This invention relates to methods of manufacturing rod-like bodies by zone melting with the use of a magnetic high-frequency field produced by a coil and extending in the axial direction of the rod, a molten zone being formed inside the coil. It also relates to apparatus for zone-melting rod-like bodies by means of inductive high-frequency heating. A method and apparatus of this kind have been described, for example, in the article by S. H. Keck and others in the journal "Review of Scientific Instruments," 25 (February), page 311 of the 1954 edition.

Known methods have the disadvantage, more particularly if the bodies to be manufactured have a large diameter, for example a diameter larger than 1 cm., that the boundary surfaces or interface between the molten zone and the solid parts of the rod show strong curvatures. These may give rise inter alia to irregularities in the crystal structure, but they are also detrimental in far less as they impede the formation of a molten zone extending across the whole cross-section of the rod, more particularly of thick rods.

An object of the invention is inter alia to provide a method which permits of influencing the shape of the boundary surfaces, more particularly of obtaining flatter boundary surfaces. According to the invention, at least one other field viewed in the axial direction adjacent and of opposite sense to the first field, is produced by the addition of at least one additional coil without a molten zone being formed inside the last-mentioned coil. The two fields must naturally have the same frequency. Thus a high-frequency current should pass through the additional coil in a sense opposite to that of the current through the first coil. It should be noted that the induction current produced in the additional coil by the first field is in itself too small to be able to produce a resultant field of opposite sense. The method according to the invention must not be confused with the conventional method of purifying by zone-melting a rod-like body in an elongated crucible, wherein a few molten zones are produced inside a corresponding number of high-frequency coils and wherein juxtaposed coils are traversed by a high-frequency current in opposite directions for the purpose of preventing the zones from melting together. The fields of the coils associated with these zones usually have the same intensity in contradistinction to the fields of the coils in the method according to the invention wherein the intensity of the field of the additional coil is less than the intensity of the field of the first coil. By preference the first-mentioned intensity is at most two thirds and at least one third of the last-mentioned intensity. The intensity of a field produced by one coil is to be understood to mean herein the average field strength within this coil, when no other partial fields, produced by other coils, are present.

Two oppositely directed fields are preferably produced on each side of the first-mentioned field. A device according to the invention is characterized in that it comprises at least two such juxtaposed coils which coaxially surround a body and are coupled so as to be traversed by high-frequency currents of different intensities in opposite directions. Each coil preferably comprises only one turn. Use is preferably made of three coils which are connected together so that the central coil is connected in series with the two outer coils, which are interconnected in parallel. The distance between adjacent coils is preferably at least equal to the distance of the central coil to the surface of the rod-like body and at most twice the diameter of the central coil.

In order that the invention may be readily carried into effect, it will now be described in detail, by way of example, with reference to the accompanying diagrammatic drawing, in which:

FIG. 1 shows, partly in vertical section and partly in elevation, a portion of a device for floating-zone-melting, wherein one molten zone is produced in a rod-like body.

FIGURE 2 shows a similar rod-like body having a molten zone formed in a different way, and FIGURE 3 shows, for comparison, a similar molten zone such as produced in conventional methods.

FIGURE 4 shows schematically a circuit for feeding the coils of the apparatus of FIG. 1.

FIGURE 5 shows schematically the field distribution caused by the action of the three coils of FIG. 1.

FIGURE 6 shows schematically in vertical cross-section the heat-transport in a silicon rod, disposed within the high-frequency coils of FIGURE 1.

In all these figures corresponding parts are indicated by the same reference numerals.

Referring now to FIGURE 1, a rod-like body 1, for example of silicon or germanium, is secured at each end (not shown) to the device by means of holders (not shown).

A molten zone 3 is produced in the rod 1 by the field of a high-frequency coil 2 surrounding the rod, which coil consists of a single turn and is fed from a high-frequency current generator (not shown). The device also comprises two high-frequency coils 4 and 5 which are arranged coaxially with the coil 2 on each side thereof. Each of the coils 4 and 5 consist of a single turn and can be fed by the same high-frequency current generator. The currents traversing the coils 4 and 5 have opposite directions to that of the current through the coil 2, as indicated by arrows. The current strength in the coil 4 and in the coil 5 is smaller than that in the coil 2. The currents in the coils 4 and 5 may be, for example, half the current in the coil 2, which may be realised in a simple manner by connecting the central coil in series with the two outer coils and connecting the last-mentioned coils in parallel.

FIGURE 4 shows schematically a circuit for zone-melting with the aid of the coils 2, 4 and 5 of FIGURE 1. In this circuit the line voltage is supplied via an ammeter A to a transformer with adjustable primary to adjust the output of the transformer which is supplied to a rectifier arrangement. The output of the rectifier constitutes the D.C. supply for a high frequency generator, the high frequency output of which is supplied to the high frequency coils 2, 4 and 5 in a way as shown by the arrows. The high frequency current from the generator will pass coil 2 after which it is divided into two parts which pass the coils 4 and 5 respectively in a sense opposite to the sense in which the current passes the coil 2. Leads for combining the currents passed through the coils 4 and 5 and for conducting the resulting combined current back to the generator are present.

The intensity of the current in each of the coils 4 and 5 will thus be about half the intensity of the current in coil 2.

Due to the constant voltage of the mains, the current intensity by the ammeter is also a measure of the energy consumption of nearly all the energy being consumed by the fields of the high frequency coils. By
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adjusting the transformer the output of the generator and the energy consumption of the fields of the coils may be controlled. In this way it is possible to control the length of the molten zone 3 of FIGURE 1 by observation and adjustment of the transformer.

It is evident that a certain field distribution thus occurs near the coil 2. Due to the common action of the coils 2, 4 and 5 the boundaries or interfaces 6 and 7 of the molten zone and the two solid parts 8 and 9 of the rod are comparatively flat, as shown in FIGURE 1. The molten zone may be moved along the rod in the usual manner. To this end, the coils could be fixed in position and the rod 1 moved vertically, or the rod 1 fixed and the coils 2, 4 and 5 fixedly interconnected in the relationship illustrated in FIG. 1 and moved as a whole along the length of the rod, a typical rate being about 1 mm per minute.

As a specific example, to illustrate the invention, but which is not to be considered in any way limiting, for a rod 1 of 14 mm in diameter, the coil 2 may comprise a 4 mm wire forming a single turn 25 mms. in diameter. The coils 4 and 5 may be of the same size wire, have the same diameter, and are each spaced between 15 and 25 mms., for example about 20 mms., vertically from the center turn 2. A 6 kilowatt generator at a frequency of 5 megacycles per second may be employed. By observing the heated part of the rod within the coil 2 and suitably adjusting the feed current of the HP generator a molten zone is formed and its height is adjusted to 12 mms. at the surface of the rod.

In principle this method even permits of obtaining somewhat concave boundary surfaces of the rod parts 8 and 9 and the molten zone 3, as shown in FIGURE 2, as will be explained hereafter.

FIGURE 3 shows, for comparison, the shape of the convex boundary surfaces such as usually formed by known methods. This figure also shows that in the known method, when a comparatively long molten zone is produced, the distance between the non-melted parts of the rod is small, so that more particularly in the case of thick rods the risk is involved that the zone cannot penetrate to the core of the rod for the maximum permissible length of the zone as limited by the surface tension. This risk is less for boundary surfaces such as obtained by the method according to the invention and, in addition, the growing part of the rod contains fewer disturbances in the crystal lattice because of the flat shape of these boundary surfaces.

In order to show the effect caused by the use of adjacent coils according to the invention in comparison with the known use of only one coil, FIG. 5 shows schematically in a diagram the magnetic field strength distribution in the axial direction of the coils. The axis of abscissa indicates the field strength and the axis of ordinates the distance of the center coil 2. The points 11 and 12 indicate points within the coils 4 and 5 respectively.

The dot-dash curve 13 indicates the partial field strength of the field produced by the coil 2 alone. When only coil 2 is fed by the high frequency generator, heat will be generated only in the part of the surface parts 8 and 9 of FIGURE 6. In this figure the heat currents 14 will run from quite large surface parts within and near the coil 2 to the interior of the rod 1. The dashed curve 15 perpendicular to the curves 14 indicates an isotherm which is at the axis of the rod measured in the axial direction or nearer to the coil 2 than at the surface of the rod. As the boundary surfaces of a molten zone 3 constitute isotherms it is obvious that the boundaries 6 and 7 designed in FIG. 3 will have a form comparable to the isotherm 15 of FIG. 6.

When current is passed through the coils 4 and 5 in a sense opposite to the current passed through the coil 2 and the current is so adjusted in each of the coils 4 and 5 that 5 is half of the current strength in coil 2, the partial field strength, due to the action of coil 4 or coil 5 alone, may be represented in FIG. 5 by the interrupted curves 16 and 17 respectively. The action of the three coils together will give rise to a resultant field distribution as indicated by the full curve 18. At a point 19 between the origin of the diagram and point 11 and also at a point 20 between this origin and point 12 the resultant field strength is zero. Between points 19 and 20 a field is mainly set up by the action of the center coil 2. On both sides of this field a resultant field of opposite sense exists caused by the action of the outer coils 4 and 5.

As a consequence of this field distribution in rod 1 of FIG. 6, the heat generated at the surface parts of the rod within coil 2 and its nearest surroundings, while additional heat of less intensity will be generated at the surface parts within the other coils. In certain surface parts between the center coil 2 and the outer coils the field strength is very low or even zero, for instance at point 23 and practically no heat will be generated there. However heat will be radiated out from these surface parts and thus heat current will run from the heated parts to the cooler parts, to the heat currents 24, starting from the surface parts within coil 2 will move inwards first but will bend back to point 23. The heat currents 25 will start from within coil 4 and will again move the movement of the heat currents 24 to the surface. It is shown in FIGURE 6 the isotherms 26 and 27 will be approximately flat, the distance between the isotherm 27 and the coils, measured in the axial direction, being at the center of the rod even somewhat larger than at the surface of the rod. These isotherms may explain that the boundary of the molten zone may have a substantially flat form as shown in FIGURE 1 or even a concave form as shown in FIGURE 2.

The present invention also permits the length of the zone to be kept small, more particularly at the free surface of the rod, thus limiting the risk that this zone may flow out for materials having a comparably low surface tension, such as germanium.

It will be evident that the method according to the invention is applicable not only to floating zone-melting as above described, but also to methods of zone-melting in which the rod like bodies are supported by a crucible or in another way.

What is claimed is:

1. High-frequency zone-melting apparatus, comprising means for supporting an elongated body, at least two juxtaposed coils surrounding the body, means for applying to one of the two coils high-frequency current of given frequency in a given sense and of a magnitude establishing a magnetic field in a given direction in the body portion within the said one coil producing therein a molten zone with a given liquid-solid interface adjacent the other of the two coils, and means for applying to the other of the two coils high-frequency current of said given frequency but in a sense opposite to said given sense and of a lower magnitude establishing in the body portion within the said other coil a magnetic field intensity between about one-third and two-thirds that in the body portion within the said one coil and a resultant field within the other coil in a direction opposite to said given direction, said resultant field being insufficient to establish a molten zone in the body portion within the said other coil but causing a modification of the shape of the liquid-solid interface of the molten zone produced by the said one coil.

2. High-frequency zone-melting apparatus as set forth in claim 1 wherein the two coils coaxially surround the said body and each coil comprises only one turn.

3. High-frequency zone-melting apparatus, comprising means for supporting an elongated body, at least three juxtaposed coils surrounding the body, means for applying to the center coil of the three coils high-frequency current of given frequency and of a magnitude establishing a magnetic field in a given direction in the body portion within the said center coil.
producing therein a molten zone with a given liquid-solid interface adjacent the outer two coils, and means for applying to the outer two coils high-frequency currents of said given frequency but in a sense opposite to said given sense and of a lower magnitude establishing in the body portions within the said outer coils a field intensity between about one-third and two-thirds that in the body portion within the said center coil and a resultant field within the outer coils in a direction opposite to said given direction, said resultant field being insufficient to establish a molten zone in the body portions within the said outer coils but causing a modification of the shape of the liquid-solid interface of the molten zone produced by the said center coil.

4. Apparatus as set forth in claim 3 wherein the center coil is connected in series with the outer coils connected in parallel with one another.

5. A method of zone-melting an elongated body, comprising providing two juxtaposed coils surrounding the body, passing through one of the two coils high-frequency current in a given sense and of a magnitude sufficient to establish a magnetic field in a given direction and a molten zone within the body portion within the said one coil forming an interface of given shape with the contiguous solid portions, and passing through the other of the two coils high-frequency current of the same frequency but of opposite sense and of a magnitude insufficient to establish a molten zone within the body portion within the said other coil, said latter current being controlled to establish in the body portion within the said other coil a magnetic field having an intensity between about one-third and two-thirds that established within the body portion within the center coil and producing within the body portions within the outer coils a resultant magnetic field in a direction opposite to said given direction resulting in a modification of the shape of the interface of the molten zone within the said one coil.

6. A method of zone-melting an elongated body, comprising providing three juxtaposed coils surrounding the body, passing through the center coil high-frequency current at a given frequency, in a given sense and of a magnitude sufficient to establish a magnetic field in a given direction and a molten zone within the body portion within the center coil forming an interface of a given shape with the contiguous solid portions, and passing through the outer two coils high-frequency currents of the same given frequency but of opposite sense to said given sense and of a magnitude insufficient to establish a molten zone within the body portions within the outer two coils, said latter currents being controlled to establish in the body portions within the outer two coils a magnetic field having an intensity between one-third and two-thirds that established within the body portion within the center coil and producing within the body portions within the outer coils a resultant magnetic field in a direction opposite to said given direction resulting in a modification of the shape of the interface of the molten zone within the center coil.

7. A method as set forth in claim 6 wherein the same current is passed through the center coil connected in series with the outer coils connected in parallel with one another.

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