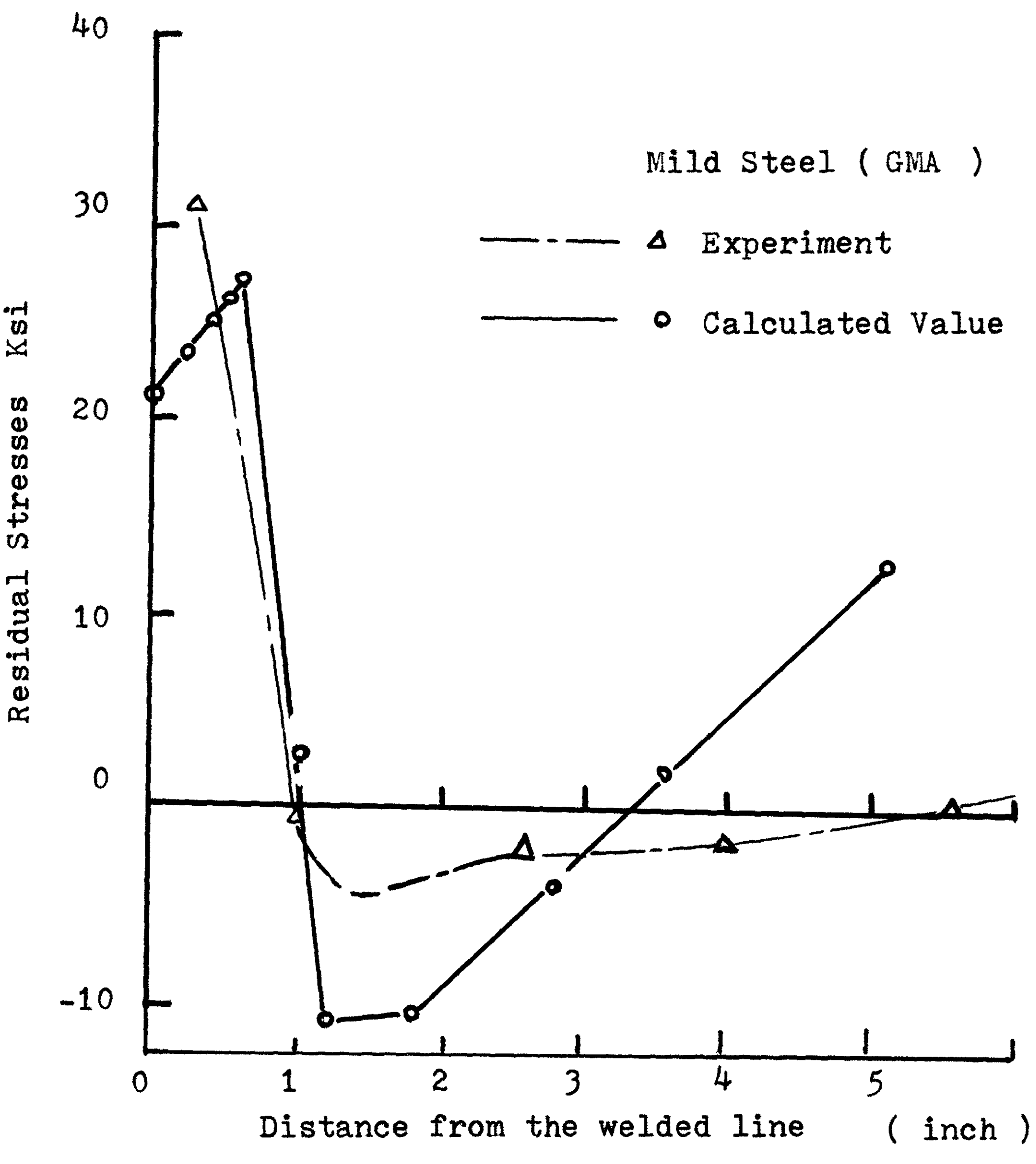


FIG. 53 RESIDUAL STRESSES DISTRIBUTION IN WELDMENT OF MILD STEEL (GMA)

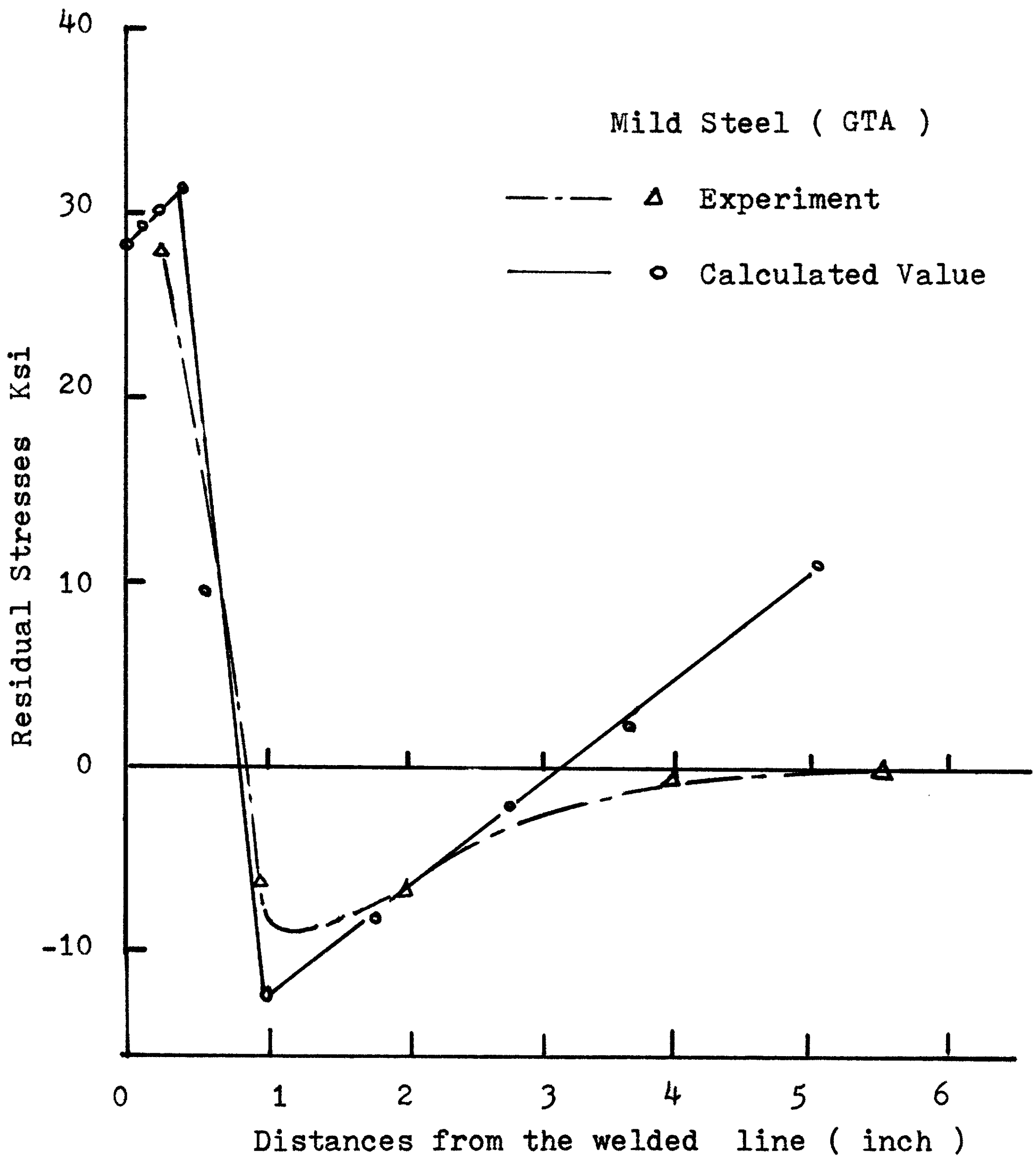


FIG. 54 RESIDUAL STRESSES DISTRIBUTION IN WELDMENT OF MILD STEEL (GTA)

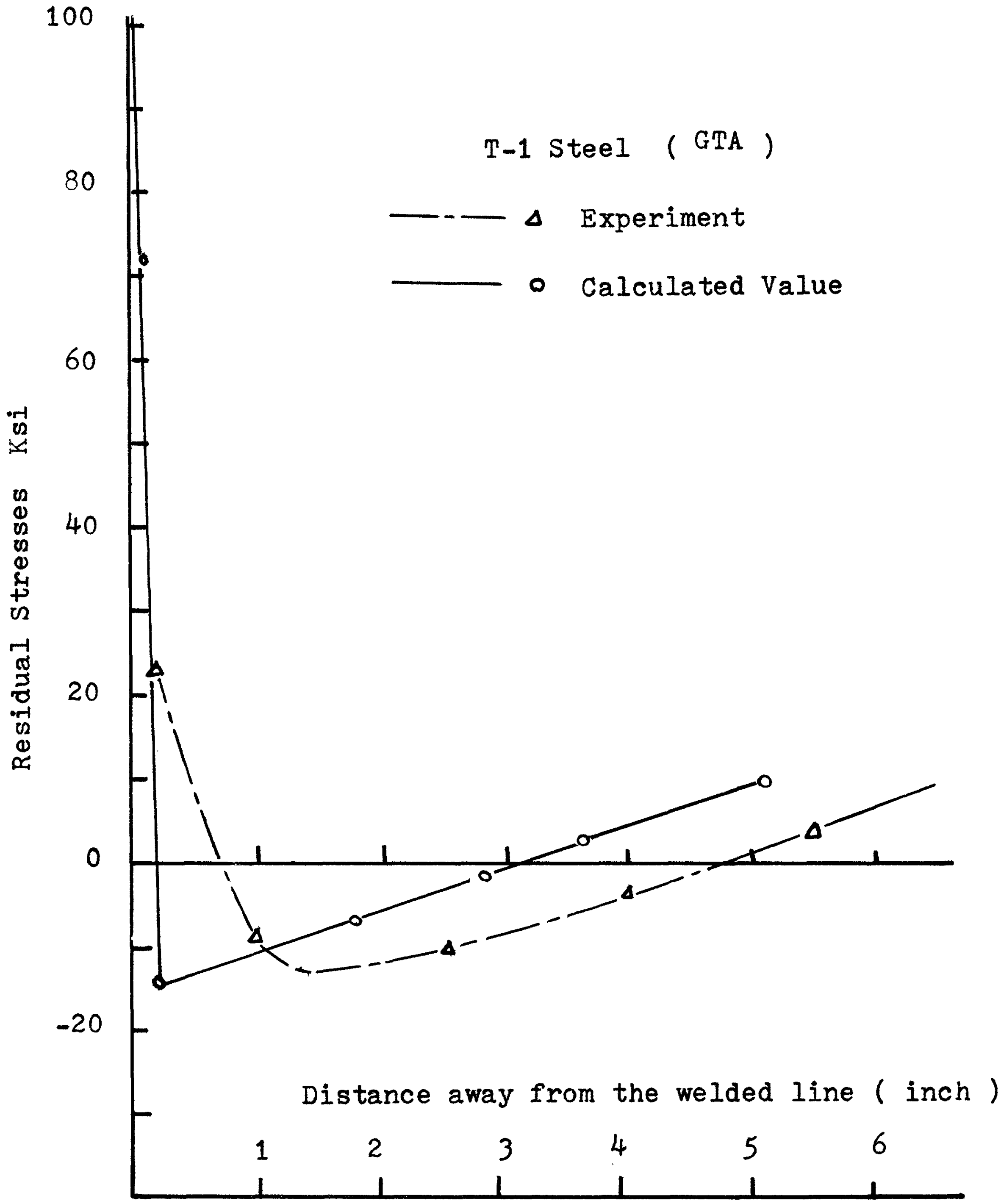


FIG. 55 RESIDUAL STRESSES DISTRIBUTION IN T-1 STEEL AFTER WELDED (GTA WELD)

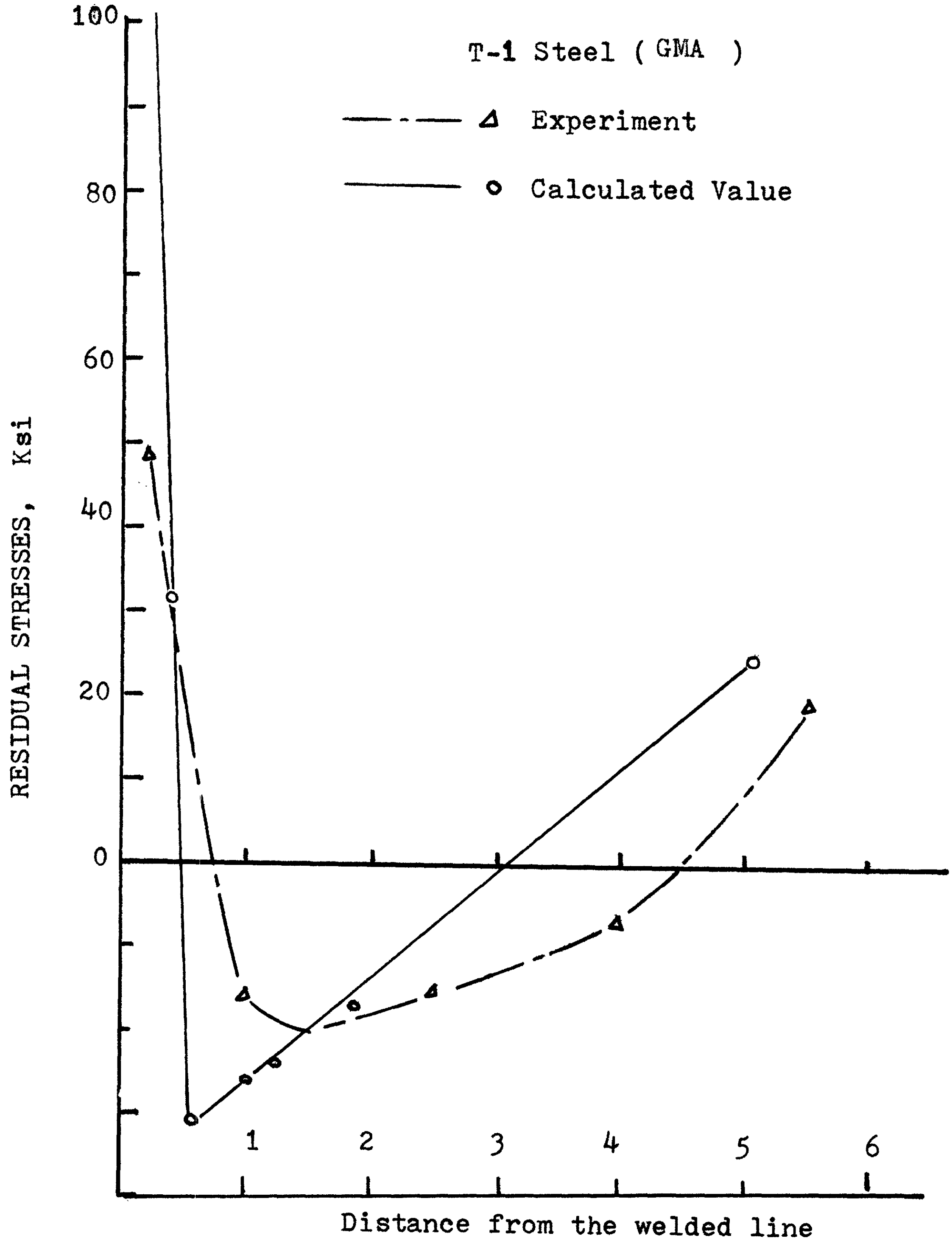


FIG. 56 RESIDUAL STRESSES DISTRIBUTION IN T-1 Steel (GMA)

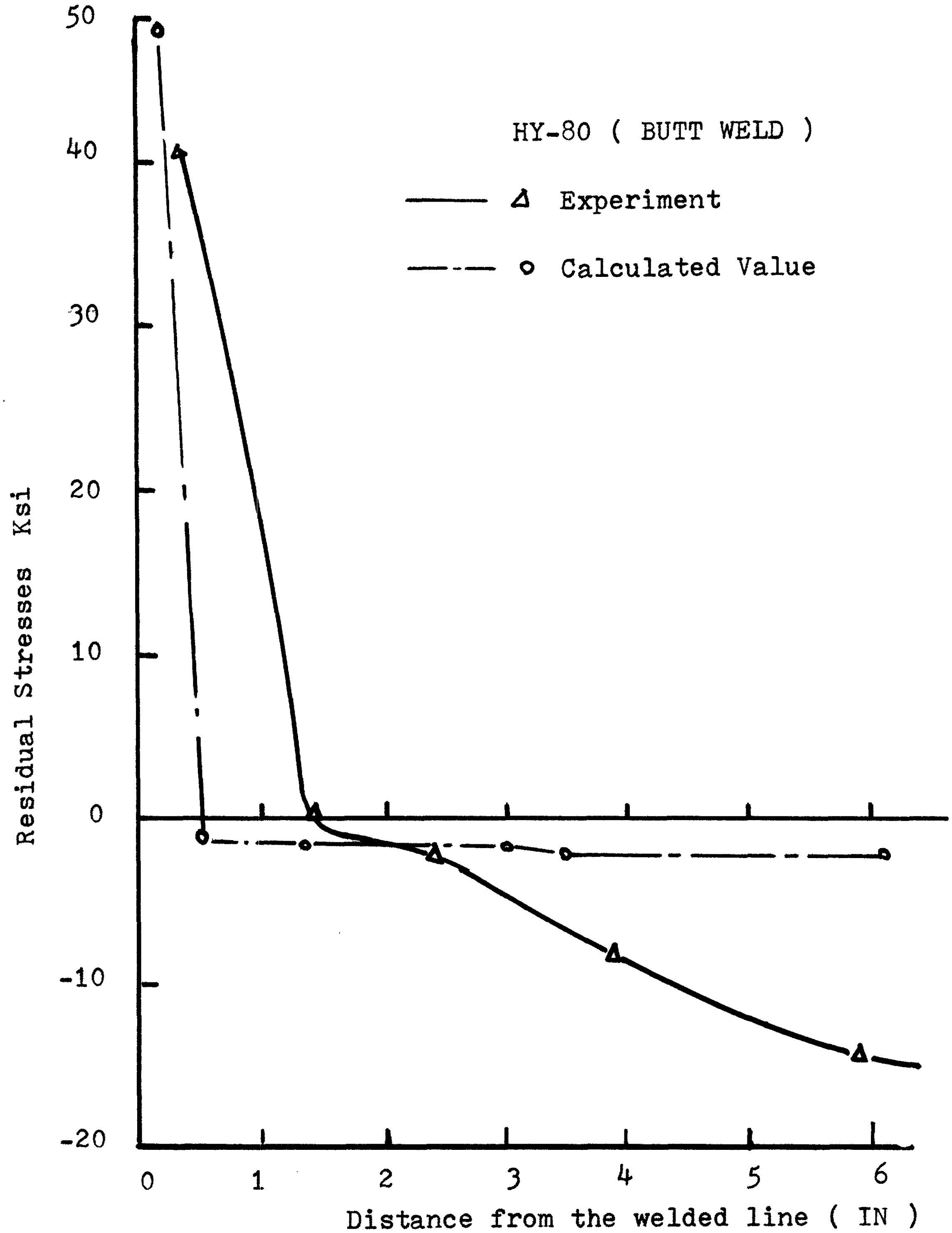


FIG. 57 RESIDUAL STRESSES DISTRIBUTION IN WELDMENT OF HY-80 (BUTT WELD)

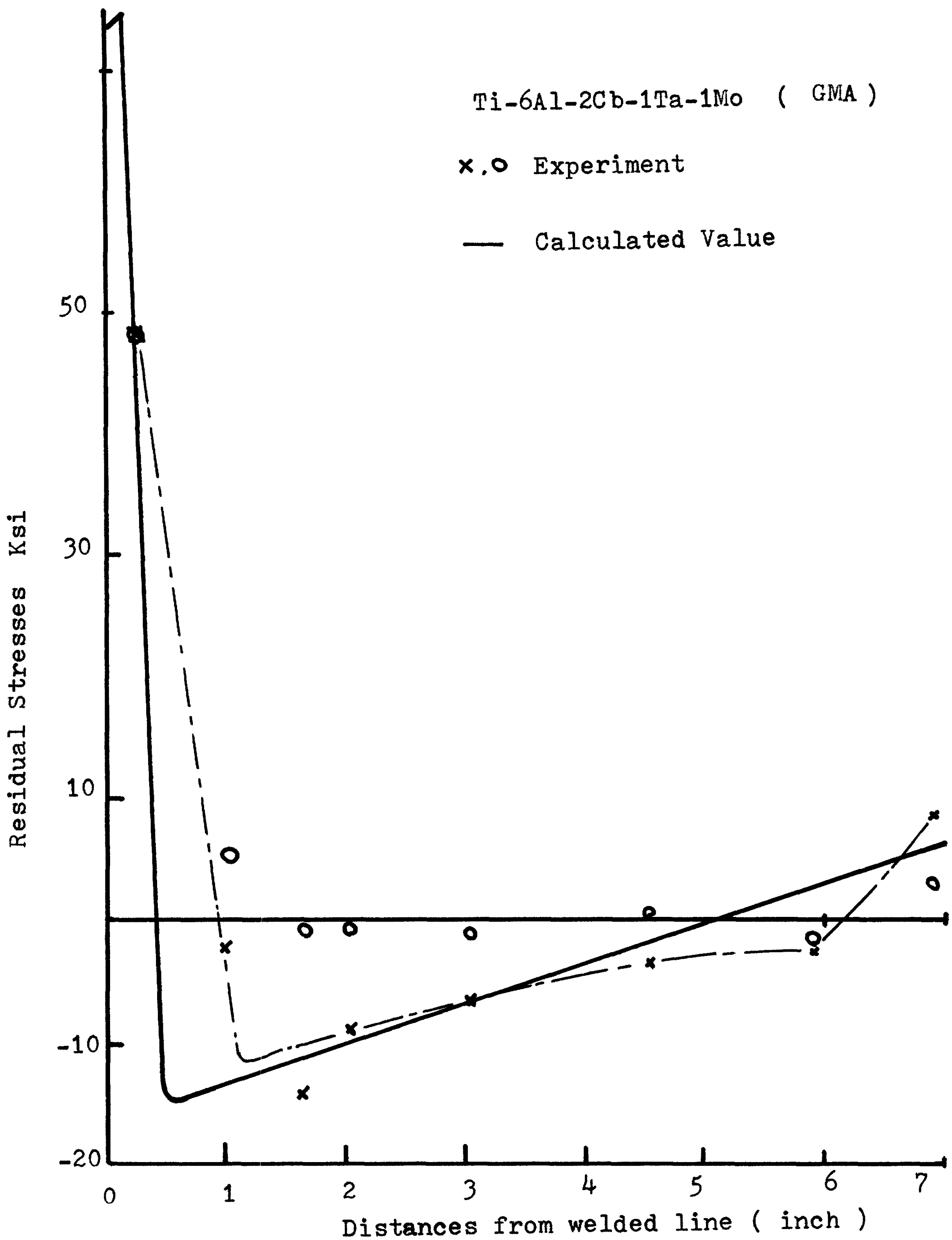


FIG. 58 RESIDUAL STRESSES DISTRIBUTION IN WELDMENT OF TITANIUM ALLOY (GMA)

B. CONCLUSIONS :

1. In comparing temperatures measured with analytical predictions by using 1-Dimensional program, good agreements were obtained if sufficient informations of temperature dependent properties of the materials were used.

2. In comparing strain changes and deflection changes with one dimensional computer program results, it is found that the comparisons are similiar for GTA welded plates but not so good for GMA welded plates.

3. In most cases, the analytical predictions for strain changes by using 1D computer program are tensions when arc just passed over, few seconds later the strain changes become compressions. This may be acceptable for lower yield strength steels (Mild steel and 308 stainless steel) but might be not for high strength steels such as HY-80 and T-1 steel.

4. The residual stresses measured in mild steel and 308 stainless steel weldments are almost as high as the yield strength (GMA) while the residual stresses measured in HY-80, T-1 steel and Ti-6Al-2Cb-1Ta-0.8Mo alloy weldments would be about 50 % of their yield strength.

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APPENDIX A

Experimental Data Reduction Program

Input Data

```
C     EXPERIMENTAL STUDY ON RESIDUAL STRESSES IN WELDMENTS IN VARIOUS MATERIALS
C     WELDING STRAIN-TEMPERATURE VARIATION: EXPERIMENATAL RESULTS.
C     INPUT CARDS TO THIS PROGRAM ARE:
C     CARD 1: NUMBER OF GAGES, VOLTS, AMPS (I5,2F6.0)
C     CARD 2:  COEFFICIENTS FOR COEFFICIENT OF THERMAL EXPANSION
C     POLYNOMIAL (4E15.7)
C     CARD 3:  COEFFICIENTS FOR YOUNG'S MODULUS POLYNOMIAL (4E15.7).
C     CARD 4:  COEFFICIENTS FOR YIELD STRESS (4E15.7).
C     CARD 5:  POISSON'S RATIO (F10.3)
C     CARD 6: STRAIN DATA: TIME; TEMP GAGE 1, TEMP GAGE 2, TEMP GAGE 3;
C             STRAIN, GAGE 1, LEG A, B, C; GAGE 2, LEG A,B, C;
C             GAGE 3, LEG A, B, C. (F8.0, 12F6.2)
C     CARD 7,8,9 ETC.  SAME TYPE OF DATA AS CARD 6.
C     UNITS:  COEFFICIENT OF THERMAL EXPANSION:  MICROSTRAIN/DEGREE
C     FAHRENHEIT;  YOUNGS MODULUS:  PSI; YIELD,STRESS: KSI; STRAINS:
C     MICROSTRAIN.
C     EXPERIMENTAL INPUT DATA
C     MILD STEEL TIG
3    12.0  295.0
 0.67995160E 01-0.13104210E-03 0.17466890E-05-0.41516390E-09
 0.30773660E 02-0.22475010E-01 0.54569240E-04-0.48667890E-07
 0.37925100E 02-0.38644170E-01 0.26984830E-04-0.12265760E-07
0.285
0.0     74.   74.   74.   0.    0.    0.    0.    0.    0.    0.    0.    0.
80.     74.   74.   74.   0.    0.    0.    0.    0.    65.   0.    0.    70.
86.     149.  79.   74.   0.    0.    90.   0.    0.    145.  0.    0.    115.
87.     164.  82.   74.   0.    0.    90.   0.    0.    145.  0.    0.    120.
90.     212.  91.   74.   0.    0.    180.  0.    0.    225.  0.    0.    145.
96.     262.  114.  78.   0.    0.    -370. 0.    0.    340.  0.    0.    235.
104.    279.  148.  88.   0.    0.    -960. 0.    0.    130.  0.    0.    305.
```

```
110.    280.  164.  97.   0.    0.    -1030.0.    0.    -65.  0.    0.    290.
127.    267.  189.  114.  0.    0.    -920. 0.    0.    -370. 0.    0.    160.
134.    263.  194.  126.  0.    0.    -865. 0.    0.    -425. 0.    0.    205.
164.    237.  198.  144.  0.    0.    -700. 0.    0.    -505. 0.    0.    -65.
182.    220.  192.  147.  0.    0.    -640. 0.    0.    -500. 0.    0.    -95.
240.    192.  178.  152.  0.    0.    -550. 0.    0.    -475. 0.    0.    -190.
300.    173.  165.  149.  0.    0.    -505. 0.    0.    -495. 0.    0.    -200.
420.    153.  149.  143.  0.    0.    -485. 0.    0.    -400. 0.    0.    -200.
600.    140.  140.  138.  0.    0.    -450. 0.    0.    -385. 0.    0.    -190.
C     MILD STEEL MIG
3     25.0 380.0
 0.67995160E 01-0.13104210E-03 0.17466890E-05-0.41516390E-09
 0.30773660E 02-0.22475010E-01 0.54569240E-04-0.48667890E-07
 0.37925100E 02-0.38644170E-01 0.26984830E-04-0.12265760E-07
0.285
0.0     91.   91.   91.   0.    0.    0.    0.    0.    0.    0.    0.    0.
50.     91.   91.   91.   0.    0.    0.    0.    0.    0.    0.    0.    0.
60.     91.   91.   91.   0.    0.    0.    0.    0.    60.   0.    0.    95.
70.     109.  94.   91.   0.    0.    615.  0.    0.    445.  0.    0.    315.
73.     144.  99.   91.   0.    0.    925.  0.    0.    700.  0.    0.    425.
78.     229.  116.  91.   0.    0.    850.  0.    0.    865.  0.    0.    625.
106.    462.  231.  135.  0.    0.    0.    0.    0.    185.  0.    0.    590.
120.    478.  321.  163.  0.    0.    0.    0.    0.    20.   0.    0.    345.
150.    445.  354.  215.  0.    0.    0.    0.    0.    -205. 0.    0.    0.
200.    382.  342.  247.  0.    0.    0.    0.    0.    -310. 0.    0.    -225.
250.    334.  318.  255.  0.    0.    0.    0.    0.    -365. 0.    0.    -300.
300.    306.  296.  251.  0.    0.    0.    0.    0.    -370. 0.    0.    -305.
480.    245.  248.  234.  0.    0.    0.    0.    0.    -375. 0.    0.    -300.
600.    225.  230.  223.  0.    0.    0.    0.    0.    -370. 0.    0.    -295.
```

```
C      T-1 STEEL TIG
3    12.0  295.
 0.61895000E 01 0.18420000E-04 0.00000000E 00 0.00000000E 00
 0.31867870E 02-0.22505860E-01 0.38341980E-04-0.25004000E-07
 0.10185860E 03-0.24662080E-01 0.20903410E-04-0.38100020E-07
0.29
0.0      72.    72.    72.    0.     0.     0.     0.     0.     0.     0.     0.     0.
70.      72.    72.    72.    0.     0.     0.     0.     0.     0.     0.     0.     0.
80.      72.    72.    72.    0.     0.     0.     0.     0.     15.    0.     0.     0.
90.      72.    72.    72.    0.     0.     240.   0.     0.     235.   0.     0.     0.
100.     91.    73.    72.    0.     0.     950.   0.     0.     630.   0.     0.     0.
105.     157.   77.    72.    0.     0.     520.   0.     0.     780.   0.     0.     55.
115.     235.   105.   76.    0.     0.     50.    0.     0.     655.   0.     0.     125.
120.     247.   119.   77.    0.     0.     -50.   0.     0.     550.   0.     0.     150.
132.     262.   148.   78.    0.     0.     -125.  0.     0.     300.   0.     0.     165.
140.     263.   166.   88.    0.     0.     -135.  0.     0.     160.   0.     0.     150.
147.     262.   183.   96.    0.     0.     -130.  0.     0.     110.   0.     0.     150.
160.     255.   190.   108.   0.     0.     -110.  0.     0.     -10.   0.     0.     125.
170.     250.   191.   117.   0.     0.     -90.   0.     0.     -40.   0.     0.     110.
190.     238.   192.   130.   0.     0.     -60.   0.     0.     -50.   0.     0.     85.
240.     210.   188.   149.   0.     0.     0.     0.     0.     -35.   0.     0.     25.
300.     192.   182.   161.   0.     0.     20.    0.     0.     -25.   0.     0.     0.
600.     163.   162.   161.   0.     0.     100.   0.     0.     -10.   0.     0.     0.
C      T-1 STEEL MIG
3    24.0  420.0
 0.61895000E 01 0.18420000E-04 0.00000000E 00 0.00000000E 00
 0.31867870E 02-0.22505860F-01 0.38341980E-04-0.25004000E-07
 0.10185860E 03-0.24662080F-01 0.20903410E-04-0.38100020E-07
```

```
0.29
0.0      78.   78.   78.   0.    0.    0.    0.    0.    0.    0.    0.    0.
60.      78.   78.   78.   0.    0.    0.    0.    0.    20.   0.    0.    0.
64.      78.   78.   78.   0.    0.    0.    0.    0.    120.  0.    0.    35.
66.      78.   78.   78.   0.    0.    0.    0.    0.    260.  0.    0.    50.
79.      78.   78.   78.   0.    0.    0.    0.    0.    675.  0.    0.    0.
85.      80.   111.  80.   0.    0.    0.    0.    0.    1465. 0.    0.    240.
90.      78.   148.  82.   0.    0.    0.    0.    0.    1375. 0.    0.    310.
100.     78.   213.  93.   0.    0.    0.    0.    0.    1150. 0.    0.    425.
110.     78.   262.  107.  0.    0.    0.    0.    0.    950.  0.    0.    520.
120.     80.   286.  127.  0.    0.    0.    0.    0.    740.  0.    0.    560.
150.     80.   348.  187.  0.    0.    0.    0.    0.    445.  0.    0.    590.
180.     80.   366.  233.  0.    0.    0.    0.    0.    265.  0.    0.    590.
250.     80.   354.  278.  0.    0.    0.    0.    0.    85.   0.    0.    625.
300.     80.   341.  298.  0.    0.    0.    0.    0.    25.   0.    0.    665.
480.     80.   324.  301.  0.    0.    0.    0.    0.    -40.  0.    0.    655.
600.     80.   294.  286.  0.    0.    0.    0.    0.    -40.  0.    0.    650.
C      308 STAINLESS STEEL TIG
3     12.0  300.0
 0.83923077E 01 0.30769230E-02 0.00000000E 00 0.00000000E 00
 0.28703120E 02-0.56899560E-02-0.79157770E-05 0.53025880E-08
 0.32736700E 02-0.37249370E-01 0.39439890E-05-0.17927220E-07
0.32
0.0      72.   72.   72.   0.    0.    0.    0.    0.    0.    0.    0.    0.
80.      72.   72.   72.   0.    0.    0.    0.    0.    0.    0.    0.    0.
85.      72.   72.   72.   0.    0.    35.   0.    0.    65.   0.    0.    0.
91.      74.   72.   72.   0.    0.    335.  0.    0.    215.  0.    0.    0.
94.      79.   73.   72.   0.    0.    470.  0.    0.    220.  0.    0.    45.
106.     126.  75.   72.   0.    0.    300.  0.    0.    460.  0.    0.    -15.
120.     212.  83.   72.   0.    0.    -650. 0.    0.    510.  0.    0.    75.
140.     260.  111.  73.   0.    0.    -1090.0.    0.    305.  0.    0.    165.
```

```
160.     272.  139.  78.   0.    0.    -1175.0.    0.    55.   0.    0.    210.
186.     272.  163.  87.   0.    0.    -1150.0.    0.    -190. 0.    0.    200.
220.     262.  178.  98.   0.    0.    -1090.0.    0.    -350. 0.    0.    160.
250.     251.  185.  110.  0.    0.    -1035.0.    0.    -450. 0.    0.    115.
300.     232.  185.  123.  0.    0.    -920. 0.    0.    -500. 0.    0.    60.
420.     203.  178.  138.  0.    0.    -875. 0.    0.    -525. 0.    0.    15.
540.     184.  169.  145.  0.    0.    -825. 0.    0.    -515. 0.    0.    0.
C      308 STAINLESS STEEL BEAD-ON-EDGE WITH GMA PROCESS
3    27.   250.
 0.83923077E 01 0.30769230E-02 0.00000000E 00 0.00000000E 00
 0.28703120E 02-0.56899560E-02-0.79157770E-05 0.53025880E-08
 0.32736700E 02-0.37249370E-01 0.39439890E-05-0.17927220E-07
0.32
0.       73.   73.   73.   0.    0.    0.    0.    0.    0.    0.    0.    0.
43.      73.   73.   73.   0.    0.    0.    0.    0.    0.    0.    0.    0.
45.      73.   73.   73.   0.    0.    50.   0.    0.    70.   0.    0.    0.
47.      73.   73.   73.   0.    0.    190.  0.    0.    140.  0.    0.    0.
48.      73.   73.   73.   0.    0.    230.  0.    0.    150.  0.    0.    -10.
50.      73.   73.   73.   0.    0.    335.  0.    0.    180.  0.    0.    -30.
53.      73.   73.   73.   0.    0.    625.  0.    0.    300.  0.    0.    -30.
55.      73.   73.   73.   0.    0.    740.  0.    0.    450.  0.    0.    20.
57.      76.   73.   73.   0.    0.    710.  0.    0.    500.  0.    0.    35.
63.      93.   73.   73.   0.    0.    375.  0.    0.    520.  0.    0.    65.
75.      166.  78.   73.   0.    0.    -375. 0.    0.    500.  0.    0.    100.
90.      208.  91.   73.   0.    0.    -850. 0.    0.    375.  0.    0.    130.
110.     228.  117.  76.   0.    0.    -1050.0.    0.    175.  0.    0.    100.
134.     231.  137.  81.   0.    0.    -1085.0.    0.    -40.  0.    0.    170.
156.     231.  153.  88.   0.    0.    -1065.0.    0.    -190. 0.    0.    150.
180.     224.  160.  96.   0.    0.    -1025.0.    0.    -300. 0.    0.    125.
240.     210.  168.  112.  0.    0.    -950. 0.    0.    -455. 0.    0.    50.
300.     197.  166.  122.  0.    0.    -890. 0.    0.    -500. 0.    0.    15.
420.     172.  155.  133.  0.    0.    -835. 0.    0.    -525. 0.    0.    -70.
```

```
C     TITANIUM ALLOY TI-6AL-2TA-1CB-0.8MO BEAD-ON-EDGE WITH GMA PROCESS
3    28.0  300.0
 0.50000000E 01 0.50000000E-03 0.00000000E 00 0.00000000E 00
 0.18325690E 02-0.11698760E-01 0.18839200E-04-0.14226140E-07
 0.10185860E 03-0.24662080E-01 0.20903410E-04-0.38100020E-07
0.32
0.0     80.   80.   80.   0.    0.    0.    0.    0.    0.    0.    0.    0.
58.     93.   84.   80.   5.    -35.  -15.  -25.  50.   50.   0.    0.    60.
60.     103.  85.   82.   -15.  -85.  -25.  -65.  80.   90.   0.    0.    80.
62.     110.  86.   83.   -20.  -85.  -50.  -65.  90.   130.  0.    0.    90.
63.     113.  87.   84.   -50.  -65.  5.    -80.  45.   155.  0.    0.    85.
64.     127.  90.   85.   -65.  -60.  40.   -95.  55.   215.  0.    0.    85.
65.     167.  91.   87.   80.   -55.  20.   -65.  105.  250.  0.    0.    90.
67.     272.  91.   90.   165.  -305. -165. -25.  210.  275.  0.    0.    100.
69.     365.  95.   92.   5.    -440. 70.   10.   295.  315.  0.    0.    115.
71.     420.  99.   95.   -185. -515. 145.  25.   350.  370.  0.    0.    125.
73.     475.  100.  -395. -510. -65.  25.   425.  430.  0.    0.    0.    125.
75.     524.  112.  105.  -475. -425. -625. 30.   515.  500.  0.    0.    130.
77.     570.  118.  112.  -405. -400. -1130.50.   505.  520.  0.    0.    300.
80.     615.  128.  120.  0.    0.    0.    65.   490.  520.  0.    0.    205.
90.     665.  164.  150.  0.    0.    0.    30.   355.  450.  0.    0.    300.
110.    628.  228.  200.  0.    0.    0.    150.  180.  0.    0.    0.    325.
200.    460.  303.  240.  0.    0.    0.    -550. -215. 10.   0.    0.    280.
300.    370.  287.  230.  0.    0.    0.    -685. -305. 35.   0.    0.    175.
360.    330.  272.  220.  0.    0.    0.    -690. -305. 65.   0.    0.    110.
480.    289.  240.  210.  0.    0.    0.    -670. -300. 80.   0.    0.    100.
600.    235.  219.  205.  0.    0.    0.    -510. -210. 100.  0.    0.    45.
```

```
C      HY-80 LOW-CARBON ALLOY STEEL BUTT WELD WITH GMA PROCESS
3    25.  300.
 0.59497580E 02 0.48719710E-02-0.64703990E-05 0.36986670E-08
 0.38678700E 02 0.22505860E-01 0.38341980E-04-0.25004000E-07
 0.81311010E 02-0.20247190E-01 0.53275590E-04-0.62909400E-07
0.29
0.0      73.    73.    73.    0.     0.     0.     0.     0.     0.     0.     0.     0.
20.      74.    73.    73.    0.     -40.   -25.   -30.   -5.    -25.   0.     0.     0.
23.      75.    73.    73.    30.    -65.   -60.   -80.   0.     -60.   0.     0.     0.
25.      76.    73.    73.    75.    -50.   -90.   95.    40.    -55.   0.     0.     0.
27.      77.    73.    73.    125.   60.    -35.   120.   90.    0.     0.     0.     0.
29.      78.    73.    73.    100.   120.   135.   90.    125.   95.    0.     0.     0.
31.      79.    73.    73.    170.   85.    165.   110.   100.   140.   0.     0.     0.
34.      81.    73.    73.    325.   0.     60.    200.   50.    85.    0.     0.     0.
37.      86.    73.    73.    400.   50.    -75.   275.   70.    0.     0.     0.     0.
40.      91.    73.    73.    350.   75.    -125.  325.   90.    -50.   0.     0.     0.
43.      101.   73.    73.    270.   85.    -125.  325.   106.   -80.   0.     0.     0.
50.      122.   76.    73.    150.   75.    -115.  300.   125.   -50.   0.     0.     0.
60.      152.   81.    73.    -125.  35.    -85.   260.   125.   -40.   0.     0.     0.
70.      169.   89.    73.    -225.  0.     -70.   220.   95.    -35.   0.     0.     0.
80.      175.   98.    73.    -290.  -20.   -60.   165.   75.    -30.   0.     0.     0.
100.     183.   114.   73.    -350.  -40.   -35.   50.    30.    -10.   0.     0.     0.
120.     181.   124.   73.    -350.  -35.   0.     0.     0.     0.     0.     0.     0.
180.     168.   134.   80.    -300.  -25.   35.    -85.   -25.   15.    0.     0.     0.
240.     157.   134.   73.    -240.  0.     45.    -90.   -20.   40.    0.     0.     0.
420.     128.   121.   73.    -125.  65.    70.    -75.   0.     50.    0.     0.     0.
600.     121.   117.   73.    -60.   80.    85.    -60.   20.    60.    0.     0.     0.
$STOP
/*
/*EOJ ********
```

APPENDIX B

Input Data For Temperature and Strain Calculations

```
//G.SYSIN DD *
25.       380.      0.55      0.50      0.322
MILD STEEL MIG
70.0    200.0   300.0   400.0   500.0   600.0   700.0   800.0   1000.0  1200.0
0.687   0.677   0.677   0.655   0.640   0.626   0.594   0.565   0.534   0.490
109.0   120.0   126.0   132.0   137.0   140.0   155.0   159.0   167.0   169.0
0.283   0.283   0.283   0.283   0.283   0.283   0.283   0.283   0.283   0.283
30.0    29.6    29.0    28.8    28.0    27.7    27.0    26.0    22.7    14.0
35.     32.     28.     26.     23.5    18.     24.5    22.8    14.2    0.0
6.50    6.65    6.80    6.95    7.10    7.25    7.40    7.60    8.05    8.5
0.      0.      0.      0.      0.      0.      0.      0.      0.      0.

01
01
0.0
0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50
6.0       2800.     71.       91.
120.      2.        200.      20.       600.      40.       50.
50000.0

12.0      295.0     0.55      0.268
MILD STEEL TIG
70.0    200.0   300.0   400.0   500.0   600.0   700.0   800.0   1000.0  1200.0
0.687   0.677   0.677   0.655   0.640   0.626   0.594   0.565   0.534   0.490
109.0   120.0   126.0   132.0   137.0   140.0   155.0   159.0   167.0   169.0
0.283   0.283   0.283   0.283   0.283   0.283   0.283   0.283   0.283   0.283
30.0    29.6    29.0    28.8    28.0    27.7    27.0    26.0    22.7    14.0
35.     32.     28.     26.     23.5    18.     24.5    22.8    14.2    0.0
6.50    6.65    6.80    6.95    7.10    7.25    7.40    7.60    8.05    8.5
0.      0.      0.      0.      0.      0.      0.      0.      0.      0.

01
01
0.0
0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50   0.50
6.0       2800.     94.       73.
120.      2.        200.      20.       600.      40.       75.
50000.0
```

```
27.         250.        0.43        0.50        0.47
308 SYAINLESS STEFL MIG
70.0      200.0     300.0     400.0     500.0     600.0     700.0     800.0     1000.0    1200.0
0.229     0.240     0.255     0.271     0.295     0.312     0.334     0.350     0.374     0.396
126.48    129.80    134.50    149.00    145.50    151.20    157.20    163.50    170.20    178.60
0.288     0.288     0.288     0.288     0.288     0.288     0.288     0.288     0.288     0.288
28.2      27.35     26.5      25.5      24.5      23.5      22.6      21.8      20.4      18.8
32.85     29.38     26.50     24.07     23.10     21.70     20.70     19.50     17.20     14.10
8.5       8.95      9.25      9.6       9.95      10.25     10.6      10.9      11.5      12.1
0.        0.        0.        0.        0.        0.        0.        0.        0.        0.

01
01
.0
0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50
6.0         2600.       51.         73.
120.        2.          200.        20.         600.        40.         40.
50000.0

12.0        324.        0.51        0.50        0.258

308 STAINLESS STEFL  TIG
70.0      200.0     300.0     400.0     500.0     600.0     700.0     800.0     1000.0    1200.0
0.229     0.240     0.255     0.271     0.295     0.312     0.334     0.350     0.374     0.396
126.48    129.80    134.50    149.00    145.50    151.20    157.20    163.50    170.20    178.60
0.288     0.288     0.288     0.288     0.288     0.288     0.288     0.288     0.288     0.288
28.2      27.35     26.5      25.5      24.5      23.5      22.6      21.8      20.4      18.8
32.85     29.38     26.50     24.07     23.10     21.70     20.70     19.50     17.20     14.10
8.5       8.95      9.25      9.6       9.95      10.25     10.6      10.9      11.5      12.1
0.        0.        0.        0.        0.        0.        0.        0.        0.        0.

01
01
0.0
0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50
6.0         2400.       97.         72.
120.        2.          200.        20.         600.        40.         75.
50000.0
```

```
25.0      420.0     0.55      0.50      0.333
T-1 STEEL MIG
70.0      200.0     300.0     400.0     500.0     600.0     700.0     800.0     1000.0    1200.0
0.473     0.498     0.511     0.525     0.528     0.532     0.525     0.517     0.476     0.417
112.78    115.94    120.16    124.37    128.59    132.80    138.07    143.34    156.00    177.07
0.283     0.283     0.283     0.283     0.283     0.283     0.283     0.283     0.283     0.283
30.0      29.6      29.0      28.8      28.0      27.7      27.0      26.0      22.7      14.0
105.      104.      103.      102.      100.      97.0      95.0      88.0      67.5      35.5
6.50      6.65      6.80      6.95      7.10      7.25      7.40      7.60      8.05      8.5
0.        0.        0.        0.        0.        0.        0.        0.        0.        0.

01
01
.0
0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
6.0       2800.     67.       78.
120.      2.        200.      10.       600.      40.       60.
50000.0

12.0      295.0     0.48      0.50      0.255
T-1 STEEL TIG.
70.0      200.0     300.0     400.0     500.0     600.0     700.0     800.0     1000.0    1200.0
0.473     0.498     0.511     0.525     0.528     0.532     0.525     0.517     0.476     0.417
112.78    115.94    120.16    124.37    128.59    132.80    138.07    143.34    156.00    177.07
0.283     0.283     0.283     0.283     0.283     0.283     0.283     0.283     0.283     0.283
30.0      29.6      29.0      28.8      28.0      27.7      27.0      26.0      22.7      14.0
105.      104.      103.      102.      100.      97.0      95.0      88.0      67.5      35.5
6.50      6.65      6.80      6.95      7.10      7.25      7.40      7.60      8.05      8.5
0.        0.        0.        0.        0.        0.        0.        0.        0.        0.

01
01
0.0
0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
6.0       2800.0    90.       72.
120.      2.        200.      20.       600.      40.       80.
50000.0
```

```
28.0      300.0     0.40      0.50      0.358
TIYANIUM ALLOY TI-6AL-2CB-1TA-1MO
70.00     200.0     400.0     600.0     800.0     1000.0    1200.0    1400.0    1600.0    1800.0

0.098     0.108     0.126     0.147     0.169     0.191     0.212     0.234     0.256     0.277
128.7     139.3     149.8     160.4     170.9     181.5     192.0     202.6     213.1     223.6
0.163     0.163     0.163     0.163     0.163     0.163     0.163     0.163     0.163     0.163
17.5      16.3      15.4      14.4      13.3      12.3      9.50      6.17      2.83      0.0
100.0     90.5      81.0      71.6      62.1      52.6      43.1      31.7      14.6      0.0
5.00      5.08      5.17      5.25      5931      5.37      5.48      5.57      5.64      5.70
0.        0.        0.        0.        0.        0.        0.        0.        0.        0.

01
01
0.0
0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50
6.0        1800.0     70.0       80.0
120.0      2.0        200.0      20.0       600.0      40.0       54.0
50000.0

25.0      300.0     0.69      0.50      0.483
HY-80 HIGH STRENGTH STEEL  MIG
70.0      200.0     300.0     400.0     500.0     600.0     700.0     800.0     1000.0    1200.0
0.473     0.498     0.511     0.525     0.528     0.532     0.525     0.517     0.476     0.417
112.78    115.94    120.16    124.37    128.59    132.80    138.07    143.34    156.00    177.07
0.283     0.283     0.283     0.283     0.283     0.283     0.283     0.283     0.283     0.283
30.0      29.6      29.0      28.8      28.0      27.7      27.0      26.0      22.7      14.0
82.       81.2      80.4      79.6      78.0      75.6      74.       68.4      52.       28.4
6.50      6.65      6.80      6.95      7.10      7.25      7.40      7.60      8.05      8.5
0.        0.        0.        0.        0.        0.        0.        0.        0.        0.

01
.0
0.25     0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50     0.50
7.5        2800.0     30.        73.
100.       2.         200.       10.        600.       40.        20.
50000.0
```