Oct. 20, 1970 L. L. KORB 3,535,481

HIGH FREQUENCY INDUCTION HEATING OF SEMICONDUCTIVE PLASTICS

Filed March 24, 1969

Fig. 1

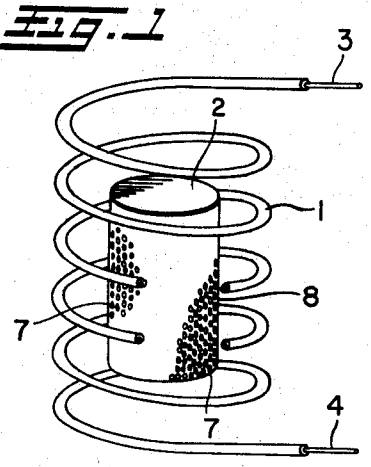
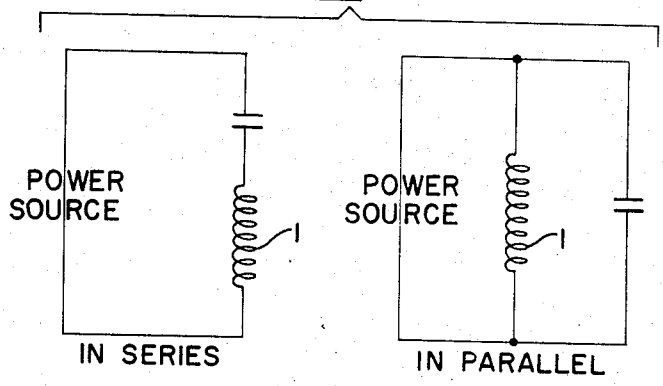


Fig. 3



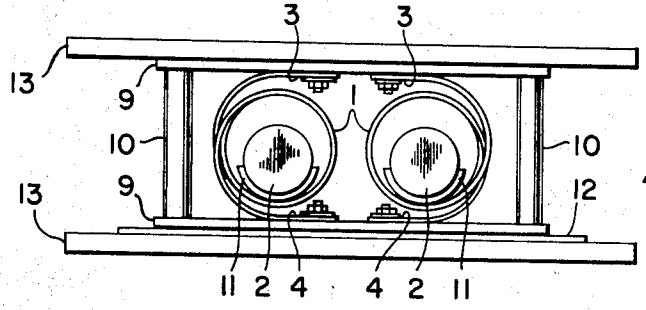


Fig. 2

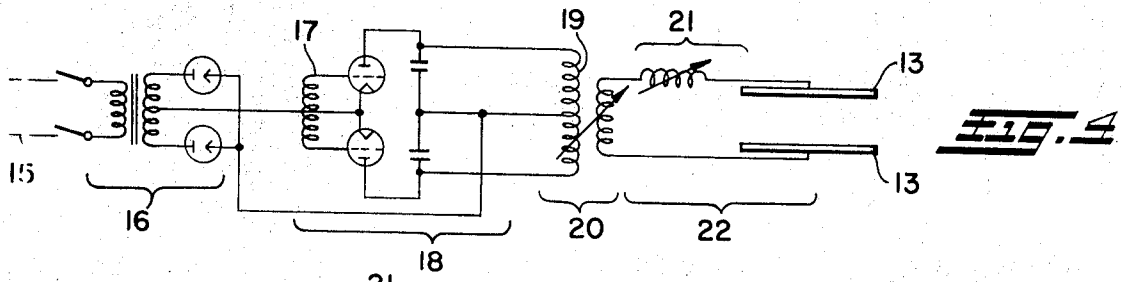


Fig. 4

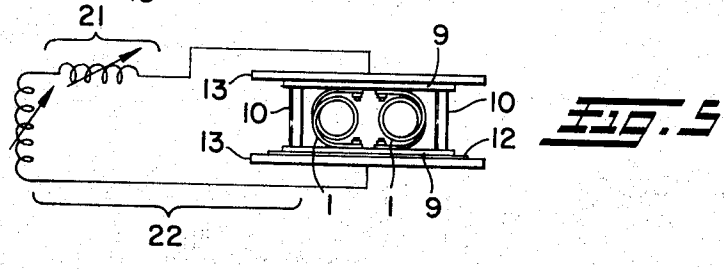


Fig. 5

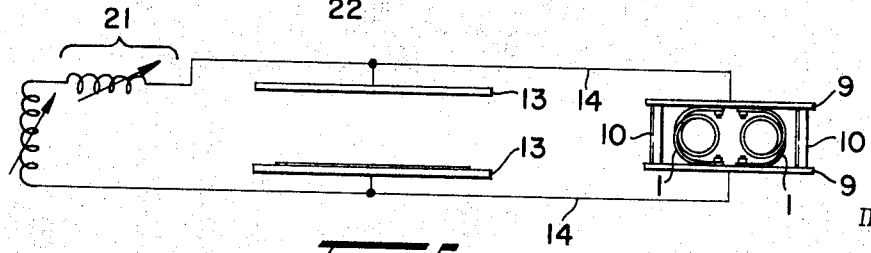


Fig. 6

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3,535,481

HIGH FREQUENCY INDUCTION HEATING OF SEMICONDUCTIVE PLASTICS

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Continuation-in-part of application Ser. No. 639,483, May 18, 1967. This application Mar. 24, 1969, Ser. No. 809,495

Int. Cl. H05b 5/00; B23k 13/02

U.S. Cl. 219—10.41 15 Claims

ABSTRACT OF THE DISCLOSURE

This invention comprises a process for heating uniformly and within seconds a shaped article containing conductive particles impregnated in a solid suspension mass such as a plastic material, the article being positioned in the interior of a coil formed by a spiral winding of one or more lengths of a metal suitable for conducting electrical charges and applying a low current, high voltage, very high frequency to the terminals of said coil.

This application is a continuation-in-part of copending application Ser. No. 639,483, filed May 18, 1967.

FIELD OF THE INVENTION

This invention relates to a method for heating a mass of a nonconductive substantially solid material, such as a plastic, impregnated with particles of a conductive material such as a conductive metal or carbon, hereinafter generally referred to as a metal. More specifically, it relates to a method for heating such a metal-impregnated nonconductive material in such a manner as to have substantially uniform heating throughout the mass. More specifically, it relates to a method for heating such a mass by the use of an induction heating coil operated at very high frequencies, that is at much higher frequencies than are normally used for induction heating.

RELATED PRIOR ART

For many purposes, a plastic material impregnated with metal particles is preformed by pressing into a shape and then heated by various means to cure the plastic to a thermoset condition. Because of the relatively nonconductive properties of the plastic component and the substantial isolation of the individual metal particles and resulting substantial insulation from each other, rather slow heating processes must be used in order to have the heat conducted into the interior for curing the resin throughout the composition. Very often the longer and more extreme temperature conditions to which the exterior surfaces are necessarily exposed as compared to the inner regions causes a higher or more complete cure of the plastic in the outer regions in comparison to the interior.

Attempts have been made to use induction heating systems for heating such compositions, but it has been found that the outer surface of the preform gets very hot while the interior remains relatively cool. It is obvious, therefore, that in induction heating at normal frequencies the outer region is being heated to an excessive amount and very little heat is being generated or transmitted to the interior. This is even more so when the preform is encased in a material which can be induction heated, such as a metal, most of the induction heating energy being concentrated in this container. Moreover, since induction heating generally requires a substantial current flowing through the induction heating coil, the coil generally requires some type of cooling, usually circulating water, to prevent overheating of the coil.

Attempts have been made to use high frequency dielectric heating systems for heating such compositions. In such systems, two flat high voltage electrodes are used as the means for transmitting a high frequency electrical field throughout the composition. However, if the electrodes are brought into contact with or very close to the preform to be heated, there is short circuiting between the electrodes and the metallic piece because of the relatively short distances. In some cases there is merely arcing between the particles in the metal impregnated plastic with very little heat generated. Sometimes carbonization occurs in the plastic between the metal particles, resulting in a completely conductive composition which short circuits the two plates in contact with or in close proximity to the molded piece. If sufficient space is maintained or an insulated sheet is inserted between each of the two electrodes and the preformed piece which is to be heated so as to avoid such short-circuiting, this reduces the efficiency of the system so that an undesirably long period is required for heating purposes.

It is believed that in such a system where there is a concentration of high frequency electrical charges the electrical conductivity of the particles causes arcing. In an induction heating system, the low frequency magnetic field is distorted by the piece, so it affects, primarily, the edge of the piece.

In summary, the features of normal induction heating are:

(1) It heats metals.

(2) It heats on the outer surface of the metal.

(3) The heating efficiency is in proportion to the current since the heat generated is related to I^2R. (The current is in the range of 50–100 amperes.) Induction heating is thus primarily a current flow phenomenon and depends on high current flowing through the coil.

(4) The frequency is generally in the range of 60 to 500,000 cycles per second and is rarely as high as 1,000,000 cycles per second. In induction heating, as the frequency of the alternating current increases, there is a corresponding decrease in the depth of heat penetration in the workpiece, and therefore higher frequencies favor surface heating.

(5) In induction heating a coil is used with the material to be heated placed in the interior of the coil.

The features of dielectric heating are:

(1) It heats nonconductive or insulating material.

(2) It heats uniformly and throughout the workpiece.

(3) The efficiency of heating is in proportion to the square of the voltage and to the frequency of the alternating current.

(4) The frequencies used are in range of 10,000,000 to 200,000,000 cycles per second. Very low current is used.

(5) In dielectric heating applied to plastics, two flat electrodes are usually used with the workpiece to be heated positioned between these electrodes. Metal in the workpiece shortens the effective distance between electrodes and can cause arcing with localized overheating.

Kohler U.S. Pat. 2,393,541 describes the use of induction heating of magnetic metals other than iron. Iron is not desired since it becomes quickly heated to redness whereas nickel alloys of chromium, copper, magnanese and aluminum and manganese-aluminum-copper alloy are heated by the induction system but in a more controllable manner. Metal particles are imbedded in a layer or film of adhesive or glue and the heat is imparted to the metal by the induction heating. This is merely the use of a normal induction heating system used to heat metal. The equipment described is the normal type of induction heating equipment and the frequencies used are in the range of several thousand to several hundred thousand, as

pointed out at the top of the second column of page 2. The fact that this is the regular kind of induction heating is evidenced not only by the frequency range specified, but also by the fact that the iron particles become red hot. The heat is transmitted to the glue by conduction and substantially confined to the thin layer of glue in which the metal alloy is imbedded since it is pointed out at the bottom of column 1 of page 2 that the adjacent bodies of wood are not heated appreciably in the 10–12 minutes used to polymerize the glue by heating the metal particles to about 170° C.

Consequently even though Kohler refers to "high frequency," he has specified this to be in the range of several thousand to several hundred thousand cycles per second.

The White U.S. Pat. 3,391,846 describes a process of heating an adhesive composition containing antiferromagnetic particles, namely sulfides or oxides. These are defined as non-conductive and the patentee teaches away from the use of metal particles and heating by induction heating as being uncontrollable and therefore undesirable.

The particles taught by White are nonmetal, namely oxides or sulfides, are nonconductive and are antiferromagnetic particles.

In fact, in column 4, patentee states, "It should be noted that the conductive metals used in the art heretofore in conjunction with relatively low frequency magnetic radiation, are for all practical purposes, completely inoperable in the present invention which employs the extremely high frequency alternating magnetic field of at least 10 megacycles per second and preferably at least 40 megacycles per second. Upon subjection to such frequencies, the conductive metal particles spark, resulting in tracking (charring of the substrate and non-uniform heat patterns."

Consequently, while metal particles have been used in a nonconductive medium, this patentee, who teaches the use of ultrahigh frequency magnetic fields for nonconductive oxides and sulfides, teaches against the use of metal particles in an ultrahigh frequency alternating field.

In the same column 4, lines 12–15, patentee White also states, "Ordinary conductive metal particles as used in prior art processes are magnetically responsive, i.e., become heated when subjected to an alternating magnetic field in the kilocycle per second range, or 1 megacycle at the most."

Hemming, U.S. Pat. No. 2,364,790, shows the application of high frequency electrostatic fields to nonconductive titanium dioxide particles suspended in an organic material. The workpiece is placed between two adjustable metal plates or electrodes and then an electrostatic field is applied using an input voltage of 2,100 and a frequency of 30 megacycles. This is the ordinary dielectric process using two flat or plate electrodes. There is no mention of the use of a coil.

As indicated above, if metal particles had been used in the Hemming system, there would merely be arcing between the particles in the metal impregnated organic material with very little heat generated, or carbonization would occur in the organic material between the metal particles, resulting in a completely conductive composition, thereby short circuiting the electrodes. If sufficient space is maintained between the electrodes and the workpiece or an insulating sheet is inserted between the electrodes and the workpiece, the efficiency of the system is reduced so that an undesirably long period is required for heating purposes.

STATEMENT OF THE INVENTION

In accordance with the present invention, it has been found that a very high frequency magnetic field can be used to beat substantially uniformly a mass of substantially solid material, such as a plastic, impregnated with particles, flakes or filaments of a conductive material, such as a conductive metal or carbon, herein generally referred to as a metal. For this purpose, it has been found satisfactory to use an induction coil so as to encompass the plastic article or piece which is to be heated and to pass a very high frequency electrical current through the coil, advantageously at a very low amperage so as to avoid generating heat in the coil. Thus, it is possible to deliver a high frequency magnetic field into the mass from various directions so that the magnetic field is able to penetrate into the innermost region of the mass and thereby generate heat quickly and uniformly throughout the mass.

In the drawings, FIG. 1 shows a perspective view of a coil used in the practice of this invention in the center of which is positioned a metal-impregnated plastic preform or shaped article on which the heating is effected.

FIG. 2 shows an assembly whereby two spiral coils are arranged horizontally between two aluminum plates for positioning between the electrodes of a dielectric heater.

FIG. 3 shows simplified electrical equivalent diagrams used for applying the very high frequency current to the coil.

FIG. 4 shows a typical high frequency dielectric heating unit circuit that can be used to supply the type of very high frequency power used in the practice of this invention.

FIG. 5 shows the load circuit portion of the circuitry shown in FIG. 4 with the two coil assembly of FIG. 2 inserted between the electrodes **13** of the circuit of FIG. 4.

FIG. 6 shows the load circuit portion of FIG. 4, but instead of having the two coil assembly of FIG. 2 inserted between the electrodes, this assembly is remote from the electrodes and connected by lead wires to the lead wires connected to the electrodes.

Since the power requirements used in the practice of this invention are very similar to those used in commercial dielectric heaters in which a nonconductive material is placed between the electrodes and heated by the high frequency field generated between the electrodes, it is possible to convert such commercial dielectric heaters to the purpose of this invention. In such case, it has been found that the workpiece can be inserted in the tank circuit coil **21** of the circuit, as shown in FIG. 4; or the coil assembly of FIG. 2 can be inserted between the two electrodes as illustrated in FIG. 5, in which case the top aluminum plate is in direct contact with the top electrode and thereby in electrical connection therewith.

As a third alternative in using the commercial dielectric circuitry, the two coil assembly of FIG. 2 can be positioned away from the two electrodes and connected to the lead wires of the electrodes as shown in FIG. 6. In such case, the wires connecting to the aluminum plates (**9**) should be shielded to avoid emission of radio frequency waves that would interfere with radio-television reception.

In operating the very high frequency circuit of FIG. 4 with the workpiece inserted in the tank circuit coil or in any of the coils shown in FIGS. 5 and 6, the method of operation is similar to that as described for the heating of a workpiece in the coil of FIG. 1. However, as previously described, if the piece is inserted directly between the two electrodes **13** of the dielectric heater (FIG. 4) there is sparking or carbonizing between the conductive particles in the workpiece and between the workpiece and the electrodes. Also, as previously described, if a Teflon shield is placed between the workpiece and each of the electrodes, there is very little heating effected, and even this takes considerable time.

It is obvious, therefore, that the process of this invention is a combination of some of the features of inductive heating and of high frequency dielectric heating. In summary, the coil of an induction heating system is used, but instead of the lower frequency, high current system used in the normal induction heating, the coil is used with an electrical high frequency power supply similar to that used in a high frequency dielectric heating system. Nevertheless, an entirely different effect is obtained by using

a coil as the heating device instead of the electrodes, as discussed in detail herein.

In positioning the workpiece inside the coil there is a spacing maintained between the preform or metal-impregnated plastic piece and the metal of the coil itself. It is noted that the same spacing between the piece and the two electrodes in a normal high frequency dielectric heating system will cause short circuiting throughout the mass as described above.

Because the frequencies and other electrical requirements for the practice of this invention are approximately those used in a dielectric heating system, it is generally convenient to convert such apparatus for the practice of this invention by inserting a spiral coil as described herein between the electrodes of the dielectric system and to connect one end of the coil to one electrode and the other end to a plate in capacitance with the other electrode. Actually, the electrodes can be removed and the lead wires for the electrodes connected to the ends of the coils. However, it is generally just as convenient to make the connections to the electrodes and have them as part of the electrical circuit with the coil performing the same functions as described herein.

In describing the present invention applicant does not intend to be committed to any particular theory or theoretical explanation for the manner in which the high frequency magnetic field effects the heating. However, it is believed that the heating is effected by the generation and collapse of a magnetic field that is transmitted into the center of the coil toward the linear axis of the coil. The presence of the metal particles or carbon particles which are either magnetizable or are in one way or another affected by the magnetic field apparently causes generation of heat in the particles as the magnetic field is generated and is then collapsed.

Whereas induction coils are generally operated at frequencies below 100,000 cycles, the freqeuncies used in the practice of this invention are at least 1,000,000 cycles, or one megacycle, advantageously at least 20 megacycles, and preferably in the range of 20–100 million cycles or megacycles. Moreover, while induction coils generally require currents greater than one amp, generally in the range of 50–100 amps, the process of this invention can advantageously employ amperages below one, generally about 0.5 amp or 500 milliamps. Furthermore, whereas induction heating systems require voltages of 220–440 volts, the voltages used in the process of this invention are advantageously at least 10,000 volts, preferably 20,000 volts or higher. However, regardless of amperage and voltage, the critical element is a frequency of at least 1 megacycle. Most economical and advantageous for such high frequencies are amperages of less than one and voltages of at least 10,000.

The process of this invention can be used on any type of composition in which metal particles are suspended in or distributed throughout a nonconductive or insulating, substantially solid material. Since there is a particular need for generating heat rapidly and uniformly throughout a resin composition for curing purposes, this process is particularly useful in curing thermosetting resins having metal particles distributed throughout.

The process of this invention is particularly useful for this purpose and is particularly adapted to such compositions because heat needs to be generated uniformly and preferably quickly throughout the mass for the purpose of curing the resin, and the distributed metal particles act as the sites for generating the heat throughout the mass. Other compositions comprising a nonconductive material in which metal particles are suspended are also suitable for the practice of this invention provided the nonconductive material is a solid or is in a sufficiently-gelled or agitated condition as to maintain the metal particles in suspension.

The process of this invention is completely unexpected for a number of reasons. Since the application of very high frequency to a workpiece having metallic particles imbedded in a plastic or organic material generally causes arcing when applied between two flat plates or electrodes, it would be expected that similar arcing or carbonization would be the result when the very high frequency is applied ot the workpiece by means of a spiral coil surrounding the workpiece. The sparking and charring of the workpiece is confirmed by the White Pat. 3,391,846 cited above. As also pointed out in the same reference, metal particles become heated in a controllable manner only when subjected to an alternating magnetic field in a frequency range much lower than used in dielectric heating and at the very most no more than one megacycle per second. Moreover, dielectric heating with very high frequencies has been used only with electrically nonconductive materials. There is no indication in any of the prior art that, by applying the very high frequency electrostatic field by means of a coil, a workpiece containing conductive or metallic particles imbedded in a nonconductive material, such as a plastic or organic material, could be controllable and rapidly heated within a very short time.

There are a number of oddities in the application of this invention which makes it even more unpredictable. For example, a steel rod placed inside the heating coil of this invention and supported on a piece of Teflon is heated uniformly to a red heat in about two minutes. However with solid pieces of copper, aluminum or lead, there is very little heating effect when they are similarly placed inside the coil. In contrast, however, preforms of phenolic material containing these metals in powdered form are heated very rapidly by this system. For example, powdered lead, having a normal coating of oxide and pressed into a preform shape, melts in less than 60 seconds. Likewise a pressed copper powder having a normal coating of oxide preheats rapidly, but if the pressed powder is sintered prior to heating according to this invention, there is very little heating effect. It appears that the oxide coating serves as sufficient insulation to permit rapid heating by the process of this invention. However, if there is continuity of metal such as produced by sintering, there is very little heating effected.

Moreover, it appears that there is little dielectric heating effected as can generally be effected on a nonconductive material. For example, a phenolic resin not containing metal does not heat at all in the system of this invention. However, when metal particles are imbedded therein, the heating is effected as described above.

Furthermore a piece of solid copper or steel, or a sintered pressed copper article will not heat dielectrically, but will cause immediate arcing unless shielded from the electrode. A pressed powdered lead preform will heat to 150° F. in 6 minutes in a high frequency dielectric field when shielded to prevent arcing. In the very high induction field of this invention, the same pressed lead preform will melt in less than 60 seconds. Obviously, therefore, there are many unpredictable differences between the process of this invention and the normal induction heating, and also between the process of this invention and dielectric heating.

While resins are the preferred type of solid or gelled material on which this process can be used, and uniform heating and curing is the principal purpose, it is possible to use other solid materials or gelled materials in which uniform heating is desired for various purposes, such as fusion as in thermoplastic resins, or even in effecting a chemical reaction between two or more components or reagents comprising the suspending material, or even between the suspending material and the metal particles suspended therein. In any case, it is contemplated that the process can be used with various compositions comprising a nonconductive solid material, including gels, in which there is suspended one or more types of metal particles. In addition to organic materials, it is possible to use inorganic nonconductive materials, such as oxides, sulfides, etc., as the insulating material, using the metal or conduc-

tive particles intermixed in the oxide or sulfide to generate heat in the composite.

Obviously, the metal must be one capable of acting as a generating site for converting electrical energy or magnetic energy from the high frequency electrical field to heat energy. Magnetizable metal particles or particles affected by magnetic fields are suitable for this purpose, such as iron, copper, aluminum, carbon, etc. Iron is particularly suitable and preferred for this purpose. Copper and aluminum particles are also suitable. The size of the particles is not critical and the size of the particles is generally determined more by the other properties desired in the resultant product. Particle sizes in the range of —325 mesh up through ¼ inch in diameter have been used very satisfactorily.

Flakes or filaments of the metal or conductive material can be used. It is generally advantageous that the flakes have a thickness up to 0.005 inch and have their largest dimension no more than about ¾ inch, preferably no more than 0.001 inch and ½ inch respectively. Filaments of the conductive material should be relatively short so as to reduce the possibility of having continuous circuits form in the mixture, and advantageously have a diameter of no more than 0.01 inch and a length of no more than two inches, preferably no more than 0.005 inch and one inch respectively. For purposes of simplicity, general reference herein to particles also includes flakes and filaments as described above.

In these compositions there need be only sufficient resin, etc., to isolate or insulate a high proportion of the particles from each other. Advantageously the proportion of resin is 1–65, preferably 1–45 percent by weight of the resin-metal compositon. However, where the resin-metal mixture contains sand or other inert filler, the proportions can be 1–95% nonconductive material (resin and filler) and 5–99% metal particles. Actually, the heating can be effected with even up to 95% resin (without filler) but in such case the curing time is extended. The corresponding volume ratio will vary according to the density of the particular resin and the particular particles being used.

As previously indicated, the process of this invention is particularly suited for heat curing thermosetting resins. Typical examples of such heat curable resins are the following types: phenol-aldehyde, e.g. phenol-formaldehyde, bisphenol-formaldehyde, phenol-acetaldehyde, phenol-furaldehyde, etc.; urea resins, such as urea formaldehyde, etc.; melamine-aldehyde resins, such as melamine-formaldehyde, etc.; epoxy resins, such as derived from dihydroxy aromatic compounds such as bisphenol, hydroquinone, catechol, resorcinol, etc., by the preparation of the diglycidyl ethers thereof; diallyl phthalate, diallyl maleate, and polyester resins such as the glycol-maleate-styrene type, etc.

However, as previously indicated, the nonconductive suspending medium need not be a thermosetting resin, but can be any nonconductive solid material in which the metal is suspended and for which it is desired to generate heat uniformly and quickly throughout the mass.

The particular apparatus used in generating the high frequency field is not critical provided it is adapted to direct the high frequency magnetic field into the mass from a variety of directions. As previously indicated, a coil such as used in induction heaters is suitable for this purpose. In many cases, the only difference is the fact that much higher frequencies and voltages, and much lower current are used to generate the high frequency magnetic field being applied to the mass or piece to be heated.

A preferred modification of such apparatus is shown in FIG. 1 where copper tubing **1** is shaped in spiral or helical form with lead wires **3** and **4** attached to the two ends of the copper tubing for connection with a source of high frequency electrical charge. The preform **2** consists of metal particles **7** distributed throughout a plastic binder or suspending medium **8**.

When it is desired to measure the temperature reached, a thermocouple needle is inserted to the center of the piece immediately after the piece is withdrawn from the coil.

The electrical system and the circuitry used for generating or delivering the high frequency current to the coil or other device used for distributing the high frequency field are similar to those used for other purposes for delivering high frequency charges, advantageously from a high voltage, low amperage system. As previously indicated, the electrical system and circuitry from a high or very high frequency dielectric system can be used with the ends of the coil connected to the electrodes or to the lead wires connected to the electrodes.

As illustrated in FIG. 2, the coil of FIG. 1 can be used in plurality and in horizontal position. In this case, the respective ends **3** and **4** of the two coils **1** are connected to the aluminum plates **9** which are separated and supported from each other by insulating (Teflon) pillars **10**. The upper aluminum plate is in direct contact with the upper electrode **13** of a dielectric heater, and the lower aluminum plate rests on an insulating sheet (Teflon) which in turn rests on the lower electrode **13** of the dielectric heater.

FIG. 3 shows simplified circuitry that can be used either in series or in parallel.

FIG. 4 represents a typical high frequency dielectric heating unit circuit, as shown in the Oct. 28, 1944 issue of "Electrical World." In ordinary use as a dielectric heater a non-conductive workpiece would be inserted between the two electrodes without the coil assembly shown in FIGS. 2 and 5.

In the dielectric heating unit circuit of FIG. 2, power source **15** supplies 60-cycle line power to full-wave rectifier **16** and then to grid coil **17** and push-pull oscillator **18**, converting the 60-cycle line power to very high frequency, low amperage, high voltage energy. As previously described, coil **19** or coil **21** can be used as the heating coil in the practice of this invention. Similar heating results can be obtained when the coil assembly of FIG. 2 is inserted between the electrodes **13** as shown in FIG. 5. Tuning inductance **21** controls the feed load circuit **22** and electrodes **13**.

FIG. 6 shows another modification in which the heating coils assembly of FIG. 2 is positioned remote from the electrodes and connected to the lead wires to the electrodes.

A solid composition in which the heat is to be generated and on which the process of this invention is particularly suitable can be prepared by pressing a mixture of resin particles and metal particles (previously well mixed by tumbling or other distributing means) in a mold having a cavity of the desired shape and size for the ultimate piece. This preformed piece, or "preform" as it is generally called, is then the piece or composition inserted in the interior of the coil or in the other appropriate device for generating a high electrical field to be directed into the preform from various directions.

The coil or other metal article which is used to generate the high frequency magnetic field can be of various types of construction although one particularly suitable because of its self-supporting character and other desirable properties for transmission of appropriate amounts and types of electrical or magnetic energy, is a coil made from a spiral winding of copper tubing. In addition to tubing, the spiral can be made of metal conductors having various other cross-sections such as square, rectangular, circular, etc. One type found particularly suitable is a copper strip of rectangular cross-section, for example, approximately ⅛" x ¾". Such a strip can be wound on a pipe or other type of mandrel to give the desired helical or spiral form, which, after the mandrel is removed, is found to be self-supporting.

It is believed, as previously indicated, that a high frequency magnetic field is sent into the piece and that this

has a magnetic effect on the metal particles. Then, as this field is generated and collapsed, there is a corresponding magnetic effect on the particles and heat is thereby generated in the individual particles.

Moreover, a very simple arrangement for providing a cylindrical type of high frequency field generating arrangement is to have a single element formed in the shape of a spiral to give an overall cylindrical configuration. This can be improved upon by having two cup-shaped arrangements at the two ends of the cylinder, likewise formed by a single element of spiral winding of decreasing diameter. Still more effective is an arrangement consisting of two cup-shaped spiral windings, at least one of which can be folded away or opened for insertion of the piece to be heated and then when the movable portion is repositioned, to form a generally spherical shaped electrode. In this manner, the general shape of the high frequency field delivering element is that of a sphere with its high frequency field being directed into the center of the piece from the maximum number of directions perpendicular to the surface of the sphere at various points on its surface and directed toward the center of the sphere.

Various methods of practicing the invention are illustrated by the following examples. These examples are intended merely to illustrate the invention and not in any sense to limit the scope of the invention nor the manner in which the invention can be practiced. The parts and percentages recited therein and all through the specification, unless specifically provided otherwise, are by weight.

In these examples, a metal coil is used as described, except that the electrical system to which the coil is connected is one adapted to deliver the extremely high frequency indicated as contrasted with the relatively low frequency normally used in induction heating. Various electrical systems can be used for providing the high frequency charge, including those rated as low as 0.5 kilowatt and up to 50 kilowatts and even higher if considered practical. In each case, the specimen to be heated is placed inside the coil and out of contact with the coil. This is supported in the coil by an insulating material that will not be heated inductively, in this specific instance a piece of molded plastic rod made from polytetrafluoroethylene, which is available on the market under the trademark "Teflon."

The specimens used for heating in these particular examples are preforms made in a cylindrical mold having a diameter of 1⅛" and in each case, unless otherwise specified, 65 grams of molding material is used. On view of the difference in specific gravity of the various molding mixtures, the height of preform produced will vary accordingly. Normally a pressure of about four tons per square inch is used to make the preform. When it is desired to measure the temperature, a needle thermocouple is pushed into the center of the specimen immediately after the specimen is withdrawn from the coil.

EXAMPLE I

Copper tubing of ¼ inch diameter is shaped in a spiral having an inner diameter of 2¼ inches with six turns or convolutions and an overall coil length of approximately 6 inches. The two ends of this coil are connected with a high frequency electrical source adapted to deliver 34.5 megacycles. The preform in this case is made from a mixture of 80 percent finely divided iron powder of no more than 200 mesh and 20 percent of a phenol-formaldehyde two-stage resin containing the normal modifiers. Upon exposure to the high frequency magnetic field indicated above, the specimen reaches a temperature of 260° F. in 10 seconds. When an identical specimen is exposed to the same high frequency field between the two electrodes in a dielectric heating system with no protective shield but space between the specimen and the electrodes, arcing develops and no heat is produced.

EXAMPLE I*a*

A commercial dielectric heater adapted to deliver a very high frequency (circuitry shown in FIG. 4) is used to apply an electrostatic field of 60 megacycles on a preform of iron powder and resin as described in Example I, supported on a sheet of Teflon between the two horizontal electrodes. With no protective shield but the supporting sheet and space between the workpiece and the electrodes, arcing occurs and no heat is produced in the piece. Then the coil used in Example I is placed horizontally between the two horizontal electrodes supported by a sheet of Teflon placed on the bottom electrode and one end of the coil connected to the top electrode. The workpiece is inserted in the coil. The bottom of the coil is in capacitance with the bottom electrode by virtue of the Teflon sheet separating them. Upon applying an alternating current at a frequency of 60 megacycles the workpiece positioned inside the coil is heated to 230° F. within 15 seconds. Similar results are obtained when the coil is positioned away from and not between the two electrodes, and also when the electrodes are removed, and in both cases the ends of the coil connected to the lead wires previously connected to the electrodes as shown in FIG. 6.

EXAMPLE I*b*

The same dielectric heater of Example I*a* and FIG. 4 is used with the two aluminum plate and two coil assembly shown in FIG. 2. A workpiece similar to that of Example I is placed in each of the coils resting on and separated from direct contact with the coil by Teflon carriers as shown in FIG. 2. One end of each coil is connected to the top aluminum plate and the other end in each case is connected to the bottom aluminum plate. The top aluminum plate is in direct contact with the top electrode, and the bottom aluminum plate is in capacitance with the bottom electrode by virtue of the insulating sheet (Teflon) between them. When power is applied to the circuit at a frequency of 60 megacycles the workpieces are each heated to 230° F. within 15 seconds. When, instead of using the assembly of FIG. 2 between the electrodes, a workpiece is placed in the tank circuit coil and supported by a Teflon sheet, the application of the same frequency produces similar heating results. Similar heating results are obtained when the assembly is positioned remote from the electrodes and connected as shown in FIG. 6.

EXAMPLE II

The procedure of Example I is repeated except that the mixture used in preparing the preform is one having 20 percent finely divided iron powder of 200 mesh or finer, 20 percent af aluminum powder of 200 mesh or finer, and 60 percent of a phenol-formaldehyde two-stage resin having the normal modifiers. Under the same conditions as described in Example I, the temperature at the center reaches 235° F. in ten seconds, and when the identical preform is placed in the dielectric heater, operated at the same high frequency but without any shield between the piece and the electrodes, arcing results and no heat is produced.

EXAMPLE III

A coil is prepared from a flat copper strip having a rectangular cross-section of ⅛" x ¾", shaped into a spiral having 2½ inches internal diameter and 3½ convolutions to give an overall coil length of approximately five inches. A preform similar to that used in Example I is inserted in the coil as previously described and exposed to a high frequency electrical field of 74.3 megacycles. Within five seconds the center of the preform reaches a temperature of 310° F. When this same high frequency electrical field is applied in a dielectric heating system as described above, arcing is produced but no heat.

EXAMPLE IV

The procedure of Example III is repeated using the preform mixture of Example II. In this case a temperature of 260° F. is obtained within five seconds. Likewise when a similar high frequency field is applied in the dielectric heating system, arcing is produced but again no heat.

EXAMPLE V

A coil of ¼ inch copper tubing is made with an inside diameter of five inches and two convolutions spaced so that the overall length of the coil is approximately 3 inches. This coil is used with a preform identical to that used in Example I with a high frequency electrical charge of 25.5 megacycles. Under these conditions a temperature of 205° F. is reached within ten seconds. When the preform of Example II is substituted and the same conditions applied, a temperature of 145° F. is reached within 10 seconds. When preforms identical to these two preforms are heated in the dielectric heater under the frequency conditions used in this example, arcing results without heating.

EXAMPLE VI

A coil is prepared from ¼ inch copper tubing with five convolutions having an inner diameter of 3.5 inches and an overall coil length of approximately six inches. When a preform identical to that used in Example I is inserted and exposed to a high frequency field of 32 megacycles at approximately ½ kilowatt, a temperature of 210° F. is reached within 60 seconds, and a temperature of 270° F. is reached in 80 seconds. When an identical preform sample is tested under corresponding conditions in a dielectric heater as in Example II, arcing results without producing any heat.

EXAMPLE VII

The procedure of Example VI is repeated using a preform identical to that of Example II. A temperature of 150° F. is reached in 60 seconds when the frequency is 32 megacycles, and a temperature of 210° F. is reached in 80 seconds. Likewise, when the corresponding frequency is applied to an identical sample in the dielectric heater, as in Example II, arcing is produced without any heat.

EXAMPLE VIII

A coil is prepared using ¼ inch copper tubing to form a spiral having an inner diameter of 2⅜ inches and six turns to give an overall coil length of approximately eight inches. With the preform of Example I, a frequency of 34.2 megacycles produces a temperature of 300° F. within 60 seconds. When the preform of Example II is used at a frequency of 34.2 megacycles, a temperature of 285° F. is produced in 60 seconds. The identical preforms used in the dielectric heater, as described above, at the corresponding frequencies, produce arcing without any heating.

EXAMPLE IX

Using the coil of Example VIII and the electrical conditions applied, a preform is used made from 29 grams of a composition consisting of 40 parts wood flour, 40 parts of phenol-formaldehyde two-stage resin, 5 parts powdered graphite and 15 parts of highly conductive carbon black. A temperature of 230° F. is reached within 40 seconds.

EXAMPLE X

The procedure of Example IX is repeated using as the preform material 30 grams of a mixture of 15 percent two-stage phenol-formaldehyde resin and 85 percent of a 200 mesh aluminum powder. Under the electrical conditions applied, a temperature of 280° F. is reached within 20 seconds.

EXAMPLE XI

The procedure of Example VIII is repeated using as the preform composition, 32 grams of a mixture of 20 percent of a two-stage phenol-formaldehyde resin and 80 percent of 200 mesh aluminum powder. In this case, a temperature of 215° F. is reached within 40 seconds.

EXAMPLE XII

The procedure of Example VIII is repeated using as the preform composition 77 grams of a mixture of 10 percent epoxy resin and 90 percent of an iron powder of 200 mesh. The epoxy resin is a commercial product made from the diglycidyl ether of bisphenol containing dicyanodiamide and butyldimethylamine in appropriate amounts to catalyze polymerization upon heating. Under the electrical conditions of Example VIII a temperature of 155° F. is reached within 40 seconds.

EXAMPLE XIII

The procedure of Example XII is repeated using 70 grams of the mixture of 10 percent epoxy resin and 90 percent of iron flakes having a maximum dimension of ¼ inch and a thickness of 0.002 inch. A temperature of 340° F. is reached in 10 seconds.

EXAMPLE XIV

The procedure of Example VI is repeated using a preform having a diameter of 2.5 inches and a weight of 265 grams. With the application of a high frequency electrical field of 74.3 megacycles, a temperature of 350° F. is reached within 12 seconds.

EXAMPLE XV

The procedure of Example V is repeated using the same electrical conditions with a preform of identical composition but having a diameter of 2.5 inches and a weight of 265 grams. A temperature of 280° F. is reached within 10 seconds.

EXAMPLE XVI

The following procedure illustrates the use of the process of this invention for preparing sintered powdered metal products by using very low proportions of resin (0.5–5%) and high proportions of the metal powder such as iron, copper, copper-lead, copper-tin, etc., so as to carbonize the phenolic resin binder and to sinter the metal particles together. For example, a mixture containing 98% finely divided iron powder coated with 2% of phenol-formaldehyde resin by solution coating or physical blending is made into a preform shape and treated in the coil under the conditions of Example I. In 25–30 seconds, the sample is heated to a bright red heat with the phenolic resin carbonized and the metal particles sintered. The resultant product is porous as illustrated by the absorption of lubricating oil when poured onto the surface of the article. Such a product can be used for self-lubricating bearings. The porosity of the product is increased as the proportion of resin is increased.

EXAMPLE XVII

The procedure of Example XVI is repeated twice using copper powder of 200 mesh and 40 mesh respectively. In both cases porous products are obtained. The 40 mesh product is tested satisfactorily for filtering and the 200 mesh product as a self-lubricating bearing.

EXAMPLE XVIII

The procedure of Example I is repeated twice with similar results using in place of the iron powder, iron flakes in one case having a thickness of less than 0.001 inch and maximum dimension of less than ¼ inch, and in the other case, iron filaments of about 0.001 inch diameter and about ½ inch in length.

EXAMPLE XIX

The following procedure illustrates the use of the process of this invention for preparing shell molds and cores

used in foundry casting of liquid metals by including small percentages of metal flakes or filaments in the normal mixtures of sand and resin. These metal particle-modified, shell molding mixtures are placed in paper tubes or other containers or patterns not affected by the very high frequency electromagnetic field and, when treated in the coil and under the conditions of Example I, a very rapid temperature rise is induced to cure the thermoset resin and adhere the particles into a useful shape. For example, a mixture containing 5% phenolic resin, 15% finely divided iron powder and 80% sand is physically blended and placed in a glass tube and then treated in the coil and under the conditions of Example I. In 25–30 seconds the resion is brought to the curing temperature and the ensuing mass when cooled exhibits properties similar to shell molding patterns and cores.

EXAMPLE XX

The procedure of Example XIX is repeated a number of times successfully using as the container different types of plastic tubing, namely polyethylene, polypropylene, polystyrene, phenol-formaldehyde resin and polyester resin.

EXAMPLE XXI

The structure of Example XIX is repeated using, in place of the iron powder, iron flakes having a thickness of less than 0.001 inch and maximum dimensions of less than 0.25 inch and using solution coating rather than physical blending. When treated in the coil and under the conditions of Example I this brings the resin to the curing temperature in 10–15 seconds.

EXAMPLE XXII

The procedure of Example XXI is repeated twice using, in one case, 5% phenolic resin, 5% iron flakes and 90% sand. This mixture when treated in the coil and under the conditions of Example I will bring the resin to the curing temperature in 25–30 seconds. In the other case the mixture is 5% phenolic resin, 25% iron flakes, 70% sand. This mixture when treated in the coil and under the conditions of Example I will bring the resin to the curing temperature in 8–10 seconds.

While the descriptions and examples herein illustrate the use of a single continuous coil, it is contemplated that a number of such coils can be used intertwined with the helices or convolutions of one coil positioned in between and spaced from the convolutions of one or more other coils. Such plurality of coils can be independently connected to a high frequency electrical charge or can actually be connected either in parallel or series with each other. However, since the same general effect is accomplished by having a single continuous coil of the same number of total convolutions as would be obtained in a plurality of such overlapping or intertwining coils, it is generally simpler and preferred to use a single coil, having the desired total number of convolutions.

Various shapes and sizes of shaped articles can be used in the practice of this invention. Instead of spirally wound coils a flat spiral can be formed with electrical connections similar to those shown in FIG. 6 and the coil located where it can be used for large flat objects.

While certain features of this invention have been described in detail with respect to various embodiments thereof, it will, of course, be apparent that other modifications can be made within the spirit and scope of this invention, and it is not intended to limit the invention to the exact details shown above except insofar as they are defined in the following claims.

The invention claimed is:

1. The process of controllably heating by virtue of applying a magnetic field in a variety of directions to a shaped article, said shaped article comprising an intimate mixture of a nonconductive substantially solid material and particles of a conductive material capable of generating heat upon exposure to a very high frequency magnetic field and selected from metals or carbon, comprising the steps of positioning said article inside a spiral coil of an electrically conductive metal and applying to said coil an alternating electrical voltage having a frequency greater than 1 megacycle until the desired temperature is produced in said article.

2. The process of claim **1** in which said electrical charge has a frequency of at least 20 megacycles.

3. The process of claim **1** in which said electrical charge has a frequency of 20–100 megacycles.

4. The process of claim **3** in which said particles comprise iron particles.

5. The process of claim **3** in which said particles comprise copper particles.

6. The process of claim **3** in which said particles comprise aluminum particles.

7. The process of claim **3** in which said particles comprise conductive carbon particles.

8. The process of claim **3** in which said substantially solid material comprises a thermosetting resin.

9. The process of claim **1** in which said article comprises 1–95 percent by weight of said substantially solid material and 5–99 percent by weight of said heat-generating particles.

10. The process of claim **9** in which said article comprises 1–65 percent by weight of a thermosetting resin as said substantially solid material.

11. The process of claim **10** in which said resin is a phenol-formaldehyde resin.

12. The process of claim **10** in which said resin is a polymer of a diglycidylether of a dihydroxy aromatic compound.

13. The process of claim **10** in which said resin is a polymer of the diglycidylether of bisphenol.

14. The process of claim **9** in which said substantially solid material is a mixture of sand and a thermosetting resin.

15. The process of claim **14** in which said thermosetting resin is a phenol-formaldehyde resin.

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