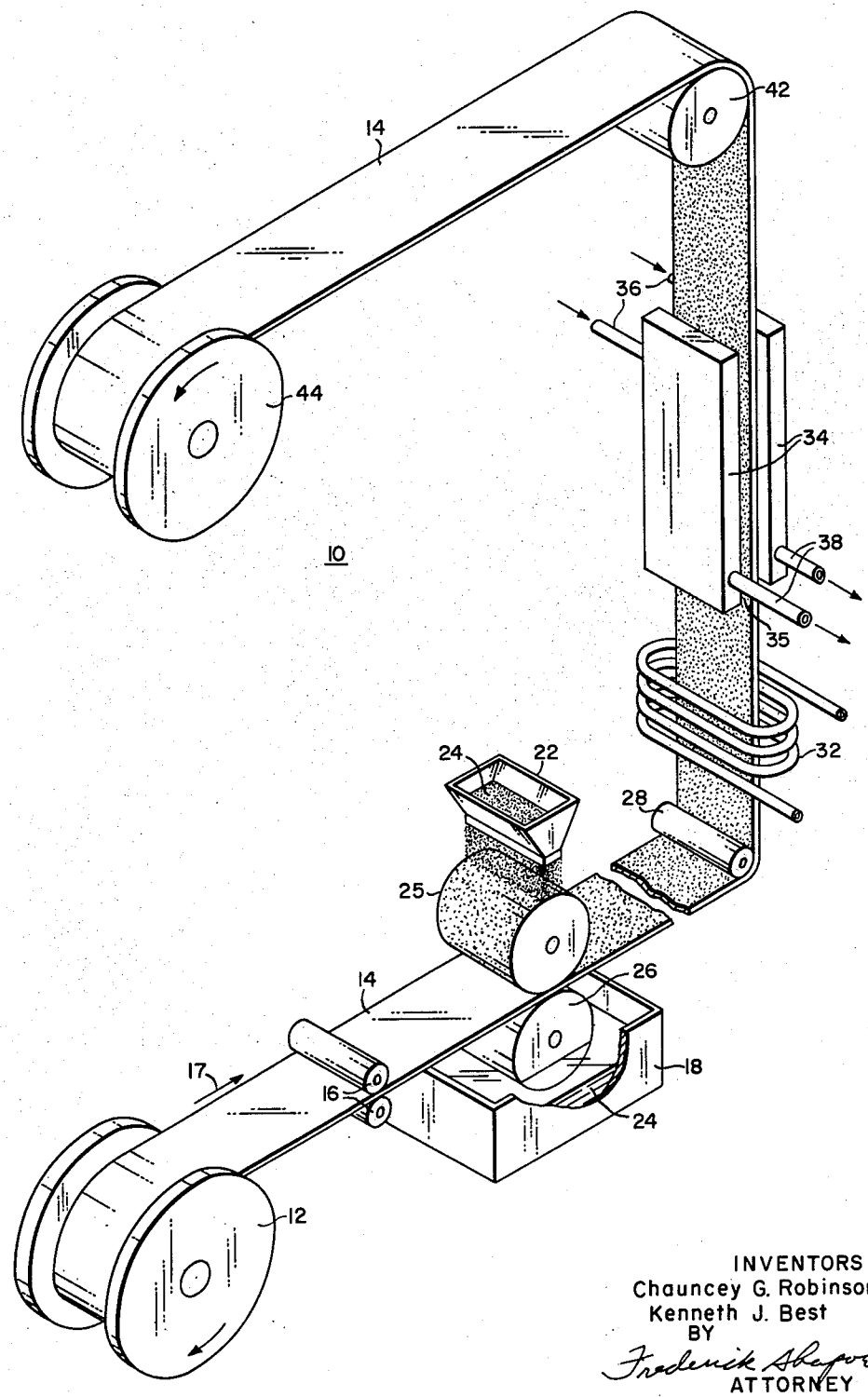
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INDUCTION ANNEALING OF MAGNETIC ALLOY SHEET

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INVENTORS
Chauncey G. Robinson &
Kenneth J. Best
BY
Frederick Shepard
ATTORNEY

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INDUCTION ANNEALING OF MAGNETIC ALLOY SHEET

Chauncey G. Robinson, Muncie, Ind., and Kenneth J. Best, Sharon, Pa., assignors to Westinghouse Electric Corporation, East Pittsburgh, Pa., a corporation of Pennsylvania

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This invention relates to a method for heating elongated magnetic material in the form of sheet and strip and the like, by means of induced high frequency electrical means to accomplish stress relief of the material and to improve the flatness thereof. The invention is particularly applicable to oriented silicon-iron alloy sheets.

In producing magnetic alloy sheet material for use in motors, generators, and transformers, the sheet invariably undergoes numerous treatment cycles involving hot and cold working and annealing, primarily to develop desired magnetic properties in the sheet at final desired gauge. Furthermore, coatings of insulating materials are often applied to the sheet surfaces during the processing. While the desired magnetic properties have been emphasized in the steps applied to the alloy sheet by this processing, it is found that stresses and strains are developed in the sheet material, which if not relieved or removed, will affect the dimensional stability and the flatness of the sheet and will degrade the magnetic characteristics of cores made therefrom for subsequent use. Stresses and strains may result from coiling, shipping, and handling of magnetic sheets in the process of converting the sheets to cores. Accordingly, it is usual to give the magnetic sheet a final stress relief anneal as the last step in the treatment of cores prepared from the material. Sometimes an additional separate anneal is applied to the sheet material or punchings thereof before it is made into cores in order to reduce stresses and strains.

Present practice in stress relief of the magnetic alloy sheet as illustrated in Burgwin Patent 2,351,922 involves first moving the sheet slowly through a gas or electrically heated radiant chamber to raise the temperature of the sheet to about 700° C. to 850° C. The sheet is moved horizontally and tension is maintained on the alloy sheet by supporting rolls at the entrance and exit of the furnaces. The sheet is air cooled after leaving the furnace and before it is recoiled.

The radiant type of annealing treatment which has been described above has certain disadvantages. For example, the great structural mass of the furnaces used requires large amounts of fuel or electric energy to heat the furnace walls, which heat energy would be better employed in heating the magnetic alloy sheet. Further, it is difficult to control the temperature in the alloy sheet, and to obtain a uniform temperature gradient across the sheet due to the large area of the furnace walls which must be heated to a precisely predetermined temperature, edge effects in the sheet, and the large quantity of alloy sheet whic his simultaneously undergoing heating to the desired temperature. Also, in start-up operations, the attaining of the desired temperature level in the furnace involves raising the temperature slowly to the operating level, and this prolonged time at elevated temperature below operable levels is wasteful, for until operating temperature level is reached, no satisfactory sheet material may be processed.

However, the most serious shortcoming of the prior art and practices in magnetic sheet annealing is the fact that non-uniform temperature gradients are produced in the sheet so that the isothermal lines are not straight and perpendicular to the edge of the sheet. The isothermal lines across a sheet heated in the usual radiant furnace

are deep curves, often non-symmetrical, which cause waves, buckles, and ripples to form in the sheet. Therefore different tensions develop in different portions of the sheet and the metal may stretch or be warped non-uniformly. On cooling too, non-uniform gradients may occur and further cause permanent waves, buckles, and ripples to develop. The cooled sheet is not flat and has less than optimum magnetic properties when made into a core.

Accordingly, it is the object of this invention to provide a method for annealing a traveling magnetic alloy sheet by means of longitudinal flux induction heating in which a narrow transverse band of the magnetic sheet is raised to a predetermined temperature with extreme isothermal uniformity transverse of the edge of the sheet, and a uniformity of temperature gradient longitudinally of the sheet, whereby optimum stress relief of the sheet is achieved and an extremely flat magnetic sheet is produced.

It is another object of this invention to provide a process for annealing traveling iron-silicon magnetic alloy sheet, and particularly oriented magnetic sheet, including coating the sheet with a thin insulating coating, heating the coated sheet by means of longitudinal flux induction heating in which a narrow transverse band of the sheet perpendicular to the edges is rapidly and isothermally raised to an annealing temperature in the range of from 725° C. to 775° C., and in which a uniform temperature gradient is maintained longitudinally of the sheet during heating, cooling the sheet by passing the sheet between radiant cooling plates thereby maintaining a uniform temperature gradient longitudinally of the sheet during cooling, whereby optimum stress relief of the sheet is achieved, and the sheet is characterized by an absence of waves, buckles, and ripples.

Other objects of this invention will, in part, be obvious and will, in part, appear hereinafter.

For a better understanding of the nature and the objects of this invention, reference should be had to the following detailed description and to the drawing, in which the figure depicts in perspective an annealing line suitable for the practice of the process of this invention.

In accordance with this invention there is disclosed a method for annealing magnetic alloy sheet so that the annealing temperature is attained in a narrow band transverse of the sheet in an extremely uniform manner, whereby stress relief of the alloy sheet is achieved and magnetic alloy sheet of extreme flatness is produced. The process involves sequentially providing the sheet with a phosphate or other reactive composition coating, passing the sheet vertically upward through, and axially of, a heating station comprising a high frequency induction coil whereby a narrow transverse band of the alloy sheet is raised to annealing temperature with isothermal lines being substantially straight and perpendicular to the edge of the sheet, continuing the vertical upward movement of the sheet through a cooling station comprising a dead air chamber having radiant cooling surfaces or walls, and thereafter coiling or cutting the cooled alloy sheet.

The figure shows an annealing line **10** in which the process of this invention was successfully practiced. More particularly, the figure shows a coil **12** of magnetic alloy sheet **14** comprising, for example, silicon iron, which may include from 1% to 6% silicon. The coil **12** rotates in a clockwise direction and the magnetic sheet is drawn in a horizontal line of travel, first, to pinch rolls **16**. The pinch rolls **16** comprise means for maintaining tension on the sheet **14** during its passage through the annealing line. The alloy sheet, moving in the direction indicated by the arrow **17**, next passes between coating rolls **25** and **26**. The upper roll **25** is positioned beneath a hopper **22** containing a reactive insulating coating ma-

terial 24. The material 24 in the hopper 22 drips on the roller 25 to apply to the upper coating roll 25 a sufficient quantity of the coating material which it deposits and spreads as a uniform coating on the upper surface of the sheet 14. The lower coating roll 26 is partly submerged in a container 18 containing a quantity of the coating material 24. As the roll rotates it picks up coating material and deposits a thin film of the material on the bottom of the sheet 14. The coated sheet 14 then passes around idler roll 28, about which the sheet makes a 90° turn, so that the direction of travel is changed to vertically upward. The sheet, in its vertical upward movement passes through, essentially axially thereof, an induction coil 32 which raises the temperature of the alloy sheet to a critical annealing temperature in a short distance of travel and in a short time. The induction coil heats the sheet extremely uniformly from edge to edge to effect straight isothermals substantially perpendicular to the edge of the sheet. Also a uniform temperature gradient exists in the longitudinal direction of the sheet. Only a few seconds at the temperature anneals the sheet fully. No waves, buckles, or ripples are observed in the sheet.

The sheet continues its upward movement through a narrow dead air chamber 35 which is formed by a pair of flat radiant cooling plates 34 which may be liquid or vapor cooled. In the annealing line shown in the figure, a pair of water inlets 36 and a pair of water outlets 38 are provided so that cold water may be circulated through the cooling plates to maintain the plates at the desired low temperature. The chamber 35 enables cooling of the sheet with great uniformity to a temperature below 400° C. so that the isothermal lines are substantially straight and perpendicular to the sheet edges, and no waves, buckles, or ripples are produced in the sheet.

After cooling, the sheet continues its upward movement to a second idler roll 42 about which the sheet is again turned 90° to a horizontal direction of movement for coiling about the reel 44 which is rotated by a motor (not shown).

In some cases it may be desirable after the sheet has passed through the dead air chamber 35 to cool the sheet to room temperature with an air blast, a water mist spray, or the like. This may be accomplished, in one embodiment, by turning the sheet to a vertically downward line of travel after horizontal movement has been established by the upper idler roll 42. The downward vertical line of travel would carry the sheet through a second cooling chamber provided with means for directing an air blast on the magnetic sheet. Additional cooling chambers may be employed as required to reduce the temperature of the sheet sufficiently to facilitate subsequent handling thereof.

In operation, the reel 12 rotates to allow the sheet 14 to uncoil and pass into the annealing line. The pinch rolls 16 and the power applied to reel 44 determine the tension on the sheet. The coating composition may comprise aqueous phosphoric acid solution which may contain small amounts of magnesium oxide or other refractory materials. An aluminum phosphate coating composition in water can be applied. During the annealing, the heat in the sheets causes water in the film of the coating composition to evaporate and the acids to react with the surface of the metal to form a tenacious insulating coating.

The induction coil 32 raises the temperature of the sheet in a narrow band by means of longitudinal flux induction heating. The sheet, as it travels through the induction coils, reaches red heat only momentarily. This is strikingly visibly apparent, for a straight narrow high temperature red band is visible transverse of the sheet and reaches from edge to edge. Thus, the extremely uniform straight isothermal heating of the sheet to annealing temperature is clearly evident.

Electrical current over a broad range of frequencies will be satisfactory in the induction coils; for example, alternating current of from as little as 1000 cycles to as much as 50 megacycles may be employed. From the point of view of electrical efficiency, a frequency for induction heating of the order of 100 kilocycles is ideal for silicon steel from 5 to 15 mils thick. Magnetic alloy sheet material has also been treated with success in accordance with this invention at a frequency of about 450 kilocycles. A relatively narrow preferred range of frequencies in which good results may be expected is from 75 to 500 kilocycles.

As a practical matter, as frequency is decreased the induction coil becomes longer, and at 10,000 cycles, for instance, the number of induction coil turns would have to be so many that its length would create a difficult problem in handling and guiding the strip or sheet, and in addition, the electrical efficiency of the process would be low. At very high frequencies a more complicated system is needed for transmitting power from the high frequency generator to the induction coil, a very difficult problem of high voltage insulation of the induction coil exists, and electrical efficiency of the process is low. While the induction coil may be made relatively short, for example, an inch or less, and still be effective to raise the temperature of the sheet to the desired level, it has been found that the induction coil should be long enough, that is, a foot or more, so that the temperature gradient along the sheet within the inductor coil will not be so steep as to set up permanent strains in the material due to its thermal expansion during heating. In general, the preferred length of the induction coil will be in the range of from 2 to 6 feet. However, it may be longer in some cases.

The handling and guiding of the moving sheet is aided by the use of longitudinal flux from an encircling induction coil because the sheet automatically tends to take up a central position within the coil rather than being attracted to the inductor pole faces, as would be the case if a transverse flux induction coil arrangement had been employed.

The optimum temperature for the annealing treatment of 3 to 3.5% silicon steel, for instance, is about 750° C., but a broader temperature range from 725° C. to 775° C. will give satisfactory results. Thus, the temperature of the steel is raised from about 25° C. to about 750° C. in an extremly short time, for the length of the induction coil is ordinarily less than 10 feet, and the speed of the sheet will lie in the range from 20 to 400 feet or more per minute. It should be noted that the sheet material heats up rapidly to the Curie temperature (about 750° C.), but at that temperature, the steel having lost its magnetic character, large increases in the energy input to the induction coil are required to have the effect of appreciably raising the temperature. Thus, there is an inherent temperature control by reason of the properties of the steel and the characteristics of longitudinal induction flux. This greatly contributes to the close temperature control of which this process is capable.

The water-cooled radaition plates are, in one case, each spaced at a distance of one inch from the sheet surfaces, one plate being on either side of the sheet. The length of the dead air chamber depends on the speed of the travel of the sheet therethrough. It will usually be from 5 to 8 times the length of the induction coil. The dead air chamber does not necessarily cool the sheet to room temperature, but effects a substantial decrease in temperature to a temperature at which the steel is not plastic, below 400° C., as for example, from 750° C. at the entrance thereof to less than 400° C. at the exit thereof. As indicated previously, the temperature of the sheet can be brought down rapidly to room temperature after passing through the dead air chamber by a series of air blasts, water spray, or the like; or it can be cooled slowly by exposing a considerable length to the ambient.

It should be noted that the tension on the sheet in passing through the annealing line is controlled by two means, first, the pinch rolls which have been mentioned

before and secondly, by the height of the tower, for the weight of the sheet will result in tension in the vertical portion of the sheet. A maximum tension of about six pounds per inch of sheet width is permitted.

In an actual apparatus of the type disclosed, which is used for stress relief annealing of oriented magnetic alloy sheet material, a height of from about 50 to 55 feet for the vertical or working portion of the line accommodates an induction coil and cooling chamber of appropriate length. Thus, the induction coil is about 6 feet in length and the cooling chamber is about 40 feet in length. The sheet, eleven inches in width, is moved through the annealing line at a speed of about 200 feet per minute. The process is successfully practiced employing a power input of about 450 kva. A substantial amount of magnetic 3% silicon-iron alloy sheet material has been successfully processed. The results are better than the results obtained from the conventional radiant heat annealing furnaces as to flatness and improved magnetic properties. Of course, sheets from 3 to over 20 inches in width may be processed in the apparatus described provided appropriate changes in sheet speed, and length of induction coil and cooling chamber are made.

In another annealing line, a vertical or working portion of nearly 100 feet is employed with the cooling chamber alone being of the order of 70 feet in length, and with sheet speeds in excess of 300 feet per minute being employed.

In summary, the process of the invention provides a most precise control of temperature and temperature changes in the sheet, both in the heating and cooling stages of annealing. The sheet reaches the desired maximum annealing temperature in a narrow "red heat" band of uniform temperature which reaches from edge to edge of the sheet. Further, the longitudinal temperature gradient of the sheet during heating is such that the increase in temperature is gradual, and in general, the temperature transverse of the sheet is essentially uniform. The manufacturing costs are reduced, due to the decreased space requirement for annealing lines of this type, and because the amount of heat energy required is drastically lower than conventional furnaces, and far less heat energy is wastefully dispersed or lost by the process of this invention.

The present process also has advantages in effecting a rapid reaction between the sheet as it reaches 725° C. and higher with a thin coating of a reactive composition such as aqueous phosphoric acid (for example, 5 to 35% H_3PO_4), alone, or with a small amount of magnesia (for instance, 1% to 10% by weight of the composition) or aluminum hydrate (in the ratio of at least 2 parts per part of H_3PO_4) dissolved therein. The high temperature flashes off the water and causes the acidic composition to react with the sheet surface to form a thin highly electrically insulating refractory film thereon.

It is to be understood that the above description and drawing are illustrative of this invention and not in limitation thereof.

I claim as my invention:

1. In a continuous method for obtaining stress relieved magnetic alloy sheet of extreme flatness and having an insulating film on the surfaces thereof, in which the magnetic sheet is sequentially heated to annealing temperatures and cooled, the improvement comprising the steps of, coating the moving sheet with an insulating coating composition, moving the coated sheet upwardly axially of a vertically disposed encircling induction coil energized with high frequency current to produce a longitudinal flux in the sheet whereby a narrow transverse band of the sheet is rapidly raised to a temperature in the range from 725° C. to 775° C., the isothermal lines being substantially straight and perpendicular to the edges of the sheet, thereafter continuing the vertical upward movement of the sheet to effect cooling by radiation to cooled surfaces on either side thereof with cooling faces substantially parallel to the sheet surfaces and closely spaced thereto to provide a substantially dead air chamber, whereby the sheet is cooled to a predetermined temperature below 400° C.

2. In a continuous method for obtaining stress relieved magnetic alloy sheet of extreme flatness and having an insulating film on the surfaces thereof, in which the magnetic sheet is sequentially heated to annealing temperatures and cooled, the improvement comprising the steps of coating the moving sheet with an insulating coating composition, moving the coated sheet upwardly axially of a vertically disposed encircling induction coil energized with high frequency current of about 100 kilocycles to produce a longitudinal flux in the sheet whereby a narrow transverse band of the sheet is rapidly raised to a temperature of about 750° C., the isothermal lines being substantially straight and perpendicular to the edges of the sheet, thereafter continuing the upward vertical movement of the sheet to effect cooling by radiation to water-cooled radiators on either side thereof with cooling faces substantially parallel to the sheet surfaces and closely spaced thereto to provide a substantially dead air chamber, whereby the sheet is cooled to a predetermined temperature below 400° C.

3. In a continuous method for obtaining stress relieved magnetic alloy sheet of extreme flatness in which the magnetic sheet is sequentially heated to annealing temperatures and cooled, the improvement comprising the steps of, moving the magnetic alloy sheet in a vertical direction upwardly axially of an encircling induction coil energized with high frequency current of from 1000 cycles to 50 megacycles to produce a longitudinal flux in the sheet whereby a narrow transverse band of the sheet is rapidly raised to the Curie point of the alloy, the isothermal lines being substntially straight and perpendicular to the edges of the sheet, thereafter continuing without deviation the upward vertical movement of the sheet to effect cooling by radiation to cooled surfaces on either side thereof with cooling faces substantially parallel to the sheet surfaces and closely spaced thereto provide a substantially dead air chamber, whereby the sheet is cooled to a predetermined temperature below 400° C.

4. In a continuous method for obtaining stress relieved magnetic alloy sheet of extreme flatness and having an insulating film on the surfaces thereof, in which the magnetic sheet is sequentially heated to annealing temperatures and cooled, the improvement comprising the steps of, coating the moving sheet with an insulating coating composition, moving the coated sheet vertically upwardly at a speed of from 20 to 400 feet per minute and axially of an encircling induction coil energized with high frequency current of from 75 to 500 kilocycles produce a longitudinal flux in the sheet whereby a narrow transverse band of the sheet is rapidly raised to a temperature in the range from 725° C. to 775° C., the isothermal lines being substantially straight and perpendicular to the edges of the sheet, thereafter continuing the upward vertical movement of the sheet without deviation to effect cooling by radiation to cooled surfaces on either side thereof with cooling faces substantially parallel to the sheet surfaces and closely spaced thereto to provide a substantially dead air chamber, whereby the sheet is cooled to a predetermined temperature below 400° C.

5. In a continuous method for obtaining stress relieved magnetic alloy sheet of extreme flatness and having an insulating film on the surfaces thereof, in which the magnetic sheet is sequentially heated to annealing temperatures and cooled, the improvement comprising the steps of, coating the moving sheet with an insulating coating composition comprising an aqueous acid phosphate solution, moving the coated sheet in a vertical path upwardly axially of an encircling induction coil energized with high frequency current to produce a longitudinal flux in the sheet whereby a narrow transverse band of the sheet is rapidly raised to a temperature in the range from 725°

C. to 775° C., the isothermal lines being substantially straight and perpendicular to the edges of the sheet, the temperature effecting a reaction between the applied coating composition and the sheet to produce thin electrically insulating film on the surfaces of the sheet, thereafter continuing the upward movement of the sheet in said vertical path to effect cooling by radiation to cooled surfaces on either side thereof with cooling faces substantially parallel to the sheet surfaces and closely spaced thereto provide a substantially dead air chamber, whereby the sheet is cooled to a predetermined temperature below 400° C.

6. In a continuous method for obtaining stress relieved magnetic alloy sheet of extreme flatness and having an insulating film on the surfaces thereof, in which the magnetic sheet is sequentially heated to annealing temperatures and cooled while the sheet is moving in a vertical direction, the improvement comprising the steps of, coating the moving sheet with a reactive coating composition, comprising an aqueous acid phosphate solution, moving the coated sheet in a vertical path upwardly at a speed of from 20 to 400 feet per minute and axially of an encircling induction coil energized with high frequency current of from 75 to 500 kilocycles to produce a longitudinal flux in the sheet whereby a narrow transverse band of the sheet is rapidly raised to a temperature in the

range from 725° C. to 775° C., the isothermal lines being substantially straight and perpendicular to the edges of the sheet, the temperature effecting a reaction between the applied reactive composition and the sheet to produce a thin electrically insulating film on the surfaces of the sheet, thereafter continuing the upward movement of the sheet in said vertical path to effect cooling by radiation to cooled surfaces on either side thereof with cooling faces substantially parallel to the sheet surfaces and closely spaced thereto to provide a substantially dead air chamber, whereby the sheet is cooled to a predetermined temperature below 400° C.

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