

Oct. 27, 1964

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3,154,623

DEVICES FOR PURIFYING MATERIALS BY ZONE REFINING METHODS

Filed Oct. 11, 1961

4 Sheets-Sheet 1

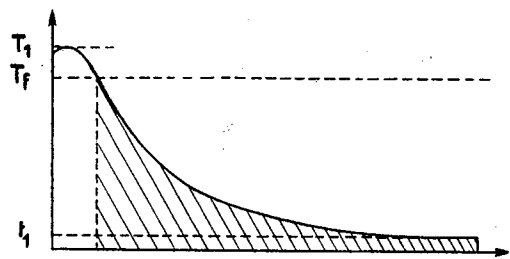


FIG. 1

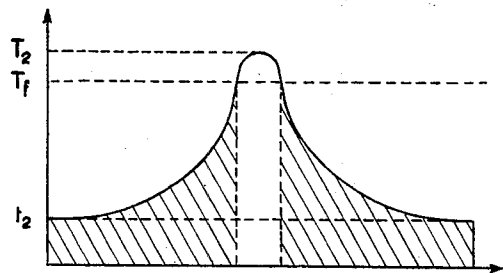


FIG. 2

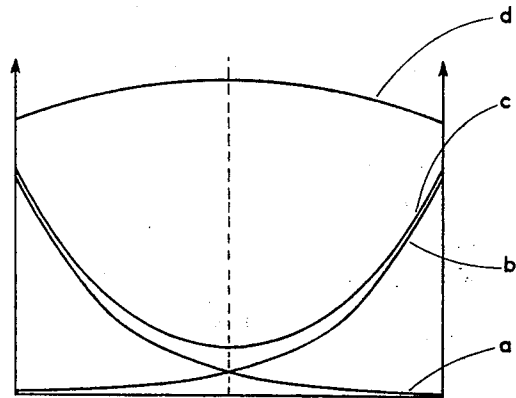


FIG. 3

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4 Sheets-Sheet 2

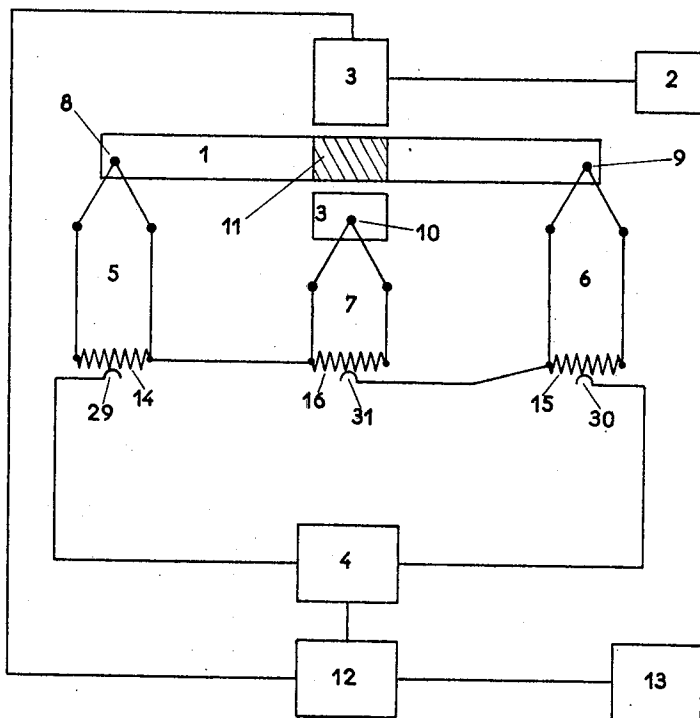


FIG. 4

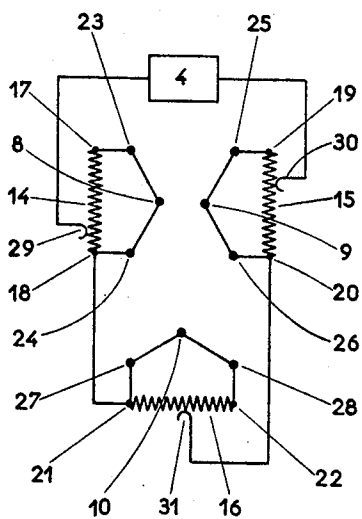


FIG. 5

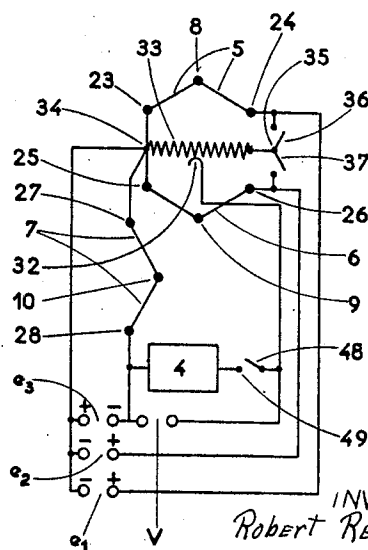


FIG. 6

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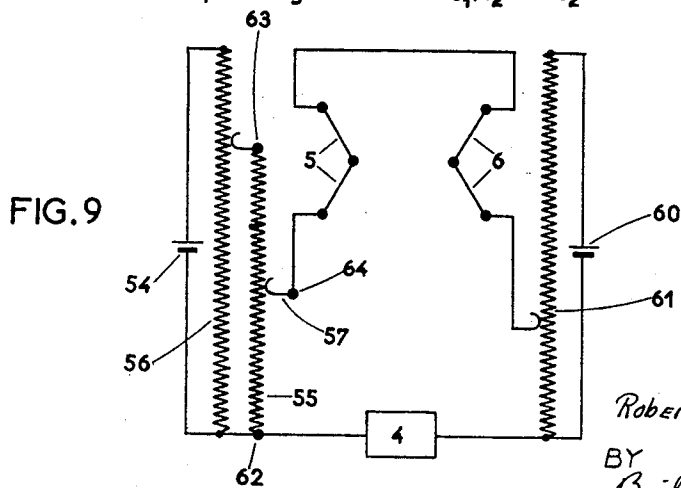
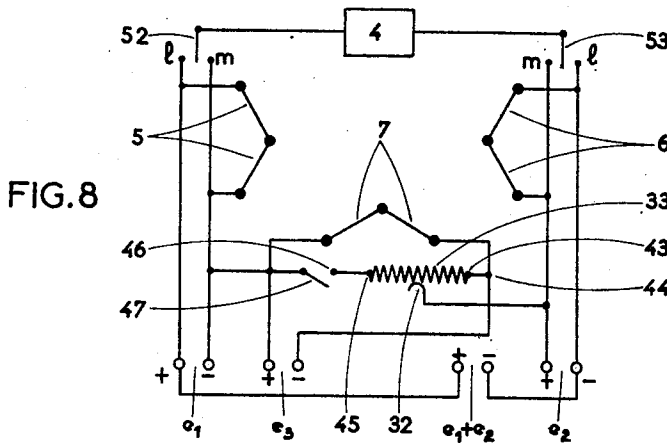
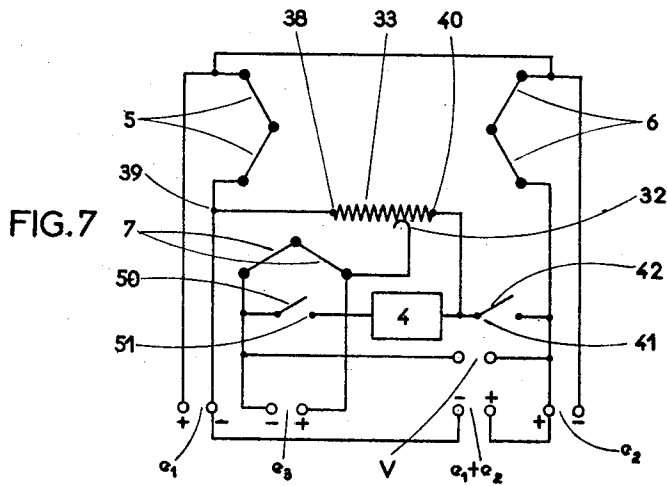
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4 Sheets-Sheet 4

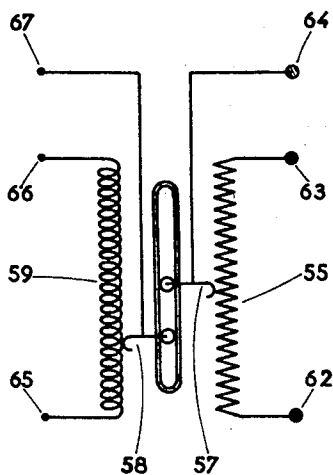


FIG. 10

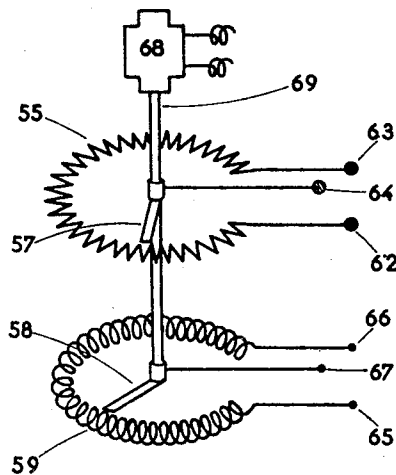


FIG. 11

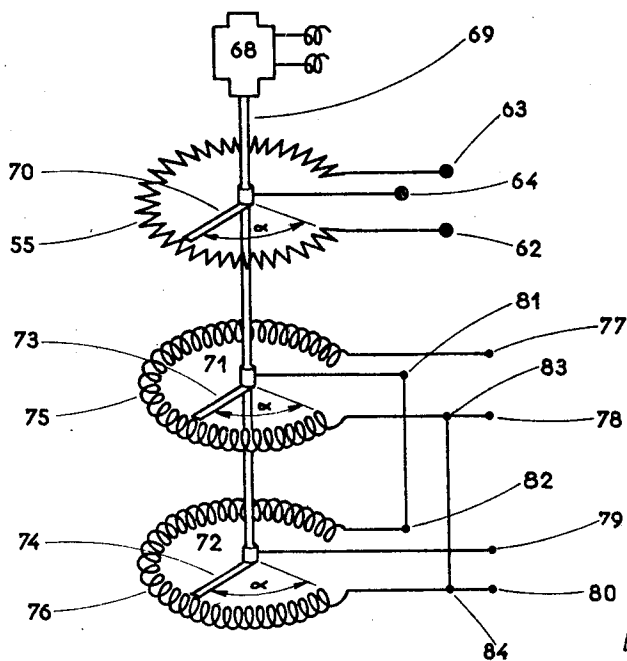


FIG. 12

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1

3,154,623

DEVICES FOR PURIFYING MATERIALS BY ZONE REFINING METHODS

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Claims priority, application France, Oct. 14, 1960, 841,136

8 Claims. (Cl. 13—1)

The present invention relates to the technique for producing high purity materials by the zone refining method, which consists in causing a relatively narrow molten zone to travel from one end to the other of a small ingot or bar, otherwise solid and the length of which is great as compared with the width of the molten zone, so as to modify the distribution of the solid impurities having coefficients of solubility different in the solid phase and in the molten phase respectively. This method permits, in particular, of preparing very pure metals and semi-conductors, either pure or doped in a very accurate manner.

It is known that the devices used for the purification of materials by the zone refining method comprise a heating element which is given a relative movement with respect to the element to be treated so as to obtain the desired displacement of the molten zone.

In such apparatus, efficiency of treatment depends in particular upon the regularity of movement of the solidification surface, upon the dimension of the molten zone and upon the thermal gradient between the liquid phase and the solid phase.

In the devices generally used in this technique, it is not possible constantly to maintain these conditions of good operation due to variations of the thermal losses during the displacement of the heating element along the material to be treated, as shown by the curves of FIGS. 1 and 2 of the annexed drawings. These curves show the variations of the temperature measured along a bar made of a substance which is a good conductor of heat, for the same length, or width, of the molten zone and the two following positions of the heating element:

At the starting end of the bar for FIG. 1,
In the middle part of the bar for FIG. 2.

To obtain these curves, the position of the molten zone along the bar has been plotted in abscissas and the temperatures in ordinates. T_1 and T_2 are the maximum temperatures in the molten zone, in the two cases respectively. T_f is the melting point of the material to be purified. t_1 and t_2 are the temperatures of the ends of the bar.

These curves show in particular that the thermal losses by radiation are greater when the heating element is located in the middle part of the bar than when it is located at one end.

In these conditions, in order to keep the width of the molten zone constant during its displacement along the bar, it is necessary either to modify the supply of calories from the source of heat, so as to compensate at any time for the thermal losses, or to keep the heating power constant and to act directly upon the factors which produce and determine the heat losses.

The easier method consists in modifying the heating conditions of the source of heat so as to compensate for the thermal losses but such a compensation, which must necessarily be performed in a continuous manner, is difficult to obtain in a correct manner with the means presently available because said means only permit of effecting the compensation either too early or too late and in both cases in a very sudden manner.

This invention is based upon the fact that a relation has been found to exist between the heating power and a

2

thermal factor depending directly upon the position of the molten zone during its displacement along the bar, this thermal factor being the temperature of two—or several—points located on opposite sides of the middle of the bar.

FIG. 3 of the appended drawings shows the variations of the power of the heating element and of the temperatures of the ends of the bar for a molten zone of a given width in accordance with the position thereof along the bar.

In FIG. 3, the position of the molten zone, measured from the starting end of the bar, was plotted in abscissas and the temperature in ordinates and curves *a*, *b*, *c*, *d* were thus traced.

Curve *a* shows the variation of the temperature of the starting end of the bar.

Curve *b* shows the variation of the temperature of the finishing end of the bar.

Curve *c* shows the variation of the sum of the temperatures of the respective ends of the bar that is to say the sum of the ordinates of curves *a* and *b*.

Curve *d* shows the variation of the heating power of the source of heat necessary to maintain a molten zone of constant width, this heating power being indicated by the temperatures of a point of the heating element.

These curves, which correspond to a bar of symmetrical shape and to a rate of travel of the molten zone equal to zero, have a common axis of symmetry at mid-distance between the starting end and the finishing end of the bar.

When the rate of travel of the molten zone is not zero but is very small (averaging some centimeters per hour for instance), the curves that are obtained are similar to the preceding ones but they are slightly different due to the fact that they undergo a small translation toward the finishing end of the bar, the greater as the rate of travel is higher.

The present invention is based upon the application of these curves in order to maintain at a substantially constant value the width of the molten zone travelling at a given rate along a given element made of a material having a good thermal conductivity. It permits of obtaining a correct regularity of the displacement of the solidification surfaces.

According to this invention, means are provided for maintaining at least one molten zone of a bar at a substantially constant width, or length, by causing the variations of power of the heating means to be controlled by the variations of temperature of at least two points of the bar disposed on opposite sides of the middle part thereof.

For this purpose, the temperature of said points of the bar and the heating power are transformed into magnitudes all of the same nature, for instance electric voltages.

A linear function, continuous and definite, of the temperatures and of the heating power is kept constant so as to produce, in response to any increase of the sum of these temperatures, a reduction of the heating power and inversely.

In the particular constructions with which this invention is concerned, the heating power is represented by a temperature which is combined with at least the temperatures of the respective ends of the bar to be treated.

To determine the temperatures, use is made of suitable means such as resistors, thermistors, photoelectric cells and in particular at least three thermocouples disposed in the following manner: one is electrically insulated in the heating element and each of the two others are electrically and chemically insulated at the respective ends of the bar.

Furthermore, in order to avoid any soiling of the bar by the elements constituting the thermo-couples, these thermo-couples are disposed in a portion of the bar kept

at a temperature compatible with their normal operation without deterioration and for this purpose, if necessary, in a portion of the bar sufficiently removed from the extreme molten zones.

In the case where the heating element is operated by a high frequency field, the corresponding thermo-couple may be placed in an auxiliary solid body subjected to the direct action of said field.

Instead of determining the heating power of the source of heat by means of the temperature of one of its points, it is possible to use means supplying a direct voltage of the order of one millivolt varying in accordance with this power, which is combined with the electromotive forces of the thermo-couples disposed at the starting and finishing ends of the bar respectively.

From the general point of view, the invention is applicable to all devices permitting the various treatments requiring the formation of a molten zone, in particular in order to prepare single crystals, to incorporate and distribute in a homogeneous manner one or several impurities in a solid phase as in the case of semi-conductor dopings, and so on.

However it is particularly advantageous for the purification of substances which are good conductors of heat according to the zone refining method, whatever be the nature of the heating means that are used (electric furnace, fuel combustion furnace, high frequency field, electronic bombardment). Some complementary indications will now be given in the case where use is made of thermocouples to transform into magnitudes of the same nature the temperatures to be combined together and the heating power.

T_1 and T_2 are the temperatures of two points located on opposite sides of the middle of the bar.

P is the instantaneous supply power of the heating source.

F_1 and F_2 are continuous functions of T_1 and T_2 respectively, these functions increasing when T_1 and T_2 increase.

F_3 is a function of the instantaneous power P , which may either increase or decrease when P increases.

The form of functions F_1 , F_2 and F_3 is determined by the nature of the detecting means that are used (such as thermo-couples).

a , b , c are coefficients depending upon the lay-out of the apparatus, the thermal constants of the bar and the length, or width, of the molten zone.

According to this invention, the following basic relation is maintained:

$$aF_1(T_1) + bF_2(T_2) + cF_3(P) = C_1 \quad (I)$$

In this relation:

(1) Coefficients a and b are always of the same sign, coefficient c being either positive or negative;

(2) F_3 is a function of the heating power P which increases when P increases in the case of coefficient c being positive and decreases when P increases in the case of coefficient c being negative;

(3) C_1 is a constant depending upon the characteristics of the measurement apparatus and which is chosen as great as possible in order to increase sensitivity.

Due to the fact that temperatures T_1 and T_2 are compelled to rise above the temperature of the cold source as soon as the generator of calories starts working and as relation (I) is always complied with, it follows that, for any position of the hot source along the bar, a thermal equilibrium is established after some time of operation. Once the equilibrium is reached, the corresponding values of temperature T_1 and T_2 on the one hand and the heating power on the other hand are unique for a given lay-out, that is to say for given values of ratios

$$\frac{a}{C_1}, \frac{b}{C_1}, \frac{c}{C_1}$$

If, for each of three static positions along the bar of a molten zone of the desired width, the corresponding values of T_1 , T_2 and P (or those of their functions $F_1(T_1)$, $F_2(T_2)$ and $F_3(P)$) are determined experimentally after thermal equilibrium has been reached, a system of three equations is obtained which permits of calculating the values of the constants with respect to one of them, for instance a , b , and c with respect to C_1 , their absolute values being determined by practical considerations relative to their order of magnitude (such for instance as the scale of the measurement apparatus that is used).

It should be noted that the equilibrium values of temperatures T_1 and T_2 and of the heating power P , for a given position of the molten zone along the bar, are substantially the same when the source of heat is stationary as when it is moving at a low rate of travel (some centimeters per hour).

Therefore, if the device is adjusted for the values of a , b , c , C_1 corresponding to three static positions of the molten zone, the width of this zone will be compelled to pass during its displacement along the bar, through the value chosen for the three positions that are considered.

Experience taught that it suffices to comply with these conditions to obtain along the bar a molten zone of substantially constant width.

Of course, it is possible to dispose along the bar to be treated a number of thermo-couples greater than two, in the case of a single molten zone.

If there are n thermo-couples, relation (I) becomes:

$$aF_1(T_1) + bF_2(T_2) + \dots + nF_n(T_n) + cF(P) = C_2 \quad (II)$$

$T_1, T_2, \dots, T_n$ being the temperatures of the hot welds of the n thermo-couples. By making $n+1$ determinations of the values $T_1, T_2, \dots, T_n$ for $n+1$ positions of the source of heat, the width of the molten zone that is considered will necessarily pass $n+1$ times through the chosen value in the course of its movement. It follows that the greater number n the higher the stability of the molten zone during its displacement.

In case of displacement along the bar of several molten zones of equal or different respective widths, obtained simultaneously by means of several equidistant sources of heat which travel along a path limited to the distance between them (each of the sources of heat at the end of its travel coming to treat the molten zone precedingly heated by the adjacent source), the thermal losses of the central zone will be little modified during the displacement, since each of them is located between two molten zones, with the exception of the zones located at the ends. As a matter of fact, considering by way of example the molten zone located at the starting end of the bar, the heat losses will increase as the portion of the bar not subjected to the radiations of the first heat source increases and in order to compensate for them, it will be necessary to increase the heating power of said first heat source.

For the molten zone located at the finishing end of the bar, the heat losses will decrease as the last source of heat is coming nearer and nearer to the end of the bar.

Referring to the curves shown by FIG. 3, which relate to a single molten zone, it will be seen that the power correction of the source of heat is due nearly exclusively to the variations of the temperature of the starting end of the bar (curve a) during the first portion of the displacement, and subsequently to the temperature of the finishing end of the bar (curve b) during the second portion.

Thus when several heating elements are used, the power of each of the external sources of heat may be corrected separately by the only temperature of the bar end nearer thereto, adjustment of the power of the intermediate sources being kept constant. It will therefore be seen that the invention permits of causing the length of one or several molten zones to pass through different values

chosen according to the needs during their displacement along the bar.

Finally the device according to the invention does not require moving the molten zone from one end of the bar to the other end. As a matter of fact, the displacement of the molten zone may be limited to a given portion of the bar, in such manner as to dispose the thermo-couples in the sufficiently cooled portion comprised between the end position of the molten zone and each of the ends of the bar.

This particular arrangement of the thermo-couples permits of avoiding any deterioration of the apparatus and any soiling of the material to be treated so that the invention may be applied to the treatment of refractory elements.

Preferred embodiments of the present invention will be hereinafter described with reference to the accompanying drawings, given merely by way of example and in which:

FIG. 4 is a plan view of a device according to the invention wherein the thermo-couples are mounted in series each of them being connected to a potentiometer.

FIG. 5 shows on an enlarged scale the mounting of the thermo-couples and potentiometer in the device of FIG. 4.

FIG. 6 relates to a lay-out for the measurement of the thermo-electric forces in the case where the thermo-couple at the starting end and the thermo-couple at the finishing end of the bar are mounted in shunt and the whole of these two thermo-couples is connected in series with that of the heating element.

FIG. 7 is also concerned with a lay-out for the measurement of the thermo-electric forces but it applies to the case where the thermo-couples disposed at the respective ends of the bar are mounted in series at the ends of a common potentiometer.

FIG. 8 relates to a lay-out for the measurement of thermo-electric forces wherein the measurement potentiometer is mounted on the thermo-couple provided in the heating element.

FIGS. 9, 10 and 11 illustrate lay-outs for placing the instantaneous heating power under control of the sum of the thermo-electric forces of the thermo-couples disposed at the ends of the bar, the regulating apparatus comprising a zero galvanometer or a millivoltmeter.

FIG. 12 shows a device of the same kind as those of FIGS. 9, 10 and 11 consisting of several auto-transformers mounted in series.

In the following description, other characteristics of the invention will become apparent.

As shown by FIG. 4, a device according to the invention comprises a bar 1 of the material to be treated, a motor 2 for moving along bar 1 the source of heat 3, which may be an electric furnace, a regulating apparatus 4 comprising a suitable measurement apparatus and receiving electromotive forces from thermo-couples 5-6-7, the hot welds 8-9-10 of which are disposed in the following manner: welds 8 and 9, corresponding to thermo-couples 5 and 6, at the respective ends of bar 1, weld 10 of thermo-couple 7 in the source of heat 3 which produces the molten zone 11 and elements 12, connected to a source 13 for the supply of calories, for controlling the heating power of this source 3.

FIG. 4 also shows a general lay-out for the thermo-couples that are used and which may consist of any suitable elements and in particular suitable metals and alloys as commonly used in the manufacture of thermo-couples such as:

Copper-constantan (Cu 55%, Ni 45%);
Platinum-platinum and rhodium alloy (Pt from 87 to 70
90%, Rh from 13 to 10%);
Chromel (Ni 90%, Cr 10%)—alumel (Ni 94%, Cr 3%,
Al 2%, Si 1%).

According to the lay-out of FIG. 4, each of the thermo-

couples 5-6-7 is connected with a potentiometer 14-15-16 respectively and the whole of these potentiometers is connected to regulator 4 comprising any measurement device such as millivoltmeter or zero galvanometer.

It will be advantageous to make use of potentiometers made of manganin (from 70 to 80% of Cu, 4 to 26% of Mn, 2 to 12% of Ni) in view of the low contact potential of this alloy with copper. All the connections will be made of copper in order to reduce as much as possible the auxiliary resistances of the circuit.

FIG. 4 does not show the means for producing and adjusting the displacements of heating element 3 along bar 1, such means being well known in the prior art.

Adjustment of the heating element will be advantageously obtained through any devices working either by gradual adjustment or by switching on and off.

Considering the potentiometer circuits of FIG. 5, which show details of the embodiment of FIG. 4, it is found that the manganin-copper contact potentials, such as 17-18, 19-20, 21-22 are always of opposed sign and furthermore equal since they originate at two points of a potentiometer which may be considered as thermally homogeneous.

For the thermo-couples, the cold welds at 23-24, 25-26, 27-28 being kept at a constant temperature (room temperature) the thermo-electric forces e_1 , e_2 , e_3 obtained respectively at the terminals of potentiometer 14, 15, 16 are equal to the contact potentials of the elements constituting the thermo-couple, with the possible difference of a constant. For practical purposes, thermal forces e_1 , e_2 , e_3 are those active in the device and which are measured by the opposition method for three static positions of a molten zone of given width along the bar to be treated, after thermal equilibrium has been obtained. The sum of the elementary thermo-electric forces being kept constant since it is sent to regulator 4, of a known type for a thermo-couple, having a fixed index the "too cold" and "too hot" positions of which respectively deliver the "hole" and "part" heating powers, the following relation exists between these electromotive forces:

$$de_1 + fe_2 + ge_3 = C_3 \quad (\text{III})$$

in which:

d , f , g and C_3 are constants depending upon the lay-out characteristics of the bar to be treated and upon the width that is chosen for the molten zone 11,

e_1 and e_2 are given functions of the temperatures T_1 and T_2 of the respective ends of the bar, and

e_3 is a given function of the heating power of the heating element 3.

As the automatic temperature regulator 4 is adjusted for a given thermo-couple and a given circuit resistance R_0 , it is therefore necessary (if it is desired to be able to use the scale of this apparatus directly to determine the index position from the value V of the voltage across the terminals that has been previously calculated) to have always the equivalent resistance R of the circuit equal to the value R_0 fixed by the constructor. It is therefore necessary to adjust the total resistance R of every potentiometer to a suitable value.

For practical purposes, knowing the value R_0 of the resistance imposed for the thermo-couple circuit and the values of the thermo-electric forces e_1 , e_2 , e_3 of the respective thermo-couples for two or three static positions of the heating element along the bar, it is possible to determine the value of the total resistance R of every potentiometer. Known formulas then permit of determining from this value of the total resistance, the positions of the sliding members 29, 30, 31 of the respective potentiometers.

It then suffices to calculate the potential difference across the terminals of the regulator, in order to fix the proper position of the regulator index.

It should be noted that if it is desired to maintain a constant adjustment of the apparatus for the successive

passages of the molten zone 11 along the bar 1 to be treated, it is necessary to keep the shape of the bar 1 unchanged, which can be easily obtained by giving this bar an angle of inclination on the horizontal.

Obviously, the mounting of the thermo-couples may be effected in many different ways and in particular as shown by way of indication on FIGS. 6, 7 and 8.

These figures illustrate three different lay-outs, on the one hand when thermo-couples 5 and 6 are mounted in series or in shunt, and on the other hand when the potentiometer is mounted on the thermo-couple 7 disposed in the heating element.

In these figures, reference numerals 5, 6 and 7 designate the thermo-couples, 8, 9 and 10 the hot welds, 23-24, 25-26, 27-28 the cold welds and 4 the regulator.

Furthermore, these figures show:

(1) The sliding member 32 of potentiometer 33, which is connected:

In the case of FIG. 6, to the junction point 34 of thermo-couples 5 and 6 mounted in shunt and to the common terminal 35 of switches 36 and 37;

In the case of FIG. 7, through its end 38 to the junction point 39 of thermo-couple 5 and mounted in series with thermo-couple 6 and through the other end 40 to the terminal 41 of switch 42;

In the case of FIG. 8, through its end 43 to the terminal 44 of thermo-couple 7, which is disposed in the heating element, and through 45 to the terminal 46 of switch 47;

(2) On FIG. 6, switch 48 connected to the terminal 49 of the regulator;

(3) On FIG. 7, switch 50 the terminal 51 of which is connected to regulator 4;

(4) On FIG. 8, switches 52 and 53 which are each of the two positions type, that is to say which may be placed on contact studs *m* or *l*.

In order to effect, with the arrangement of FIGS. 6, 7 or 8, measurements of the thermo-electric forces (e_1 , e_2 , e_3) of the potential across the terminals of the regulator or to couple them in normal working conditions, the following operations are to be effected:

Measurement of the Thermo-Electric Forces

Figures	Position of sliding member 32 on the potentiometer	Position of the switches	Measurement of—
6	At point 34	36 and 37 open, 48 closed	e_1 and e_2
7	At point 40	36 and 37 open, 48 open	e_3
8	At point 43	42 open, 50 closed	e_1 and e_2
	do	47 open, 52 and 53 in position <i>m</i>	e_3
	do	47 open, 52 and 53 open	

Measurement of Potential *V* Across the Terminals of Regulator 4

Figures	Position of sliding member 32 on the potentiometer	Position of switches
6	Suitable position	36 and 37 closed, 48 open.
7	do	42 closed, 50 open.
8	do	47 closed, 52 and 53 in position <i>l</i> .

In Working Position

Figures	Position of sliding member 32 on the potentiometer	Position of switches
6	Suitable position	36—37—48 closed.
7	do	42—50 closed.
8	do	47 closed, 52 and 53 in position <i>m</i> .

Description will now be given of particular arrangements wherein the instantaneous heating power is con-

trolled by the sum of the electromotive forces of the thermo-couples placed at the ends of the bar.

This heating power may be adjusted in particular by action upon the feed voltage in the case where an electric heating is used or upon the biasing of the grid of a triode of the oscillatory circuit when heating is obtained by means of a high frequency field.

In this last case, in view of the fact that the power supplied by a high frequency generator is a value which increases with the value of the grid bias voltage, it is possible to collect from this grid voltage an electromotive force proportional, after a suitable amplification, to the sum of the thermo-electric forces of the thermo-couples at the respective ends of the bar. It may be of advantage to use as intermediate a direct voltage which will be hereinafter called "reference voltage," in relation to a factor determining the heating power, such for instance as the position of the brush of an auto-transformer, or of a feed rheostat, or the coupling of the induction regulator, or the value of the phase shift of the voltage of the grids of thyratrons.

This "reference voltage," which will be designated by *e* and is a continuous function of the heating power, may be either a well defined fraction of the feed voltage or a potential difference obtained for instance by means of the arrangement diagrammatically illustrated by FIGS. 9, 10 and 11.

This arrangement comprises an auxiliary direct current source 54, two potentiometers 55 and 56, the displacement of the sliding member 57 being linked with that of the brush 58 of the auto-transformer 59 which controls the power of the heating element.

This arrangement keeps at a constant value the sum of the thermo-electric forces of thermo-couples 5 and 6 on the one hand and of the reference voltage on the other hand, opposing their sum to a direct voltage obtained by means of source 60 and potentiometer 61 and using for this purpose a temperature regulator 4 with a zero galvanometer, mounted in such manner that the "too hot" position corresponds to an increase of the sum of the electromotive forces and therefore to a reduction of the heating power and also of the value of the reference voltage.

These figures show the terminals 62 and 63 of the potentiometer and also the terminal 64 of sliding member 57, the terminals 65 and 66 for branching with the feed network and the terminals 65 and 67 serving to the connection of the heating element.

It should be noted that in this arrangement, regulator 4, which includes a zero galvanometer, associated with source 60 and potentiometer 61, may be replaced by a millivoltmeter regulator or any other suitable apparatus capable of keeping at a constant value the sum of the magnitudes above considered. It is also possible to oppose the sum of the thermo-electric forces of the thermo-couples at the respective ends of the bar to the reference voltage through a zero galvanometer regulator 4, so that the "too hot" position of the galvanometer (corresponding to an absolute value of the sum of the thermo-electric forces of the thermo-couples greater than the value of the reference voltage) produces an increase of the reference voltage.

In this case, the arrangement must be such that an increase of the reference voltage corresponds to a decrease of the feed voltage. For this purpose it suffices, the feed network being still connected to the terminals 65 and 66 of the auto-transformer, to dispose the heating element between the terminals 66 and 67.

On the other hand, in the arrangement of FIG. 9, it is necessary to eliminate source 60, potentiometer 61 and to reverse the polarities of source 64.

Finally it is also possible to use several auto-transformers mounted in series as shown by FIG. 12 which corresponds to a construction comprising two auto-transformers.

The apparatus of FIG. 12 comprises essentially the following elements:

A motor 68 capable of rotating in both directions (either from left to right or from right to left) which drives a shaft 69 carrying a sliding member 70 moving along potentiometer 55; this potentiometer permits of obtaining the "reference voltage" and comprises for this purpose terminals 62-63 and 64 which are connected in the same manner as illustrated with reference to FIG. 9.

Two auto-transformers 71 and 72 comprising brushes 73 and 74 rigid with shaft 69 and movable along windings 75 and 76, these parts being electrically connected together, as shown by the drawings, that is to say in such manner that the primary of one is fed from the secondary of the other in order to obtain, in response to variations of the "reference voltage," variations of power different from those obtained by means of a single auto-transformer; for this purpose, the feed network is connected with the terminals 77 and 78 of the first auto-transformer whereas the heating element is connected with the terminals 79 and 80 of the secondary transformer, the terminal 81 of the brush of auto-transformer 71 is connected with a terminal 82 of auto-transformer 72 and finally the terminal 83 of auto-transformer 71 is connected with a terminal 84 of auto-transformer 72.

In the arrangements that comprise an auto-transformer associated with a potentiometer where the resistance increases linearly, the "reference voltage" e , added to the sum of the thermo-electric forces ($e_1 + e_2$) varies linearly as a function of the voltage V across the terminals of the heating element.

In the case of a single auto-transformer, if α designates the ratio (always positive) defining the position of sliding element 70 on potentiometer 55 and therefore the value of the "reference voltage" e with the possible difference of a constant factor, the following relations exist:

$$\begin{aligned} e &= A\alpha & \text{(IV)} \\ V &= B\alpha + C_4 & \text{(V)} \end{aligned}$$

in which:

(a) A , B , C_4 are constants which are given for a determined lay-out;

(b) A is positive if the power of the heating source increases when the reference voltage e increases;

(c) C_4 is always positive;

(d) Ratio α , voltage V , and power P of the heating source are magnitudes which are always positive.

These various lay-outs lead to relations between the heating power and the thermo-electric forces e_1 and e_2 of the same type as that of the general relation (I).

Of course, the law of variation of the resistance of potentiometer 55 as a function of the position α of sliding member 70 might be any function of α . In this case, $e = dF(\alpha)$, d being a constant.

What I claim is:

1. A device for the treatment of a bar of a heat conducting material which comprises, in combination, a heating element movable along said bar to form a molten zone thereof travelling along said bar, two means for measuring the temperatures of said bar at two points thereof located on opposite sides of its middle part, respectively, means for translating the values thus measured of said

temperatures into respective magnitudes, both of the same nature, means for measuring the power of said heating element, means for translating the value thus measured of said heating power into a magnitude also of the same nature, and means operatively connected with said heating element to vary the heating power thereof, to maintain the width of the molten zone substantially constant, said means being responsive to variations of said three magnitudes for keeping at a substantially constant value a linear function of said three magnitudes, this linear function being the sum of three terms, the two first terms being of the same sign and being each a function of one of the two first mentioned magnitudes, respectively, which increases in absolute value when the corresponding magnitude increases and inversely, the third term being of a sign opposed to that of the two first mentioned magnitudes which increases in absolute value when said third magnitude increases and inversely.

2. A device according to claim 1 wherein said magnitudes are potential differences.

3. A device according to claim 1 wherein said means for measuring the heating power of said heating element are means for measuring the temperature of one of the points of said element.

4. A device according to claim 1 wherein said magnitudes are potential differences, and said third magnitude is a direct voltage proportional to said heating power.

5. A device according to claim 1 wherein said means for measuring said temperatures and said means for translating the values thus measured of said temperatures into said two first mentioned magnitudes are combined together in the form of thermo-couples, whereas said means for measuring said heating power and said means for translating the value thus measured of said heating power into the third mentioned magnitude are combined together in the form of a thermo-couple, the means for keeping said linear function at a substantially constant value comprising potentiometers connected with said thermo-couples to form said function and a regulator connected with said potentiometers.

6. A device according to claim 5 wherein said two first mentioned thermo-couples are mounted in portions of said bar remote from the end positions of the molten zone.

7. A device according to claim 1 wherein said magnitudes are potential differences and the last mentioned means comprise an auto-transformer having a brush the position of which determines the heating power.

8. A device according to claim 1 wherein said magnitudes are potential differences and the last mentioned means comprise a feed rheostat having a brush the position of which determines the heating power.

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