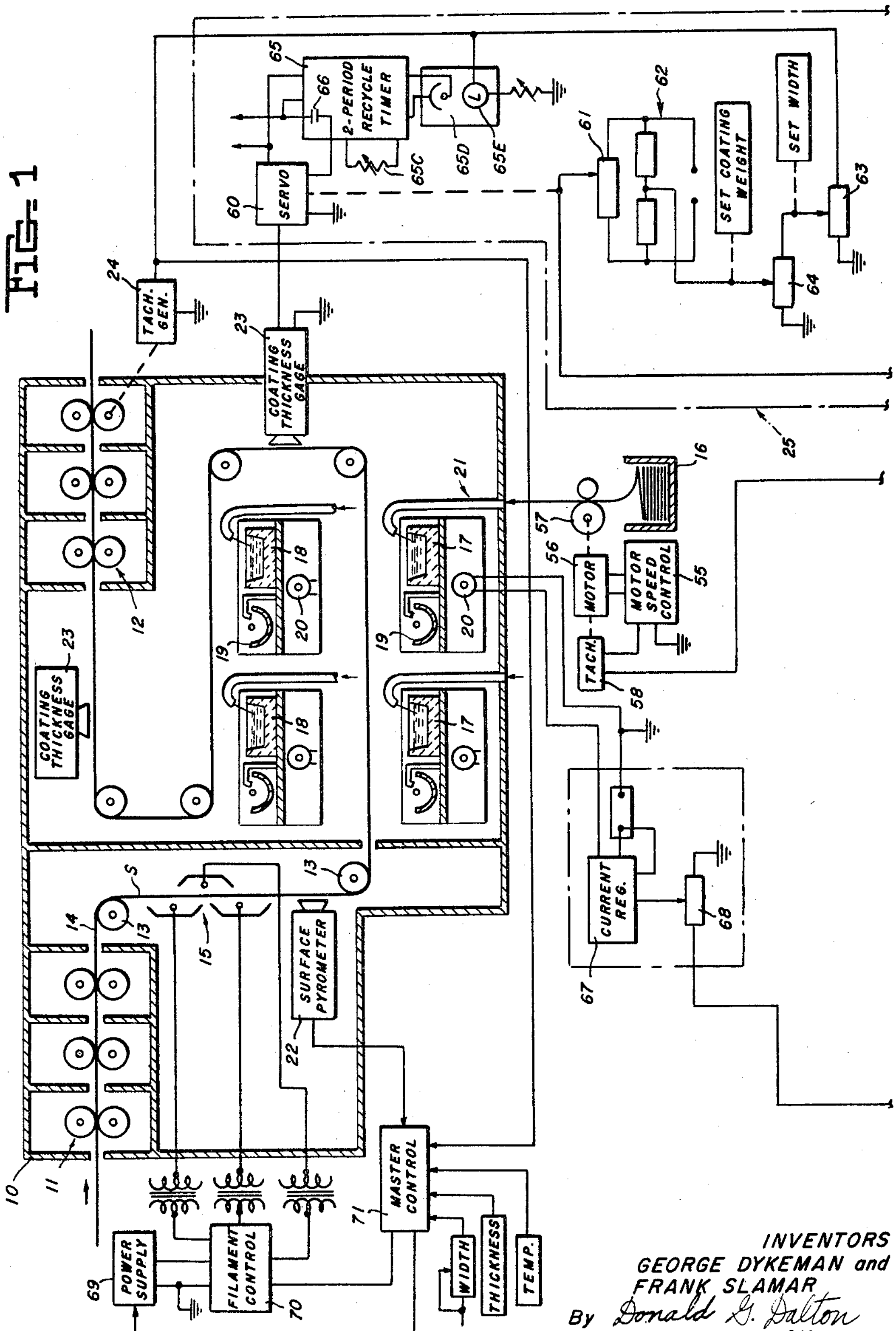
Aug. 20, 1968 G. DYKEMAN ET AL 3,397,672

CONTROL SYSTEM FOR VAPOR-DEPOSITION COATING APPARATUS

Filed Nov. 10, 1965 2 Sheets-Sheet 1

FIG. 1

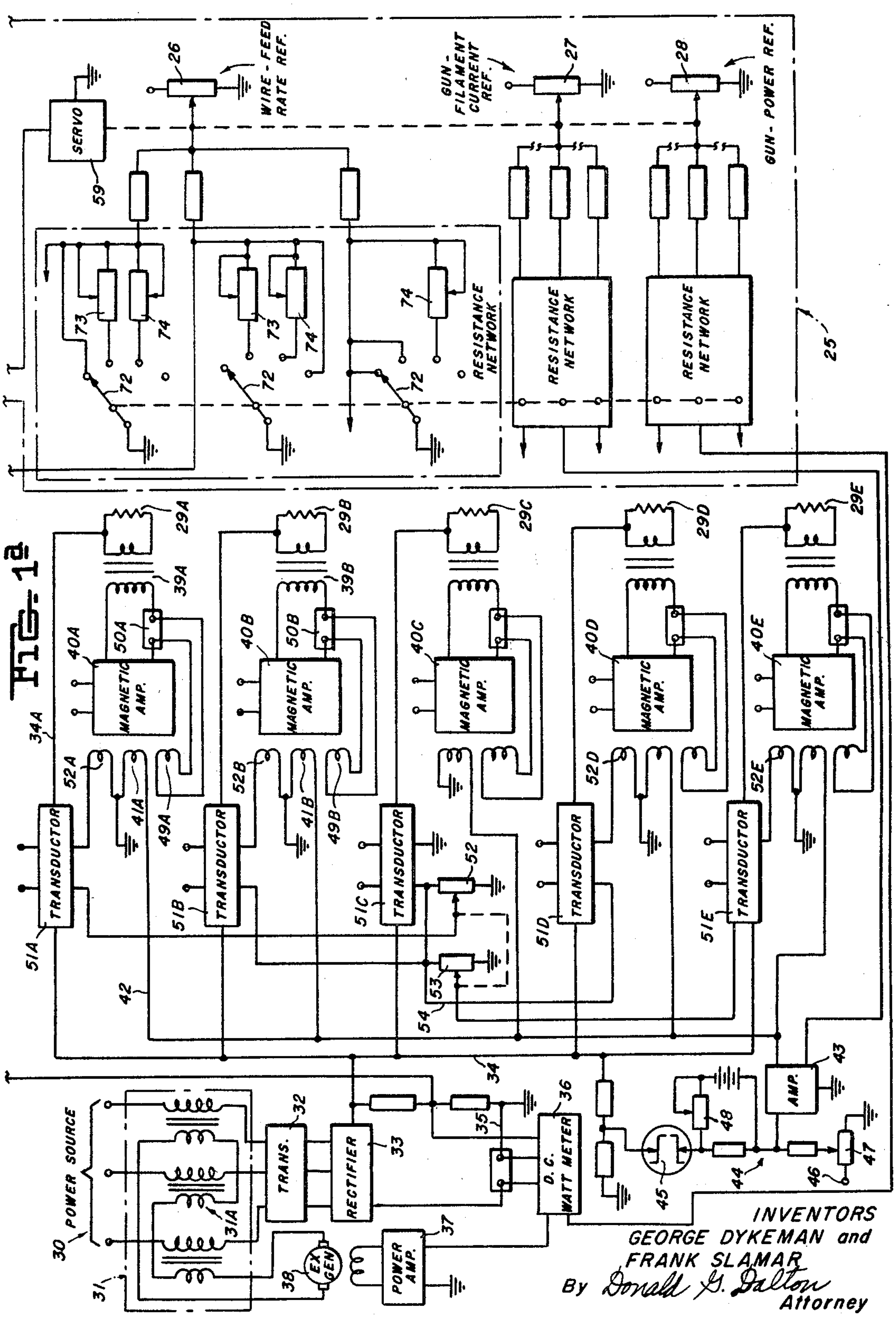


INVENTORS
GEORGE DYKEMAN and
FRANK SLAMAR
By Donald G. Dalton
Attorney

Aug. 20, 1968 G. DYKEMAN ET AL 3,397,672

CONTROL SYSTEM FOR VAPOR-DEPOSITION COATING APPARATUS

Filed Nov. 10, 1965 2 Sheets-Sheet 2



INVENTORS
GEORGE DYKEMAN and
FRANK SLAMAR
By Donald G. Dalton
Attorney

United States Patent Office

3,397,672

Patented Aug. 20, 1968

1

3,397,672

CONTROL SYSTEM FOR VAPOR-DEPOSITION COATING APPARATUS

George Dykeman, Dormont Borough, and Frank Slamar, Monroeville, Pa., assignors to United States Steel Corporation, a corporation of Delaware

Filed Nov. 10, 1965, Ser. No. 507,103
10 Claims. (Cl. 118—5)

ABSTRACT OF THE DISCLOSURE

A plurality of electron guns spaced across the width of a strip traveling through a vacuum chamber, serving to vaporize coating metal in a crucible, are controlled in response to the speed of the strip and the thickness of the deposited coating, to maintain the latter uniform. A differential is maintained between the guns adjacent the strip edges and those nearer the center line, to obtain uniform deposition transversely of the strip. A second series of guns used for preliminarily degassing the strip, is controlled in accordance with the temperature of strip entering the chamber, to insure proper heating and release of occluded gases.

This invention relates to a control system for adjusting the several conditions involved in the continuous coating of strip material in a vacuum, by deposition of metal vapor thereon, according to the speed of travel of the strip. More particularly, it relates to a system for controlling the evolution of vapor from the surfaces of molten pools of the coating metal to insure a substantially uniform thickness of coating both transversely and longitudinally of strip.

BACKGROUND OF THE INVENTION

In the vapor-deposition coating of continuous strip material, it is desirable to arrange an elongate crucible transversely of the strip travel and to heat the top surface of a charge of coating metal therein. This may conveniently be done by electron bombardment using a plurality of so-called electron guns (emitters) positioned alongside the crucible and disposed end-to-end relative to each other. The paths of the electron beams from the guns to the surface of the metal in the crucible are controlled by magnetic fields transverse to the beams, as shown in Simons U.S. Patent No. 3,046,936. It is also desirable to use several of these crucible-gun arrangements spaced along the path of the strip when thick coatings are desired. It is the object of our invention to control both the total power applied to the surface of the metal in the crucible and the distribution of power among the several guns to provide a pre-selected curve of rate of metal vaporization along the length of the crucible (i.e., transversely of the strip), and to control the rate of supplying make-up metal to the crucibles in accordance with strip speed and to produce on the strip a coating of uniform thickness longitudinally and transversely thereof.

Beam power as used herein is the power delivered to the surface of the metal in the crucible by an individual electron-beam gun. A selected beam power may be achieved at either a relatively high voltage and low level of beam-current or vice versa. The use of electron guns as heating sources in high-vacuum continuous processes involves the resolution of conflicting sets of operating characteristics. For example, linear control of power is desirable but an electron gun is basically a nonlinear device. Again, uninterrupted flow of power is desirable but ionization discharges occur frequently due to impurities brought in by the process materials causing momentary short circuits to the power supply. Wide-range power

2

variations are required, furthermore, to match process variations, yet normal operation of simple electron-gun devices is limited to small operating ranges. A simple electron-gun device is desirable because the gun must work in an atmosphere that would contaminate the electrode structure of more complex guns. Wide-range control, however, has prior to our invention required control grids and accessory electrodes incorporated in the more complex guns to vary current flow and maintain focus of the electron beam on the object to be heated.

SUMMARY OF THE INVENTION

It is an object of this invention to control a multitude of simple electron guns so as to obtain uniform heating of a crucible much larger than an individual electron-gun source. According to our invention, the beam-power and filament-heating circuits of the gun are interconnected so as to maintain total power distribution according to preselected references and vary the total power as required by process variations and thus to maintain preselected heating of a crucible or of the continuous strip material itself.

For this purpose, the electron-beam guns must be operated within controlled voltage, beam-current and filament-current (temperature) ranges. For example, if the filament (emitter) temperature is sufficiently high to make available more electrons than can be attracted to the crucible metal at maximum voltage (emission limited), beam power may be altered by varying the voltage. Second, if the voltage is sufficient to attract from the filament to the metal in the crucible the maximum quantity of electrons the filament can emit (temperature limited), then power density may be controlled by varying filament current (temperature). Furthermore, if the filament is temperature limited and the voltage is below maximum, beam power may be controlled by varying both filament temperature and voltage until either the first or second condition described above is achieved.

BRIEF DESCRIPTION OF THE DRAWINGS

A complete understanding of the invention may be obtained from the following detailed description and explanation which refer to the accompanying drawings illustrating the present preferred embodiment.

In the drawings:

FIGURE 1 is a diagrammatic showing of vapor-deposition coating apparatus and partial circuit diagram of the control system of our invention; and

FIGURE 1*a* is the remainder of the control-system diagram.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now in detail to the drawings and, for the present, particularly to FIGURE 1, the apparatus with which our invention is adapted to be used comprises a vacuum chamber **10** having entrance and exit roll seals **11** and **12**. Chamber **10** is evacuated by suitable pumps (not shown) to a low pressure such as .02–.1 micron of mercury. Guide rolls **13** in the chamber cause strip **14** passing therethrough to travel first beside electron-beam gun preheaters **15** and then in reverse directions over pairs of elongated transversely disposed refractory crucibles **17** and **18** for coating both sides thereof. Groups of electron-beam guns **19** (such as the Model 60–850 gun made by Ultek Corporation, Palo Alto, Calif.) extend end-to-end along each crucible and electromagnets **20** are mounted on appropriate core structures to provide fields for maintaining the desired curvature of the beams as aforesaid. Wire-feed apparatus **21** for each crucible supplies make-up coating metal, e.g., aluminum, from storage **16**. A surface pyrometer **22** (such as Model TD–3, made by Radiation Electronics Company, Chicago, Ill.) measures the temperature of the strip after preheating and coating thickness gages **23** (such as the "Quantrol" Analyzer made by Applied Research Laboratories, Inc., Glendale, Calif.) measure the thickness of the coating applied to one side of the strip. A tachometer generator **24** generates a voltage proportional to the speed of strip traversing chamber **10** and this voltage applies a signal to a master controller **25** now to be described.

The system of our invention is responsive to a master control, the elements of which, enclosed within dotted rectangle **25**, hereinafter designated a controller, include potentiometers **26**, **27** and **28** which are adjusted automatically to give the wire-feed rate, gun filament current and gun-power input, respectively, suitable for depositing the desired weight of coating on the strip for a given speed of travel thereof.

FIGURE 1*a* shows the control system for the filaments **29A**, **29B**, etc., of the group of five electron guns disposed end-to-end, associated with one of the crucibles **17**, as indicated at **19**. Each crucible has a similar set of guns. The electron-beam power input to each set of guns is obtained from a primary source **30**, through a three-phase saturable-core reactor **31** (commercially available from electrical manufacturers such as General Electric Company), a transformer **32** and rectifiers **33** (such as the silicon rectifier made by Westinghouse Electric Corporation), which provide a high direct voltage (5,000–15,000 v.) across buses **34** and **35**, the positive of which (**35**) is grounded. The power input drawn from these buses is measured by a wattmeter **36** (such as Weston Instruments Model 1483) delivering a signal voltage which is opposed by that from potentiometer **28**, through a resistance network (to be described in detail later) the difference being applied to a power amplifier **37** (such as that made by Norbatrol Electronics Corporation, Pittsburgh, Pa.). The output from the amplifier energizes the field winding of an exciter generator **38** driven by a constant-speed motor (not shown). Generator **38** energizes the several control windings **31A** of reactor **31**. The result is a closed-loop control circuit whereby the reactor is energized to maintain a constant power input by correcting the applied voltage according to the setting of potentiometer **28**, depending, however, upon other variable conditions as will be explained subsequently.

The filaments **29A**, **29B**, etc. of the electron-beam guns are connected to a supply of heating current through transformers **39A**, **39B**, etc., under the control of magnetic amplifiers **40A**, **40B**, etc., similar to amplifier **37**, which are themselves connected to the A-C power supply. Each of these amplifiers has a control winding **41A**, **41B**, etc. connected to a bus **42** from an amplifier **43**. Amplifier **43** is connected to and derives its input from filament-control potentiometer **27** through a resistance network (to be described in detail later), and a voltage tapped from bus **34** by a voltage-divider network **44** including a Zener diode **45** (such as that made by International Rectifier Corporation) a local source **46** of bias voltage and a manually set potentiometer **47**. Accordingly, the current supplied to all filaments **29A**, **29B**, etc. is controlled by the difference between the voltage from potentiometer **27** and that from network **44**. Potentiometer **47** governs the proportionality between the voltage tapped from bus **34** and that from potentiometer **27**. Network **44** modifies the input to amplifier **43** only if the voltage on bus **34** is above or below a desired operating range fixed by the selection of the zener diode **45** and the setting of a potentiometer **48** controlling the application of bias voltage thereto.

Amplifiers **40A**, **40B**, etc. also have control windings **49A**, **49B**, etc. energized in accordance with the individual filament-currents, as by shunts **50A**, **50B**, etc. Individual control of the heating currents to the several filaments is effected by transductors **51A**, **51B**, etc. The transductors are magnetic amplifiers (such as the direct-current transformers made by Magnetic Controls Company, Minneapolis, Minn.) connected to an A-C power source and receiving individual input current signals from high-voltage bus **34**, and are connected to the filaments individually. Thus the direct-current outputs of the transductors, i.e., isolated signals proportional to the high-voltage supply currents to the several filaments, are also applied to magnetic amplifiers **40A**, **40B**, etc., to regulate filament temperatures and maintain the proper relation thereof to the density of electron-beam discharge from the filaments to the crucible.

We provide means for maintaining a marginal excess in the beam-currents from the outer guns over that from the inner guns, to improve the uniformity of the coating thickness transversely of the strip. This means includes further control windings **52A**, **52B**, **52D** and **52E** on amplifiers **40A**, **40B**, **40D** and **40E**, respectively. There is no such winding on amplifier **40C**. These windings are energized by the outputs of transductors **51A**, **51B**, **51D** and **51E**, respectively. By potentiometers **52** and **53**, which are mechanically coupled, transductors **51A** and **51E** are set to energize filaments **29A** and **29E** at a higher level than that of filaments **29B**, **29C** and **29D** the transductors **51B**, **51C** and **51D** of which all operate at the same level by virtue of their common connection **54**. Since transductor **51C** does not affect amplifier **40C**, the latter energizes filament **29C** at a minimum level. Amplifiers **40B** and **40D** energize filaments **29B** and **29D** at a higher level and amplifiers **40A** and **40E** energize filaments **29A** and **29E** at a still higher level. This produces an increasing evaporation rate from the center of crucible **17** toward each end, and thereby offsets the decrease in coating thickness adjacent the strip edges which would otherwise result.

A second control function exercised by controller **25** is to determine suitable power distribution among the several successive crucibles **17**, **17**. It is usually desirable to proportion the power equally among the several crucibles used, although it is recognized that special advantage can be taken of the nonlinear relationship between power and evaporation rate by proportioning the power in a different manner. To effect the desired division of power between the gun-control systems of two or more crucibles, a multiple-contact switch **72** is used to select resistors **73**, **74** which divide the reference signal by one, one-half, or one-third, depending on whether one, two, or three crucibles are in use. As shown in FIGURE 1*a*, either the first or the third may be used alone, the first and second used together, or all three used together. Additional network configurations would permit other combinations. Since the signal dividing resistors **73** and **74** are adjustable, various proportions can be set, i.e., all three crucibles could be operated on "100% power reference signal."

A third control function exercised by controller **25** is to vary the rate at which wire-feed mechanism **21** operates. For this purpose, a controller **55** (such as Type "C" Basic Electronic Governor made by Linde Div., Union Carbide Corporation) varies the speed of motor **56** driving wire-feed pinch rolls **57**. Controller **55** responds to the difference between the voltage from potentiometer **26** and that produced by a tachometer generator **58** coupled to motor **56**.

The several potentiometers **26**, **27** and **28** of controller **25** are driven in unison by a servo **59** (such as Model 6102 made by Solar Electronics Company, Hollywood, Calif.), in accord with variations in thickness of coating deposited on strip S from the desired value, and variations in strip speed. Signals of thickness variations observed by gage **23** are supplied to an intermediate servo **60** (similar to servo **59**) mechanically coupled to a potentiometer **61** which applies a voltage to servo **59**. Potentiometer **61** is connected in a bias-voltage network **62** which receives input from potentiometers **63** and **64** for introducing thereto voltages corresponding to preselected strip widths and coating thicknesses, respectively.

A strip-speed measurement is taken from tachometer generator **24**. The voltage from generator **24** is applied to potentiometers **63** and **64** and thus combines with the preset width and coating-thickness adjustments to affect network **62**. Timer **65** (to be described in detail below) causes a periodic adjustment of potentiometer **61**, if needed, by servo **60**, and potentiometer **61** affects servo **59**. Servo **59** in turn actuates potentiometers **26**, **27** and **28** with the results already explained.

Timer **65** affects resetting of controller **25** in accord with the thickness of coating measured by gage **23** at a rate which varies with the strip speed thus compensating the delay between thickness measurement and controller re-adjustment for the time required for a point on the strip to travel from the crucibles **17** to the gage. The timer is a two-period sequencing timer such as that made by Square D Co., Milwaukee, Wis., and controls the operation of servo **60**. One period (the "on" period) of the timer is determined by the setting of a rheostat **65C**. The other period (the "off" period) is controlled by a variable resistor **65D**. This resistor is a photocell the resistance of which is controlled by the light from a lamp **65E** energized by voltage from tachometer generator **24**. The photocell **65D** and lamp **65E** form a combination provided in the commercially available "Raysistor" electro-optical device made by Raytheon Co., Newton, Mass.

Contacts **66** of timer **65** are closed during the "on" period and open during the "off" period. Rheostat **65C** is initially adjusted to make the "on" period sufficient to correct for a 100% error signal input to servo **60**. As strip speed increases lamp **65E** glows more brightly, reducing the resistance of photocell **65D** and, consequently, the length of the "off" periods of timer **65**. As operation of the system is continued rheostat **65C** may be adjusted to reduce the length of the "on" periods and thus shorten the times for operation of servo **60**.

If the actual coating weight as measured by gage **23** is the same as the desired coating weight according to which potentiometer **64** is set, the input to servo **59** will be determined by potentiometers **63** and **64**. If the actual coating weight differs, the action of servo **60**, timer **65** and the bias-voltage network **62** serve to increase or decrease the signal applied to servo **59** in proportion to this difference. Servo **59** proportionally increases or decreases the setting of potentiometers **26**, **27** and **28** to adjust the entire control system to a level that will provide the desired coating thickness. Since the coating operations and the thickness measurement are necessarily separated in space, the delay between coating and measurement is made proportional to line speed. As explained above, timer **65** effects the delay between corrections to servo **59** by servo **60**, so as to make the delay proportional to line speed.

The current supply to the winding of electromagnet **20** is controlled by a current regulator **67** (as an example, see application brief dated May 17, 1963, published by George A. Philbrick Researchers, Inc., Boston, Mass.) according to the input voltage of wattmeter **36** applied to a potentiometer **68**.

It is to be understood, of course, that the control system described above is intended for the electron-beam guns of one crucible and is duplicated for the guns of each of the other crucibles.

One feature of our invention remaining to be described is the control of the preheating electron guns **15**. This includes a power supply **69** (comprising units similar to **31**, **32** and **33**), a filament-control circuit **70** (duplicating all units designated by numerals **39** through **54** with and without reference letters added) and a master control **71** similar to that indicated at **25** except that, instead of coating thickness, the temperature of the strip as noted by pyrometer **22**, governs the operation, after predetermined settings for strip width, strip thickness and desired temperature have been established on potentiometers similar to those shown at **63** and **64**. It will be understood from the above that, not only the energization of the filaments of vaporizing guns **19** increases from the midpoint of the crucible toward each strip edge, but also the energization of the filaments of preheating guns **15** is similarly increased.

It will be evident from the foregoing that our invention is characterized by numerous advantages. In the first place, the system may be set up in advance for a specific desired coating thickness to be applied to strip of a certain width at a given speed of travel. The filament-current needed for these conditions, the voltage applied between filament and crucible and the power input to the electron guns will be maintained at the proper values or adjusted as necessary to assure the desired result, i.e. uniform coating thickness over the strip area, despite such possible changes in strip speed or coating thickness actually applied as may occur for various reasons. The preheating of the strip and the rate of deposition of the coating metal, furthermore, tend to decrease from the center line of the strip toward the edges. Therefore, to secure a substantially uniform heating or coating across the width compensation for this effect must be made. The desired distribution of preheating or vaporizing energy is maintained despite changes in the overall level of energy input. The system maintains suitable power input to the guns by varying the voltage or current or both as needed to suit variations in the controlling parameters.

Although we have disclosed herein the preferred embodiment of our invention, we intend to cover as well any change or modification therein which may be made without departing from the spirit and scope of the invention as set forth in the claims.

We claim:

1. In apparatus for coating traveling strip with metal by vapor deposition in a vacuum, the combination with a crucible adjacent the path of the strip adapted to contain coating metal, an electron gun adjacent the crucible having a thermionic emitter and delivering a beam of electrons to the metal therein, of means for supplying electric power to said gun, said means including voltage-control means, and means responsive to the speed of the strip effective to vary said voltage-control means.

2. Apparatus as defined in claim **1** characterized by means varying the current from said power-supply means to the emitter of said gun and said speed-responsive means including means to vary said emitter-current varying means.

3. Apparatus as defined in claim **2** characterized by means modifying the action of said current-varying means according to the voltage applied to the emitter.

4. Apparatus as defined in claim **1** characterized by means feeding make-up metal to said crucible and said speed-responsive means including means varying the speed of said make-up metal feeding means.

5. Apparatus as defined in claim **1** characterized by an electro-magnet adjacent said crucible to deflect said beam and means responsive to the voltage of said power-supply means controlling the excitation of said magnet.

6. Apparatus as defined in claim **1** characterized by said gun including a plurality of thermionic emitters spaced across the width of the strip and means varying the current supplied to the emitters adjacent the strip edges relative to that supplied to the emitters nearer the center line of the strip.

7. In an apparatus for coating traveling strip by vapor deposition in a vacuum, the combination with a crucible for holding coating metal, disposed across the strip path, a plurality of electron emitters spaced along the crucible to bombard the coating metal therein, of a saturable-core reactor having a control winding varying the power supplied to said emitters, means comparing the power supplied with a preset standard, and means controlled by said comparing means varying the energization of said control winding.

8. In an apparatus for coating traveling strip by vapor deposition in a vacuum, the combination with a crucible for holding coating metal, disposed across the strip path, a plurality of electron emitters spaced along the crucible to bombard the coating metal therein, of means for supplying power to said emitters including a magnetic amplifier for each emitter having a control winding, a transductor for each emitter energizing the control winding of the emitters' amplifier and means establishing the voltage of the emitters at a substantial negative value relative to said crucible, each transductor being connected between its emitter and said last-mentioned means.

9. Apparatus as defined in claim 8, characterized by each magnetic amplifier also having a control winding and means energizing it in accord with the current supplied by the amplifier to its emitter.

10. Apparatus as defined in claim 8, characterized by means energizing the transductors of the emitters adjacent the edges of said path to effect energization thereof at a level higher than that of the remaining emitters.

References Cited

UNITED STATES PATENTS

2,860,075	11/1958	Alexander et al.	118—49.1 X
2,746,420	5/1956	Steigerwald	118—49.1 X
2,872,341	2/1959	Stein	118—49.1 X
2,903,547	9/1959	Alexander	118—49.1 X
2,930,879	3/1960	Scatchard	118—49.1 X
3,146,335	8/1964	Samuelson	219—121
3,235,480	2/1966	Swartz et al.	118—49.1 X
3,235,647	2/1966	Hanks	219—121
3,244,855	4/1966	Cauley	250—49.5
3,270,233	8/1966	Dietrich	219—121 X
3,276,902	10/1966	Abraham	219—121
3,281,265	10/1966	Cauley	117—107.1 X
3,303,320	2/1967	Muller	118—49.1 X
3,308,263	3/1967	Schleich	219—121
3,308,264	3/1967	Ullery	219—127

MORRIS KAPLAN, *Primary Examiner.*