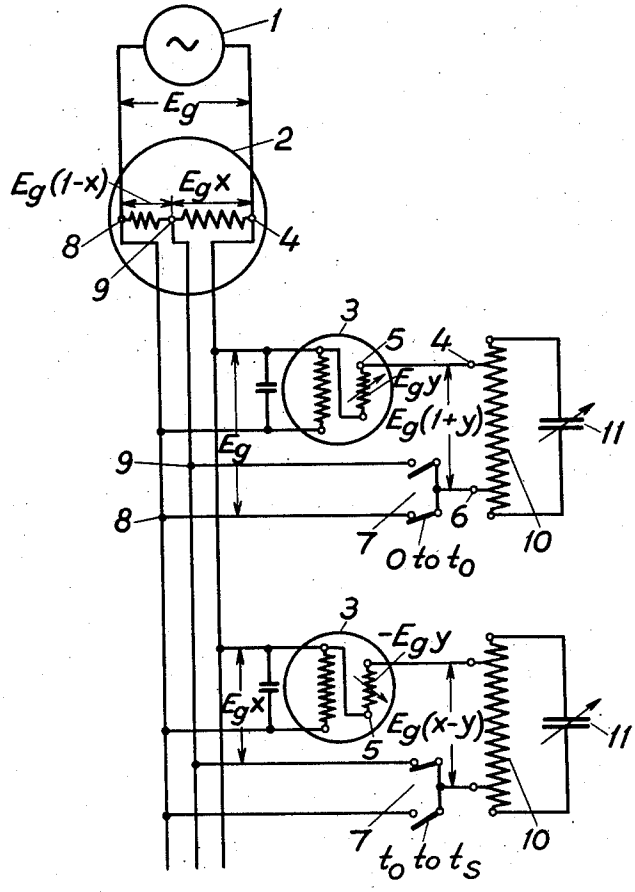
April 20, 1954 L. DREYFUS 2,676,232

ARRANGEMENT FOR THOROUGHLY HEATING OF LARGE BILLETS

Filed June 24, 1952



INVENTOR.
LUDWIG DREYFUS
BY
Eames Quirk
Attorney.

Patented Apr. 20, 1954 2,676,232

UNITED STATES PATENT OFFICE

2,676,232

ARRANGEMENT FOR THOROUGHLY HEATING OF LARGE BILLETS

Ludwig Dreyfus, Vasteras, Sweden, assignor to Allmanna Svenska Elektriska Aktiebolaget, Vasteras, Sweden, a Swedish corporation

Application June 24, 1952, Serial No. 295,240

Claims priority, application Sweden June 25, 1951

3 Claims. (Cl. 219—10.41)

1

The invention relates to a method for the electrical heating of metal bodies and to an apparatus for carrying out this method. More particularly, it relates to a method and apparatus for heating large billets of steel or the like.

It requires comparatively long periods of time for the thorough heating of large cylindrical steel billets, that is, those having an average diameter greater than 10 cm., or of steel plates having a thickness greater than 10 cm. In heating such pieces with electric fields of the frequencies produced by rotating electrical machines (that is, in the range of about 50 to 3000 cycles), the heat is generated in a limited zone near the surface of the work. The coefficient of heat conductivity

$$\lambda\left(\frac{\text{Watt}}{\text{cm.}^\circ\text{C.}}\right)$$

is so small that the heat in this surface zone is distributed rather slowly to the central part of the body. Heating at such frequencies can be carried out economically only if the furnace is effectively insulated, if the heating period t_s is kept as low as possible by a proper control of the power and proper choice of the frequency, and if the internal power consumption of the control device is kept low.

The primary object of the present invention is to provide an improved method and apparatus for the electrical heating of large pieces of metal.

Another object of the invention is to provide a process and apparatus for achieving the criteria set out above, so as to obtain economic heating of such pieces.

Further objects and advantages of the invention will appear more fully from the following description, especially when taken in conjunction with the accompanying drawing which forms a part thereof.

The drawing shows diagrammatically the circuit of a heating apparatus which can be used for carrying out the invention.

According to the invention, billets having a major dimension greater than 10 cm. (which expression is used herein to designate either cylindrical billets having a diameter greater than 10 cm. or plates having a thickness greater than 10 cm.) are heated in two heating periods. These periods are designated as "t_0" and "t_s-t_0" respectively. During the first heating period t_0, the surface temperature of the billet is heated to the highest permissible temperature. The duration of the period t_0 is preferably between T_1 and $3T_1$, where T_1 is the time constant at

2

which the temperature difference between the surface of the billet and the interior thereof is equalized when the supply of power is discontinued.

At the end of the period t_0, the supply of power p_0 (which equals

$$\frac{\text{W.}}{\text{cm.}^2}$$

is abruptly reduced. The difference of temperature between the surface layer and the center of the billet is equalized during the period t_s-t_0, during which period the temperature of the surface is maintained substantially at the value which it had at the end of period t_0 by proper control of the power.

Another feature of the invention is the provision of apparatus for carrying out the method described above. This includes a plurality of furnace units, a source of power, a voltage divider delivering different voltages, a separate voltage controlling device in series with the voltage divider for delivering an adjustable voltage to each furnace unit, and an individual change-over device for each furnace unit for connecting the units selectively to different voltages.

In the following description, δ has been used to indicate the diameter of a cylindrical billet and Δ the thickness of a plate, measured in centimeters. D has been used as generic to both δ and Δ, where the same formula is applicable to both. Where there are different formulas, they are designated by B for cylindrical billets and S for plates or sheets, respectively; as (1B) and (1S).

First heating period t_0 (sec.)

It is useless to begin heating with the largest power p_0 (that is,

$$\frac{\text{Watt}}{\text{cm.}^2}$$

of the surface of the billet) available. The mean temperature ϑ_m will then, it is true, increase very quickly to:

$$\vartheta_m=\frac{4p_0t}{\delta c} \qquad (1B)$$

$$\vartheta_m=\frac{2p_0t}{\Delta c} \qquad (1S)$$

where c designates the specific heat per unit of volume

$$\left(\frac{\text{Watt.sec.}}{\text{cm.}^3\,^\circ\text{C.}}\right)$$

But under these conditions the surface temperature will increase still more rapidly, and an excess temperature will exist corresponding to

$$\vartheta-\vartheta_m=\frac{\vartheta_m}{t}\,T_0\left(1-e^{-\frac{t}{T_1}}\right) \qquad (2)$$

The time constant at which the excess temperature $\vartheta-\vartheta_m$ is generated during the heating period and equalized during the cooling period is represented by the formulas:

$$T_1=\left(\frac{\delta}{7.664}\right)^2\cdot\frac{c}{\lambda} \qquad (3B)$$

$$T_1=\left(\frac{\Delta}{2\pi}\right)^2\cdot\frac{c}{\lambda} \qquad (3S)$$

It will be seen that the excess temperature, as the time t increases, approaches

$$\vartheta-\vartheta_m=\left(\frac{\vartheta_m}{t}\right)T_0 \qquad (4)$$

A high speed of heating

$$\frac{\vartheta_m}{t}$$

thus results in a high excess temperature $\vartheta-\vartheta_m$ of the surface of the billet, especially if the time constant T_0 is not kept as low as possible.

T_0 is proportional to T_1, but it also depends to a great extent on the frequency ν, the permeability μ and the inverse value of the resistivity ρ (which equals

$$\text{ohm}\ \frac{\text{mm.}^2}{\text{m.}})$$

and is a very complicated function of the dimensionless parameter

$$\xi=0.2\pi\sqrt{\frac{\nu}{2000}\cdot\frac{\mu}{\rho}}\cdot\delta \qquad (5B)$$

$$\xi=0.2\pi\sqrt{\frac{\nu}{1000}\cdot\frac{\mu}{\rho}}\cdot\Delta \qquad (5S)$$

The following values are chosen for T_0:

$$T_0=3.67T_1 f_m(\xi) \qquad (6B)$$

$$T_0=\frac{\pi^2}{2}T_1 f_m(\xi) \qquad (6S)$$

The values for $f_m(\xi)$ are:

ξ	For cylinders	For plates
0	0.167	0.267
1	0.170	0.267
2	0.172	0.270
3	0.191	0.282
4	0.225	0.308
5	0.265	0.348
6	0.296	0.388
8	0.340	0.448
10	0.369	0.487
above 10	$\frac{1}{2}-\frac{\sqrt{2}}{\xi}+\frac{2}{\xi^2}$	$\frac{2}{3}-\frac{2}{\xi}+\frac{2}{\xi^2}$

It is clear that, in order to reduce the excess heating of the surface as much as possible, the value of ξ should be kept as low as possible, considering the electrical efficiency of the furnace. This can be accomplished by making ξ as low as possible, but:

$$\xi\geq 2.5 \qquad (7B)$$

$$\xi\geq\frac{2.5}{\sqrt{2}} \qquad (7S)$$

In treating pieces having different thickness at the same frequency, the lower limit of the frequency is determined by a consideration of the piece having the smallest dimension D_{min}. Assuming for steel that

$$\rho=1.1\ \text{ohm}\ \frac{\text{mm.}^2}{\text{m.}}$$

the frequency will be:

$$\nu=350\left(\frac{10}{D_{min}}\right)^2 \qquad (8)$$

From this equation, it will be seen that pieces having values of D greater than 25 cm. can be heated with conventional frequencies of 50 to 60 cycles. There is no upper limit for the frequency, but there is ordinarily no particular advantage in going beyond the range:

$$\nu=350\text{ to }2000\left(\frac{10}{D_{min}}\right)^2 \qquad (9)$$

Upon heating with a high supplied power p_0, the temperature of the surface rises quickly above the Curie point, at which all iron alloys become non-magnetic. Thereafter, it increases slowly to θ_0=1,300° C., for instance. This limit should preferably not be exceeded where forging is to be carried out at 1200° C. In the vicinity of the highest permissible temperature θ, at the end of period t_0, the supplied power is decreased, according to the present invention.

If the total heating period t_s is considered, from the beginning when the billet is cold until it reaches its final temperature θ_{ms}, the supplied power is applied almost the whole period to a billet heated to the non-magnetic range, so that it is permissible to base the calculations on the assumptions that $\mu=1$ and ρ is constant, even during the period t_0.

According to Equation 2, an average temperature is attained when $t=t_0$

$$\vartheta_{m0}=\frac{\vartheta}{1+\frac{T_0}{T_1}\varphi\left(\frac{t_0}{T_1}\right)} \qquad (10)$$

where

$$\varphi\left(\frac{t_0}{T_1}\right)=\frac{1-e^{-\frac{t_0}{T_1}}}{\frac{t_0}{T_1}} \qquad (11)$$

which will have the following values:

$\frac{t_0}{T_1}$	0	0.2	0.4	0.6	0.8	1.0	1.2	1.4
$\varphi\left(\frac{t_0}{T_1}\right)$	1.000	0.905	0.825	0.751	0.689	0.632	0.583	0.538
	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0
	0.499	0.464	0.432	0.404	0.379	0.356	0.335	0.317

Second heating period, t_s-t_0 (sec.)

At the end of period t_0, the power should be decreased, first by a large amount at once, and then continuously or step by step at a lower rate. According to the invention, the power should be controlled during the final heating period t_s-t_0 in such a way that the surface temperature θ is kept as exactly as possible at the highest permissible value. When $t=t_s$, at which time the average temperature of the billet has reached the forging temperature θ_{ms}, the heating is interrupted.

The variation of the temperature is represented by the differential equation:

$$\frac{d\vartheta}{dt}=\frac{d\vartheta_m}{dt}\left[1+\frac{T_0}{T_1}\right]-\frac{\vartheta-\vartheta_m}{T_1} \qquad (12)$$

From this equation it follows that after interruption of the power supply (that is, when

$$\frac{d\vartheta_m}{dt}=0)$$

the internal temperature differences $\vartheta-\vartheta_m$ are equalized according to the formula:

$$\frac{d(\vartheta-\vartheta_m)}{dt}+\frac{\vartheta-\vartheta_m}{T_1}=0 \qquad (13)$$

that is, according to the function:

$$\vartheta-\vartheta_m=(\vartheta-\vartheta_{ms})e^{-\frac{t-t_s}{T_1}} \qquad (14)$$

It also follows that with a constant supply of power (when

$$\frac{d\vartheta_m}{dt}$$

is constant) the excess temperature of the surface follows the differential equation:

$$\frac{d(\vartheta-\vartheta_m)}{dt}+\frac{\vartheta-\vartheta_m}{T_1}=\frac{d\vartheta_m}{dt}\frac{T_0}{T_1} \qquad (15)$$

the solution of which

$$\vartheta-\vartheta_m=\frac{d\vartheta_m}{dt}T_0\left(1-e^{-\frac{t}{T_1}}\right) \qquad (16)$$

already has been used in Equation 2.

For the second heating period (t_s-t_0) Equation 12 must be solved for constant surface temperature (ϑ being constant,

$$\frac{d\vartheta}{dt}=0)$$

Equation 12 thus is simplified to

$$\frac{d(\vartheta-\vartheta_m)}{dt}+\frac{\vartheta-\vartheta_m}{T_0+T_1}=0 \qquad (17)$$

with the solution

$$\vartheta-\vartheta_m=(\vartheta-\vartheta_{m0})e^{-\frac{t-t_0}{T_0+T_1}} \qquad (18)$$

During this period the supplied power must therefore be controlled in such a manner that the excess temperature of the billet surface decreases according to an e-function with the time constant T_0+T_1, which again shows the importance of the requirement of reducing T_0 as much as possible by choosing a sufficiently low frequency (Equation 7).

In order to realize this equalization of temperature with constant surface temperature, a power p is required as follows:

$$p=\frac{\delta c}{4}\frac{d\vartheta_m}{dt}=\frac{\delta c}{4}\cdot\frac{\vartheta-\vartheta_{m0}}{T_0+T_1}\cdot e^{-\frac{t-t_0}{T_0+T_1}} \qquad (19B)$$

$$p=\frac{\Delta c}{2}\frac{\vartheta-\vartheta_{m0}}{T_0+T_1}\cdot e^{-\frac{t-t_0}{T_0+T_1}} \qquad (19S)$$

The desired forging temperature ϑ_{ms} then is reached after a heating period:

$$t_s=t_0+(T_0+T_1)\ln\frac{\vartheta-\vartheta_{m0}}{\vartheta-\vartheta_{ms}} \qquad (20)$$

which therefore represents the shortest possible heating time to be attained without exceeding a given value ϑ of the surface temperature.

The power control

The power supplied to the surface of the work during the first heating period t_0 is expressed according to the Equations 1, 2 and 16 by

$$p_0=\frac{\delta c}{4}\cdot\frac{d\vartheta_m}{dt}=\frac{\delta c}{4T_0}\cdot\frac{\vartheta-\vartheta_{m0}}{1-e^{-\frac{t_0}{T_1}}} \qquad (21B)$$

$$p_0=\frac{\Delta c}{2T_0}\cdot\frac{\vartheta-\vartheta_{m0}}{1-e^{-\frac{t_0}{T_1}}} \qquad (21S)$$

During the second t_s-t_0, the power control must begin according to Equation 19 with a value

$$p_{t_0}=\frac{\delta c}{4}\frac{\vartheta_m-\vartheta_{m0}}{T_0+T_1} \qquad (22B)$$

$$p_{t_0}=\frac{\Delta c}{2}\frac{\vartheta-\vartheta_{m0}}{T_0+T_1} \qquad (22S)$$

The power must be reduced abruptly at $t=t_0$ in the proportion

$$p_0:p_{t_0}=1:\frac{T_0}{T_0+T_1}\left[1-e^{-\frac{t_0}{T_1}}\right] \qquad (23)$$

The shorter t_0 is made, that is, the higher the heating speed, the more the degree of discontinuity of the high-frequency load increases without shortening the total heating period t_s in a corresponding degree. For this reason an order of magnitude is recommended for t_0

$$t_0=T_1 \text{ up to } 2T_1 \text{ or up to } 3T_1 \qquad (24)$$

and for the power control at $t=t_0$ a power proportion:

$$p_0:p_{t0}=1:\frac{T_0}{T_0+T_1}\ [0.632 \text{ up to } 0.865 \text{ or up to } 0.950] \qquad (25)$$

Whether, after the abrupt decrease at t_0, the decrease of power to p_{ts} at $t=t_s$ is effected continuously or stepwise in several steps depends on the means used for the control of the voltage of the furnace coil.

All the formulae are approximative, partially since radiation losses from the charge have been neglected. The calculated values, therefore, have to be increased with increases in such losses. It has, however, already been mentioned that only very small heat losses may be counted on because of the comparatively long heating time required for large billets in high-frequency furnaces, and therefore errors involved by neglecting these losses are small.

The arrangement for the power control

It follows from the above that the thorough heating of billets having 15 to 30 cm. diameter takes 5 to 30 minutes, which is much more than the time required for the forging or pressing operation itself. In practice, therefore, a great number of (N) billets will always be heated simultaneously. For this purpose there are two alternatives. Either a few (n) furnaces are provided, each accommodating many

$$\left(\frac{N}{n}\right)$$

billets, and provided with several succeeding heating zones acting with different amounts of power on the billets, the billets being conveyed through said zones without interruption; or, a comparatively large number

$$\left(\frac{N}{n}\right)$$

of furnace units are employed each accommodating a few (n) billets, the latter being held stationary within the same furnace during the whole heating period. The last mentioned alternative is to be preferred when it is necessary to avoid oxidation as much as possible, as the furnace units then may be easily closed and filled

with a protecting gas. But, with respect to the feeding of the billets, the first alternative is considerably simpler. In this case, it will be noticed, all n furnaces work with the same constant voltage. In the other alternative, however, the control of the supplied power is effected by controlling the voltage of the furnace coil, which control, it is true, is performed according to the same program for all

$$\frac{N}{n}$$

furnaces but with a relative delay of phase

$$\frac{t_s}{N/n}$$

for furnaces which are charged and discharged one after the other. Although the

$$\frac{N}{n}$$

furnace units which are switched in are equal, the amounts of power and the voltages must be different at the same moment in different units. The coils of the furnaces, therefore, cannot be connected in parallel, but their terminal voltages must be adjustable individually, while the total power of the equipment is generated with constant voltage E_g in one or more parallel-connected generators.

The problem of carrying out a power control according to the proportion $p_0 : p_{ts} \approx 1 : 0.1$ by means of cheap control devices for each furnace unit may be solved according to the invention in a manner which is shown on the drawings by way of example.

The voltage E_g produced within the generator 1 or power station is divided by means of a voltage divider 2, arranged in the primary station or in the forge, according to the proportion $x : 1-x$, where

$$x \approx \frac{1+\sqrt{\frac{p_{ts}}{p_{t0}}}}{2\sqrt{\frac{p_0}{p_{t_0}}}-\left(1-\sqrt{\frac{p_{ts}}{p_{t_0}}}\right)} \qquad (26)$$

To each furnace unit the constant voltages E_g, $E_g x$, $E_g (1-x)$ are applied.

Furthermore, a comparatively small adjustable voltage $\pm E_g y$ is inserted in series with the voltage $E_g x$, where

$$y \approx \frac{1-\sqrt{\frac{p_{ts}}{p_{t0}}}}{2\sqrt{\frac{p_0}{p_{t0}}}-\left(1-\sqrt{\frac{p_{ts}}{p_{t0}}}\right)} \qquad (27)$$

3 is a voltage control arrangement. If the voltage $E_g y$ is to be controlled continuously, this voltage may be generated in a booster-generator, an induction regulator or a slide transformer or the like. If only stepwise control is desired, a regulating transformer with a tap-changing switch may be used. In any case the one "generator connector tap" 4 of the furnace coil 10 is connected to the free end 5 of the winding producing the voltage $E_g y$ while the other "generator connector tap" 6 is connected through a change-over switch or two switches 7 either to the free end 8 of the voltage divider 2 or to its intermediate pole 9.

By these arrangements the following control program is performed: The furnace unit is started with a voltage $E_g (1 \mp y)$, where the ratio y and its sign is adjusted automatically for constant supplied power p_0 during the first heating period t_0, as shown by the position of the switch 7 in the upper furnace unit. At the end of this period ($t = t_0$) the switch 7 is changed over and connects the coil to the voltage $E_g (x+y)$ as shown by the position of the switch in the lower furnace unit. Thus the power decreases instantaneously according to the proportion

$$(x+y)^2 : (1+y)^2 = p_{t_0} : p_0 \qquad (28)$$

Thereafter the adjustable auxiliary voltage is altered automatically from $E_g y$ to $-E_g y$ (as indicated by the changed direction of the arrow in the voltage control means 3) corresponding to a decrease of power in the proportion:

$$(x-y)^2 : (x+y)^2 = p_{t_s} : p_{t_0} \qquad (29)$$

after which the furnace coil, when $t = t_s$, is disconnected automatically.

The essential feature of this solution of the control is that the expensive control device which generates the adjustable voltage $E_g y$ need be dimensioned only for low internal power consumption.

11 designates a capacitance which is automatically controlled in the usual way in resonance with the reactance of the furnace coil.

I claim:

1. Method of thoroughly heating electrically to forging temperature billets having a thickness greater than 10 cm. by currents and frequencies generated in rotating machines, which comprises heating the billet during a first period and thus increasing the surface temperature of the billet to substantially the highest permissible value, and during a second heating period controlling the power supplied to the billet so as to maintain substantially the same surface temperature, the duration of the said first period being between 1 and 3 times the time constant at which the temperature differences between the surface of the billet and the interior thereof is equalized when the supply of power is discontinued, the power at the end of the first period being abruptly reduced in the proportion

$$1 : \frac{T_0}{T_0+T_1}\left(1-e^{-\frac{t_0}{T_1}}\right)$$

where T_0 is the quotient of the difference between the surface temperature ϑ and the average temperature ϑ_m of the billet divided by the rate of increase of the temperature

$$\frac{d\vartheta_m}{dt}$$

at which such difference occurs, and during the said second heating period the power being decreased in the proportion

$$1 : e^{-\frac{t-t_0}{T_0+T_1}}$$

2. Method according to claim 1, in which the current frequency is within the range of about 350 to 2000 times

$$\left(\frac{10}{D_{min}}\right)^2$$

where D_{min} is the smallest major dimension of billets being treated.

3. Apparatus for carrying out the process of claim 1, comprising a plurality of furnace units, at least one generator supplying a constant voltage E_g, a voltage divider connected between said generator and said furnace units and arranged to supply to each furnace unit voltages E_g, $E_g x$ and $E_g (1-x)$, an individual control device for each

furnace unit adapted to connect in series with voltage $E_g x$ a variable voltage $\pm E_g y$, and a separate change-over device for each furnace unit for selectively connecting to the furnace unit a voltage $E_g (1 \mp y)$, in which y is variable, during a first heating period, and a voltage variable from $E_g (x+y)$ to $E_g (x-y)$ during a second heating period.

References Cited in the file of this patent

UNITED STATES PATENTS

Number	Name	Date
2,046,718	Bletz	July 7, 1936
2,363,719	Cooper et al.	Nov. 28, 1944
2,400,472	Strickland	May 14, 1946
2,429,819	Jordan	Oct. 28, 1947
2,452,365	Frederick	Oct. 26, 1948
2,511,026	Wadhams et al.	June 13, 1950
2,517,869	Grapp	Aug. 8, 1950
2,521,880	Storm	Sept. 12, 1950
2,588,304	Storm	Mar. 4, 1952