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Mechanical test, high temperature
Induction heating
Instrumentation

WAL TR 116/1 ✓

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APPLICATION OF INDUCTION HEATING TO SHORT-TIME ELEVATED TEMPERATURE TENSILE TESTING

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TECHNICAL REPORT NO. WAL TR 116/1

BY

ALBERT P. LEVITT

ANTHONY G. MARTIN

JUNE 1959

O.O. PROJECT: TB4-004, HIGH TEMPERATURE MATERIALS
D/A PROJECT: 5B93-32-004

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APPLICATION OF INDUCTION HEATING TO SHORT-TIME ELEVATED TEMPERATURE TENSILE TESTING

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TITLE

APPLICATION OF INDUCTION HEATING TO SHORT-TIME ELEVATED TEMPERATURE TENSILE TESTING

ABSTRACT

Techniques and apparatus were investigated and developed for conducting short-time elevated temperature tensile tests utilizing high frequency induction heating. By use of this method, metal specimens are heated rapidly to a predetermined temperature and then loaded at various strain rates. Proportional temperature control equipment for the induction heater was developed for this testing technique. Tensile test data were obtained at 600°, 800°, and 1000°F on 120 plain and welded titanium alloy specimens. Typical results obtained are given and the limitations and possibilities of the technique discussed.

Albert P. Levitt
ALBERT P. LEVITT
Mechanical Engineer

Anthony G. Martin
ANTHONY G. MARTIN
Electronic Engineer

APPROVED:

J. F. Sullivan
J. F. SULLIVAN
Director
Watertown Arsenal Laboratories

REPORT APPROVED
Date- 9 June 59
WAL Board of Review
Chairman-

INTRODUCTION

The full and proper utilization of materials for rockets and guided missiles is dependent on knowledge of the properties of the materials at high temperatures. Since some missile components attain high temperatures in a very short time, simulation of these conditions is required in order to obtain the necessary property data. For this purpose tensile specimens must be heated rapidly to the test temperature in a matter of seconds.

Methods of rapid heating applicable to tensile testing include induction heating, resistance heating (by direct application of electrical power to the specimen), and the immersion in hot molten substances. Resistance heating and immersion heating techniques are the methods which have been used generally in the past.

Induction heating offers the following advantages over other heating methods:

a. It prevents overheating of the necked-down region of the loaded specimen as necking progresses.

b. It permits heating the specimen without direct contact of the specimen with the heat source.

c. It eliminates the problem of specimen contamination by the heating medium.

In order to exploit the capabilities of induction heating, an investigation was conducted on its use for short-time elevated temperature tensile tests. Techniques and equipment evolved were put to use in tests on titanium alloy specimens for a project conducted for the Army Ballistic Missile Agency.

DESCRIPTION OF APPARATUS AND SPECIMENS

Test System

Figure 1 is a photograph of the assembled test system. It consists of a 20 kva output induction heater which is used in conjunction with a Tinius Olsen Universal Testing Machine. By means of an especially designed electronic control circiut, the test specimen shown mounted on the tensile tester is rapidly heated by the surrounding induction coil to a predetermined temperature. The test specimen may be loaded before or after heating, as desired, and pulled over a range of strain rates. Figure 2 is an enlarged view of the test specimen mounted in the induction work coil. A detailed description of each element of this testing system follows.

Induction Heater

The induction heater available for this study was a 20 kva output Scientific Electric unit operating at an output frequency of 450 kc. A three-phase full-wave rectifier provided the high d-c voltage which

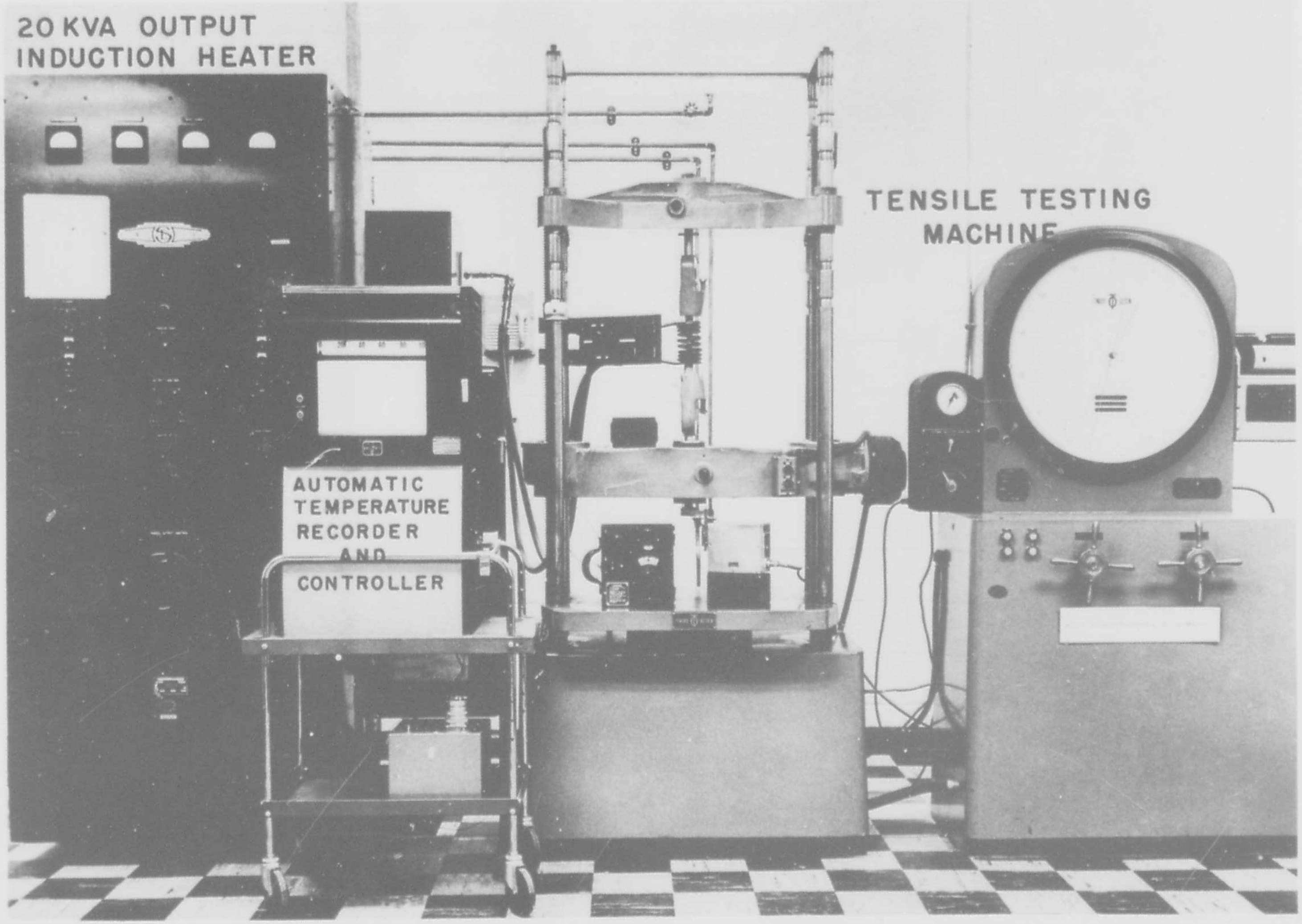

FIGURE I HIGH TEMPERATURE TENSILE TESTING APPARATUS

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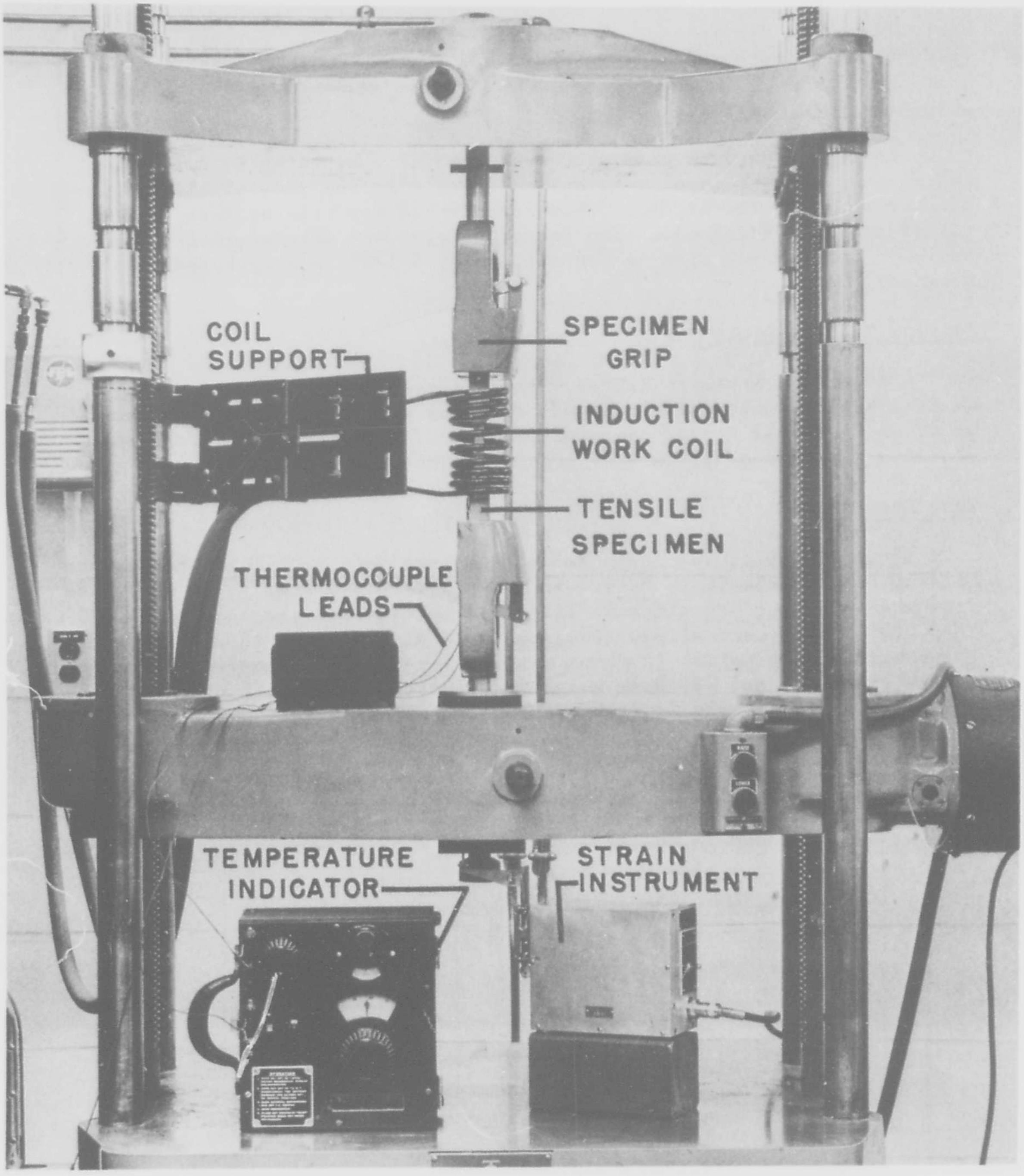

FIGURE 2 CLOSEUP OF TEST SPECIMEN, INDUCTION COIL, AND INSTRUMENTATION.

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supplied the power for the oscillator circuit. Since the power output depends on the d-c voltage, it was decided to control temperature by controlling the d-c voltage. A control system for this purpose was developed by the authors and will be described later.

Induction Work Coil

The induction work coil used consisted of nine turns of 5/16"-OD copper tubing. The turns were spaced closely at the ends of the coil and farther apart at the middle. This compensated for greater heat loss at the ends of the specimens. The proper spacing was determined experimentally. The over-all size was approximately 5-1/2" in length and 3" in diameter.

Testing Machine Equipment

A 60,000-lb capacity Tinius Olsen universal-type hydraulic testing machine equipped with an electronic recorder was utilized in the tests. An Olsen Universal Strain Instrument, in conjunction with the recorder, provided a record of cross-head travel versus load.

Test Specimens

About 120 specimens, both welded and unwelded, were furnished by the Welding Research Section, Watertown Arsenal Laboratories. They were made from sheets of various titanium alloys in thicknesses ranging from 0.031" to 0.078". From each alloy, specimens were divided into three groups: (1) unwelded base metal, (2) base metal welded at right angles to the length of the specimen, and (3) base metal welded along the length of the specimen. The over-all size of each specimen was 9" in length and 1" in width. The gage section was 2" long and 1/2" wide. The specimen configuration is given in Figure 3.

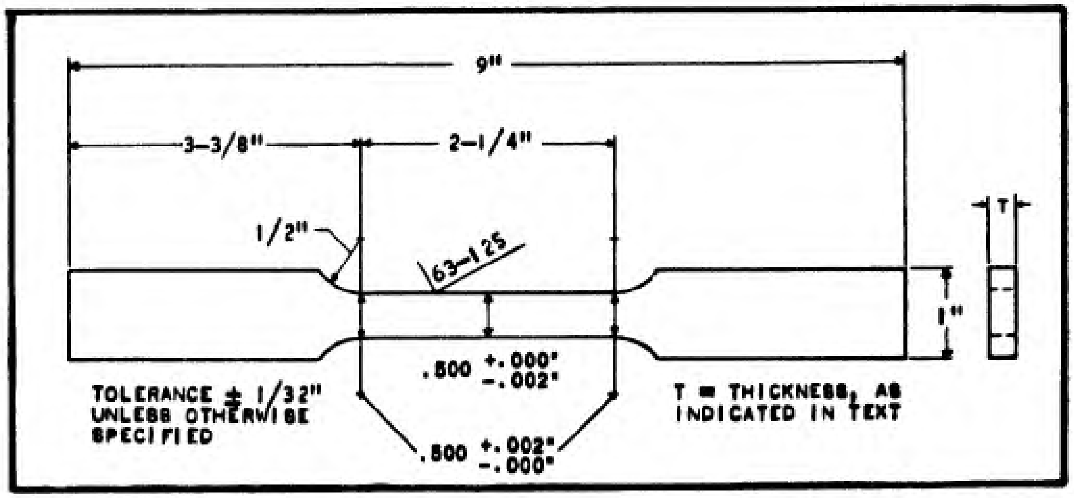


FIGURE 3: FLAT TENSILE SPECIMEN FOR 2-INCH GAGE LENGTH

Temperature Sensing Elements

Two types of high temperature sensing elements are generally used for recording and controlling purposes: total radiation pyrometers and thermocouples. Either type can be used with the control apparatus which has been developed. Radiation pyrometers have the advantage of not requiring physical contact and of being usable at temperatures above the range of thermocouples. However, below 800°F the low voltage output of fast-response radiation pyrometers limits their usefulness; also, their accuracy depends on the thermal emissivity of the specimens. Consequently, for tests which were made at 600°, 800°, and 1000°F, chromel-alumel thermocouples were used.

The thermocouple wire consisted of duplex fibreglass-insulated B&S gauge No. 28 chromel and alumel wire. The ends were bared and the two wires individually spot-welded on the specimens at points approximately 1/32" apart. This method of joining the thermocouple to the specimen has the advantage of not interposing any mass between the thermocouple junction and the specimen's surface. Since the specimen and thermocouples are exposed to cool surroundings, a conventional thermocouple bead could introduce an error through having the actual point of contact between the two wires separated from the specimen's surface by the thermocouple bead.

Three such thermocouples were utilized. These were located at the top, middle, and bottom positions on the test section. The middle thermocouple was used for measurement and control purposes. The end thermocouples served for checking temperature distribution. Filter circuits were placed between the thermocouples and the temperature measuring instruments to bypass induced r-f currents.

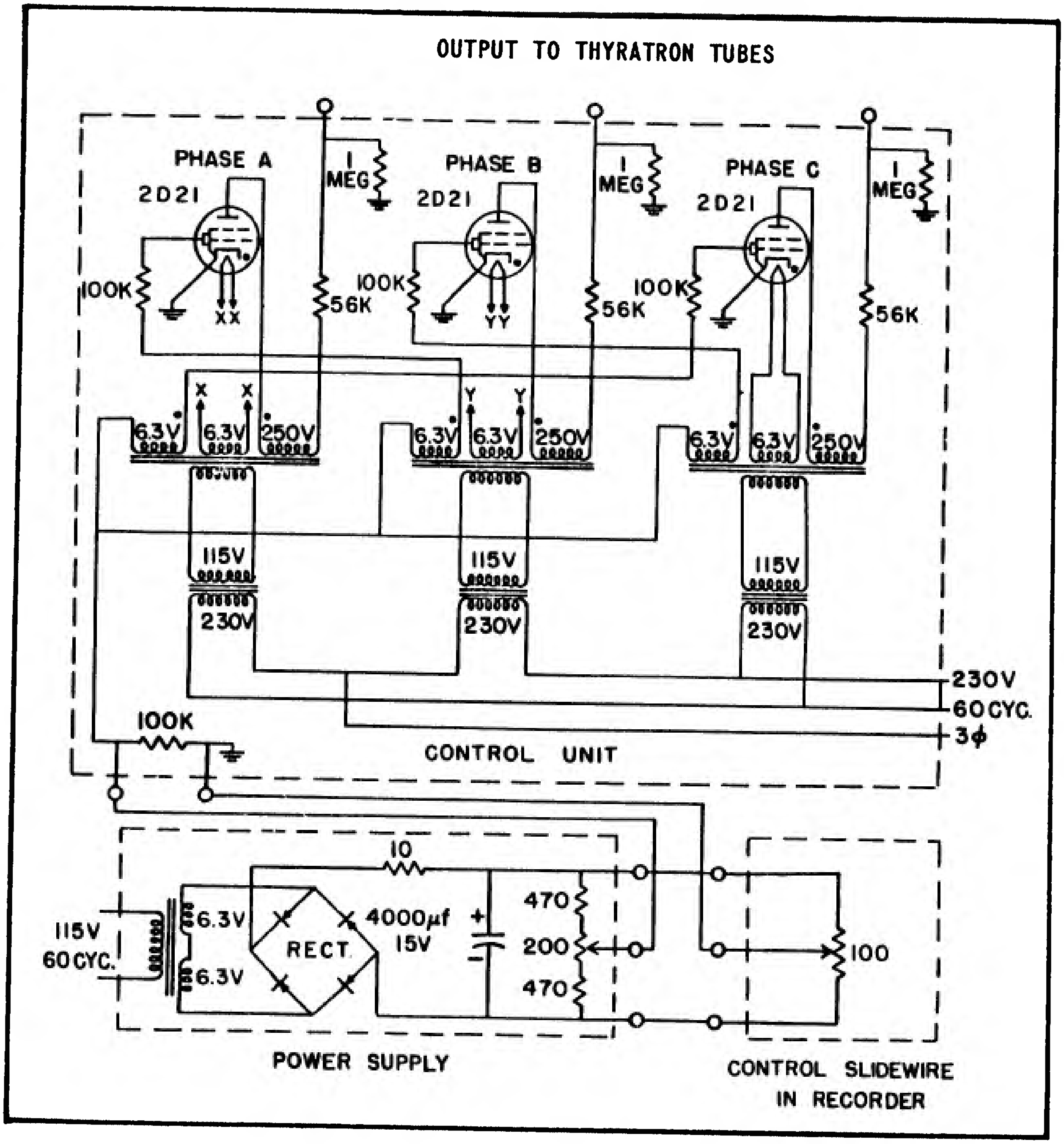
Temperature Instruments

The end thermocouples were connected to a twin-input, hand-operated, temperature indicator. The middle thermocouple was connected through a reference junction maintained at 150°F to a recorder-controller calibrated in millivolts and equipped with a control slidewire. The slidewire is mechanically lined to the recorder pen drive such that the position of the wiper arm varies with the deviation of the temperature from the manually set control point, within a band width of ± 5% of scale range.

Control Equipment

A. Bridge Circuit

The control slidewire is connected into a bridge circuit powered by a 12-volt d-c power supply. The bridge circuit and power supply are diagrammed in Figure 4. The bridge output is a d-c voltage that varies in amplitude and polarity with the temperature deviation. An adjustment is provided to enable varying the balance point slightly.



CIRCUIT DIAGRAM OF POWER SUPPLY, CONTROL SLIDEWIRE, AND CONTROL UNIT

FIGURE 4

B. Control Unit

The control unit converts variations of the bridge output into variations of the time at which control pulses are generated by miniature thyratrons. The circuit is illustrated in Figure 4. For the sake of simplicity, approximations of thyratron characteristics are used in the discussion. It shall be assumed that the tubes start conducting current at the instant the grid becomes positive, provided that the plate is positive; also, that once current flows, it will continue until the plate voltage approaches zero.

Voltage from Phase A of the line voltage is applied to the plate of a 2D21 thyratron. Voltage from Phase B, lagging A by 120° is applied to the grid. In the absence of other grid voltage, the time at which the tube starts conducting is advanced or retarded accordingly.

When the tube fires, current instantly flows in the plate circuit and a pulse appears at the output transformer. A pulse is produced once every cycle. Its timing is controlled by the deviation of the temperature from the control point. The other phases produce pulses in the same fashion once every cycle, the pulses in any phase lagging or leading pulses in other phases by 120°. These pulses are applied to rectifier tubes in the induction unit rectifier section.

The rectifier section employed six type 575A diodes. Three of these were replaced by type 678 thyratrons (grid-controlled rectifiers) of equivalent current and voltage ratings, one for each phase. These were placed in the positive side of the rectifier circuit to provide a common cathode connection. A battery supply was added to bias the grids negatively, preventing current flow in the absence of control pulses. A pair of filament transformers with high voltage insulation were connected back-to-back to couple each grid to the proper output signal from the control unit. This circuit is illustrated in Figure 5.

Power control is achieved by controlling, in each cycle, the time during which the rectifier tubes conduct. When a control pulse appears in the grid circuit of one phase, it overcomes the negative bias voltage and permits current flow which then continues until the plate-to-cathode voltage approaches zero.

In a three-phase full-wave rectifier, the voltage across each thyratron is not a simple sine wave voltage; it is a double-peaked voltage due to added components from the other phases. Maximum output is obtained with the trigger pulse at 30°. When the pulse is retarded in response to a rise in temperature (as the temperature approaches the control point), the output drops. If the temperature keeps rising, the output gradually drops until it reaches a low level (as the control pulse approaches 180°) and then abruptly drops to zero. Unless the input required is very low, a condition of equilibrium is rapidly reached, such that the input power is just sufficient to maintain the temperature of the specimen at a level within the control band.

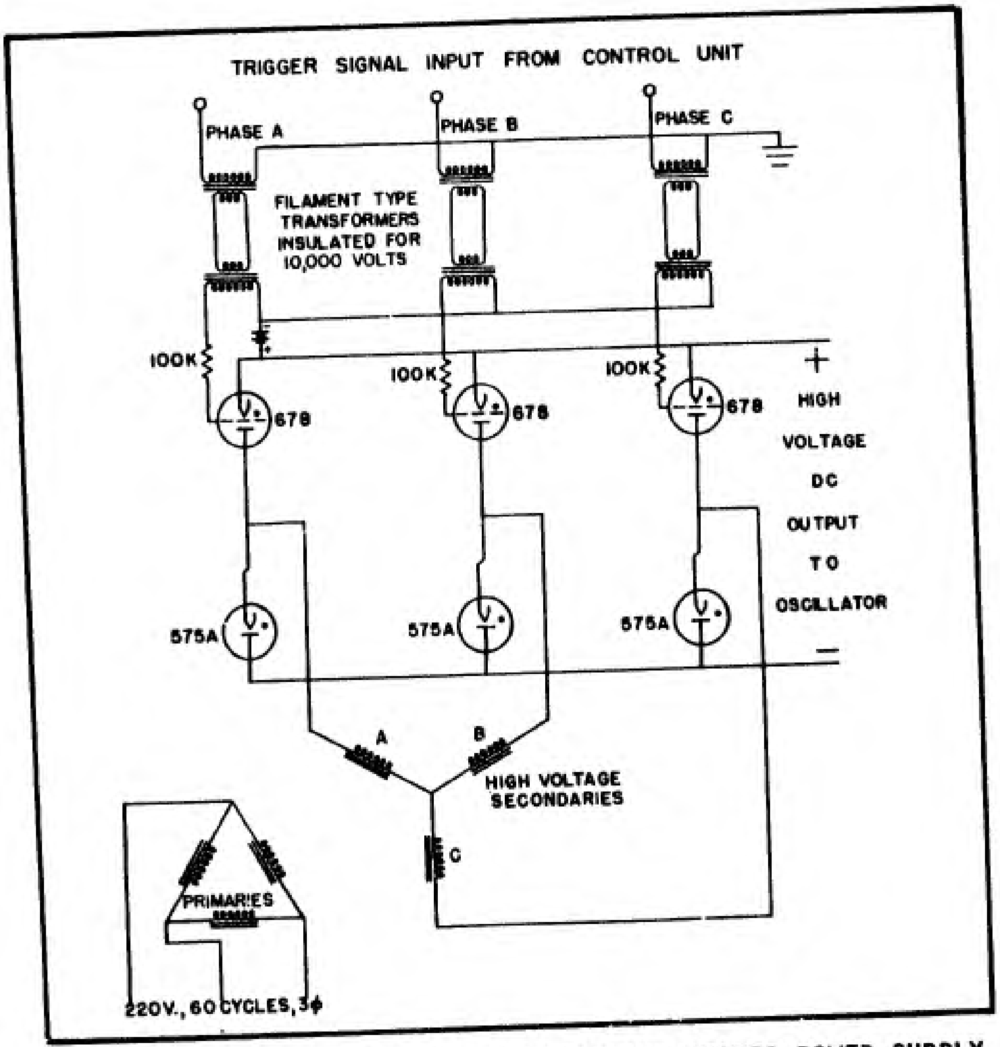


FIGURE 5: CIRCUIT DIAGRAM OF INDUCTION HEATER POWER SUPPLY

OPERATING PROCEDURE

Very fine scribe marks were made at each end and at the middle of the 2" test section of the specimen. Thermocouple wires were then attached at each mark, using a Unitek spot-welder. The thermocouple wires were then connected through r-f filter networks to the temperature indicating and controlling instruments. The specimen was placed inside the induction coil and inserted in V-grips to a depth of one inch at each end. The control indicator was set manually to a point slightly less than that corresponding to the desired temperature.

The induction heater power was then turned on. After the temperature had risen and stabilized, a readjustment was made in the control indicator to bring the temperature to the desired point. The temperatures at the ends of the test section were checked. If the over-all temperature spread was more than 20°F, the power was turned off, the thermocouples and the location of the specimen within the coil were checked. Any required adjustments were then made. With a few exceptions, the temperature difference was kept well below 20°F.

The exceptions were among the welded specimens, particularly the transversely welded specimens. These developed a higher temperature at the middle (the weld area) than at the ends. For this reason, in these specimens the middle thermocouple was placed just above the weld zone. This procedure was adopted after observing in initial tests that the transversely welded specimens all fractured in the base metal and produced strength-temperature curves almost identical with those for the base metal.

DISCUSSION

The heating rate of the specimens was observed to vary considerably with variations in thickness. It may be noted that the heating rate decreased with reduction in thickness. The reason for the decrease in heating rate can be understood by considering the effects on heat input of thickness, electrical and magnetic properties, and induction heater frequency. For various specimen thicknesses typical curves of temperature versus time are reproduced in Figure 6 for a test temperature of

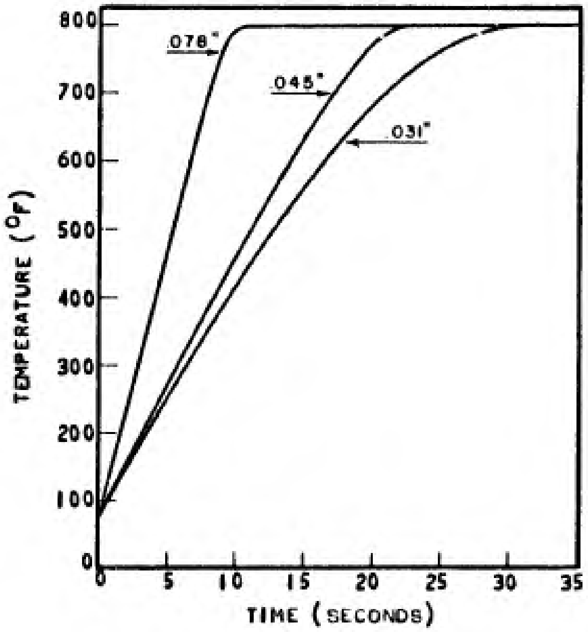


FIGURE 6: TYPICAL HEATING CURVES FOR TITANIUM SPECIMENS OF VARIOUS THICKNESSES HEATED INDUCTIVELY

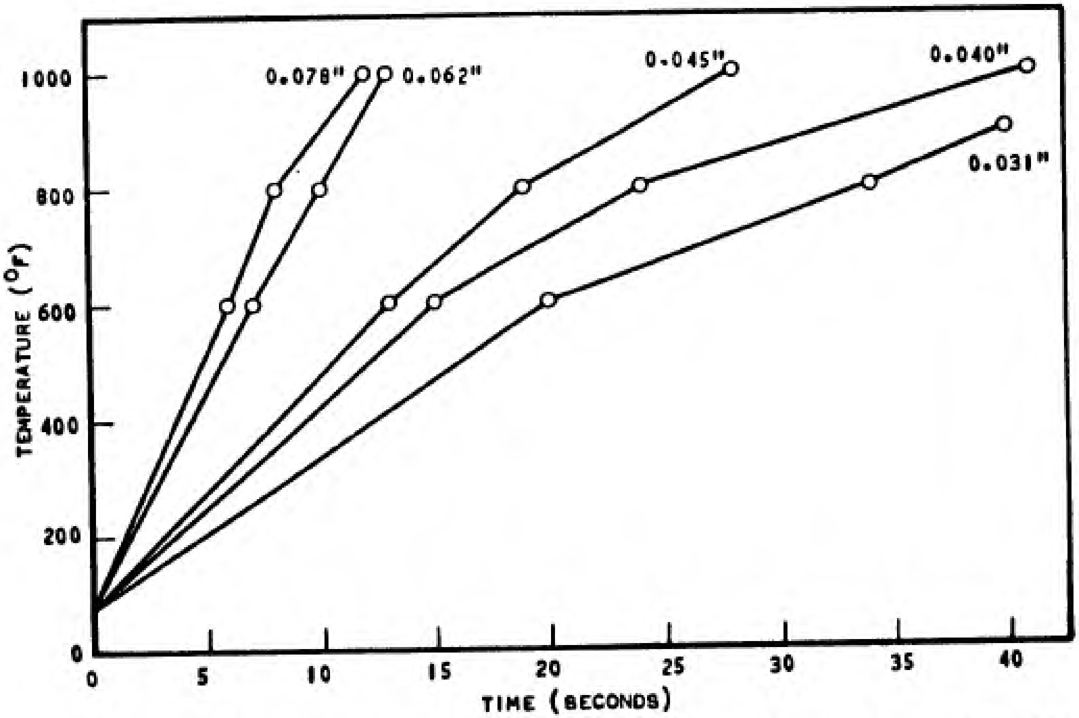


FIGURE 7: AVERAGE TIME TO HEAT TITANIUM SPECIMENS OF SEVERAL THICKNESSES TO EQUILIBRIUM TEMPERATURES

800°F. Figure 7 shows curves plotted from experimental data for average total time required to reach and level off at each test temperature for each thickness.

A characteristic of induction heating is that maximum heating takes place at the surface of electrically conductive materials. This is due to the fact that the current density decreases exponentially with increasing depth from the surface. The depth at which the current density is 36.8% of the surface value is known as the depth of penetration and is given by the equation:

$$\delta = \frac{1}{2\pi}\sqrt{\frac{\rho}{\mu f}} \text{ centimeter}$$

or $$\delta = 0.0627\sqrt{\frac{\rho}{\mu f}} \text{ inch}$$

where δ = depth of penetration

ρ = resistivity in microhm-centimeters

μ = relative permeability

f = frequency in kilocycles.

For a frequency of 450 kilocycles and for nonmagnetic materials or magnetic materials at temperatures above the Curie point where magnetic properties disappear ($\mu = 1$), the equation above for the depth of penetration may be expressed as follows:

$$\delta = 0.00295 \sqrt{\rho} \quad \text{inch.}$$

For magnetic materials below the Curie point, δ is much smaller, since μ is very large.

The average power density in an inductively heated strip (whose thickness is many times smaller than the width) is related to the ratio of thickness to depth of penetration by the equation:

$$p/v = \frac{1}{4} Ho^2 \mu f \frac{\delta}{t} \left[\frac{\sinh t/\delta - \sin t/\delta}{\cosh t/\delta + \cos t/\delta}\right] \quad *$$

where
p/v = power density in watts/centimeter^3
Ho = peak magnetizing force in oersteds
μ = relative permeability
f = frequency in cycles per second
δ = depth of penetration
t = specimen thickness.

If thickness is the only variable in the right hand side of the equation, the power density becomes

$$p/v = k' \frac{\delta}{t} \left[\frac{\sinh t/\delta - \sin t/\delta}{\cosh t/\delta + \cos t/\delta}\right]$$

where k' is a constant equal to $1/4\ Ho^2 \mu f$.

Since $v = At$, where A is the area of one side of the strip, the power absorbed is

$$p = k'' \left[\frac{\sinh t/\delta - \sin t/\delta}{\cosh t/\delta + \cos t/\delta}\right]$$

where k'' is a constant equal to $Ak'\delta$.

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*Derived from Equation (24.31), Industrial Electronics Reference Book, Westinghouse Electric Corporation, 1948, p. 381.

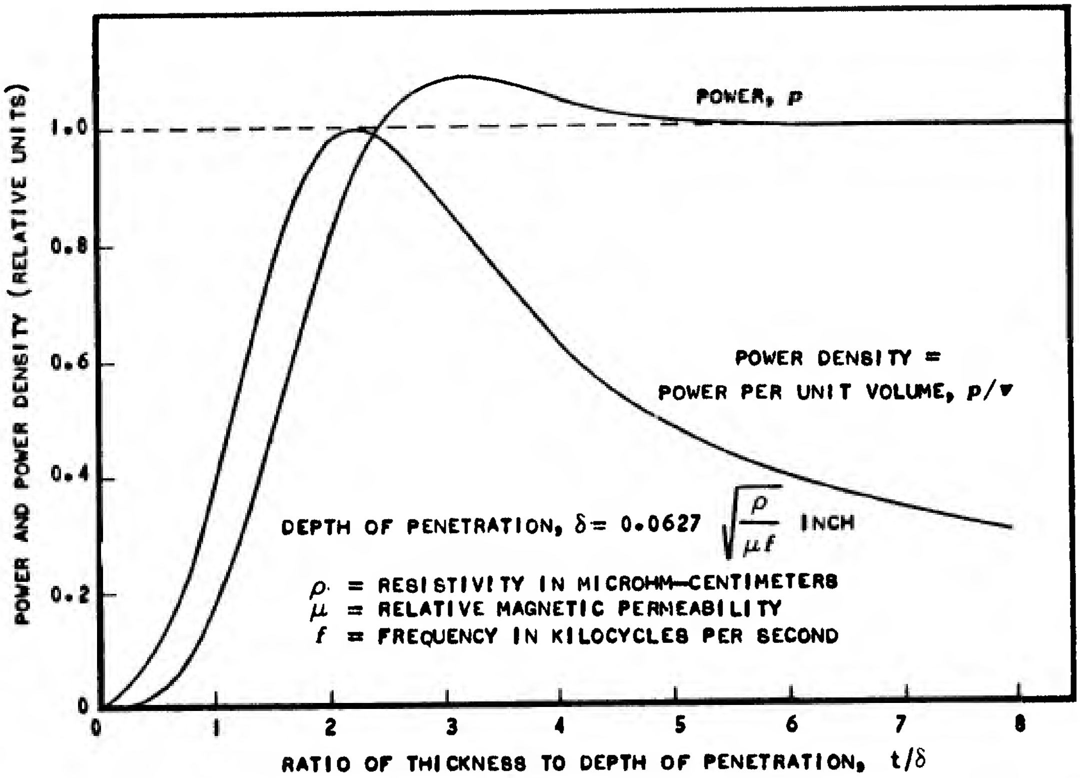

FIGURE 8: VARIATION OF POWER AND POWER DENSITY IN INDUCTIVELY HEATED FLAT TENSILE SPECIMENS WITH CHANGE OF RATIO OF THICKNESS TO DEPTH OF PENETRATION

Power density p/v and power p are shown as functions of t/δ in Figure 8. The power density rises rapidly from zero thickness, to maximum or near maximum at values of t between 2 and 2.5 and then diminishes gradually with increasing thickness. The absorbed power rises rapidly to a maximum value at $t/\delta = \pi = 3.14$ and then gradually settles to a slightly lower level.

For the thicknesses involved, the total surface area can be considered to vary only slightly. Heat loss through convection and radiation are then practically independent of thickness. If conduction loss is kept small, the total heat loss will change very little with changes in thickness.

Although maximum power density occurs at $t/\delta = 2.25$, the power available can be efficiently utilized with a much greater thickness. However, the time required to raise the greater mass to a given temperature is correspondingly increased.

As t/δ is reduced below 2, both power density and absorbed power decrease rapidly. Not only is the heating rate reduced but the maximum attainable temperature is less.

The resistivity of pure titanium increases from 55 microhm-centimeters at 68°F to 142 microhm-centimeters at 1000°F. Since it is not magnetic ($\mu = 1$), the depth of penetration at 450 kilocycles changes from 0.022" at 68°F to 0.035" at 1000°F. The optimum thickness correspondingly changes from 0.050" at 68°F to 0.079" at 1000°F. The thicknesses of the specimens tested ranged from 0.031" to 0.078". Their resistivities were not determined. However, the heating rates obtained are consistent with resistivities of approximately the same magnitude as for pure titanium. For thicknesses of less than 0.062" the rate of heating decreases rapidly as the thickness is reduced.

It did not prove feasible to heat the thinnest specimens to 1000°F because of overheating of the specimen-gripping apparatus. The situation can be improved by changing the over-all length of the specimens from 9" to 12". This would permit greater separation between the induction coil and the grips and minimize induced currents in the grips.

With few exceptions, the time taken to heat each specimen to the test temperature and to make necessary adjustment ranged from 20 to 60 seconds. An additional 10 to 30 seconds were expended in pulling the specimen at a platen speed of approximately 1" per second. Temperatures at the middle were maintained within ± 10°F of the stated temperatures with fluctuations within these limits of less than ± 5°F. In 27 cases out of 120, the specimens required readjustment due to excessive thermal gradients. The additional time during which the specimens were heated did not cause any discernible change in the mechanical properties.

The tests were made in duplicate at 600°, 800°, and 1000°F. Data showing yield strength, tensile strength, and elongation as a function of temperature are plotted in Figure 9. Full details on the mechanical test results are reported in WAL TR 401/301.* This report points out that the strength-temperature curves of the specimens welded transversely were almost identical with those for the base metals and that the specimens with welds in the axial direction possessed greater strength.

The determinations of yield strength and ultimate strength were made from recordings of crosshead travel versus load. The results obtained for yield and ultimate strength showed good reproducibility. However, the slope of a given curve in the elastic region is affected by elastic deformation of portions of the specimen beyond the gage length, the specimen holders, and the testing machine. Thus, Young's modulus cannot be determined from these curves without applying proper corrections.

The rates of heating and the test data obtained met the requirements of the group requesting the tests. The rate of heating can be raised further by decreasing the heat losses. Since power input is dependent on the coupling between the coil and the specimen, it can be increased by

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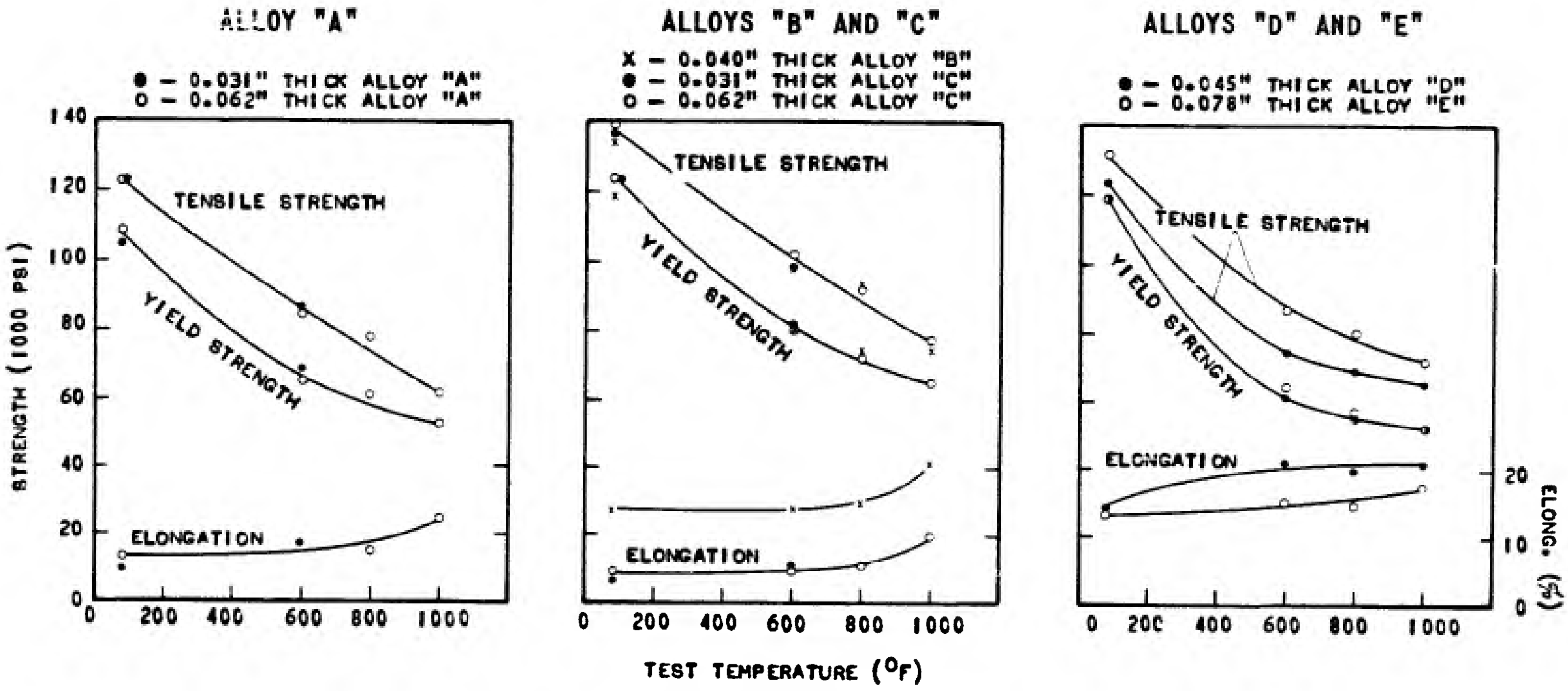
***HARTBOWER, C. E. and ORNER, G. M., "Feasibility of Titanium for Welded Missiles," Watertown Arsenal Laboratories Technical Report WAL TR 401/301, August 1958.*



ELEVATED-TEMPERATURE TENSILE PROPERTIES OF TITANIUM ALLOYS AS OBTAINED BT SHORT-TIME INDUCTION HEATING TECHNIQUES (Hartbower & Orner)

FIGURE 9

reducing the coil diameter, thus reducing the distance between the coil and the specimen. However, the diameter should not be reduced to the extent that localized zones of heating occur in the areas of the specimen closest to the coil turns.

Along with increasing the efficiency of power transfer, it is important to reduce heat losses. Causes of heat loss, in order of importance for this application are: radiation, convection, and conduction. Radiation can be reduced by a reflective heat shield between the coil and the specimen. Convection can be controlled by forming a closed chamber around the specimen which may be evacuated if desired. Conduction losses are small since the cross section areas of the specimens are small. Further reduction in their magnitude can be effected by increasing the length of the specimens as was suggested for preventing the overheating of specimen grips. With proper control of these factors, rates of heating of several hundred degrees per second should be possible with the present equipment.

While the highest test temperature reported here is 1000°F, this equipment is capable of testing specimens at temperatures higher than 2500°F. It is anticipated that temperatures, heating rates, and strain rates to be encountered in future Ordnance weapon systems will continue to increase, therefore effort is currently directed at greatly extending the capacity of this system by appropriate modification or replacement of the units of the present system.

SUMMARY

Induction heater control apparatus was developed and techniques evolved for the use of induction heating in short-time high temperature tensile tests. The apparatus and techniques were used successfully in conducting tensile tests on titanium specimens at temperatures of 600°, 800°, and 1000°F. With few exceptions, the total time expended for heating and testing a single specimen was less than 1-1/2 minutes of which the major portion was heating time. It appears possible to make further substantial increases in the capacity of the system, and work is in progress to accomplish this.

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