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(54) **Electromagnetic meniscus control in continuous casting**

(57) A strip casting apparatus comprises a pair of counter-rotating rolls (49,52) having mutually facing surfaces and a vertically extending space therebetween for containing a pool of molten metal (65) having a top surface. A meniscus is located where the top surface of the molten metal pool contacts each of the mutually facing surfaces. Various expedients are provided for electromagnetically controlling the meniscus. In one embodiment, the electromagnetic force for controlling the meniscus is generated by a conductive coil (82) through which is flowed a time-varying current. In another embodiment, a magnetic member is employed with the coil to influence the magnetic field produced by the coil.

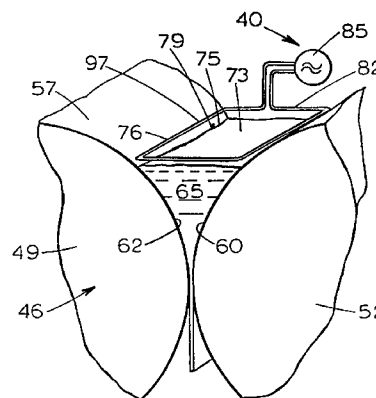


FIG. 1

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Description

BACKGROUND OF THE INVENTION

5 [0001] The present invention relates generally to apparatuses and methods for magnetically controlling molten metal and more particularly to an apparatus and method for magnetically controlling the top surface of a pool of molten metal between two continuous strip casting rolls.

10 [0002] An example of an environment in which the present invention is intended to operate is an arrangement for continuously casting molten metal directly into strip (*e.g.*, steel strip). Such an apparatus typically comprises a pair of horizontally spaced rolls mounted for rotation in opposite rotational senses about respective horizontal axes. The two rolls are typically composed of copper or steel. The two rolls define a horizontally disposed, vertically extending gap therebetween for receiving the molten metal. The gap defined by the rolls tapers arcuately in a downward direction. The side-

15 [0003] Molten metal in the gap forms a pool having a top surface. Typically, molten metal is supplied to the pool by a submerged entry nozzle having an exit port located below the top surface of the pool. The rolls are cooled and, in turn, cool the molten metal as the molten metal from the pool descends through the gap.

20 [0004] A meniscus is formed at the location where the top surface of the molten metal pool contacts the surface of a roll (the meniscus location). At the meniscus, the top surface of the pool tapers downwardly to form a valley at the roll surface. The meniscus is characterized by an angle β defined between the meniscus and the surface of the roll. When meniscus angle (β) is relatively large, as it is in a conventional strip casting apparatus, a strip having poor surface quality may result.

25 [0005] In addition to poor surface quality, a strip cast in a conventional apparatus may have nonuniform thickness. Waves of molten metal are formed in the pool adjacent the exit port of the nozzle and radiate away from the nozzle. When a wave reaches the surface of a roll, the portion of the wave contacting the roll solidifies. The crests of the wave extend higher onto the surface of a roll than do the troughs of the wave. Because of the relatively higher location that crests attain on the surface of a roll, metal from the crests has more time to cool and to solidify than metal from the troughs, resulting in thicker strip portions where the crests contact the roll than where the troughs contact the roll. Thus, the waves cause the strip to have nonuniform thickness. The nonuniformity of the strip thickness increases with increases in the amplitude of the waves.

30 [0006] Because the metal in the crests has more time to cool than the metal in the troughs, the metal in the crests may be at a lower temperature than the metal in the troughs. The unequal temperatures of the crests and troughs results in stresses in the strip which, in turn, may produce cracks along a longitudinal direction of the strip.

35 [0007] If the sidewalls of the molten metal pool are contained by electromagnetic forces from a horizontal magnetic containment field, additional waves on the top surface of the pool are generated by the interaction of the horizontal magnetic containment field and the vertical eddy current loops that the containment field induces in the pool's sidewalls. Stirring in the pool is caused by eddy currents and produces a "waterfall-effect" on the molten-metal sidewall (*i.e.*, a vertical molten metal flow along the sidewall).

40 [0008] To decrease the angle of the meniscus (β) and dampen the waves, conventional strip casting apparatuses have employed surface boards. A surface board has a concave curvature complementary to the convex curvature of a roll and is placed adjacent a roll. Molten metal located between a surface board and a roll has a smaller meniscus angle (β) than if the surface board were absent. Also, a surface board dampens the waves by providing a barrier that mechanically prevents the molten metal waves from contacting the roll. However, a surface board is consumable, typically lasting for only a single heat and resulting in a significant recurring cost when producing steel strip in an apparatus employing a surface board.

SUMMARY OF THE INVENTION

45 [0009] The present invention is directed to strip casting apparatuses and methods for dealing with the above-described problems which can arise when strip casting. More particularly, the apparatus and methods of the present invention are directed to magnetically controlling the meniscus formed at the location where the top surface of the molten metal pool contacts one of the mutually facing roll surfaces.

50 [0010] This is accomplished by generating an electromagnetic field for performing one or more of the functions described below. One such function is to reduce the amplitude of the waves adjacent the meniscus location. Another function is to form a barrier between the waves and the roll surface adjacent the meniscus location. A further function is to control the angle of the meniscus.

55 [0011] Structure for controlling the meniscus is positioned adjacent the meniscus location, on the outside of the roll at that location, and generates an electromagnetic field which acts on the pool top surface adjacent that location to control the meniscus there. The structure for controlling the meniscus includes an electrically conductive coil through which

flows a time-varying current to generate the electromagnetic field.

[0012] In some embodiments, the coil may have a coil portion positioned adjacent the meniscus location for directly generating the electromagnetic field sufficiently close to that location to enable the electromagnetic field to perform one or more of the functions described above without the interposition of a magnetic member for influencing the field. In other embodiments, a highly permeable magnetic member is employed to shape the electromagnetic field in a manner which enhances the ability of the electromagnetic field to perform one or more of the functions described above with less current than without the magnetic member. In embodiments having mechanical sidewall control, the structure for controlling the surface waves may extend along the top surface of the sidewall of the molten metal pool.

[0013] Other features and advantages are inherent in the methods and apparatus claimed and disclosed or will become apparent to those skilled in the art from the following detailed description in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014]

FIG. 1 is a fragmentary perspective showing a strip caster employing an embodiment of an apparatus of the present invention;

FIG. 2 is a schematic circuit diagram for the apparatus of FIG. 1;

FIG. 3 is a side elevational view, partially in section, of a strip caster employing the embodiment of FIG. 1;

FIG. 3A is a cross-section of a coil similar to the coil of FIG. 3 and having a splash guard;

FIG. 4A is an enlarged, fragmentary side elevational view, partially in section, showing the embodiment of FIG. 1 and molten metal waves affected by an electromagnetic force;

FIG. 4B is a schematic diagram illustrating the direction of electromagnetic repulsion at a location in the electromagnetic field of FIG. 4A;

FIG. 5 is an enlarged, fragmentary side elevational view of a portion of a strip caster showing molten metal waves unaffected by an electromagnetic force;

FIG. 6 is a fragmentary sectional view taken along line 6--6 in FIG. 3 with some parts removed;

FIG. 7 is an enlarged, fragmentary side elevational view, partially in section, showing the embodiment of FIG. 1 and a meniscus affected by an electromagnetic force;

FIG. 8 is an enlarged, fragmentary side elevational view of a portion of a strip caster showing the meniscus unaffected by an electromagnetic force;

FIG. 9 is a fragmentary perspective, partially in section, showing a strip caster employing another embodiment of an apparatus of the present invention;

FIGS. 10A and 10B are schematic circuit diagrams for the apparatus of FIG. 9;

FIG. 11A is a fragmentary, side elevational view, partially in section, of a strip caster employing the embodiment of FIG. 9 shown without an electromagnetic field;

FIG. 11B is a fragmentary, side elevational view, partially in section, of the embodiment of FIG. 9 shown with an electromagnetic field;

FIG. 12 is a fragmentary, side elevational view, partially in section, of a strip caster employing another embodiment of the present invention and shown with a magnetic field;

FIG. 13 is a schematic diagram of an apparatus of the present invention having a magnetic member;

FIG. 14A is a fragmentary, side elevational view, partially in section, of a strip caster employing an embodiment of the apparatus of FIG. 13;

FIG. 14B is a fragmentary, side elevational view, partially in section, of a strip caster employing another embodiment of the apparatus of FIG. 13;

FIG. 15 is a fragmentary, side elevational view, partially in section, of a strip caster employing a further embodiment of the apparatus of FIG. 13;

FIG. 16A is a schematic diagram similar to FIG. 10B but illustrating an apparatus having magnetic members;

FIG. 16B is a fragmentary, side elevational view, partially in section, of a strip caster employing an embodiment of the apparatus of FIG. 16A;

FIG. 17 is a fragmentary, side elevational view, partially in section, of a strip caster employing another embodiment of the apparatus of FIG. 16A;

FIG. 18A is a fragmentary, side elevational view, partially in section, of a further embodiment of the apparatus of FIG. 16A;

FIG. 18B is a fragmentary, cross-sectional view taken along line 18B--18B in FIG. 18A;

FIG. 19 is a fragmentary, side elevational view, partially in section, of still another embodiment of the apparatus of FIG. 16A;

FIG. 20 is a schematic diagram of another apparatus of the present invention having magnetic members;
 FIG. 21 is a fragmentary, side elevational view, partially in section, of an embodiment of the apparatus of FIG. 20;
 FIG. 22A is a fragmentary, side elevational view, partially in section, of another embodiment of the apparatus of FIG. 20;
 FIG. 22B is an exploded view of the magnetic member shown in FIG. 22A;
 FIG. 23 is a schematic diagram of an apparatus of the present invention having another arrangement of magnetic members;
 FIG. 24 is a fragmentary, side elevational view, partially in section, of an embodiment of the apparatus of FIG. 23;
 FIG. 25 is a fragmentary, side elevational view, partially in section, of another embodiment of the apparatus of FIG. 23;
 FIG. 26 is a fragmentary, side elevational view, partially in section, of still another embodiment of the apparatus of FIG. 23;
 FIG. 27 is a schematic diagram of an apparatus of the present invention having still another arrangement of magnetic members;
 FIG. 28 is a fragmentary, side elevational view, partially in section, of an embodiment of the apparatus of FIG. 27;
 FIG. 29 is a fragmentary, side elevational view, partially in section, of another embodiment of the apparatus of FIG. 27;
 FIG. 30 is a fragmentary, side elevational view, partially in section, of another embodiment of the apparatus of FIG. 27; and
 FIG. 31 is a fragmentary, side elevational view, partially in section, of an apparatus of the present invention employing a plate for producing an electromagnetic field.

DETAILED DESCRIPTION

[0015] Designated generally at 40 in FIGS. 1-3 is an apparatus, in accordance with the present invention, for magnetically controlling a meniscus formed in a continuous strip caster 46. Continuous strip caster 46 may be a conventional strip caster having first and second counter-rotating rolls 49, 52, respectively, with respective first and second mutually facing surfaces 57, 60 that define a space 62 for containing a pool 65 of molten metal. A nozzle 70 (FIG. 3) for feeding molten metal into pool 65 is disposed between rolls 49, 52. Molten metal pool 65 has a pool top surface 73, and a meniscus 75 is formed adjacent a meniscus location 79 where pool top surface 73 contacts either of the mutually facing roll surfaces 57, 60.

[0016] Apparatus 40 includes an arrangement 76 positioned adjacent meniscus location 79 for generating an electromagnetic field which acts on pool top surface 73 to control meniscus 75. As seen in FIG. 1, arrangement 76 may comprise an electrically conductive coil 82 and a device 85 electrically connected to coil 82 for flowing a time-varying current through coil 82 to generate the electromagnetic field. As discussed in more detail below, conductive coil 82 may be a copper tube through which water is flowed to cool coil 82. Device 85 is shown schematically in FIGS. 1 and 2 and may include a conventional power supply or any other power source capable of supplying suitable amounts of current. The coil 82 may be similar to loops used for electromagnetic confinement during vertical casting of aluminum. Such loops are described in U.S. Patent Nos. 4,982,796 and 4,905,756, the disclosures of which are hereby incorporated by reference.

[0017] The principle behind the control of meniscus 75 is electromagnetic repulsion. Current flowing through coil 82 creates an electromagnetic field around the coil. The magnetic field is depicted by isomagnetic lines 86 in FIGS. 3 and 4A. A flux path is designated at 87. The strength of the electromagnetic field increases with an increase in the current flowed through coil 82.

[0018] As seen in FIG. 4B, electromagnetic repulsion or magnetic pressure F at a particular location is proportional to the cross-product of (i) the magnetic field strength, B , at that location and (ii) the eddy current i_e induced in metal at that location by the magnetic field there. The location depicted in FIG. 4B is designated at 89 in FIG. 4A. Electromagnetic repulsion F , at meniscus location 79, is proportional to the cross-product of (i) the magnetic field strength, B , at meniscus location 79 and (ii) the eddy current i_e induced in meniscus 75 by the magnetic field at meniscus location 79. Because the eddy currents i_e are produced by the magnetic field, the electromagnetic repulsion, F , is proportional to the square of the magnetic field strength, B . Magnetic pressure F can therefore be expressed as $B^2/(2\mu)$ where μ is the magnetic permeability of the molten metal. Magnetic permeability is discussed in more detail below. The magnetic pressure, F , at a particular location, urges molten metal there in a direction (i) that is perpendicular to a tangent of the isomagnetic line at that location and (ii) that is perpendicular to the eddy current flow as illustrated in FIG. 4B.

[0019] The strength of the electromagnetic field is inversely related to the distance between molten metal pool 65 and coil 82 from which the electromagnetic field emanates. Thus, if the distance doubles between (a) molten metal pool 65 and (b) coil 82, the strength of the electromagnetic field B at pool 65 drops to one-half its former strength, and the magnetic pressure F drops to a quarter its former magnitude ($F \propto B^2$).

[0020] Pool top surface 73 has waves 88 (FIGS. 4A, 5, and 6) formed from molten metal exiting nozzle 70 (FIG. 3). Waves 88 normally move in a direction having a component extending toward meniscus location 79. As seen in FIG. 6, waves 88 result in a series of crests 91 and troughs 94 where molten metal contacts the surface of a roll (in FIG. 6, surface 57 of roll 49). Because the molten metal in crests 91 spends more time adjacent roll surface 57 than does molten metal in troughs 94, molten metal in crests 91 has more time to solidify than does molten metal in troughs 94. Because there is non-uniformity in solidification time, there is non-uniformity in the thickness of the resulting strip across the width of the strip. Moreover, the larger the amplitude of waves 88, the greater the non-uniformity of the strip thickness which is manifest as strip surface non-uniformity. Also, because the molten metal in crests 91 spends more time adjacent roll surface 57 than does molten metal in troughs 94, molten metal in crests 91 has more time to cool than does molten metal in troughs 94. Molten metal in crests 91 is therefore at a lower temperature than molten metal in troughs 94. The temperature differences between crests 91 and troughs 94 cause stresses in the strip which may produce cracks in the strip along a longitudinal direction.

[0021] To improve strip surface quality and uniformity, coil 82 (not shown in FIG. 6) is employed to generate an electromagnetic field which reduces the amplitude of waves 88 adjacent meniscus 75. Figure 4A depicts waves 88 dampened by the electromagnetic field from coil 82, whereas FIG. 5 depicts undampened waves 88 in a strip caster that does not have coil 82 or any other source of wave-dampening electromagnetic force.

[0022] As seen in FIGS. 7 and 8, pool top surface 73, at meniscus location 79, and roll surface 57 adjacent meniscus location 79, define an angle of the meniscus (designated β). Coil 82 generates an electromagnetic field which controls meniscus angle β . Decreasing meniscus angle β can improve the surface quality of the resulting strip. FIG. 7 depicts a meniscus angle β which is relatively small due to the electromagnetic pressure resulting from the electromagnetic field applied by coil 82, whereas, in FIG. 8, the meniscus angle β is relatively large due to the absence of coil 82 or any other source of angle β -reducing electromagnetic force.

[0023] Another solution to strip surface non-uniformity caused by waves 88 is to form a barrier. Coil 82 may be employed to generate an electromagnetic field for forming a barrier between waves 88 and roll surfaces 57, 60. As seen in FIG. 4A, the electromagnetic field generated by coil 82 is interposed between waves 88 and a roll surface, essentially preventing waves 88 from reaching the roll surface (surface 57 in FIG. 4A).

[0024] As seen in FIGS. 1 and 3, coil 82 may include a coil portion 97, positioned adjacent meniscus location 79, for directly generating the electromagnetic field sufficiently close to meniscus location 79 to enable the electromagnetic field to perform any of the functions listed above, *i.e.*, dampening molten metal waves 88, controlling the meniscus angle β , or forming a barrier between waves 88 and a roll surface 57 or 60.

[0025] Coil 82 is composed of a conductive material such as copper. The lateral cross-section of coil 82 may be circular, as seen in FIG. 3, rectangular, square, triangular, elliptical, or any other shape suitable for conducting current. Coils 82 shown in the Figures are hollow to enable the circulation of cooling water through the coil. Water cooling may be necessary when the current conducted by coil 82, and the frequency of the magnetic field produced thereby, are such that coil 82 generates too much heat to be satisfactorily cooled by air cooling.

[0026] Usually, a magnetic field strength of at least about 100 gauss at surface 73 of the molten metal is sufficient to control meniscus 75. When the distance between coil 82 and meniscus 75 is about 0.25-1.0 inches (6.5-25.4 mm), and the current is about 200-1000 amps, the resulting magnetic field strength is sufficient to achieve the desired control over meniscus 75. Of course, other distances from meniscus 75 are also effective, depending upon the amount of current flowing through coil 82. When meniscus 75 is not subjected to the influence of an electromagnetic field, a part of meniscus 75 farthest from an adjacent roll surface (*e.g.*, roll surface 57) typically is located about 4-12 mm away from the adjacent roll surface. Because meniscus 75 extends only about 4-12 mm in a direction away from the adjacent roll surface, to control meniscus 75, a strong magnetic field may have to be directed very close to the adjacent roll surface. The maximum distance that meniscus 75 extends in a direction away from an adjacent roll surface, when not subjected to the influence of an electromagnetic field, varies depending on the rate of rotation of rolls 49, 52, along other variables.

[0027] Leakage flux is designated at 98 in the drawings (FIG. 3 and many of the drawings discussed below) and is defined as electromagnetic flux that does not provide significant control over the meniscus or significant wave dampening.

[0028] Molten metal may splash onto coil 82 when the coil is close to top surface 73 of molten metal pool 65. To protect coil 82, coil 82 may be sheathed in a splash guard 100 such as a ceramic housing or some other non-conducting material as illustrated in FIG. 3A. If the distance between coil 82 and top surface 73 of the molten metal has to be increased to accommodate splash guard 100, the current required to achieve a particular magnetic field strength adjacent meniscus location 79 may have to be increased accordingly.

[0029] The rolls and the pool have a magnetic permeability μ , where μ is a measure of the ability of a material to concentrate magnetic field lines and can also be analogized as the magnetic conductivity of a flux path. The rolls and the pool also have a resistivity, ρ . An alternating magnetic field has a frequency, f , which equals the frequency of the time-varying current. When the alternating magnetic field is applied to the surface of a conductive material having resistivity, ρ , and permeability, μ , the magnetic field and the eddy current density in the material are attenuated and phase shifted

as they penetrate the material. The distance, δ , from the surface of the material to where the field has been attenuated to 0.367 of the field strength at the surface, is called skin depth (δ) which is defined by the following equation:

$$\delta = \left(\frac{\rho}{\mu \pi f} \right)^{1/2}$$

The total exponentially decaying field in a material is equivalent to an imaginary, uniformly distributed field that is confined to the skin of the material to a depth δ . For steel at its melting point, ρ is about 140 micro- Ω cm. For a water-cooled copper roll, ρ is about 1.73 micro- Ω cm. The skin depths (δ) for different frequencies (f) are shown below in Table 1 for molten steel (Fe) and room temperature copper (Cu).

TABLE 1

$f(\text{Hz})$	300	1,000	3,000	10,000
$\delta_{\text{Fe}}(\text{cm})$	3.43	1.88	1.09	0.59
$\delta_{\text{Cu}}(\text{cm})$	0.38	0.21	0.121	0.066

[0030] The melting point of steel is well above the Curie-temperature of approximately 700°C, resulting in non-magnetic properties in molten steel even when casting low carbon steel. The Curie-temperature is defined as the temperature at which the steel loses its magnetic properties.

[0031] The smaller the skin depth, the less electromagnetic stirring or agitation of molten metal that occurs and, consequently, the better the control of meniscus. High frequency magnetic fields penetrate less deeply than low frequency magnetic fields. At a frequency of 10,000hz, stirring perturbs the pool top surface very little, so that the surface moves in a relatively smooth fashion. At 300 hz, stirring may be violent, often causing intolerable surface perturbations.

[0032] A disadvantage of higher frequencies is greater heating from eddy currents. The power dissipation per unit area (P/A) in the molten metal pool is

$$\frac{P}{A} = \frac{\rho}{2\delta} \left(\frac{B}{\mu} \right)^2$$

Power dissipation for a given magnetic flux density (B) is inversely proportional to skin depth (δ). Because skin depth (δ) is inversely proportional to the square root of frequency (f), power dissipation is proportional to the square root of frequency (f).

[0033] Shown below in Table 2 is the power dissipation, from eddy currents, for molten steel and room temperature copper rolls, at a surface field strength (B) of 100 gauss.

TABLE 2

f	300	1,000	3,000	10,000	Hz
$(P/A)_{\text{Fe}}$	0.129	0.235	0.405	0.749	W cm^{-2}
$(P/A)_{\text{Cu}}$	0.0144	0.026	0.045	0.083	W cm^{-2}

[0034] In particular, at the relatively low strength fields (100 gauss) shown in Table 2, it is advantageous to operate the electromagnetic meniscus control arrangement at frequencies greater than about 3khz to reduce stirring. Heating of copper roll surfaces, when coil 82 generates 100 gauss fields, is negligible at any of these frequencies, as illustrated in Table 2.

[0035] Typically, rolls are cooled by circulation of water in the interior of those rolls to facilitate the solidification of strip on roll surfaces. Cooling of rolls in conventional strip casting is necessary because molten metal pool is a source of heat for rolls and, in conventional strip casting, it is generally desirable to keep rolls relatively cool.

[0036] Conventional cooling structure for cooling rolls may be sufficient to cool rolls subjected to the

magnetic field from coil 82 as a further source of heat. If there is too much heating of roll surfaces 57, 60, when coil 82 is employed, when coil 82 should be spaced relatively far from roll surfaces 57, 60 to reduce the strength of the magnetic field at the roll surfaces. However, a magnetic field having a strength substantially greater than 100 gauss will heat up roll surfaces 57, 60.

[0037] Some heating of roll surfaces 57, 60 by operation of coil 82 may be desirable at meniscus location 79 because such heating may increase the uniformity of the resulting strip surface. Heated roll surfaces 57, 60 delay the solidification of crests 91 (FIG. 6) of molten metal, thereby lowering the discrepancy between (i) the solidification time of crests 91 and (ii) the solidification time of troughs 94 (FIG. 6). One or more of any of the following may be employed to increase the heating of roll surfaces 57, 60: positioning coil 82 relatively close to roll surfaces 57 and 60, increasing the current flowed through coil 82, or increasing the frequency of the magnetic field.

[0038] As previously noted, rolls 49, 52 are typically composed of copper or steel. Another way to increase the heating of roll surfaces 57, 60 is to construct rolls 49, 52 from a material having a lower thermal conductivity, a lower electrical conductivity, or a higher magnetic permeability than copper or steel. For example, a copper roll may be coated with nickel or a nickel-based alloy. When exposed to the same magnetic field, the nickel coating, which has a relatively lower thermal conductivity than copper or steel, a relatively lower electrical conductivity than copper, and a relatively higher magnetic permeability than copper or steel, results in a higher roll surface temperature than a copper or steel roll surface.

[0039] In another embodiment, shown in FIGS. 9-11B, coil 82 comprises first and second coil portions 103, 106, respectively, electrically connected to one another and located adjacent meniscus location 79. As seen in FIGS. 9-11B, second coil portion 106 is disposed substantially parallel to first coil portion 103 adjacent meniscus location 79. Second coil portion 106 may be disposed in other orientations with respect to first coil portion 103. For clarity of illustration, coil 82 is shown to be solid in FIG. 9, although coil 82 may be hollow, as shown in FIGS. 11A,B.

[0040] The magnetic field is shown by isomagnetic lines 109 in FIG. 11B. In FIG. 11B and subsequent figures depicting embodiments having first and second coil portions, the direction of the current is indicated by an X symbol in the center of one coil portion and by a dot in the center of the other coil portion. The X symbol denotes current directed into the page containing the drawing, whereas the dot symbol denotes current directed out of the page. The direction that the magnetic field flows around a coil portion is determined by applying the familiar right-hand rule to the direction of the current flowing through that coil portion.

[0041] With respect to the magnetic fields shown by isomagnetic lines 109 in FIG. 11B, and with reference to a space 111 between adjacent first and second coil portions 103, 106, the respective magnetic fields produced there by first coil portion 103 and second coil portion 106 run in the same direction. Thus, in the space between first coil portion 103 and second coil portion 106, the magnetic fields produced by the respective coil portions reinforce one another.

[0042] The coil in FIGS. 1-4A is called a wide-loop coil because the area enclosed by coil 82 in FIGS. 1-4A is relatively large and spans substantially the width of top surface 73 of pool 65. In contrast, coil 82 in FIGS. 9-12 forms two narrow loops 110 (FIGS. 10A, 10B), each loop 110 enclosing a relatively small area. Wide-loop coils tend to produce eddy currents in the top surface of the entire pool and also tend to have high inductance compared to narrow-loop embodiments. Narrow-loop embodiments require significantly lower volt-amperes than wide-loop embodiments.

[0043] Referring to FIGS. 9-12, the space between coil portions 103 and 106 (space 111) is much smaller than a space 112 enclosed by wide-loop conductor 82 of FIG. 2. A comparison of the magnetic flux lines of FIG. 3 (wide-loop) and FIGS. 11B and 12 (narrow loops) shows that the magnetic field is concentrated in a much smaller volume of space with the narrow-loop embodiments of FIGS. 9-12. Also, the eddy-current losses and eddy-current stirring are restricted to much smaller volumes.

[0044] The inductance, L , of the current loops is roughly proportional to the area enclosed by the conductors. Therefore, the inductance of the narrow-loop embodiments of FIGS. 9-12 is much smaller than the inductance of the wide-loop embodiment of FIGS. 1-3.

[0045] Power losses in the resistance of the system are equivalent to (a) losses in the coil conductor and (b) eddy current losses in the molten metal as the eddy currents flow in one skin depth of the molten metal surface. The losses in the coil conductor equal I^2R , where I is the current through the coil and R is the resistance of the coil. The eddy current losses are equal to $(I_e)^2R_e$, where I_e is the amount of eddy currents flowing through the molten metal and R_e is the molten metal resistance. Assuming the same current is required for meniscus control using (a) the embodiment of FIG. 4 (wide-loop) and (b) the embodiments of FIGS. 11 and 12 (narrow-loop), the power supply requirements are roughly proportional to the circuit inductance L . Since the inductance of the narrow-loop embodiments (FIGS. 9-12) is much smaller than the inductance of the wide-loop embodiment (FIGS. 1-3), the power requirements for the embodiments of FIGS. 9-12 are much smaller than for the embodiment shown in FIGS. 1-3.

[0046] More particularly, the embodiments of FIGS. 9-12, which have first and second coil portions 103, 106, require only about one-third or less the volt-amperes required by the embodiment of FIGS. 1-4A, which does not have a second coil portion, to produce a magnetic field having a particular strength adjacent meniscus location 79.

[0047] In the embodiments of FIGS. 9-12, the orientation of a plane 118 (FIGS. 11B, 12) that bisects both coil portions

103, 106 affects both the electromagnetic force that reaches meniscus location 79 and the electromagnetic force that is exerted on pool surface 73 away from meniscus 75, as illustrated in FIGS. 11B and 12.

[0048] For example, as seen in FIG. 12, second coil portion 106 may be positioned at substantially the same height as first coil portion 103 relative to pool top surface 73. For the most effective meniscus control, coil portions 103, 106 should have a location and orientation which directs at least some of the electromagnetic field toward meniscus location 79, and this is accomplished with the embodiments of both (a) FIGS. 9-11 and (b) FIG. 12.

[0049] Each of the first and second coil portions 103, 106 may be sheathed within a protective layer or splash guard 100, as discussed above in connection with the embodiment of FIG. 3. Alternatively, a single splash guard may be employed to cover both coil portions.

[0050] The apparatus of FIG. 13 is another wide, one-loop apparatus. Apparatus 40 of both FIG. 13 and the corresponding embodiment depicted in FIG. 14A comprises a pair of magnetic members 121, each associated with at least a part of coil 82 and each disposed adjacent a respective roll surface 57, 60 (only roll surface 57 is shown in FIG. 14A). In FIG. 13, each magnetic member 121 is represented by a series of inverted U-shaped, yoke-and-arm symbols. As seen in FIG. 14A, each magnetic member 121 has a yoke 124 connecting a pair of arms 127. One or both of arms 127 may be substantially perpendicular to yoke 124.

[0051] Each arm 127 terminates in a magnetic pole portion at an outer end 128. A part of the length of coil 82 is received between the pair of arms 127 of magnetic member 121. As seen in FIG. 14A, magnetic member 121 may comprise a tapered portion 126 adjacent roll surface 57 to facilitate placing pole portion 128 adjacent roll surface 57. Magnetic field lines are designated at 125 in FIG. 14A and in subsequent figures depicting embodiments having magnetic members.

[0052] Magnetic member 121 may be formed from stamped laminations of ferromagnetic steel conventionally used in magnetic members operating at audio-frequencies greater than about 1000hz. Alternatively, magnetic member 121 may be formed from tape-wound laminations of ferromagnetic steel. Magnetic member 121 may instead be composed of any suitable ferromagnetic material having a relatively high magnetic permeability, such as ferrite. The space between coil 82 and magnetic member 121 is filled with heat-conducting, electrically insulating material 120. Material 120 not only provides electrical insulation for conductor 82, but also it makes water-cooled conductor 82 a heat sink by transmitting the heat produced by eddy-current losses in magnetic member 121 to the water-cooled conductor 82. Alternatively, a layer of air may be disposed between coil 82 and magnetic member 121 to prevent a short circuit from developing between magnetic member 121 and coil 82. Suitable structure (not shown) may be employed to maintain a space between magnetic member 121 and coil 82 to provide such a layer of air.

[0053] A refractory splash guard, similar to splashguard 100 shown in FIG. 3A, may enclose magnetic member 121 and coil 82.

[0054] The shape of magnetic member 121 and the shape of conductor 82 determine the shape of the magnetic field produced by coil 82. Thus, it may be desirable to use a magnetic member 121 having a shape other than the shape shown in FIG. 14A. For example, magnetic member 121 may extend around more or less of the cross-section of coil 82 than magnetic member 121 shown in FIG. 14A. Magnetic member 121 and coil conductor 82 are shaped and positioned to optimize the magnetic field near meniscus location 79.

[0055] The embodiment depicted in FIG. 14B is similar to the embodiment of FIG. 4A except that the embodiment of Figure 14B has a magnetic member 121A. Magnetic member 121A is similar to magnetic member 121 except that the cross-sectional shape of magnetic member 121A is semi-circular rather than u-shaped. Also, the lateral cross-sectional shape of coil 82 is substantially circular in FIG. 14B whereas, in FIG. 14A, the lateral cross-sectional shape of coil 82 is substantially rectangular.

[0056] Magnetic member 121 provides a flux path which has a relative permeability, μ_r , which is more than a 1000-times larger than air. The current required to push the flux through magnetic member 121 is negligible compared to the current required to push flux along a flux path 129 (FIGS. 14A, B). Therefore, to produce near meniscus location 79 a flux density of 100 gauss requires a current through coil 82 that produces 100 gauss over flux path 129. A comparison with the wide-loop apparatus of FIGS. 1-4 shows that flux path 87 (FIG. 4A), is much longer than flux path 129 in FIGS. 14A and 14B. The magnetizing current through coil 82 is $I = Bl/\mu$, where I equals the flux path length. The current required is thus proportional to the flux-path-length, l . From inspection of FIGS. 4A, 14A, and 14B, it is seen that flux path 129 is less than half of flux path 87. By adding magnetic members 121 and 121A (FIGS. 14A-B) to wide-loop conductor 82 of FIGS. 1-4, the current requirements are cut to less than half, and the power requirements ($P = I^2 R$) are cut to less than one-quarter. Also, the corresponding eddy-current losses and stirring in surface 73 due to the current in coil 82 of (a) the apparatus of FIG. 3, is more than quadruple the corresponding losses and stirring due to the current in coil 82 of (b) an apparatus such as that shown in FIG. 13.

[0057] A magnetic member or members provide a high permeability region which, compared to air, is relatively easy for the magnetic field to flow through. In effect, magnetic member 121 replaces air, which has a relatively low permeability, as the path of the magnetic field: the magnetic field flows through yoke 124, out of one of the arms 127, and then into the other arm 127. Although the magnetic field of the embodiments of FIGS. 14A-B must still travel through air in a

part of the magnetic field path (through flux path 129), magnetic member 121 shortens path 129 and, therefore, increases the strength of the magnetic field at meniscus location 79 for a particular amount of current.

[0058] Magnetic member 121 is shaped and positioned so that no part of member 121 is interposed between coil 82 and meniscus location 79. If a portion of magnetic member 121 were interposed between coil 82 and meniscus location 79, the magnetic field would tend to flow substantially solely within magnetic member 121, and thus, little magnetic field would reach meniscus location 79. As noted above, the relatively high permeability of magnetic member 121, compared to air, is the reason that the magnetic field favorably flows through magnetic member 121. Thus, outer ends 128 of arms 127 of the embodiments of FIGS. 14A-B are spaced from one another, and magnetic member 121 is shaped and positioned so that no portion of magnetic member 121 is interposed between meniscus location 79 and coil 82. The configuration of these embodiments thus produces a magnetic field, emanating from coil 82 and flowing between outer ends 128 of arms 127, which is more concentrated in the direction of meniscus location 79 than would occur if a portion of magnetic member 121 were interposed between coil 82 and meniscus location 79. Also, the configuration of these embodiments produces a more concentrated electromagnetic field in the direction of meniscus location 79 than would coil 82 in the absence of magnetic member 121.

[0059] For the reasons discussed in the preceding paragraph, in all embodiments herein in which a magnetic member is associated with a coil or a coil portion and is employed to shape or strengthen the magnetic field near meniscus 75, the magnetic member is configured or positioned so that no portion of that magnetic member is interposed between (a) the associated coil or coil portion and (b) meniscus location 79 in a manner that will interfere with the ability of the magnetic field to control the amplitude or angle of the meniscus.

[0060] Magnetic member 121 comprises structure, such as arms 127, for directing the electromagnetic field in a manner which enables the electromagnetic field to perform any of the functions described above (*i.e.*, dampening molten metal waves 88, controlling the meniscus angle β , or forming a barrier between waves 88 and a roll surface 57 or 60).

[0061] In the embodiments of FIGS. 14A and 14B, flux path 129, located between outer ends 128, 128 of arms 127, 127 is the area having the strongest magnetic field. As seen in FIG. 14A, one arm 127 of magnetic member 121 may be positioned directly above meniscus 75 and the other arm 127 may be positioned farther from the adjacent roll surface 57. By so positioning magnetic member 121, the strongest magnetic field is located over a portion of pool 65 adjacent meniscus 75 to efficiently control meniscus 75.

[0062] Magnetic member 121 may be placed in other orientations with respect to roll surfaces 57, 60 or pool top surface 73. For example, magnetic member 121 may be disposed directly above that part of a roll surface 57 or 60 adjacent meniscus location 79 rather than above pool surface 73. In addition, magnetic member 121 may be angularly oriented so that both arms 127 point generally in the direction of meniscus location 79. The effectiveness of various orientations of magnetic member 121 at controlling meniscus 75 depends, in part, upon the cross-sectional shapes of both magnetic member 121 and conductor 82, as illustrated by FIGS. 14A and 14B.

[0063] The current required to achieve a particular magnetic field strength at a particular location of pool top surface 73 may change when the shape of magnetic member 121 is changed. The volt-amperes required for the embodiments of FIGS. 13 and 14A-B to produce a particular electromagnetic field strength adjacent meniscus location 79 are about 50% less than the volt-amperes required for the embodiments of FIGS. 1-4A to produce the same electromagnetic field strength adjacent meniscus location 79. The efficiency of the embodiments of FIGS. 13 and 14A-B results from magnetic member 121 providing a flux path (flux path 129) which is significantly shorter than flux path 87 (FIG. 4A) of the embodiment of FIGS. 1-4A.

[0064] As seen in FIG. 15, apparatus 40 may include an L-shaped magnetic member 130 having adjoining arms 131 and 132 extending from a mutual junction at 133. Arms 131 and 132 each terminate in poles 134a and 134b, respectively. Arms 131 and 132 diverge from one another and may be substantially perpendicular to one another. This embodiment may cause more heating of roll 49 than is caused by the embodiments of FIGS. 14A-B because the flux penetrates roll surface 57 along a greater distance in this embodiment than in the embodiments of FIGS. 14A-B. The volt-amperes required by the embodiment of FIG. 15 in order to produce a particular electromagnetic field strength adjacent meniscus location 79 are about the same as the volt-amperes required by the embodiments of FIGS. 14A-B in order to produce the same electromagnetic field strength adjacent meniscus location 79.

[0065] The apparatus of FIG. 16A is similar to the narrow-loop embodiments shown in FIGS. 9-12 but with magnetic members 135 added to reduce the current requirement to less than half and to reduce leakage flux.

[0066] FIG. 16B depicts an embodiment in accordance with the configuration of FIG. 16A and includes magnetic member 135, and longitudinal first and second coil portions 137, 139. Second coil portion 139 may be disposed substantially parallel to first coil portion 137 adjacent meniscus location 79, as seen in FIG. 16B. Arms 140 and 141 terminate in pole portions 142, 143, respectively. A yoke 144 on magnetic member 135 comprises first and second opposing sides 147, 150. First side 147 of yoke 144 and arms 140, 141 define a channel 151 that receives first coil portion 137. Second coil portion 139 is disposed adjacent to second side 150 of yoke 144 outside channel 151.

[0067] The apparatus of FIG. 16A is essentially the narrow-loop apparatus of FIGS. 10A-B, but with magnetic members. The apparatus of FIG. 16A has lower current requirements than the apparatuses of FIGS. 10A-B. Additionally, in

the embodiment shown in FIG. 16B, the magnetic field is shaped by magnetic member poles 142, 143 and by the shape of conductor 82.

[0068] In the embodiment shown in FIG. 16B, arm 140 is disposed above a location adjacent meniscus location 79, and arm 141 is disposed directly over pool top surface 73, but farther from meniscus location 79 than arm 140. The magnetic containment field is generated by this embodiment between poles 142 and 143 in an area 152. When magnetic member 135 is in the position shown in FIG. 16B, a relatively strong magnetic field is applied adjacent meniscus 75.

[0069] Magnetic member 135 may be located at other positions with respect to roll 49. For example, magnetic member 135 may be disposed directly above that part of a roll surface 57 or 60 adjacent meniscus location 79 rather than above pool surface 73. In addition, magnetic member 135 may be angularly oriented so that arms 140, 141 point generally in the direction of meniscus location 79. The effectiveness of various orientations of magnetic member 135 at controlling meniscus 75 depends, in part, upon the cross-sectional shape of magnetic member 135 and the shape of first coil portion 137.

[0070] The volt-amperes required for the apparatus of FIG. 16A and the embodiment of FIG. 16B to produce an electromagnetic field having a particular strength adjacent meniscus location 79 are (a) about one-half of the volt-amperes required by the embodiments of FIGS. 9-12 and (b) about 15% of the volt-amperes required by the embodiment of FIGS. 1-3 to produce an electromagnetic field having the same strength adjacent meniscus location 79. This is so because the embodiment of FIG. 16B is a narrow-loop configuration with magnetic members, thereby producing a flux path through air in area 152 that is shorter than in the flux paths of the embodiments of FIGS. 9-12.

[0071] Second coil portion 139 may be positioned with respect to magnetic member 135 at a location other than adjacent to second side 150 of yoke 144. For example, in an embodiment similar to the embodiment of FIG. 16B, second coil portion 139 may be positioned adjacent an outside surface 153 of either one of arms 140 or 141.

[0072] As seen in FIG. 17, apparatus 40 may comprise an L-shaped magnetic member 155 having arms 157 and 159. Magnetic member 155 may be made from tape-wound core sections. Arms 157 and 159 diverge from one another and may be substantially perpendicular to one another. Coil portion 137 is received between arms 157 and 159. Arms 157 and 159 each terminate in a pole portion and are positioned so that magnetic member 155 has no arm adjacent a side 160 of first coil portion 137 that is proximal to pool 65.

[0073] Some leakage flux 98 is associated with coil portion 139 as illustrated in FIG. 17. The configuration of FIG. 17 may produce more heat at roll 49 than the embodiment of FIG. 16B produces there because, in the configuration of FIG. 17, the flux flows in roll surface 57 along a greater distance than in the embodiment of FIG. 16B. The volt-amperes required by the embodiment of FIG. 17 in order to produce a particular electromagnetic field strength adjacent meniscus location 79 are about the same as the volt-amperes required by the apparatus of FIG. 16A and the embodiment of FIG. 16B in order to produce the same electromagnetic field strength adjacent meniscus location 79.

[0074] Another embodiment of the present invention with an L-shaped magnetic member is shown in FIGS. 18A-B and 19. This embodiment comprises a magnetic member 167 and water-cooled, longitudinal coil portions 161, 164. Member 167 may be assembled from thin, stamped L-shaped laminations as illustrated in FIG. 18B. Member 167 has arms 168 and 169 terminating in pole portions 173, 176, respectively. Arms 168 and 169 diverge substantially and may be substantially perpendicular to one another, as seen in FIGS. 18A and 19. A copper eddy-current shield 170 is placed over the outer surface of member 167, with a heat-conducting, insulating material 171 placed between magnetic member 167 and shield 170. Without shield 170 there could be excessive leakage flux around coil portion 161.

[0075] Referring to FIG. 18A, copper coil portion 161 is brazed to outer shield 170 to make the shield a heat sink. Coil portion 164 has a substantially triangular lateral cross-section with an elongated side 172 proximal to meniscus location 79. Coil portion 164 shapes the magnetic field near meniscus 75. An electrically insulating, heat-conducting material 177 is placed between magnetic member 167 and coil portion 164 so that coil portion 164 serves as a heat sink for magnetic member 167. Pole portion 173 may be tapered as shown in FIG. 18A in order to define a surface that is substantially parallel to a plane tangential to roll surface 57 at a location 178 on roll surface 57. Location 178 defines that portion of surface 57 nearest pole portion 173.

[0076] Figure 19 shows another embodiment employing a magnetic member 167. A shield 170 is brazed to each coil portion 161 and 164. The shields 170 and the shape of poles 173, 176 of member 167 determine the distribution of the magnetic flux. As seen in FIG. 19, poles 173 and 176 may be tapered to shape the magnetic flux. Also, coil portions 161, 164 may have substantially rectangular lateral cross-sections, as seen in FIG. 19. Alternatively, like the coil portions of FIG. 18A, coil portion 161 in FIG. 19 may have a substantially circular lateral cross-section, and coil portion 164 in FIG. 19 may have a substantially triangular lateral cross-section.

[0077] The volt-amperes required by the embodiments of FIGS. 18 and 19 in order to produce a particular electromagnetic field strength adjacent meniscus location 79 are about the same as the volt-amperes required by the apparatus of FIG. 16A and the embodiment of FIG. 16B in order to produce the same electromagnetic field strength adjacent meniscus location 79.

[0078] In the apparatus of FIG. 20, conductor 82 comprises two narrow loops associated with magnetic members 186.

As described below, a magnetic member 186 may be M-shaped (186A, FIG. 21) or T-shaped (186B, FIG. 22).

[0079] The embodiment shown in FIG. 21 comprises longitudinal first and second coil portions 180, 183. Second coil portion 183 is disposed adjacent meniscus location 79, and first coil portion 180 extends alongside and is spaced from second coil portion 183. Second coil portion 183 may be disposed substantially parallel to first coil portion 180 adjacent meniscus location 79, as shown in FIG. 21. Magnetic member 186A is made from stamped laminations and comprises a yoke 189, an outer first arm 192, an inner second arm 195, and an outer third arm 198. Each arm extends from yoke 189 and terminates at a pole portion 199. Pole portions 199 of arms 192, 198 may be tapered, as shown in FIG. 21. At least a part of second coil portion 183 is received in a channel defined between first arm 192, second arm 195, and yoke 189. At least a part of first coil portion 180 is received in a channel defined between second arm 195, third arm 198, and yoke 189.

[0080] Heat-conducting, electrically insulating material 171 may be placed between coil portions 180, 183 and magnetic member 186A to prevent a short circuit from developing. Material 171 also makes water-cooled conductor 82 a heat sink by transmitting the heat produced by eddy-current losses in magnetic member 186A to coil portions 180, 183.

[0081] Magnetic member 186A includes structure, such as arms 192, 195, and 198, and pole portions 199 for directing the electromagnetic field in a manner which enables the electromagnetic field to perform any of the control functions described above (*i.e.*, dampening molten metal waves 88, controlling the meniscus angle β , or forming a barrier between waves 88 and a roll surface 57 or 60). The magnetic field produced by coil portion 183 shapes meniscus 75. The field produced by coil portion 180 dampens the molten metal waves. Arms 192, 195, and 198 of magnetic member 186A and the shape of coil portions 180, 183 may be changed for directing the magnetic field in a manner which optimizes meniscus control and damping of molten metal waves. The volt-amperes required by the embodiment of FIG. 21 in order to produce a particular electromagnetic field strength adjacent meniscus location 79 are about the same as the volt-amperes required by the apparatus of FIG. 16A and the embodiment of FIG. 16B in order to produce the same electromagnetic field strength adjacent meniscus location 79.

[0082] The embodiment of FIG. 22A employs a T-shaped magnetic member 186B comprising a center arm 201 between diverging arms 203 and 205. Arms 203, 205 may be substantially co-planar. Arm 201 may be substantially perpendicular to arms 203, 205. Arms 201, 203, and 205 each terminate in a pole portion 207. Pole portions 207 of arms 203, 205 may be tapered. At least a part of coil portion 183 is located adjacent arms 201, 203. At least a part of coil portion 180 is located adjacent arms 201, 205. Coil portion 183 and pole portions 207 of arm 203 and arm 201 shape a field for controlling meniscus 75. Coil portion 180 and pole portions 207 of arm 205 and arm 201 shape a field for damping molten metal waves.

[0083] Magnetic member 186B may be made from stamped laminations. In order for the magnetic field to follow the path depicted in FIG. 22A, the laminations should be oriented as shown in the butt-joint depicted in FIG. 22B. In particular, the planes defined by the laminations of arms 203 are substantially parallel to the planes defined by the laminations of arms 205. The planes defined by the laminations of arm 201 are perpendicular to the planes defined by the laminations of arms 203, 205. Alternatively, arms 201, 203, and 205 may be cut out from tape-wound cores and then assembled.

[0084] Coil portion 183 may be substantially triangular in lateral cross-section. Heat-conducting, electrically insulating material 171 may be placed between coil portions 180, 183 and magnetic member 186B to prevent a short circuit from developing. Material 171 also makes water-cooled conductor 82 a heat sink by transmitting the heat produced by eddy-current losses in magnetic member 186B to the water-cooled conductor 82. It is important to place an electrically insulating, heat-conducting material 210 between center arm 201 and each of arms 203, 205.

[0085] Magnetic member 186B includes structure, such as arms 201, 203, 205, and pole portions 207 for directing the electromagnetic field in a manner which enables the electromagnetic field to perform any of the control functions described above (*i.e.*, dampening molten metal waves 88, controlling the meniscus angle β , or forming a barrier between waves 88 and a roll surface 57 or 60). The magnetic field produced by coil portion 183 shapes meniscus 75. The field produced by coil portion 180 dampens molten metal waves. Arms 201, 203, 205, and pole portions 207 of magnetic member 186B and the shape of coil portions 180, 183 may be changed for directing the magnetic field in a manner which optimizes control and damping of molten metal waves. The volt-amperes required by the embodiment of FIGS. 22A-B in order to produce a particular electromagnetic field strength adjacent meniscus location 79 are about the same as the volt-amperes required by the apparatus of FIG. 16A and the embodiment of FIG. 16B in order to produce the same electromagnetic field strength adjacent meniscus location 79.

[0086] An apparatus having longitudinal first and second coil portions 221, 224 is shown in FIG. 23, and an embodiment thereof is shown in FIG. 24. This embodiment has a first magnetic member 227 associated with first coil portion 221, and a second magnetic member 230 associated with second coil portion 224. Referring to FIG. 24, first magnetic member 227 has a yoke 233, and arms 236, 239 extending therefrom. Arms 236, 239 terminate in pole portions 250, 252, respectively. At least a part of first coil portion 221 is received in a channel defined by yoke 233 and arms 236, 239. Second magnetic member 230 has a yoke 242, and arms 245, 248 extending therefrom. Arms 245, 248 terminate in pole portions 254, 256, respectively. Pole portions 250, 256 may be tapered, as shown in FIG. 24. At least a part of sec-

ond coil portion 224 is received in a channel defined by yoke 242 and arms 245, 248. Arm 239 of first magnetic member 227 is disposed adjacent arm 245 of second magnetic member 230.

[0087] Second magnetic member 230 comprises structure, such as pole portions 254, 256, cooperating with first magnetic member 227 for directing the electromagnetic field in a manner which enables the electromagnetic field to perform one or more of the functions described above (*i.e.*, dampening molten metal waves 88, controlling the meniscus angle β , or forming a barrier between waves 88 and a roll surface 57 or 60).

[0088] The positions of magnetic members 227 and 230 are independently adjustable and permit shaping of the field near meniscus 75 by member 230 and shaping of the field for damping the molten metal pool waves by member 227. Magnetic members 227, 230 may be made from tape-wound laminations of ferromagnetic steel or from stamped laminations. Heat-conducting, electrical insulation 171 is placed between coil portions 221, 224 and respective magnetic members 227, 230. Heat-conducting, electrical insulation 171 makes coil portions 221, 224 act as heat sinks by transmitting the heat produced by eddy-current losses in magnetic members 227, 230 to respective coil portions 221, 224.

[0089] The embodiment of FIG. 25 has first and second L-shaped magnetic members 290A, 293. Member 290A has arms 296, 299 connected at a junction 302 and terminating at pole portions 305, 308, respectively. Arms 296 and 299 diverge from one another and may be perpendicular to one another. Pole portions 305, 308 may be tapered as shown. Coil portion 221 is received between arms 296, 299 of magnetic member 290A and may be shaped so that a side 310 distal from meniscus 75 is rounded. Pole portions 305, 308 and coil portion 221 produce a field for damping the waves on surface 73 of pool 65.

[0090] Second magnetic member 293 has arms 311, 315 connected at a junction 318 and terminating at pole portions 321, 324, respectively. Arms 311 and 315 diverge from one another and may be perpendicular to one another. Arm 311 is oriented generally perpendicular to a plane that is tangential to an adjacent roll surface (surface 57 in FIG. 25) at a location 327 constituting the portion of roll surface 57 closest to pole portion 321. Arm 315 is oriented generally parallel to a plane tangential to that part of the adjacent roll surface (surface 57 in FIG. 25) that contains location 327. Pole portion 321 defines a surface generally parallel to the tangential plane that contains location 327. Pole portions 321 and 324 and coil portion 224 produce a field that controls meniscus 75.

[0091] FIG. 26 depicts a variation of the embodiment of FIG. 25 comprising a magnetic member 290B similar to magnetic member 290A but having an untapered pole portion 308A. A coil portion 221A having a substantially circular lateral cross-section is disposed between arms 296, 299 of magnetic member 290B. Coil portion 224 may have a substantially rectangular lateral cross-section and, as seen in FIGS. 25 and 26, a long dimension of the rectangle may face an adjacent roll surface (roll surface 57 in FIGS. 25 and 26). Pole portions 305, 308A and coil portion 221A produce a field for damping the waves on surface 73 of pool 65.

[0092] As seen in FIGS. 23-26, second coil portion 224 may be disposed substantially parallel to first coil portion 221 adjacent meniscus location 79.

[0093] The volt-amperes required by the apparatus of FIG. 23 and corresponding embodiments FIGS. 24-26, in order to produce a particular electromagnetic field strength adjacent meniscus location 79, are about the same as the volt-amperes required by the apparatus of FIG. 16A and the embodiment of FIG. 16B in order to produce the same electromagnetic field strength adjacent meniscus location 79.

[0094] An apparatus having longitudinal first and second coil portions 331 and 334 is shown in FIG. 27. This apparatus has only a single magnetic member 337 adjacent both coil portions. FIGS. 28-30 illustrate different embodiments of the apparatus of FIG. 27.

[0095] Referring to FIG. 28, a magnetic member 337A comprises a yoke 340, and a pair of arms 343, 346 each terminating in a pole portion 350. Arm 346 is disposed proximal to an adjacent roll surface (surface 57 in FIG. 28) and is oriented generally perpendicular to a plane that is tangential to the roll surface and that contains a location 353. Location 353 is the portion of roll surface 57 closest to arm 346. Pole portion 350 of arm 346 defines a surface 356 that is substantially parallel to the plane that is tangential to surface 57 and contains location 353. Yoke 340 and arms 343, 346 define a channel that receives at least a part of each coil portion 331, 334. Coil portion 334 and pole portion 350 of arm 346 produce a magnetic field that controls the shape of meniscus 75. Coil portion 331 and pole portion 350 of arm 343 produce a magnetic field that dampens molten metal waves. As seen in FIG. 28, coil portions 331, 334 may have a substantially circular lateral cross-section.

[0096] Referring to FIG. 29, a magnetic member 337B comprises a yoke 370 terminating in a first pole portion 373 proximal to roll surface 57 and a second pole portion 376 distal from roll surface 57. Pole portion 373 may be tapered as shown in FIG. 29 so that pole portion 373 defines a surface 377. Surface 377 is substantially parallel to a plane that is tangential to roll surface 57 and that contains a location 380 on roll surface 57. Location 380 is the portion of roll surface 57 closest to pole portion 373. Pole portion 376 may also be tapered, as shown in FIG. 29. Coil portion 334 and pole portion 373 produce a magnetic field that controls the shape of meniscus 75. Coil portion 331 and pole portion 376 produce a magnetic field that dampens molten metal waves. Coil portions 331, 334 may have a substantially triangular lateral cross-section, as shown in FIG. 29.

[0097] Referring to FIG. 30, a magnetic member 337C comprises a yoke 390 joining a first arm 403 and a second

arm 406. First arm 403 is disposed distal from an adjacent roll surface (surface 57 in FIG. 30) and terminates in a pole portion 408. Second arm 406 is disposed proximal to an adjacent roll surface (surface 57 in FIG. 30) and terminates in a pole portion 409. Pole portion 409 may be tapered, as shown, so that pole portion 409 defines a surface 412. Surface 412 is substantially parallel to a plane that is tangential to the adjacent roll surface and that contains an area 415 of the adjacent roll surface. Area 415 is the area of the adjacent roll surface that is nearest pole portion 409. Pole portion 408 may also be tapered. Coil portions 331 and 334 are received between arms 403, 406 and may be rectangular in cross-section. Coil portion 334 and pole portion 409 produce a magnetic field that controls the shape of meniscus 75. Coil portion 331 and pole portion 408 produce a magnetic field that dampens molten metal waves.

[0098] Magnetic members 337A-337C confine the flux path and reduce the current requirements. There is no leakage flux in these embodiments, in contrast to the embodiments of FIGS. 11A-B and 12 having leakage flux 98.

[0099] Magnetic members 130 (FIG. 15), 135 (FIG. 16), 155 (FIG. 17), 167 (FIGS. 18 and 19), 186 (FIGS. 20-22B), 227 and 230 (FIGS. 23 and 24), 290A, 290B, and 293 (FIGS. 25 and 26), and 337 (FIGS. 27-30) may be formed from stamped laminations of ferromagnetic steel conventionally used in magnetic members operating at audio-frequencies. Alternatively, magnetic members 130, 135, 155, 186B, 227, 230, 290A, 290B, and 293 may be formed from tape-wound laminations of ferromagnetic steel. More generally, magnetic members may be composed of any suitable ferromagnetic material having a relatively high magnetic permeability, such as ferrite.

[0100] The space between coil 82 and any of these magnetic members may be filled with heat-conducting, electrically insulating material to prevent the occurrence of a short circuit between the coil and a magnetic member during operation. Such a material not only provides electrical insulation for coil 82, but also it makes water-cooled coil 82 a heat sink by transmitting the heat produced by eddy-current losses in the adjacent magnetic member to the water-cooled coil 82. Alternatively, an air space may be provided between coil 82 and the adjacent magnetic member to prevent a short circuit from developing between the magnetic member and coil 82. Suitable structure (not shown) may be employed to maintain a space between coil 82 and the adjacent magnetic member to provide such a layer of air. This alternative would not act as a heat sink.

[0101] A refractory splash guard (not shown), similar to splashguard 100 shown in FIG. 3A, may enclose any of the magnetic members and coil 82. Such splash guards perform a function similar to that performed by splash guard 100 discussed above in connection with the apparatus of FIG. 3. The splash guards may follow the contours of the respective magnetic members and coil portions.

[0102] In embodiments having first and second coil portions and first and second magnetic members, such as the embodiments of FIGS. 24-26, a first splash guard (not shown) may be provided to enclose both the first coil portion and the first magnetic member, and a second splash guard (not shown) may be provided to enclose both the second coil portion and the second magnetic member. Alternatively, for those embodiments having first and second coil portions and first and second magnetic members, a single splash guard may enclose all of the coil portions and their respective magnetic members.

[0103] Although coil 82 is shown as being hollow in the embodiments previously discussed, the conductor of apparatus 40 need not be hollow in order to be water cooled. For example, as shown in FIG. 31, apparatus 40 may comprise a wide-loop coil formed from a solid, conductive, narrow plate 450 having a curved lateral cross-section with the convex side facing pool top surface 73. Conductive tubes 453 are attached to a side 456 of conductive plate 450 remote from an adjacent roll surface (roll surface 57 in FIG. 31). In this embodiment, cooling water is circulated through tubes 453 to extract heat from plate 450. Plate 450, rather than tubes 453, is connected to a power supply (not shown). Operation of the embodiment of FIG. 31 produces a magnetic field designated at 460.

[0104] The foregoing detailed description has been given for clearness of understanding only, and no unnecessary limitations should be understood therefrom, as modifications will be obvious to those skilled in the art.

Claims

1. In a continuous strip caster comprising a pair of counter-rotating rolls having respective mutually facing surfaces defining a space for containing a pool of molten metal having a pool top surface, wherein a meniscus is formed at each location where said pool top surface contacts one of said mutually facing roll surfaces, an apparatus for magnetically controlling each of said menisci, said apparatus comprising:

control means, positioned adjacent each such location, on the outside of the roll at that location;
said control means comprising means for generating an electromagnetic field which acts on said pool top surface adjacent that location to control said meniscus there.

2. In a continuous strip caster as recited in claim 1 wherein said continuous strip caster comprises a nozzle for feeding molten metal into said pool, and said pool top surface comprises waves formed in response to molten metal exiting said nozzle, said waves normally moving in a direction having a component extending toward each of said loca-

tions, and wherein said control means comprises:

means for generating an electromagnetic field which reduces the amplitude of said waves adjacent said meniscus.

3. In a continuous strip caster as recited in claim 1 wherein said pool top surface, at said location, and said roll surface there, define an angle of said meniscus, and said control means comprises:

means for generating an electromagnetic field which controls said angle of said meniscus.

4. In a continuous strip caster as recited in claim 1 wherein said continuous strip caster comprises a nozzle for feeding molten metal into said pool, and said pool top surface comprises waves formed in response to molten metal exiting said nozzle, said waves normally moving in a direction having a component extending toward each of said locations, and wherein said control means comprises:

means for generating an electromagnetic field for forming a barrier between said waves and said roll surface adjacent said location.

5. In a continuous strip caster as recited in each of claims 1 through 4 wherein:

said control means comprises an electrically conductive coil; and
said apparatus comprises means for flowing a time-varying current through said coil to generate said electromagnetic field.

6. In a continuous strip caster as recited in claim 5 wherein said coil comprises a wide-loop coil.

7. In a continuous strip caster as recited in claim 6 wherein:

said control means comprises a magnetic member associated with said wide-loop coil; and
said magnetic member comprises means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic field to perform the function thereof recited in any of claims 1 to 4 with less current than without said magnetic member.

8. In a continuous strip caster as recited in claim 7 wherein:

said wide-loop coil has a coil portion positioned adjacent said meniscus location; and
said coil portion has a lateral cross-sectional configuration comprising means cooperating with said magnetic member for shaping said electromagnetic field.

9. In a continuous strip caster as recited in claim 7 wherein:

said magnetic member is composed of stamped laminations of ferromagnetic steel or tape-wound laminations of ferromagnetic steel or ferrite.

10. In a continuous strip caster as recited in claim 5 wherein said coil comprises:

means, including a coil portion positioned adjacent said location, for directly generating said electromagnetic field sufficiently close to said location to enable said electromagnetic field to perform the function thereof recited in any one or more of claims 1 to 4, without the interposition of a magnetic member for influencing said field.

11. In a continuous strip caster as recited in claim 10 wherein:

said coil is a wide-loop coil; and
said coil portion has a lateral cross-sectional configuration comprising means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic field to perform said function thereof.

12. In a continuous strip caster as recited in claim 10 wherein said coil comprises:

means for enabling said electromagnetic field to perform at least any two of said functions.

13. In a continuous strip caster as recited in claim 5 wherein said coil comprises a narrow-loop coil.

5 14. In a continuous strip caster as recited in claim 13 wherein:

said control means comprises a magnetic member associated with said narrow-loop coil; and
said magnetic member comprises means for shaping said electromagnetic field in a manner which enhances
the ability of said electromagnetic field to perform the function thereof recited in any of claims 1 to 4 with less
10 current than without said magnetic member.

15. In a continuous strip caster as recited in claim 14 wherein said magnetic member comprises:

means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic
15 field to perform at least any two of said functions with less current than without said magnetic member.

16. In a continuous strip caster as recited in claim 14 wherein:

said narrow-loop coil comprises a first coil portion extending alongside said meniscus location and a second
20 coil portion electrically connected to said first coil portion and extending alongside and spaced from said first
coil portion;

said first coil portion has a lateral cross-sectional configuration comprising means cooperating with said mag-
netic member for shaping said electromagnetic field (a) to control said meniscus or (b) to control said angle of
said meniscus or to do both (a) and (b).
25

17. In a continuous strip caster as recited in claim 16 wherein:

said second coil portion has a cross-sectional configuration comprising means cooperating with said magnetic
member for shaping said magnetic field (c) to reduce the amplitude of said waves adjacent said meniscus or
30 (d) to form a barrier between said waves and said roll surface adjacent said meniscus location or to do both (c)
and (d).

18. In a continuous strip caster as recited in claim 14 wherein:

said magnetic member is composed of stamped laminations of ferromagnetic steel or tape-wound laminations
35 of ferromagnetic steel or ferrite.

19. In a continuous strip caster as recited in claim 13 wherein said narrow-loop coil comprises:

40 a first coil portion extending alongside said meniscus;
a second coil portion extending alongside and spaced from said first coil portion; and
means for electrically connecting said first coil portion to said second coil portion.

20. In a continuous strip caster as recited in claim 19 wherein:

45 said first and second coil portions are disposed a substantially equal distance above said pool top surface.

21. In a continuous strip caster as recited in claim 19 wherein:

50 said first coil portion comprises means for generating an electromagnetic field which acts on said pool top sur-
face adjacent said location (a) to control said meniscus there or (b) to control said angle of said meniscus or
both (a) and (b); and
said second coil portion comprises means for generating an electromagnetic field which (c) reduces the ampli-
tude of said waves adjacent said meniscus or (d) forms a barrier between said waves and said roll surface
55 adjacent said meniscus location or does both (c) and (d).

22. In a continuous strip caster as recited in claim 21 wherein:

said first coil portion has a lateral cross-sectional configuration comprising means for shaping said electromagnetic field to enhance the ability of said electromagnetic field (a) to control said meniscus or (b) to control said angle of said meniscus or to do both (a) and (b).

5 **23.** In a continuous strip caster as recited in claim 22 wherein:

said second coil portion has a lateral cross-sectional configuration comprising means for shaping said electromagnetic field to enhance the ability of said electromagnetic field (c) to reduce the amplitude of said waves or (d) to form a barrier between said waves and said roll surface adjacent said location or to do both (c) and (d).

10

24. In a continuous strip caster as recited in claim 14 wherein said narrow-loop coil comprises:

a longitudinal first coil portion adjacent said location; and
a longitudinal second coil portion electrically connected to said first coil portion;
15 each of said first and second coil portions having a substantially triangular lateral cross-section.

25. In a continuous strip caster as recited in claim 5 wherein said control means comprises:

20

a first magnetic member positioned adjacent said location and comprising a pair of arms, each of said arms terminating at a pole portion;
said coil having a part which is received between said pair of arms;
said first magnetic member comprising means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic field to perform the function thereof recited in any of claims 1 to 4 with less current than without said first magnetic member.

25

26. In a continuous strip caster as recited in claim 25 wherein:

30

said coil comprises a narrow-loop coil including a first coil portion adjacent said location and a second coil portion electrically connected to said first coil portion;
said first magnetic member comprises a yoke; and
said yoke and said pair of arms define a channel that receives at least a part of each of said first and second coil portions.

27. In a continuous strip caster as recited in claim 25 wherein said first magnetic member comprises:

35

means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic field to perform at least any two of said functions with less current than without said first magnetic member.

28. In a continuous strip caster as recited in claim 25 wherein:

40

said first magnetic member comprises a longitudinal portion;
said longitudinal portion of said first magnetic member has a semi-circular lateral cross-section;
said coil part received between said pair of arms has a longitudinal portion; and
said longitudinal portion of said coil part has a circular lateral cross-section.

45

29. In a continuous strip caster as recited in claim 25 wherein:

50

said first magnetic member comprises a yoke connecting said pair of arms;
each of said arms is substantially perpendicular to said yoke;
said coil part received between said pair of arms has a longitudinal portion; and
said longitudinal portion of said coil part has a rectangular lateral cross-section.

30. In a continuous strip caster as recited in claim 25 wherein:

55

said arms of said first magnetic member diverge from a mutual junction;
said coil part received between said pair of arms has a longitudinal portion;
and said longitudinal portion has a lateral cross-section which is either rectangular or triangular.

31. In a continuous strip caster as recited in claim 25 wherein:

said coil comprises a narrow-loop coil including a longitudinal first coil portion adjacent said location and a longitudinal second coil portion electrically connected to said first coil portion;
 said first coil portion is the coil part which is received between said pair of arms on said first magnetic member;
 said first magnetic member comprises a yoke having first and second opposing sides;
 said first side of said yoke and said pair of arms define a channel that receives said first coil portion; and
 said second coil portion is disposed adjacent to said second side of said yoke outside said channel.

32. In a continuous strip caster as recited in claim 25 wherein:

said coil comprises a narrow-loop coil including a longitudinal first coil portion adjacent said location and a longitudinal second coil portion electrically connected to said first coil portion;
 said arms of said first magnetic member diverge substantially from a mutual junction; and
 said first coil portion is the coil part which is received between said pair of arms on said first magnetic member.

33. In a continuous strip caster as recited in claim 32 wherein:

said first coil portion has a lateral cross-section which is either substantially triangular or rectangular; and
 said second coil portion has a lateral cross-section which is either substantially circular or rectangular.

34. In a continuous strip caster as recited in claim 33 wherein:

one of said pair of arms is proximal to an adjacent mutually facing roll surface;
 the other of said pair of arms is distal from said adjacent mutually facing roll surface; and
 said pole portion of said arm proximal to said adjacent mutually facing roll surface is tapered when said first coil portion has a substantially triangular lateral cross-section.

35. In a continuous strip caster as recited in claim 5 wherein:

said coil comprises a narrow-loop coil;
 said control means further comprises first and second magnetic members associated with said narrow-loop coil; and
 said magnetic members comprise means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic field to perform the function thereof recited in any of claims 1 to 4 with less current than without said magnetic members.

36. In a continuous strip caster as recited in claim 35 wherein said magnetic members comprise:

means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic field to perform at least any two of said functions with less current than without said magnetic members.

37. In a continuous strip caster as recited in claim 35 wherein:

said narrow-loop coil comprises a longitudinal first coil portion adjacent said location and extending alongside said meniscus, and a longitudinal second coil portion extending alongside and spaced from said first coil portion;
 said coil includes means for electrically connecting said first coil portion to said second coil portion;
 said first magnetic member is positioned adjacent said meniscus location and said second magnetic member is spaced from and adjacent said first magnetic member;
 said first magnetic member comprises means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic field to act on said pool top surface adjacent said location (a) to control said meniscus there or (b) to control said angle of said meniscus or to do both (a) and (b), with less current than without said first magnetic member; and
 said first coil portion has a lateral cross-sectional configuration comprising means cooperating with said first magnetic member for shaping said electromagnetic field.

38. In a continuous strip caster as recited in claim 37 wherein:

said second magnetic member comprises means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic field (c) to reduce the amplitude of said waves adjacent said meniscus or (d) to form a barrier between said waves and said roll surface adjacent said meniscus location or to do both (c) and (d), with less current than without said second magnetic member;

and said second coil portion has a lateral cross-sectional configuration comprising means cooperating with said second magnetic member for shaping said electromagnetic field.

39. In a continuous strip caster as recited in claim 35 wherein:

said narrow-loop coil comprises a longitudinal first coil portion adjacent said location and extending alongside said meniscus, and a longitudinal second coil portion extending alongside and spaced from said first coil portion;

said coil includes means for electrically connecting said first coil portion to said second coil portion;

said first magnetic member is positioned adjacent said location and comprises a pair of arms, each of said arms terminating at a pole portion;

at least a part of said first coil portion is received between said pair of arms on said first magnetic member;

said second magnetic member is disposed adjacent said first magnetic member;

said second magnetic member comprises a pair of arms, each of said arms terminating at a pole portion; and

at least a part of said second coil portion is received between said pair of arms of said second magnetic member.

40. In a continuous strip caster as recited in claim 39 wherein:

said arms of each of said magnetic members diverge from a mutual junction;

said first coil portion has a rectangular lateral cross-section in which the long dimension of the rectangle faces an adjacent roll surface; and

said second coil portion has a lateral cross-section which is either circular or rounded.

41. In a continuous strip caster as recited in claim 39 wherein:

said first magnetic member comprises means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic field to act on said pool top surface adjacent said location (a) to control said meniscus there or (b) to control said angle of said meniscus or to do both (a) and (b), with less current than without said first magnetic member; and

said second magnetic member comprises means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic field (c) to reduce the amplitude of said waves adjacent said meniscus or (d) to form a barrier between said waves and said roll surface adjacent said meniscus location or to do both (c) and (d), with less current than without said second magnetic member.

42. In a continuous strip caster as recited in claim 5 wherein said control means comprises:

a magnetic member positioned adjacent said location and comprising a pair of arms, each of said arms terminating at a pole portion;

said coil comprising a narrow-loop coil having first and second coil portions electrically connected to one another and spaced from one another;

one of said arms of said magnetic member being received between said first and second coil portions;

said magnetic member comprising means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic field to perform the function thereof recited in any of claims 1 to 4 with less current than without said magnetic member.

43. In a continuous strip caster as recited in claim 5 wherein said control means comprises:

a magnetic member positioned adjacent said location and comprising a yoke, a first arm, a second arm, and a third arm, each of said arms extending from said yoke and each of said arms terminating at a pole portion;

said second arm being disposed between said first arm and said third arm;

said coil comprising a narrow-loop coil having first and second coil portions electrically connected to one another and spaced from one another;

at least a part of said first coil portion being located between said first arm and said second arm;

at least a part of said second coil portion being located between said second arm and said third arm;
said magnetic member comprising means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic field to perform the function thereof recited in any of claims 1 to 4 with less current than without said magnetic member.

5 44. In a continuous strip caster as recited in claim 5 wherein said control means comprises:

a magnetic member positioned adjacent said location and comprising a first arm, a second arm, and a third arm, each of said arms terminating at a pole portion;
10 said first arm being substantially co-planar with said third arm;
said second arm being substantially perpendicular to each of said first and third arms;
said coil comprising a narrow-loop coil having longitudinal first and second coil portions electrically connected to one another and spaced from one another;
at least a part of said first coil portion being located adjacent said first arm and said second arm;
15 at least a part of said second coil portion being located adjacent said second arm and said third arm; and
said magnetic member comprises means for shaping said electromagnetic field in a manner which enhances the ability of said electromagnetic field to perform the function thereof recited in any of claims 1 to 4 with less current than without said magnetic member.

20 45. In a continuous strip caster as recited in claim 44 wherein:

said first coil portion has a triangular lateral cross-section;
and said second coil portion has a rectangular lateral cross-section.

25 46. In a continuous strip caster as recited in each of claims 1 through 4 wherein:

said control means comprises a wide-loop coil formed from an electrically conductive plate having a curved lateral cross-section with the convex side facing said pool top surface; and
said apparatus comprises means for flowing a time-varying current through said plate to generate said electromagnetic field.
30

35 47. A method for magnetically controlling a meniscus formed in a continuous strip caster comprising a pair of counter-rotating rolls having respective mutually facing surfaces defining a space for containing a pool of molten metal having a pool top surface, said meniscus being formed at each location where said pool top surface contacts one of said mutually facing roll surfaces, said method comprising the steps of:

positioning adjacent each such location, on the outside of the roll at that location, means for generating an electromagnetic field; and
employing said generating means to generate an electromagnetic field which acts on said pool top surface adjacent that location to control said meniscus.
40

48. A method as recited in claim 47 and comprising:

providing a nozzle for feeding molten metal into said pool;
45 forming waves on said pool top surface in response to molten metal exiting said nozzle, said waves normally moving in a direction having a component extending toward said location; and
employing said electromagnetic field to reduce the amplitude of said waves adjacent said meniscus.

50 49. A method as recited in claim 47 wherein said pool top surface, at said location, and said roll surface there, define an angle of said meniscus, and wherein said method comprises:

employing said electromagnetic field to control said angle of said meniscus.

55 50. A method as recited in claim 47 and comprising:

providing a nozzle for feeding molten metal into said pool;
forming waves on said pool top surface in response to molten metal exiting said nozzle, said waves normally moving in a direction having a component extending toward said location; and

employing said electromagnetic field to form a barrier between said waves and said roll surface.

51. A method as recited in each of claims 47 through 50 and comprising:

5 employing an electrically conductive coil to generate an electromagnetic field; and
flowing a time-varying current through said coil to generate said electromagnetic field.

52. A method as recited in claim 51 and comprising:

10 providing said coil as a wide-loop coil.

53. A method as recited in claim 52 and comprising:

15 associating a magnetic member with said wide-loop coil; and
employing said magnetic member to shape said electromagnetic field in a manner which enhances the ability
of said electromagnetic field to perform the function thereof recited in any of claims 47 to 50 with less current
than without said magnetic member.

54. A method as recited in claim 53 and comprising:

20 employing said magnetic member to shape said electromagnetic field in a manner which enhances the ability
of said electromagnetic field to perform at least any two of said functions with less current than without said
magnetic member.

55. A method as recited in claim 51 and comprising:

25 positioning a portion of said coil adjacent said location; and
directly generating said electromagnetic field sufficiently close to said location to enable said electromagnetic
field to perform the function thereof recited in any one or more of claims 47 to 50, without the interposition of a
30 magnetic member for influencing said field.

56. A method as recited in claim 55 wherein said step of directly generating said electromagnetic field comprises:

35 directly generating said electromagnetic field sufficiently close to said location to enable said electromagnetic
field to perform at least any two of said functions.

57. A method as recited in claim 51 and comprising:

40 providing said coil as a narrow-loop coil.

58. A method as recited in claim 57 and comprising:

45 associating a magnetic member with said narrow-loop coil; and
employing said magnetic member to shape said electromagnetic field in a manner which enhances the ability
of said electromagnetic field to perform the function thereof recited in any of claims 47 to 50 with less current
than without said magnetic member.

59. A method as recited in claim 58 and comprising:

50 employing said magnetic member to shape said electromagnetic field in a manner which enhances the ability
of said electromagnetic field to perform at least any two of said functions with less current than without said
magnetic member.

60. A method as recited in claim 57 and comprising:

55 providing said narrow-loop coil with a first coil portion extending alongside said meniscus and a second coil
portion extending alongside and spaced from said first coil portion.

61. A method as recited in claim 60 and comprising:

employing said first coil portion to generate an electromagnetic field which acts on said pool top surface adjacent said location (a) to control said meniscus there or (b) to control said angle of said meniscus or to do both (a) and (b); and
employing said second coil portion to generate an electromagnetic field (c) to reduce the amplitude of said waves adjacent said meniscus or (d) to form a barrier between said waves and said roll surface or to do both (c) and (d).

62. A method as recited in claim 61 and comprising:

providing said first coil portion with a lateral cross-sectional configuration which enhances the ability of said electromagnetic field (a) to control said meniscus or (b) to control said angle of said meniscus or to do both (a) and (b).

63. A method as recited in claim 62 and comprising:

providing said second coil portion with a lateral cross-sectional configuration which enhances the ability of said electromagnetic field (c) to reduce the amplitude of said waves adjacent said meniscus or (d) to form a barrier between said waves and said roll surface or to do both (c) and (d).

64. A method as recited in claim 51 and comprising:

providing said coil as a narrow-loop coil;
associating first and second magnetic members with said narrow-loop coil; and
employing said magnetic members to shape said electromagnetic field in a manner which enhances the ability of said electromagnetic field to perform the function thereof recited in any of claims 47 to 50 with less current than without said magnetic members.

65. A method as recited in claim 64 and comprising:

employing said first and second magnetic members cooperatively to shape said electromagnetic field in a manner which enhances the ability of said electromagnetic field to perform at least any two of said functions with less current than without said magnetic members.

66. A method as recited in claim 64 and comprising:

providing said narrow-loop coil with a first coil portion extending alongside said meniscus and a second coil portion extending alongside and spaced from said first coil portion;
employing said first coil portion to generate an electromagnetic field which acts on said pool top surface adjacent said location (a) to control said meniscus there or (b) to control said angle of said meniscus or to do both (a) and (b);
employing said first magnetic member to shape said electromagnetic field in a manner which enhances the ability of said electromagnetic field to act on said pool top surface adjacent said location (a) to control said meniscus there or (b) to control said angle of said meniscus or to do both (a) and (b) with less current than without said first magnetic member;
employing said second coil portion to generate an electromagnetic field (c) to reduce the amplitude of said waves adjacent said meniscus or (d) to form a barrier between said waves and said roll surface or to do both (c) and (d); and
employing said second magnetic member to shape said electromagnetic field in a manner which enhances the ability of said electromagnetic field (c) to reduce the amplitude of said waves adjacent said meniscus or (d) to form a barrier between said waves and said roll surface or to do both (c) and (d) with less current than without said second electromagnetic member.

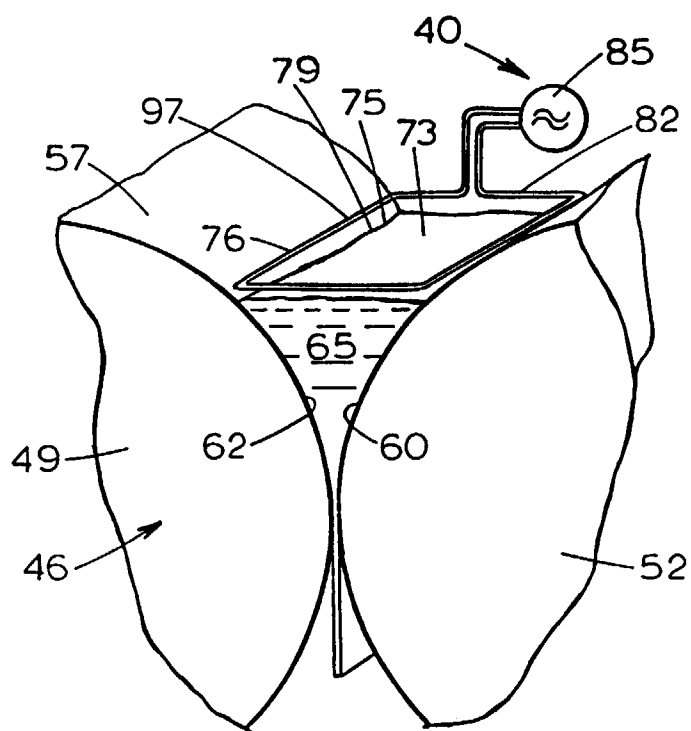


FIG. 1

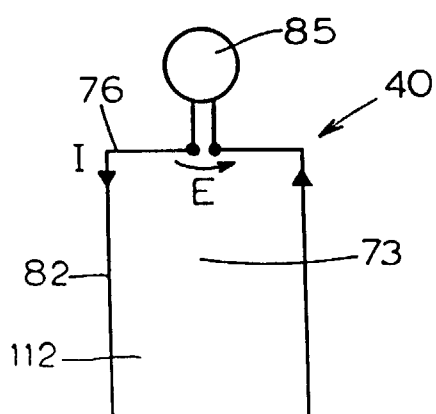


FIG. 2

FIG. 3

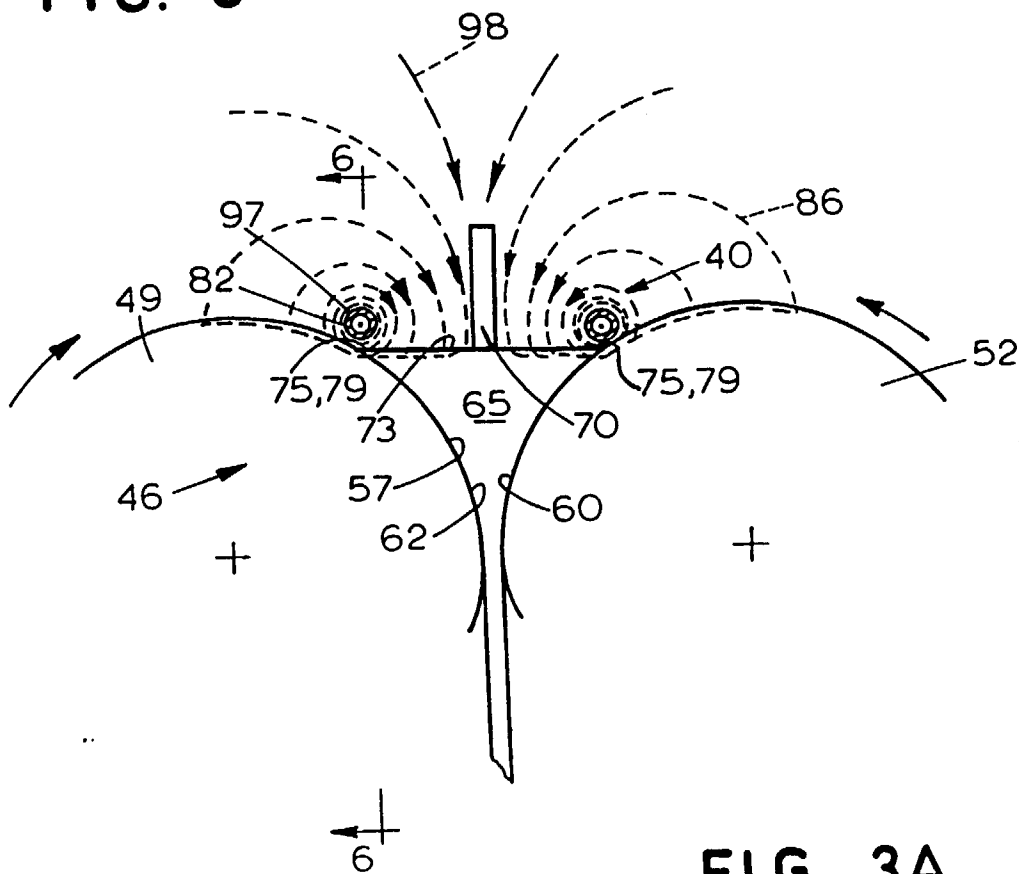


FIG. 3A

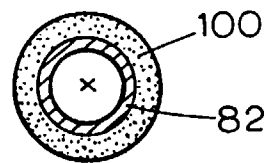


FIG. 4A

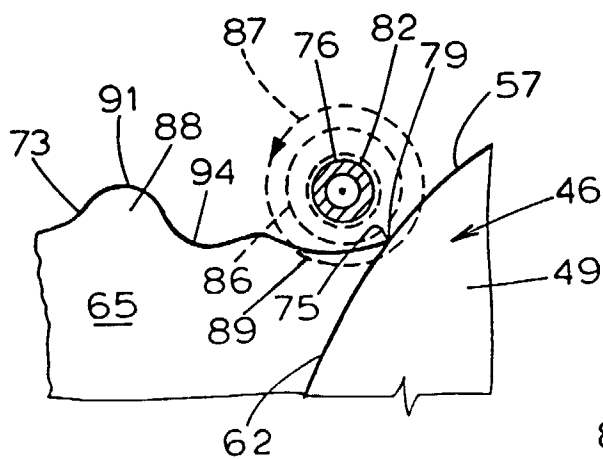


FIG. 4B

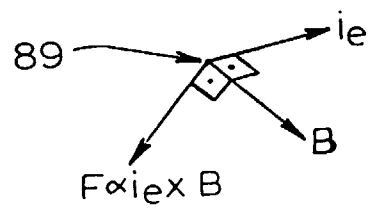


FIG. 5

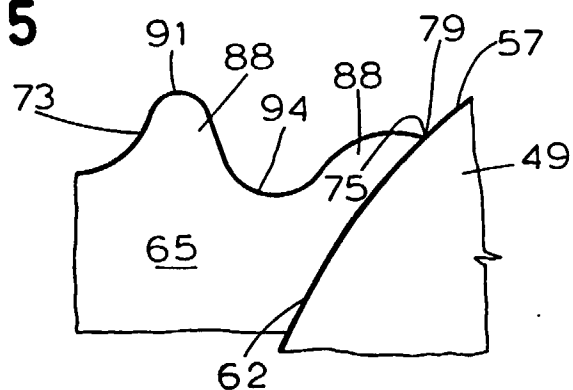


FIG. 8

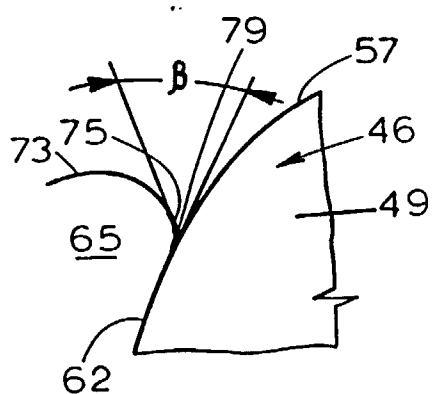


FIG. 7

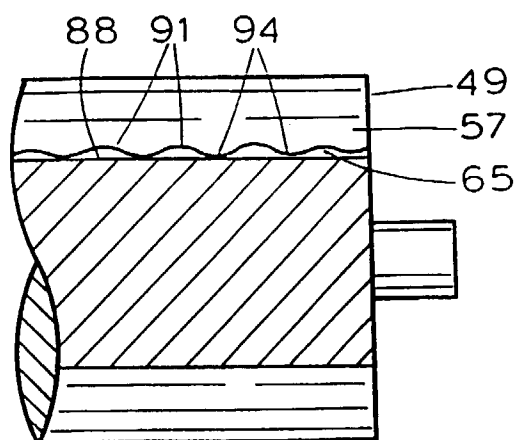
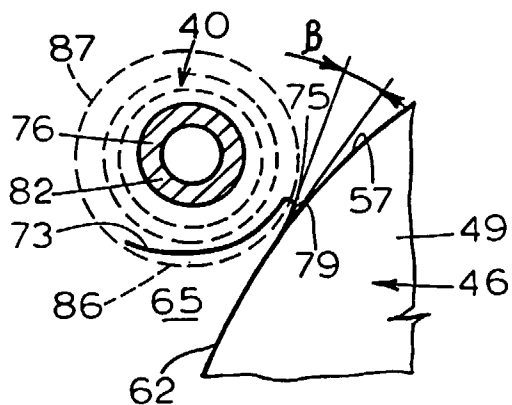
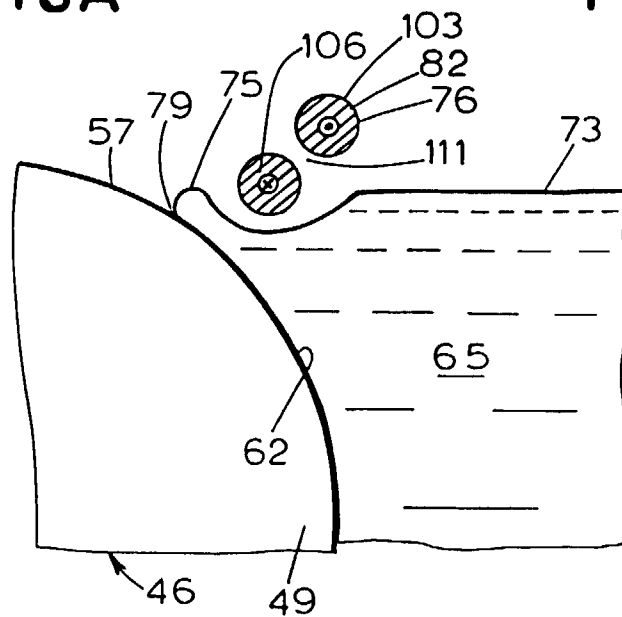
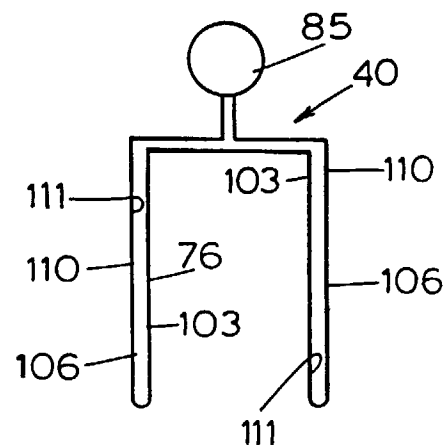
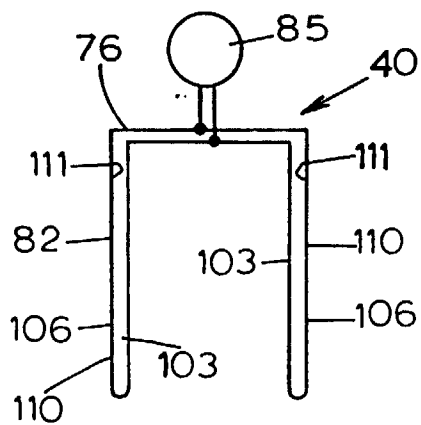
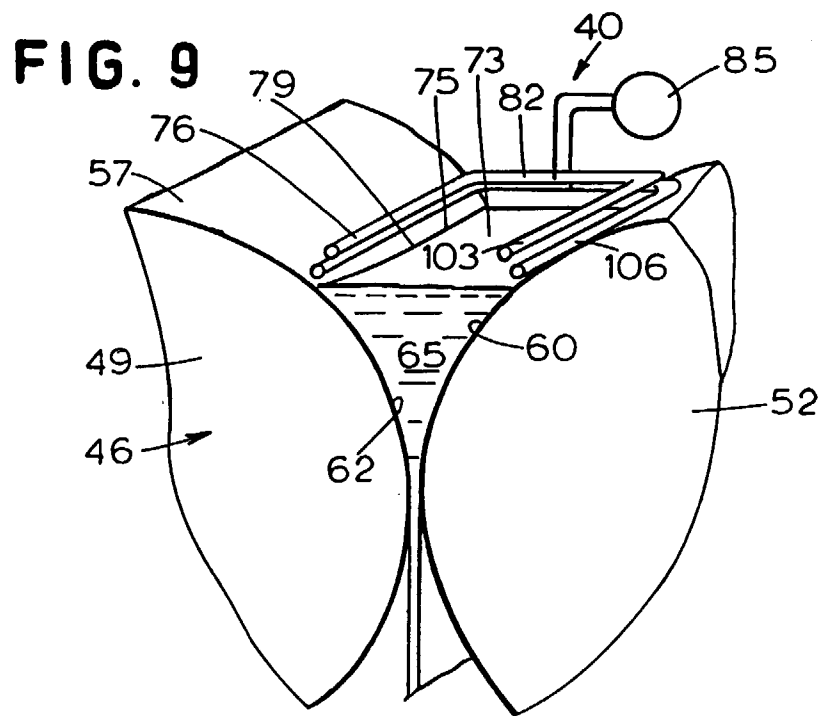


FIG. 6



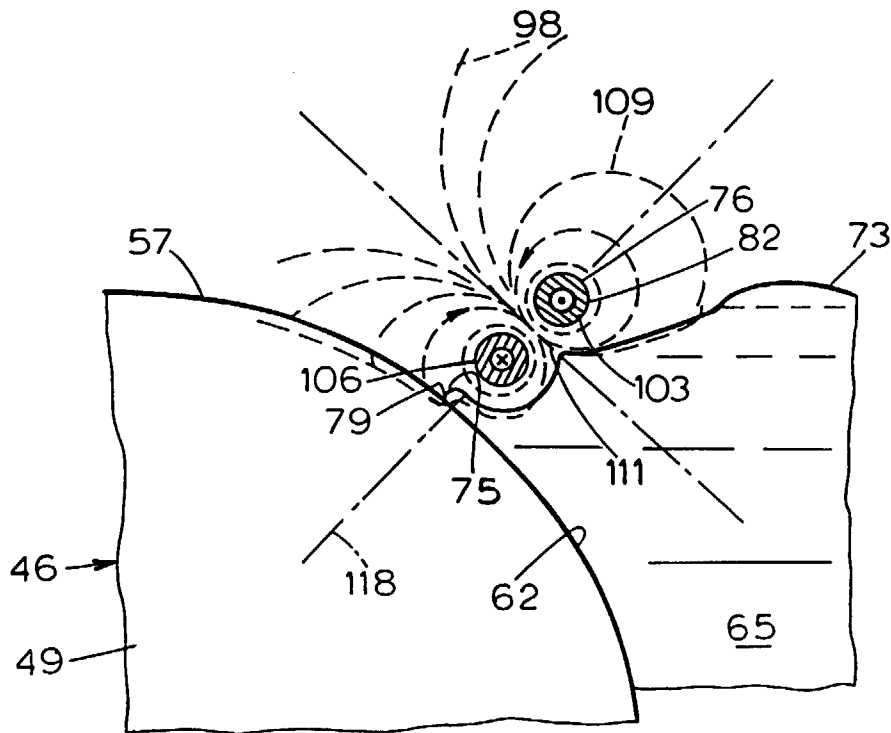


FIG. 11B

FIG. 12

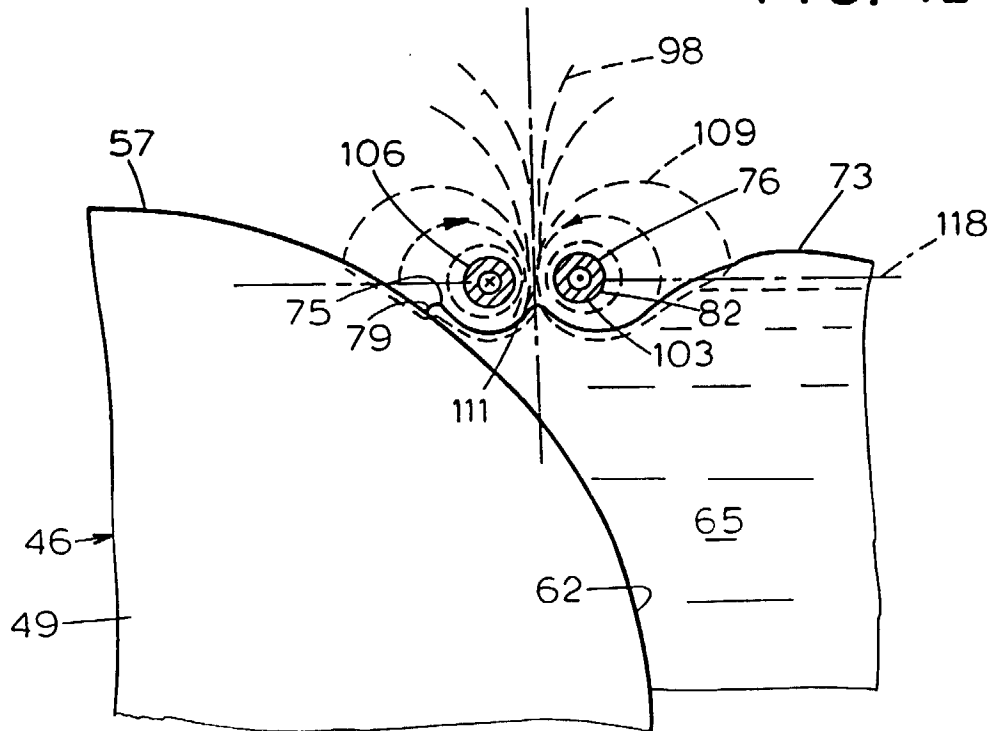


FIG. 13

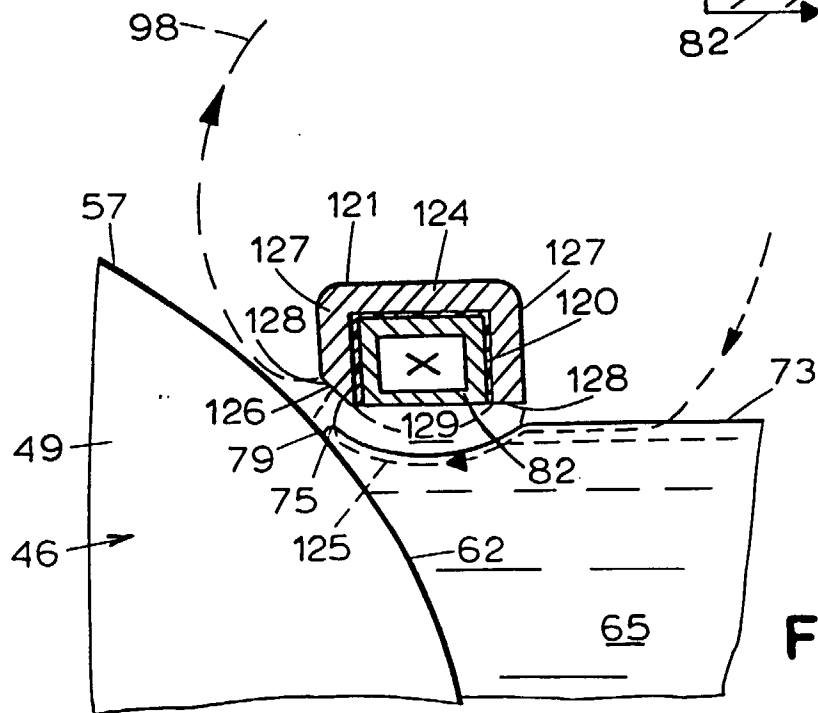
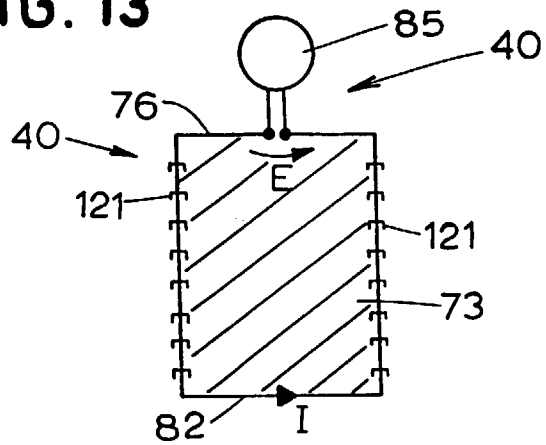


FIG. 14A

FIG. 14B

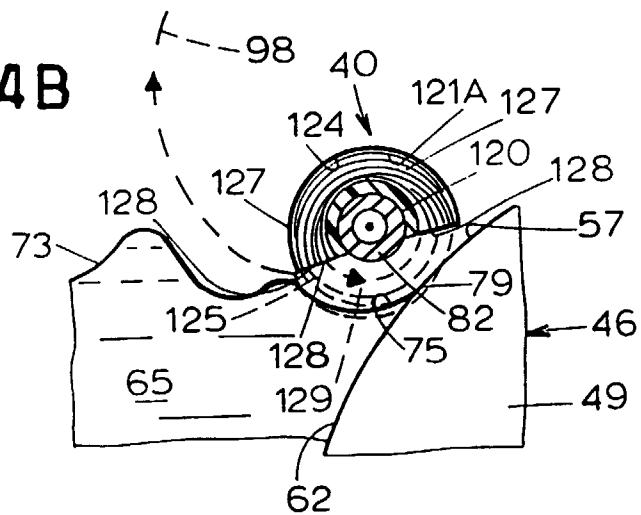


FIG. 15

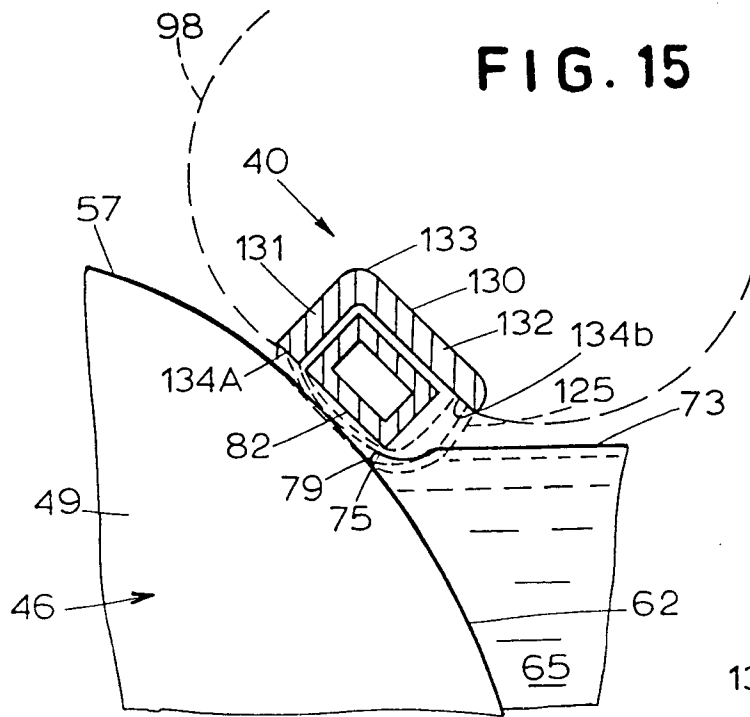


FIG. 16A

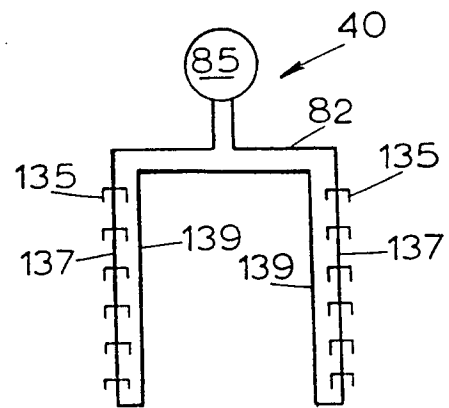
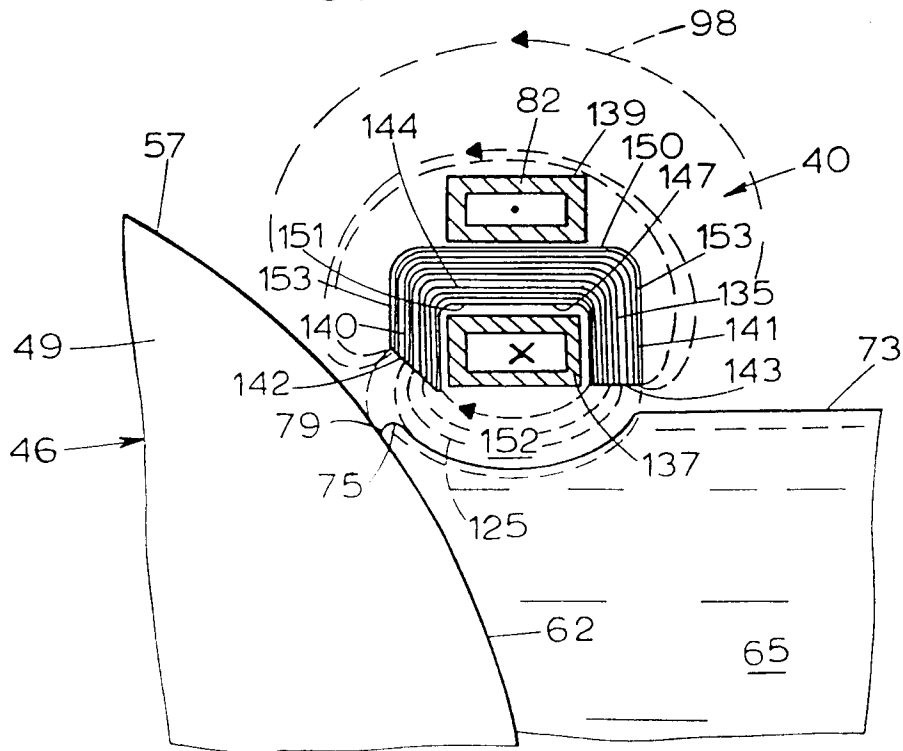


FIG. 16B



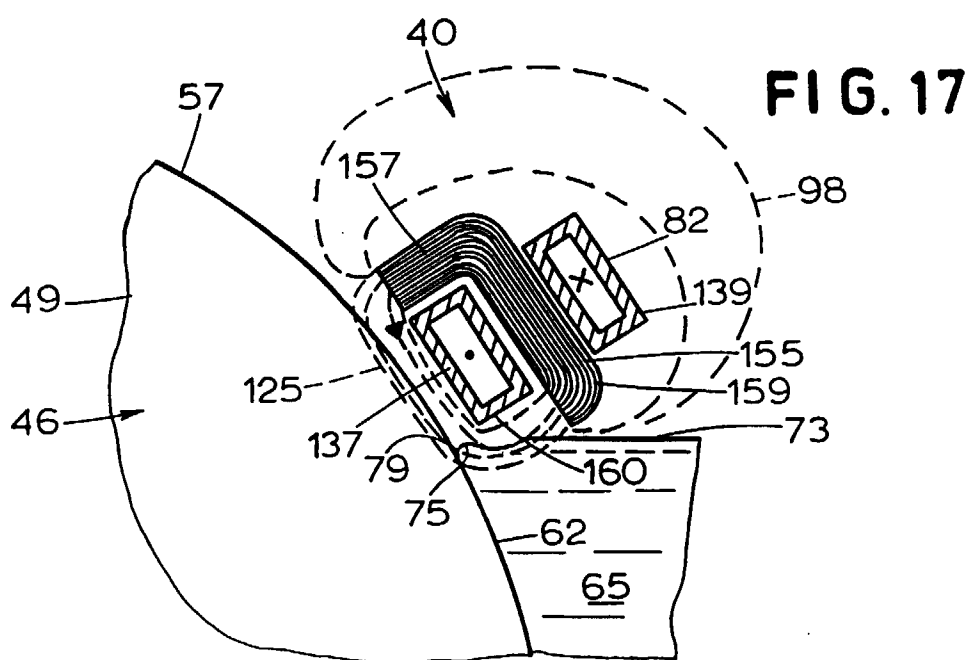
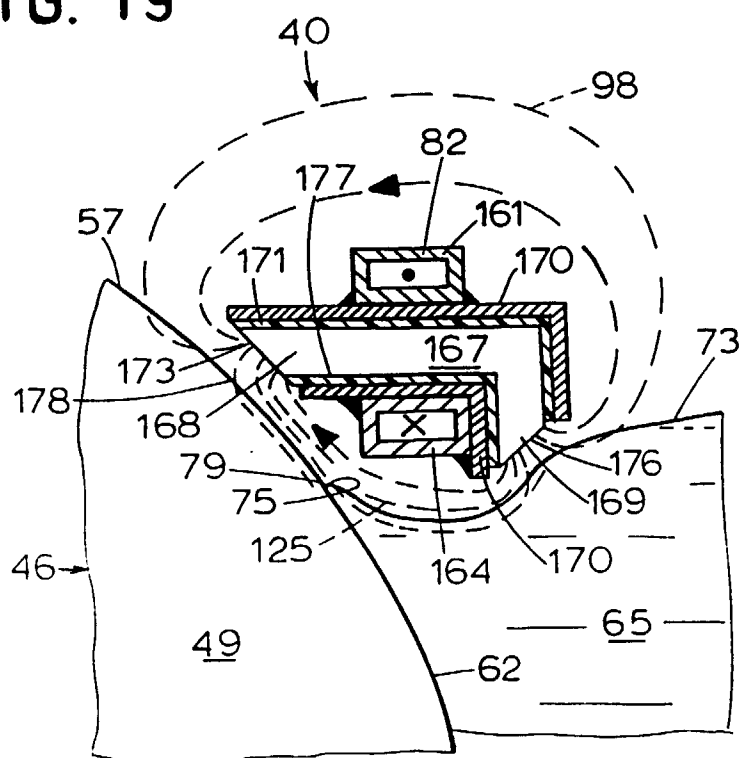


FIG. 19



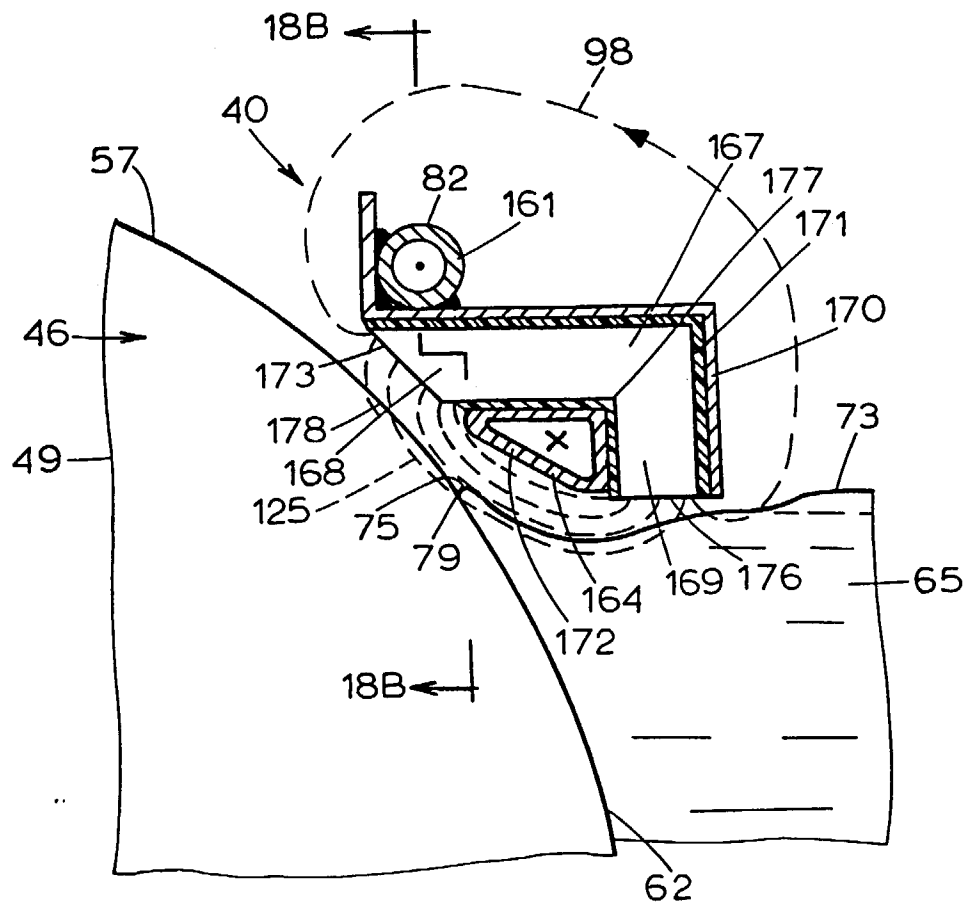


FIG. 18A

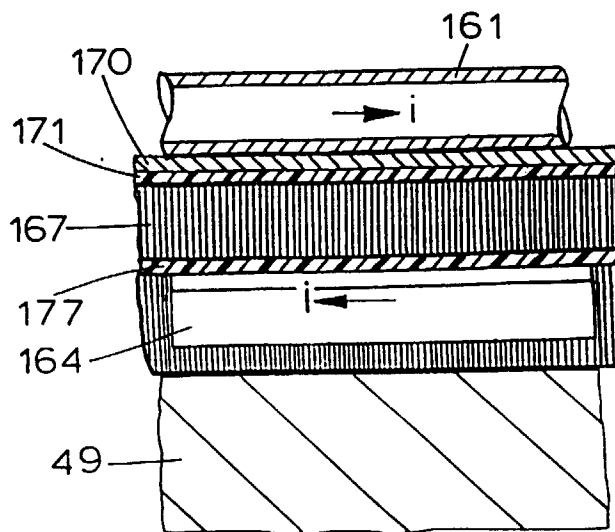


FIG. 18B

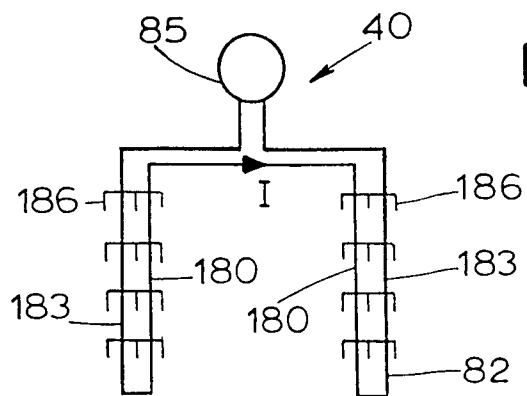


FIG. 20

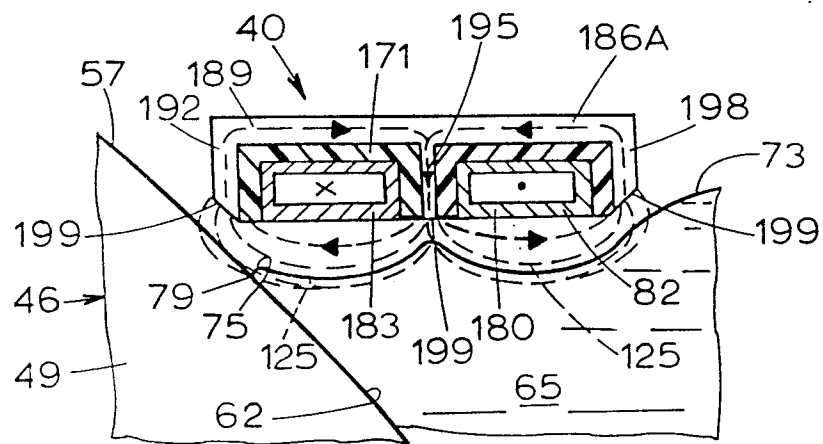


FIG. 21

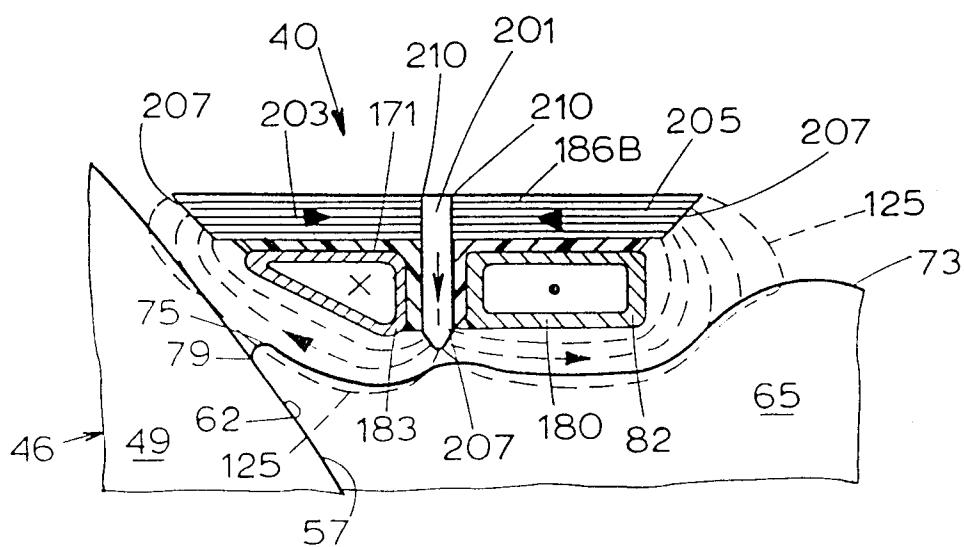


FIG. 22A

FIG. 22B

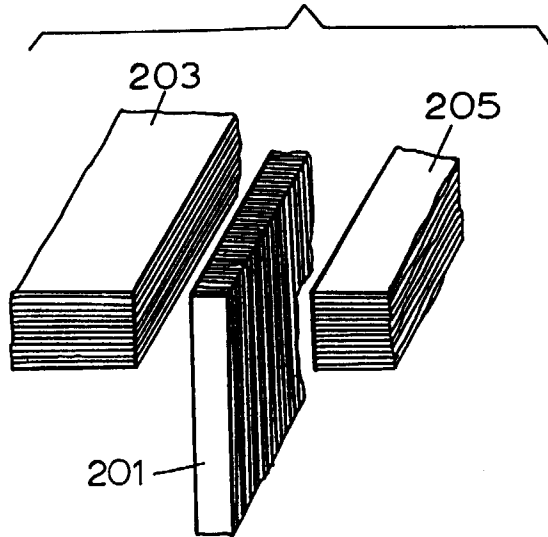


FIG. 23

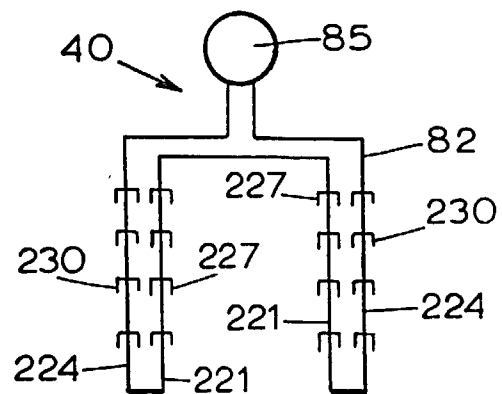
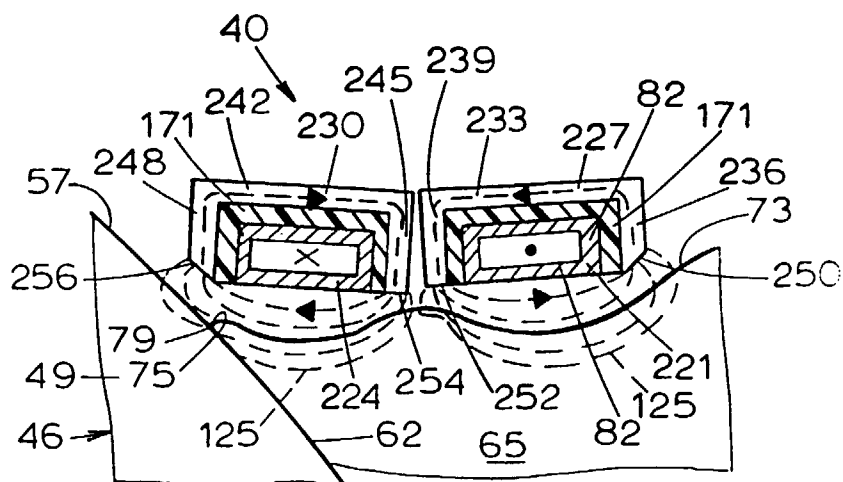


FIG. 24



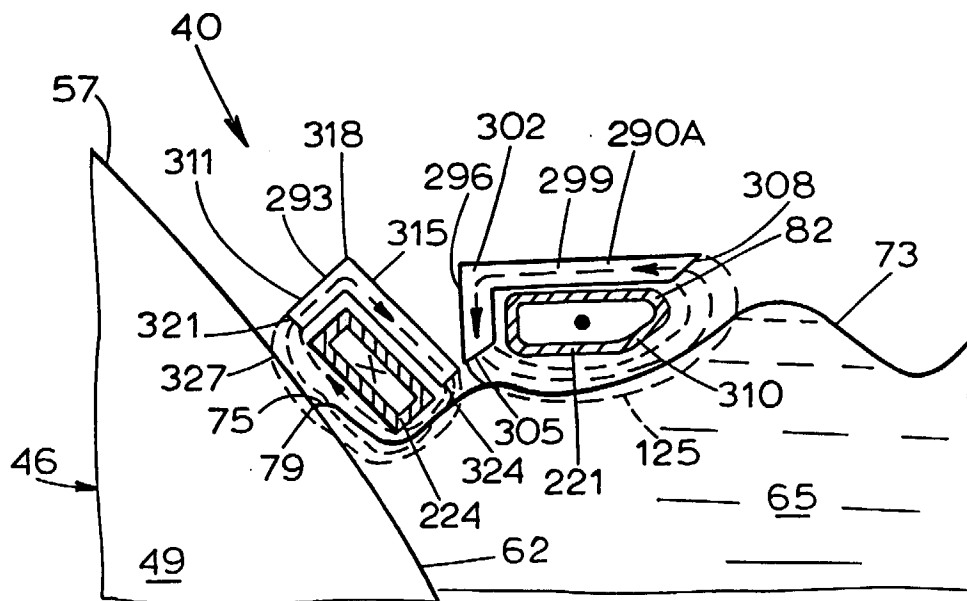


FIG. 25

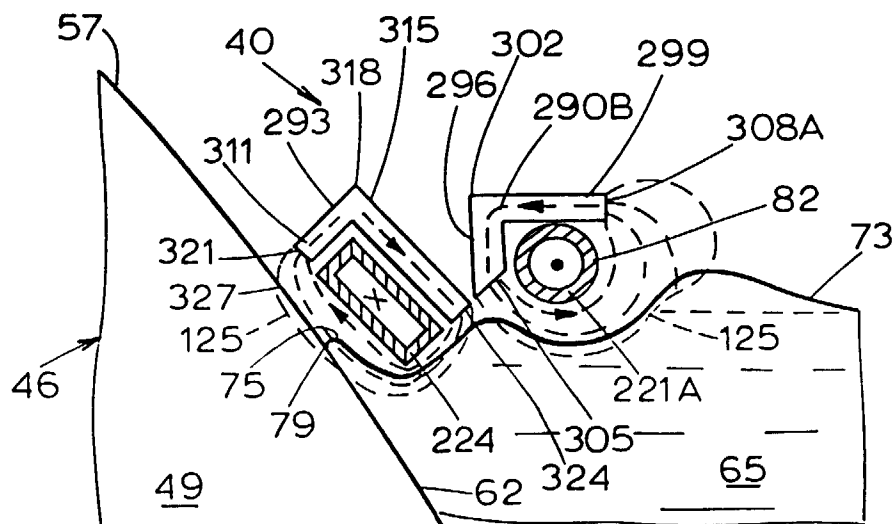


FIG. 26

FIG. 27

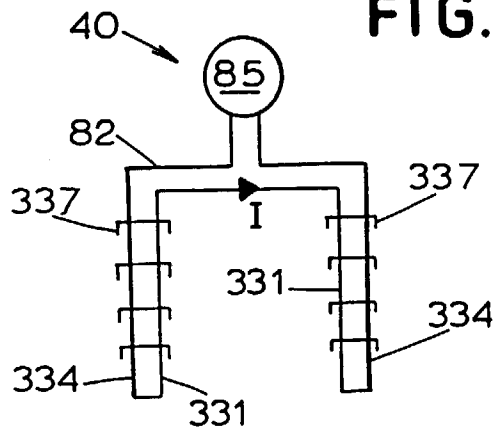


FIG. 28

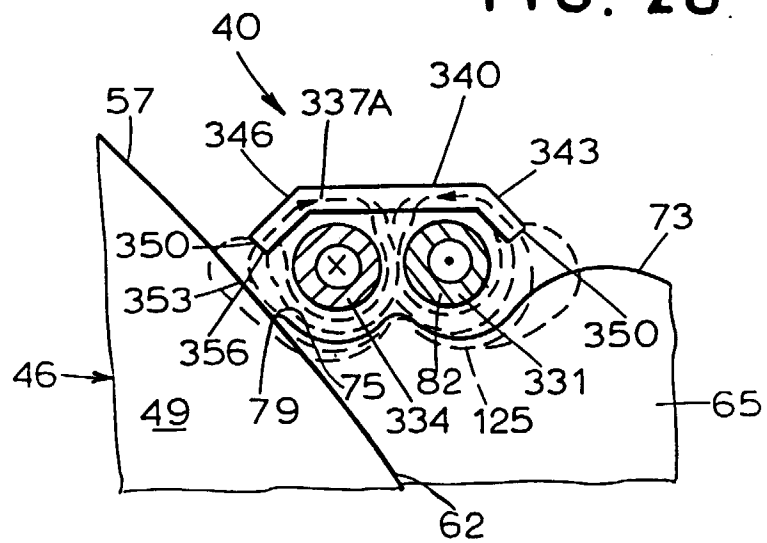
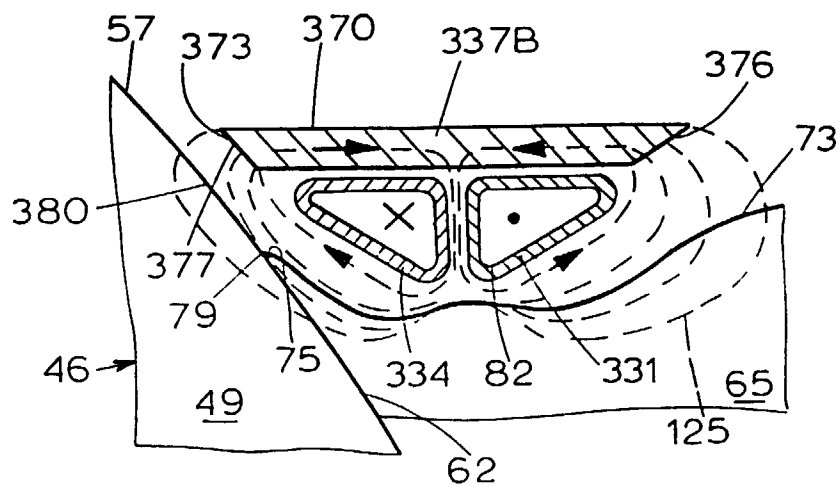


FIG. 29



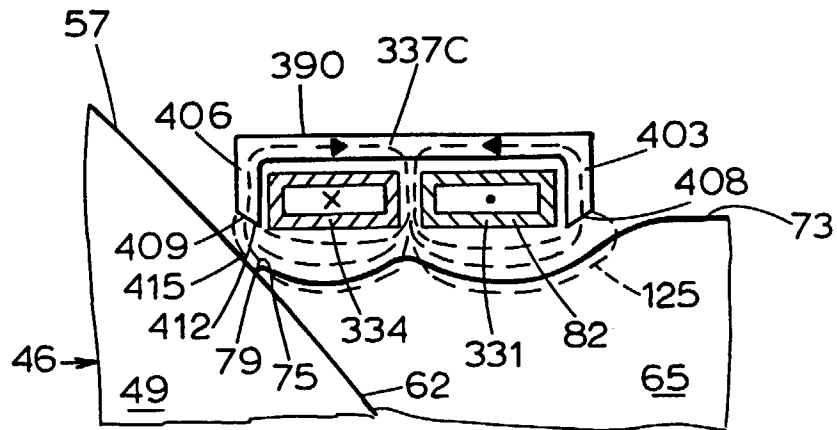


FIG. 30

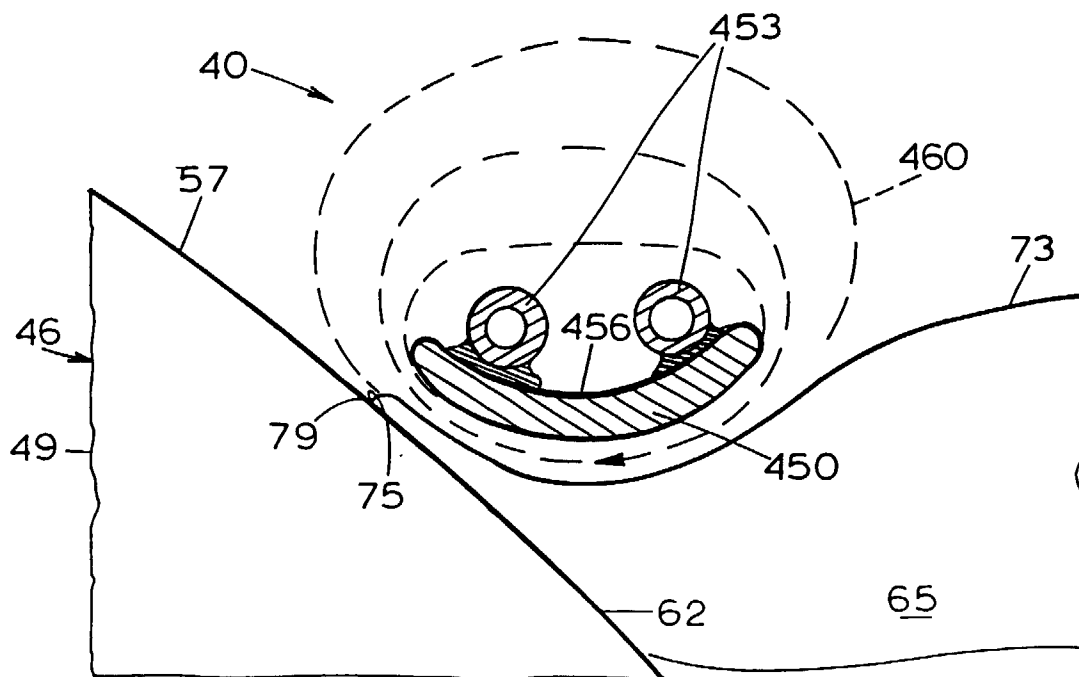


FIG. 31



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EUROPEAN SEARCH REPORT

Application Number
EP 98 11 9150

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	PATENT ABSTRACTS OF JAPAN vol. 016, no. 094 (M-1219), 9 March 1992 & JP 03 275247 A (NIPPON STEEL CORP), 5 December 1991 * abstract *	1-66	B22D27/02 B22D11/10
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D,A	--- US 4 982 796 A (LARI ROBERT J ET AL, PALOS PARK, US) 8 January 1991 * column 1, line 14 - line 17 * * column 5, line 21 - line 30 * * figures 2-9 * -----	1-66	TECHNICAL FIELDS SEARCHED (Int.Cl.6) B22D
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 4 February 1999	Examiner Peis, S
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

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04-02-1999

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US 4982796 A	08-01-1991	NONE	

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i For more details about this annex : see Official Journal of the European Patent Office, No. 12/82