June 12, 1951 F. O. SCHNURE, JR 2,556,223

INDUCTION HEATING OF FLAT METAL BY TRANSVERSE FLUX

Filed May 28, 1947

Fig. 1.

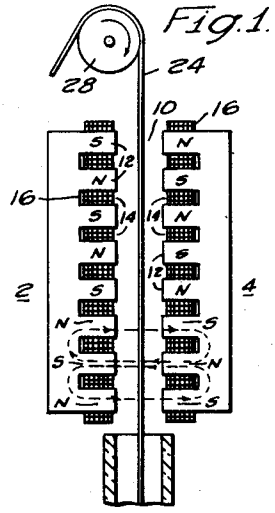


Fig. 2.

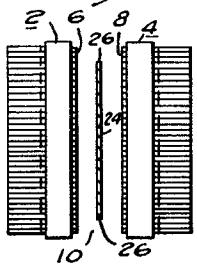


Fig. 3.

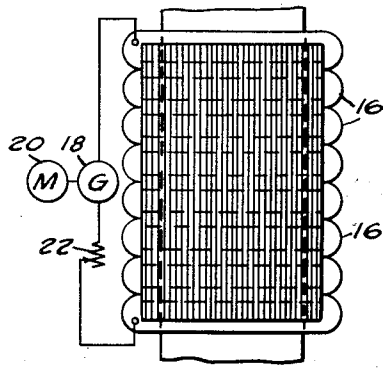
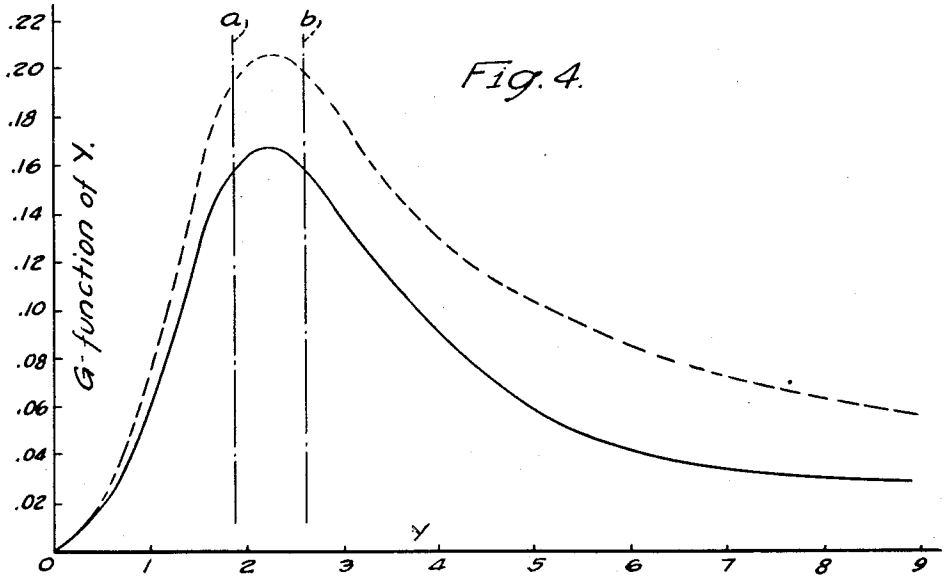


Fig. 4.



WITNESSES:

E. A. McCauley

Wm. L. Groome

INVENTOR

Frederick O. Schnure, Jr.

BY

B. L. Zangwill

ATTORNEY

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INDUCTION HEATING OF FLAT METAL BY TRANSVERSE FLUX

Frederick O. Schnure, Jr., Cleveland, Ohio, assignor to Westinghouse Electric Corporation, East Pittsburgh, Pa., a corporation of Pennsylvania

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2 Claims. (Cl. 219—13)

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My invention relates, generally, to high-frequency heating; but is more particularly directed to refinements in induction heating of elongated travelling non-magnetic metal material, such as, for example, coilable strip, by the use of transverse magnetic flux in a fashion described and claimed in the Robert M. Baker patent-application Serial No. 521,229, filed February 5, 1944, now Patent No. 2,448,009, dated August 31, 1948, to which reference may be had for further details.

My invention is herein described in connection with a preferred form in which elongated coilable metallic strip is passed longitudinally, or in the direction of its length, through an alternating magnetic field for a heat treatment. The magnetic lines pass transversely through the faces of the strip and induce electrical currents therein which heat the strip, a form of induction heating generally designated as transverse-flux induction heating. In the embodiment herein described, the flux lines which heat the strip may be considered to pass through one face of the strip, in a direct line across the strip, and then out of the other face. As described in the aforesaid Baker patent-application, the heat which is introduced into the strip by the alternating transverse magnetic flux is dependent upon a number of physical quantities or factors having to do with the magnetizing characteristics of the flux-producing induction heating apparatus, the frequency of the current used to produce the magnetization, and the resistivity and thickness of the strip being heated. As is understood in the art, the frequency of the alternation of the magnetic flux will be the same as that of the magnetizing current which produces the flux.

Commercial strip, however, does not have exactly uniform properties throughout. With predetermined heating apparatus, a variation in thickness at different parts of the moving strip has an appreciable effect on the heat introduced into the strip at such parts. Variation in resistivity, however, even those due to large changes in temperature, do not introduce as great a variation in the uniformity with which the strip can be heated.

It is a general object of my invention to inductively heat non-magnetic metal strip generally in accordance with the teachings of the aforesaid Baker patent, but in such an improved manner that variations in physical characteristics of the strip, such as described, will have no significant effect on the rate with which heat will be introduced into the strip. In accordance with my present invention, a uniform heating is

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obtained with commercial strip having varying thicknesses at different points thereof.

A prime object of my invention is to provide an induction heating apparatus and method of a type described which will automatically satisfactorily heat travelling non-magnetic metallic strip, and especially thin strip made from a metal of low radiation emissivity, such as aluminum. It is extremely difficult directly to regulate the heat input to moving heated strip of this kind. I am aware of no temperature measuring apparatus which will be satisfactory for regulating the heating equipment; and a mechanical gauge measuring device as a control for heat regulation, will mar the finish of the strip.

Advantages, methods, features and innovations of my invention, in addition to the foregoing, will be discernible from the accompanying description thereof, which is to be taken in conjunction with the attached drawing. The drawing is schematic and it is limited to such parts as will make my invention clear to one skilled in the art.

In the drawing,

Figs. 1, 2 and 3 are vertical sectional, plan, and side-elevational views of an embodiment of my invention; and

Fig. 4 shows theoretical (dashed line) and experimental (solid line) curves representing the variation of a complex function, called a G function, as ordinates, with variation in one of its determining factors, as abscissae. The G function is a function affecting the rate at which heat can be inductively introduced into strip by transverse flux.

In Figs. 1, 2 and 3, a transverse-flux induction heating furnace or apparatus is shown in simplified form. It comprises a pair of electro-magnetic field-structures **2** and **4** having flat parallel pole-faces **6** and **8**, respectively, which are spaced apart to form a shallow air-gap or work passage **10** extending the width and length of the pole-faces.

Each of the field-structures **2** and **4** comprises comb-shaped laminations formed into a magnetic core having like poles or teeth **12** and like slots **14**, alternating with each other. Magnetizing windings or coils **16** are fixed in the slots **14** and are so arranged and connected, and so energized by any suitable alternating current, that a pole **12** on one field-structure will have a polarity opposite to that of the directly opposite pole **12** on the other field-structure, as indicated by the N and S polarity designations in Fig. 1. For energizing the coils, any suitable source of alternat-

ing current power can be provided. In Fig. 3, a motor generator set is schematically represented by an alternating current generator 18 driven by a motor 20 whose speed is variable for controlling the frequency of the current supplied to the coils 16 by the generator 18. The magnitude of the current can be controlled in any suitable way, indicated schematically as a variable impedance 22.

An elongated strip 24 having edges 26 is passed through the air-gap 10 for heat-treatment. The strip 24 passes downwardly through the air-gap 10, as indicated by the arrow on the drum 28 of Fig. 1. In so moving, the strip moves longitudinally, that is, in the direction of its length. As described in the aforesaid Baker patent, the field-structures are relatively movable in planes substantially parallel to their pole-faces, so that their edges will be kept at predetermined lateral distances from the edges of the strip. Preferably, the field-structures also are adjustable in a direction perpendicular to their pole-faces, for controlling the width of the air-gap. A structure of this kind is shown in more detail and claimed in the application of R. M. Baker, G. R. Monroe and R. D. Reed, Serial No. 542,380, filed June 27, 1944, now Patent No. 2,448,010, dated August 31, 1948.

It has been shown in the aforesaid Baker patent that the heating of each cubic centimeter of strip subjected to magnetic flux alternations in an induction heating system of a type described is at a rate which can be expressed as

$$W=\frac{gH^2fG(y)\,10^{-7}}{2t} \tag{1}$$

where

W=watts per cubic centimeter;
g=air-gap thickness in centimeters;
H=peak magnetizing force, in oersteds, in the air-gap without the strip therein;
f=frequency of the magnetizing current in cycles by second;
t=thickness of strip in centimeters; and
$G(y)$=a complex function of a quantity, y, represented by the equation

$$y=p\sqrt{\frac{cft10^{-9}}{rg}} \tag{2}$$

where

c=a constant;
p=the pole-pitch of the field-structures, in centimeters;
r=the resistivity of the strip, in ohm-centimeters.

The upper line of Fig. 4 is a typical theoretical curve showing how a G function varies in accordance with y. It will be observed that the G function has a maximum value in a range between a and b on Fig. 4, or in the region where y has a value of about 2 to 2½. Beyond this region, in a range where the curve has a falling part with a negative slope, the value of the G function decreases as the value of the quantity represented by y increases. Before this region, in a range where a curve has a rising part with a positive slope, the value of the G function increases as the value of the quantity represented by y increases.

It has been the practice to so construct transverse flux heating apparatus and to so operate it that the values of y were above about 2.3. Under such circumstances, the heating will be in accordance with values of y in excess of that providing the range of maximum values of the G function; that is, in the region starting with y having a value of about 2.3 to greater values of y, or on the falling part of the curve. This was done for several reasons. The internal power factor at which the magnetic equipment utilizes A. C. power, and the efficiency of the apparatus are higher at the higher values of y than they are at the lower values of y. The internal power factor and efficiency of the apparatus are very important considerations because they affect considerably the cheapness with which the apparatus, comprising magnetic structures of several tons each, can be built and operated. Also, at the higher values of y, the curve is flatter and its slope less, so that the G function does not vary much with variations that are introduced in building the apparatus.

However, by considering the above equations, it can be seen that a variation in gauge or thickness, t, of the strip may affect the value of W in Equation 1, other things being unchanged.

Considering only the denominator of the right-hand side of Equation 1, of which t is a factor, variations in gauge or thickness, t, of the strip being inductively heated will cause a variation in the heating units W per unit volume of strip. Such variation in W will be inverse to the variation in t; that is, an increase in t is accompanied by a decrease in W, and vice versa. However, a variation in t also affects the numerator because it affects the G function which is a factor of the numerator. The manner in which the value of t affects the G function becomes apparent with reference to Equation 2 and Fig. 4. From Equation 2, an increase in t always increases y, and vice versa. From Fig. 4 a single variation in y may increase or decrease the value of the G function, depending on whether or not the heating operation is carried out on the rising part or on the falling part of the curve of Fig. 4. On the falling part of the curve (that part to the right of the value line b) an increase in y (resulting from an increase in strip gauge t) causes a decrease in the G function. On the rising part (that part to the left of value line a) an increase in y (resulting from an increase in t) causes an increase in the G function. Similarly a decrease in y (resulting from a decrease in t) may increase or decrease the G function, depending on the part of the curve involved.

If the heating is carried out with the G function on the falling part of the curve, an increase in thickness, t, of the strip results in the numerator of Equation 1 becoming smaller and the denominator becoming larger, so that the value of W decreases cumulatively when the heating is along the falling part of curve, beyond the value of y equal to b. This means that the watts per cubic centimeter introduced into the strip will decrease when the increased thickness of the strip demands more heat, and vice versa. This can be quite a handicap in instances where it is necessary to maintain the final temperature of the strip within close limits, and there are no available means for regulating the operation of the apparatus by direct measurements of gauge or temperature. The induction heating of aluminum foil by transverse flux for annealing presents a particularly difficult problem because the final temperature of the foil must be closely maintained; but the emissivity of the foil is so low that a satisfactory radiation pyrometer has not yet been developed for regulating the heating, and a satisfactory flying micrometer cannot be used for

the regulation because it would mar the surface of the strip.

In accordance with my invention, however, I provide heating of the strip on the rising part of the curve of Fig. 4, that is, in a range where the y factor has a value of about a or lower. In this range of the curve, an increase in y (resulting from an increase in strip thickness, t) causes an increase in the G function, and vice versa. Hence, when t tends to increase the G function also tends to increase, and vice versa. Accordingly, with respect to right-hand side of Equation 1, a change in the denominator factor, t, is accompanied by a change in the numerator factor, the G function, in the same direction; that is t and the G function both increase or decrease. The result is that the value of W tends to remain fairly uniform (although the strip thickness fluctuates) so long as the heating apparatus has characteristics that cause y of Equation 2 to have a value that falls on the left-hand side of the curve of Fig. 4. However, it is preferable to operate as close to the higher values of y, in the desired range, as is convenient, in order to keep the internal power factor and efficiency of the apparatus as high as possible.

To understand what happens when the operation corresponds to the rising part of the curve, consider how the rate at which heat is introduced into the strip is now affected by changes in strip gauge, t. From Equation 2 an increase in strip gauge, t, increases the value of y. From Fig. 4 an increase in y in the range of about .25 to 2, results in an increase in the value of the G function. From Equation 1, an increase in the G function tends to increase W, or the rate at which heat is introduced into the strip. However, in Equation 1 the assumed increase in the strip gauge, t, tends to decrease W, and so has a neutralizing effect on the tendency of W to increase because of the increase in the G function. Hence, the change in t produces two effects which tend to counterbalance each other when y is on the rising part of the curve of Fig. 4, whereas they are objectionably cumulative when y is on the falling part of the curve. Operation on the rising part of the G function curve automatically tends to provide a more uniform temperature in the strip.

As an indication of the operation of my invention, assume, for example, that

g equals 1.25×2.54; $f=960$ cycles; $t=.003\times2.54$

$p=4.5\times2.54$; $r=5.15\times10^{-6}$; and $c=4\pi^2$. With these values substituted in Equation 2, the y factor is equal to about 1.52. At y equal to 1.52, the G function is about 1.22 on the experimental curve of Fig. 4. At this value of the G function, it can be assumed that the heat density introduced in the strip has a value of W' watts per cubic centimeter. It the gauge increases 20%, that is, t increases 20% to $t=1.2(.003\times2.54)$, the y factor will be 1.67 and the corresponding G function will be .141. The relative heating under the new condition will be directly proportional to the change in the G function and inversely proportional to the change in thickness. In other words, the new rate W'', at which heat is introduced into the strip will be

$$W''=W'\times\frac{.141}{.122}\times\frac{1}{1.2}=.965W'$$

This is a decrease in the rate of heating of about 3.5% below that at the standard thickness, t.

If, instead of increasing, the thickness t of strip decreases 20%, the y factor becomes equal to 1.36 and the G function becomes equal to .10. When the thickness decreases by 20%, the new rate of heating is equal to 1.025W', or an increase of 2.5% over the heating at the standard thickness, t.

From the foregoing figures, it will be observed that an increase in strip thickness of 20% decreases the heating by only about 3.5%; and a decrease in the strip thickness of 20% increasing the heating by only about 2.5%. It will be obvious that a 20% variation of thickness is quite a large change in gauge even for commercial strip; but that nevertheless such large gauge-changes introduce no significant changes in the rate of heating.

Accordingly, normal fluctuations in the gauge or thickness of moving non-magnetic strip being inductively heated can cause a considerable variation in the amount of heat induced per unit volume of such strip, or can cause a substantially constant amount of heat to be induced per unit volume of such strip, depending on how the apparatus is operated. However, when a heating operation is carried out in accordance with a curve having a shape such as that of Fig. 4, a substantially uniform heating is automatically induced in each unit volume of the strip so that special precautions with respect to the thickness of the strip are not necessary.

While I have described my invention in a manner best known to me at present, it is not limited in its application because it is obvious that its teachings can be broadly applied to induction heating of the type described.

I claim as my invention:

1. A method for inductively heating commercial elongated flat non-magnetic metal material having a resistivity of r ohm-centimeters and a thickness of t centimeters, which comprises passing the material through an air-gap of g centimeters between a pair of electromagnetic cooperating field-structures producing, when magnetized, a transverse flux across the air-gap, the field-structures having magnetizing coil-means and poles and slots therebetween having a pole pitch of p centimeters, and electrically energizing said magnetizing coil-means with current having alternations of f cycles per second, while maintaining the relationship of the aforesaid quantities p, f, t, and g, such that

$$p\sqrt{\frac{4\pi^2 ft10^{-9}}{rg}}$$

is substantially in a range of 0.25 to 2.0, whereby the heat introduced by said apparatus into each unit volume of material remains substantially constant with variations in thickness of such material.

2. A method of substantially uniformly inductively heating commercial flat non-magnetic strip in a transverse-flux induction heating system of a type described, the system comprising a pair of spaced field-structures having poles and slots therebetween with a pole pitch of p centimeters, and having magnetizing coil means, the field-structures being separated by an air-gap of g centimeters, the strip having a thickness of t centimeters, which may vary at different parts of the material, and a resistivity of r ohm-centimeters, which method comprises electrically energizing the coil-means with a current having alternations of a frequency f cycles per second, to provide transverse flux across the air-gap, passing the strip through the air-gap whereby

said different parts are successively heated, and controlling the relation of the aforesaid quantities of p, f, t and g, so that

$$p\sqrt{\frac{4\pi^2 ft10^{-9}}{rg}}$$

is substantially in a range of 0.25 to 2.0, whereby the heat introduced by said apparatus into each unit volume of strip remains substantially constant with varying thicknesses of the strip-portion passing through the air-gap.

FREDERICK O. SCHNURE, JR.

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