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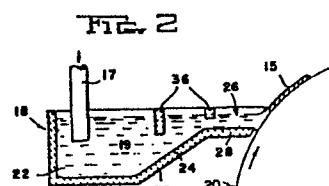
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(54) Method and apparatus for continuous casting of crystalline strip.

(55) A method is provided for directly casting molten metal (19) from the exit end (26) of a casting vessel (18) onto a moving casting surface (20) to form a continuous strip (15) of crystalline metal. The surface tension of the molten metal (19) flowing from the exit end (26) forms the top, edge and bottom surfaces of the strip (15) being cast to provide good strip surface quality, edges and structure. An apparatus is also provided including a casting vessel (18) having a molten metal receiving end (22) and an exit end (26) from which a fully developed uniform flow of molten metal (19) leaves through a U-shaped structure onto a moving casting surface (20). A direct cast strip product is also provided.



METHOD AND APPARATUS FOR CONTINUOUS CASTING  
OF CRYSTALLINE STRIP

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This invention relates to a method and apparatus for direct casting of metal alloys from molten metal to continuous strip. More particularly, it relates to feeding molten metal through an open casting vessel 05 outlet to solidify as continuous strip of desired thickness on a moving casting surface.

In conventional production of metal strip, such methods may include the steps of casting the molten metal into an ingot or billet or slab form, then typically 10 includes one or more stages of hot rolling and cold rolling, as well as pickling and annealing at any of various stages of the process in order to produce the desired strip thickness and quality. The cost of producing continuous strip, particularly in as-cast 15 gauges ranging from 0.010 inch to 0.100 inch (0.0254 to 0.254 cm) could be reduced by eliminating some of the processing steps of conventional methods. The as-cast strip could be processed conventionally, by cold rolling, pickling and annealing to final gauges of 0.002-0.040 20 inch (0.0508 to 1.016 mm).

There are known a wide variety of methods and apparatus for the production of directly cast strip. Typical of such methods are those which include spraying molten metal through a metering orifice across a gap to a 25 rapidly moving quenching surface such as a wheel or continuous belt; methods which partially submerge a rotating quenching surface into a pool of molten metal; methods which use horizontal link belts as quenching substrates upon which molten metal flows for 30 solidification; and methods of casting with twin casting rolls having a pool of molten metal therebetween.

Direct casting of metals through an orifice has long been attempted for the commercial production of strip

with good quality and structure. U.S. Patent 112,054 dated February 21, 1871 discloses a method of manufacturing flat solder wire from molten metal forced through an orifice and onto a rotating casting surface. 05 Similarly, U.S. Patent 905,758, issued December 1, 1908, discloses a method of drawing molten metal out of an outlet at the lower end of a vessel and onto a casting surface. British Patent 24,320, dated October 24, 1910, discloses a method of producing sheet or strip from 10 molten metal flowing through a tube channel having at least one side in contact with the moving casting surface. Representative of a more recent system is U.S. Patent 3,522,836 - King, issued August 04, 1970, which discloses a method of maintaining a convex meniscus 15 projecting from a nozzle and moving a surface past the nozzle orifice outlet to continuously draw off material and solidify as a continuous product. The molten material is maintained in static equilibrium at the outlet and gravitationally maintained in continuous 20 contact with the moving surface. U.S. Patent 4,221,257 - Narasimhan, issued September 09, 1980, relates to a method of forcing molten metal under pressure through a slotted nozzle onto the surface of a moving chill body.

The orifice-type casting systems are generally 25 restricted to light gauge materials having a thickness, as cast, usually of the order of less than about 0.010 inch (0.0254 cm). Such systems appear to be gauge-limited, for the moving quenching surface appears to be limited in the material which it can solidify and 30 carry away as it is delivered from the nozzle orifice. Such systems behave as a molten metal pump and transfer excess molten metal from the orifice to the quenching surface in a molten state with more heat than can be extracted to provide a suitable strip. By reducing the 35 delivery rate of the metal and/or by increasing the velocity of the quenching surface, such a condition can

be overcome, however a reduction in gauge will result.

When crystalline strip is attempted to be produced at the high speeds associated with the orifice-type casting systems, poorer quality usually results. As 05 molten metal is sprayed upon a high-speed quenching surface or is flowed out full width on a slower-moving horizontal belt, it rapidly moves away from the source of the supply in a still partially molten state. It is this condition that leads to the deterioration in quality, for 10 as the strip rapidly solidifies from the quenching surface side of the strip, shrinkage occurs which can only be moderated by a fresh supply of molten metal. Without such a fresh supply of molten metal, cracks quickly develop within the structure of the strip and 15 greatly reduce its physical properties. Attempts have been made to improve the nozzle geometry to overcome the problems associated with orifice-type casting as shown in U.S. Patents 4,274,473, issued June 23, 1981 and 4,290,476, issued September 22, 1981. A disadvantage of 20 the orifice-type casting is that the orifice meters out an amount of molten metal which, in effect, determines the gauge of the strip. Furthermore, relatively high pressure heads used in order to supply enough molten metal to the orifice and a relatively small standoff 25 distance from the casting wheel for containment of the molten metal also limits the strip gauge.

Thicker strip can be produced on a single quenching surface such as by dipping a slowly rotating quenching wheel into a static supply of molten metal to permit the 30 solidification of a much thicker strip. Molten metal solidifies on the surface of this wheel and continues to thicken at a predictable rate until it emerges from this bath of molten metal or it separates from the surface. The fresh supply of molten metal avoids the cracking 35 generally associated with solidification of a finite layer such as in orifice-type casting. Further more, an

extremely steep thermal gradient between this molten pool and the solidification front also leads directly to a more uniform internal structure and superior upper surface quality. A drawback from such a dip system comes 05 from the difficulty of keeping molten metal from solidifying upon the edges of the slightly submerged quenching wheel and having a tendency to cast a channel-like structure. Furthermore, there is the added difficulty of ensuring uniform contact between the 10 solidifying strip and the surface of the quenching wheel as it enters the molten pool, and results in poor surface quality on the cast side of the strip. Such difficulties lead to spot variations in strip gauge, wherein lighter gauge sections are produced where intimate contact is 15 reduced or lost.

Other direct casting processes have been proposed, but have not developed into commercial processes. For example, pouring of molten metal on the top of a moving casting wheel produces strip of nonuniform gauge, poor 20 edges and unacceptable quality. U.S. Patent 993,904, dated May 30, 1911, discloses an apparatus including a molten metal first vessel with a gravity discharge outlet opening into the lower part of a tray-like second vessel below the level of molten metal therein. The molten 25 metal passes out of the second vessel through an overflow to deliver molten metal to a casting wheel. U.S. Patent 3,381,739, issued May 7, 1968, discloses a method of forming sheet or strip material by flowing liquid about a surface which is wetted and bridging the distance to the 30 moving casting surface on which it solidifies.

What is needed is a method useful in commercial production for direct casting strip having surface quality comparable to or better than conventionally-produced strip. The method and apparatus of direct 35 casting should produce strip which is superior to orifice-type casting, as well as other known direct

casting processes including dip-cast systems, horizontal link belt quenching systems, and twin casting rolls. It is an objective that the method and apparatus overcome the disadvantages of known direct casting methods.

05 Furthermore, what is needed is a method and apparatus to permit the direct casting of relatively thick strip of the order of greater than 0.010 inch (0.0254 cm) and up to about 0.100 inch (0.254 cm) or more. It is desirable that the factors contributing to shrinking and cracking 10 of direct cast strip be minimized or eliminated in order to provide improved surface quality and structure of strip. Furthermore, a method and apparatus is desirable which is suitable for commercial production of strip at reduced cost and to facilitate production of new alloys.

15 The direct cast strip should have good surface quality, edges and structure and properties at least as good as conventionally cast strip.

In accordance with the present invention, a method is provided for directly casting molten metal to 20 continuous strip of crystalline material. The method includes supplying molten metal to a casting vessel having a receiving end and an exit end, the exit end being adjacent and having edges thereof parallel to a casting surface moving generally upwardly past the exit 25 end. The molten metal is fed from the receiving end to the exit end to provide a pool of molten metal having a substantially uniform flow and free upper surface in the exit end. The molten metal flows from the exit end onto the casting surface such that across the width of the 30 exit end of the casting vessel a substantially uniform flow of molten metal is presented to the casting surface. The surface tension of the flowing metal forms all the surfaces of the strip being cast. The top surface tension of the free surface of molten metal pool forms 35 the top of the cast strip, and the surface tension of the molten metal leaving the sides of the exit end forms the

edges of the cast strip. The surface tension of the molten metal leaving the bottom of the exit end maintains a meniscus between an inside surface of the bottom of the exit end and the casting surface to form the bottom of the cast strip. The depth of the molten metal in the exit end and distance between the vessel and casting surface are controlled to maintain the surface tension. The as-cast strip is removed from the casting surface.

An apparatus is also provided for directly casting molten metal to continuous strip of crystalline material comprising a movable casting surface, a casting vessel and a means for supplying molten metal to the casting vessel. The casting vessel has a receiving end, an exit end having a generally U-shaped structure adjacent the casting surface and having edges thereof substantially parallel thereto and an intermediate section to facilitate a substantially uniform flow of molten metal from the receiving end to the exit end. The U-shaped structure of the exit end has a bottom wall and diverging inside sidewall surfaces opening upwardly and having a width between the inside surfaces substantially as wide as the strip to be cast. The exit end has a fixed width along the bottom wall between the inside surfaces and a uniform cross-sectional area over a length sufficient to provide a substantially uniform flow of molten metal from the exit end. The casting surface is movable generally upwardly past the exit end of the casting vessel at a distance of between 0.005 to 0.060 inch (0.013 to 0.152 cm) therefrom at a speed of 20 to 500 feet per minute (6.1 to 152.4 metres per minute).

A continuous direct cast strip product made in accordance with the present invention is also provided.

The present invention will be more particularly described with reference to the accompanying drawings, in which:-

Figure 1 is a schematic of a strip casting apparatus

of the present invention,

Figure 2 is an elevation view in cross section of a casting vessel of the apparatus of the present invention,

Figure 2a is a detailed elevation view of Figure 2,

05 Figure 2b is another detailed view of Figure 2.

Figure 3 is a top view of the casting vessel of Figure 2,

Figure 3a is an end view of the casting vessel of Figure 3,

10 Figure 4 is an elevation view in cross section of a preferred embodiment of a casting vessel of the apparatus of the present invention,

Figure 5 is a top view of a preferred embodiment of the casting vessel of Figure 4,

15 Figure 6 is an enlarged elevation view of a preferred embodiment of the exit end of a casting vessel of the apparatus of the present invention,

Figure 7 is a photomicrograph of typical Type 304 alloy as-cast strip of the present invention, and

20 Figure 8 is a photomicrograph of a typical Type 304 alloy conventionally produced hot-rolled band.

Figure 1 generally illustrates casting apparatus 10 including transfer vessel 12 and feed tundish 14 for supplying molten metal to casting vessel 18 for directly casting molten metal on a casting surface 20 to produce continuous product in strip or sheet form 15. Molten metal 19 is supplied from vessel 12 to tundish 14 to casting vessel 18 in a conventional manner. Stopper rod 16 or other suitable means may control the flow of molten metal to casting vessel 18 such as through spout 17.

30 Casting vessel 18 is shown substantially horizontal having a receiving end and an exit end disposed adjacent to the casting surface 20.

The supply of molten metal 19 through the casting vessel 18 may be accomplished by any suitable conventional methods and apparatus of vessels, tundishes,

or molten metal pumps, for example. Vessel 12 and feed tundish 14 may be of known design and should be suitable for supplying an adequate amount of molten metal to casting vessel 18 for strip generation at the casting surface.

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Casting surface 20 may also be conventional and may take the form of a continuous belt, or a casting wheel. Preferably a casting wheel is used. The composition of the casting surface does not appear to be critical to the 10 present invention, although some surfaces may provide better results than others. The method and apparatus of the present invention have been used with casting surfaces of copper, carbon steel and stainless steel. It is important that the casting surface be movable past the 15 casting vessel at controlled speeds and be able to provide desired quenching rates to extract sufficient heat for solidifying the molten metal into strip form. The casting surface 20 is movable past casting vessel 18 at speeds which may range from 20 to 500 feet per minute 20 (6.1 to 152.4 metres per minute), preferably 50 to 300 feet per minute (FPM) (15.24 to 91.44 metres per minute), which is suitable for commercial production of crystalline material. The casting surface 20 should be sufficiently cool in order to provide a quenching of the 25 molten metal to extract heat from the molten metal for solidification of strip of crystalline form. The quench rates provided by casting surface 20 of apparatus 10 are less than 10,000°C per second and typically preferably less than 2000°C per second.

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Two important aspects of the casting surface and casting vessel are that the casting surface have a direction of movement generally upwardly past the exit end of vessel 18 and the vessel 18 a free surface molten metal pool in exit end 26. The free surface of the 35 molten metal pool in exit end 26 is essential to development of good top surface quality of the cast

strip. By "free", it is meant that the top surface is unconfined by structure, i.e., not in contact with vessel structure and free to seek its own level between receiving section 22 and exit end 26. Generally, the 05 path is oriented at an included angle  $\theta$  (Figure 2a) from about  $0^\circ$  to  $135^\circ$  from the horizontal and in the direction of metal flow as measured between the direction of metal flow at the free surface of molten metal in the exit end and the direction of movement of the casting surface at 10 the free surface in the exit end of casting vessel 18. For a casting wheel, the path of the casting surface is tangent to the free surface at the exit end of vessel 18. Preferably, the angle is between  $0^\circ$  and  $45^\circ$  from the horizontal. For a casting wheel, preferably, the vessel 15 is adjacent a position in an upper quadrant of the wheel when the free surface of molten metal is near the crown of the casting wheel, the angle is at about the  $0^\circ$  position.

20 Casting vessel 18 is essential to the method and apparatus 10 of the present invention and is better shown in figure 2 which is an elevation view of the vessel 18. Casting vessel 18 is disposed adjacent casting surface 20, preferably is substantially horizontal, and is composed of heat insulative and refractory material 25 described below. This arrangement is necessary for providing the required uniform and fully-developed flow of molten metal to the casting surface 20. Vessel 18 includes a receiving end 22 at a rearward section and an exit end 26. Preferably, receiving end 22 and exit end 30 26 have substantially the same cross-sectional area or exit end 26 has a greater cross-sectional area as measured perpendicular to the direction of metal flow from the receiving end 22 to exit end 26. Receiving end 22 is shown deeper than exit end 26 which facilitates 35 receiving molten metal 19 such as from supply spout 17 and for developing a flow of molten metal to exit end 26.

Exit end 26 of vessel 18 has a generally U-shaped structure defined by a bottom wall portion 28 and sidewalls 30, as is shown in Figure 3. Sidewalls 30 may have vertical inside surfaces 31, but preferably, the surfaces 31 of sidewalls 30 of the U-shape structure diverge to open upwardly to facilitate metal flow. The slight taper tends to improve metal flow from exit end 26, but too great a taper may cause a loss of surface tension control and flooding of molten metal. A taper of less than 10° per side and preferably 1-5° is provided.

Exit end 26 includes bottom wall 28 which has a generally planar inside portion having a length sufficient to provide a substantially uniform flow of molten metal from the exit. Preferably, the length of the planar wall portion as measured in the direction of metal flow is at least equal to the depth of molten metal pool to be contained in exit end 26. More preferably, the ratio of length to depth is at least 1:1 or greater. Exit end 26 preferably has fixed or uniform dimensions of width and height throughout the length of the planar inside surface of bottom wall 28 to define a uniform cross-sectional area in exit end 26. The width of the exit end 26 as measured between the inside surfaces 31 of sidewalls 30 along the free surface of molten metal pool is substantially as wide as the strip to be cast. Preferably, exit end 26 is positioned adjacent casting surface 20 with the ends or edges of the sidewalls 30 and bottom wall 28 defining the U-shaped structure being substantially parallel to the casting surface.

To facilitate transition flow between receiving section 22 and exit end 26, an intermediate section 24 communicating between the receiving end 22 and the exit end 26 should be provided in order to have a substantially uniform flow at exit end 26. Preferably, intermediate section 24 maintains substantially uniform cross-sectional area throughout its length from receiving

section 22 to exit end 26. Intermediate section 24 shown in Figure 3 has a gradually increasing width from the receiving end 22 to exit end 26 and, as shown in Figure 2, a gradually decreasing depth so as to maintain a substantially uniform cross-sectional area throughout its length. Intermediate section 24 may be provided with a tapered bottom wall 32 which gradually decreases the depth of the vessel 18 from the receiving end 22 to the exit end 26. Similarly, intermediate section 24 may have at least one sidewall 34 which fans outwardly in order to provide a gradually increasing width from the narrower receiving end 22 to the wider exit end 26. Figure 2 is a top view of casting vessel 18 illustrating the widening of sidewall 34 of intermediate section 24.

Figure 2 also illustrates that weirs or weir plates 36 may be used in casting vessel 18 such as in an intermediate section 24 or near where section 24 merges into exit end 26 in order to further facilitate development of uniform flow. Weir plates 36 should be made of a refractory or heat-resistant material which is also resistant to corrosion by molten metal. Kaowool refractory board, treated with a diluted colloidal silica suspension has proven satisfactory. Weirs 36 may extend across the entire width or a portion of the width of casting vessel 18. As shown in Figure 2, preferably, the molten metal level in the receiving end 22 of casting vessel 18 is at about the same level as the molten metal in exit end 26. Weirs 36 are useful for baffling or dampening the flow in order to facilitate development of a uniform fully-developed flow and to restrain movement of surface oxides and slag.

Figures 2a and 2b illustrate the use of surface tension of the flowing molten metal to form the surfaces of the strip being cast. Figure 2a is a detailed elevation view in partial cross section of exit end 26 adjacent casting surface 20. Molten metal flowing from

the exit end 26 forms and maintains a meniscus 35 between the inside surface of bottom wall 28 of the U-shaped structure and the casting surface. The surface tension forming meniscus 35 forms the bottom of the strip 15  
05 being cast. The surface tension of the free surface of the molten metal pool in exit end 26 forms a curvilinear portion 39 on the top of the molten metal in the U-shaped structure as it forms the strip product.

Figure 2b illustrates exit end 26 adjacent casting  
10 surface 20 showing solidifying metal 19 therebetween in a view from under exit end 26. The surface tension of the molten metal 19 forms the convex surfaces or meniscus 37 between exit end 26 and casting surface 20 at the inside surface 31 of sidewalls 30 near bottom wall 28.

15 A preferred embodiment of casting vessel 18 is shown in the elevation and top views of Figures 4 and 5, respectively. Vessel 18 is shown having an outer metal support shell 38, a refractory insulation 40, and a liner 42 which defines the internal surface of the casting  
20 vessel 18 and which is in contact with molten metal during casting. The construction of vessel 18 should be made from refractory material which is heat insulative and resistant to molten metal corrosion. The casting vessel may be secured to some suitable table or means to  
25 orient and position the vessel at the desired casting position relative to the casting surface or wheel 20. The exit end 26 of casting vessel 18 should have the front face or edges 33 of sidewalls 30 and bottom wall 28 which define and form the U-shaped structure contoured to  
30 the casting surface. This can be done simply by using 60 or 100-grit silicon carbide grinding paper held between the casting surface and the vessel assembly and rubbing the paper against the vessel 18 to make the edges parallel to the wheel. The front surface 33 of the  
35 casting vessel 18 may then be brush coated with zirconia cement and allowed to dry before casting.

Figures 4 and 5 illustrate a preferred embodiment of the casting vessel 18 of the present invention which is useful for casting strips of 4 inches (10.16 cm), and up to about 13 inches (33.02 cm) wide and may be useful up to 48 inches (121.92 cm) wide. The metal support shell 38 may be used depending upon the type of material used for the insulation layer 40. Insulation layer 40 may be a foamed ceramic cement insulation which would need an external support such as a metal support shell 38. In the alternative, if a standard refractory brick or block is used and cemented together into the desired shapes and then carved to achieve the desired inner and outer dimensions, then the outer shell 38 is not necessary. The vessel 18 may also be a monolithic shape formed from castable ceramic material. Liner 42 on the internal surface of casting vessel 18 is also made of an insulating refractory molten metal resistant material. It has been found that an insulating blanket of a high alumina fiber-silicate composition is useful, such as Fiberfrax brand material, that has been saturated in a diluted colloidal silica suspension and contoured within the casting vessel 18 and then dried prior to actual use.

Figures 4 and 5 also show a rear overflow element 44 including a rearwardly-sloping surface extending from the inner surface of casting vessel 18 to the outer walls of vessel 18. The height of the overflow element 44 determines the maximum depth of molten metal that may be contained in the receiving end 22 and, accordingly, the depth of the molten metal in the exit end 26 of casting vessel 18. Overflow element 44 facilitates control of the molten metal level in the casting vessel 18 which is essential to gauge and quality control of the cast strip.

Also shown in Figure 4 is a casting vessel 18 which may optionally include a cover assembly 46 in the vicinity of intermediate section 24 of casting vessel 18. Cover 46 includes downwardly-extending walls 48 and 50

joined by a bottom surface 52. The downwardly-extending walls 48 and 50 are similar to the weir plates shown in Figure 2. Cover 46 is generally composed of a refractory insulative material resistant to molten metal. Cover 46  
05 may comprise a liner, a refractory insulation layer and an outer metal shell similar to the liner 42, refractory insulation layer 40 and outer metal shell 38 of casting vessel 18. The cover 46 may extend across the entire width or part of the width of casting vessel 18 in the  
10 vicinity of intermediate section 24. It is important that the presence of a cover 46, which is useful for retaining the heat in the molten metal in the casting vessel 18, does not contact the molten metal in the receiving end 22 and exit end 26 in order to maintain the  
15 free surface in the pool in exit end 26. The cover also can extend over portions or all of rear receiving section 22 to contain a protective atmosphere therein.

Figure 6 illustrates another embodiment wherein the exit end 26 of vessel 18 is provided with a means for  
20 providing a non-oxidizing atmosphere in a zone defined above the molten metal across the width of the U-shaped structure of the exit end adjacent to the casting surface 20 together with a means for radiantly cooling the molten metal in that zone. The two features may be present  
25 separately or in combination.

Means for providing a non-oxidizing atmosphere provides a protective cover or blanket of inert or reducing gases in a zone about the molten metal in the U-shaped structure of exit end 26. The gases minimize or  
30 prevent the build-up or formation of slag and oxides on the top surface of the molten metal, which oxide could be cast into the cast strip. The non-oxidizing atmosphere may be static, or a recirculating atmosphere.

Preferably, a non-contacting cover over the zone above  
35 the molten metal pool at the exit end 26 of casting vessel 18 and at least one gas nozzle or a series of

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nozzles 56 provides a continuous flow of inert or reducing gas counter to the direction of the cast strip. Preferably the gas is introduced so that it impinges in the zone on the top of the molten metal liquid pool where 05 the strip is emerging. The embodiment may provide a protective cover for sealing the zone over the molten metal pool containing a blanket of inert or reducing gases directed into streams of gases to push any oxide away from the forming of the strip. The series of narrow 10 gas nozzles 56 is positioned along the width of the casting strip so that streams or jets of gas impact the zone wherein the strip emerges from the liquid pool. Nozzles 56 are directed counter to the casting of the strip at an angle to the plane of the formed strip, 15 preferably about  $20^{\circ} - 30^{\circ}$ . The gas blanket may be a gas selected from hydrogen, argon, helium, and/or nitrogen in order to minimize the oxides that may be formed during casting. The velocity of the gases from nozzle 56 should be quite low, for higher velocities may cause a 20 disturbance in the upper surface of the molten metal pool and result in damage to the cast strip.

Means for radiantly cooling the molten metal in the zone may include providing a coolant in the vicinity of the zone to facilitate extraction of heat from the top 25 surface of the molten metal. The coolant may be provided by a panel of tubes or pipes 54 located above the molten liquid to remove radiated heat from the molten metal.

Water or other fluid may be used as a coolant. Preferably, a cover is provided which includes a series 30 of water-cooled tubes 54 sealed to the top of the casting vessel 18 with refractory material and cement. Radiant cooling of the top surface of molten metal as it flows from the U-shaped structure of exit end 26 onto the casting surface improves the heat extraction from the top 35 surface of the solidifying molten metal to improve as-cast strip top surface quality and structure by

controlling the growth of dendritic structure in the strip.

Preferably, means for providing a non-oxidizing atmosphere and the means for radiantly cooling are used 05 in combination. A non-contacting cover for sealing the zone over the molten metal at the exit end 26 includes a cooling means to remove radiated heat from the molten metal and a non-oxidizing atmosphere means. Preferably, the cover includes a series of water-cooled tubes 54 and 10 a series of gas nozzles 56. The inert gases in this embodiment are cooled by the tubes 54 which further facilitate removal of the radiant heat. The cover containing the cooling tubes 54 seals the zone to reduce 15 oxide or slag formation which could be deposited on the strip product.

In the operation of the casting apparatus of the present invention, vessel 12, tundish 14 and casting vessel 18 are preheated to operating temperatures prior to introducing molten metal into the casting vessel 18 20 for the production of strip material. Any conventional heating means should be suitable and may be used. An air-acetylene or air-natural gas heating lance positioned in the receiving end 22, as well as providing a preheat front cover for the front edges of the casting vessel 25 U-shaped structure which will be placed adjacent the casting surface 20. Normal preheating temperatures for casting molten stainless steel may be of the order of 1900-2000°F (1038 - 1093°C). After the minimum preheat levels desired are reached, the heating lances are 30 removed and the vessel 18 is positioned adjacent the casting surface at a preset standoff distance such as between 5 and 20 mils (0.127 and 0.508 mm).

In commencing the method of directly casting alloy 35 from molten metal to continuous strip, molten metal 19 is supplied from a bulk transfer ladle or vessel 12 to a feed tundish 14 and thereafter to the casting vessel 18

which is oriented substantially horizontally. The flow of molten metal from feed tundish 14 to casting vessel 18 may be controlled and regulated by valve means such as stopper rod 16 and through spout 17 into the rear feed section or receiving end 22 of casting vessel 18. As vessel 18 begins to fill with molten metal, the molten metal begins to flow in a direction toward the exit end of the vessel and flows through an intermediate section 24 and the exit end 26 as shown in Figure 2. Casting vessel 18 permits the molten metal to flow so as to feed the molten metal to the exit end 26 of vessel 18.

Casting vessel 18 may include weirs 36 such as shown in Figure 2 to dampen and baffle the flow of molten metal 19 in order to facilitate a uniform fully-developed flow in exit end 26. The molten metal preferably maintains a substantially uniform cross-sectional area of flow from the receiving end 22 through the exit end 26. Generally exit end 26 is wider than the receiving end 22 and the U-shaped structure has a width which approximates the width of the strip to be cast. Casting vessel 18 has a casting volume having tapered and fanned intermediate section. Casting vessel 18 is designed to prevent cross flows of molten metal within the vessel while developing a uniform turbulent flow from exit end 26 across the width of the U-shaped structure in end 26 such that the fully-developed flow has the bulk of the velocities in the direction of flow from the receiving end 22 to the exit end 26. The level of moten metal in exit end 26 is about the same as the level in receiving end 22, although the depth of the molten metal will be less in exit end 26. The molten metal continues to flow from the exit end 26 onto the moving casting surface 20 such that across the width of the U-shaped structure of exit end, a substantially uniform flow of molten metal is presented to the casting surface 20. The molten metal in exit end 26 has a top surface tension and the molten metal leaving

the opening has edge surface tension which form, in part, the top and edges, respectively, of the cast strip 15. The bottom surface is formed from surface tension in the form of a meniscus between the bottom inside surface of 05 the U-shaped structure and the casting surface.

Though there is no intent to be bound by theory, it appears that the solidification of the molten metal leaving the exit end of vessel 18 commences with the molten metal contacting the casting surface as it leaves 10 the bottom of the U-shaped opening of exit end 26 of vessel 18. The strip is solidified from the pool of molten metal available to the casting surface at the exit end of vessel 18 and forms a thickness wherein the solidifying strip is continually presented with an 15 oversupply of molten metal until leaving the exit end 26 of vessel 18. Such a pool of molten metal is believed to form a substantial part of the strip thickness as it contacts the moving casting surface 20 with only a minor portion of the strip thickness resulting from molten 20 metal solidified as it was pulled out of the vessel 18 adjacent the top curvilinear surface tension portion 39. It is estimated that more than 70% and probably more than about 80% of the strip thickness results from the pool of molten metal provided adjacent the meniscus 35. The 25 molten metal solidifies from the bottom of the molten metal pool provided to the casting surface from the bottom of the U-shaped structure of exit end 26 of vessel 18.

Casting surface 20 moves past casting vessel 18 in a 30 generally upward direction from the bottom of the U-shaped opening of exit end 26 to the open top of the opening. The position of vessel 18 on the casting surface 20 and the speed of the casting surface are predetermined factors in order to achieve the quality and 35 gauge of the cast strip. If the casting surface 20 is a casting wheel, then the vessel 18 is positioned,

preferably, on an upper quadrant of the casting wheel.

By the method of the present invention, there is an important control of several factors which results in the ability to cast desired gauges of metal strip ranging 05 from 0.01 to 0.06 inch (0.0254 to 0.1524 cm) with good surface quality, edges and structure. The control of molten metal flow onto the casting surface, the speed of the casting surface, the solidification from the bottom of the molten metal pool, and the controlled depth of 10 molten metal in the pool and standoff distance from the casting surface to maintain the surface tension of the molten metal are important interrelating factors.

In order to better understand the present invention, for following examples are presented.

15 Example I

A casting vessel having the structure generally as shown in the Figure 2 but having only one weir plate 36 near the exit end 26 was constructed from hardened blocks of Kaowool refractory, which is an alumina-silica 20 composition material. It was treated by soaking it with a colloidal silica suspension dried overnight at 250°F (121°C) and then fired for 1 hour at 2000°F (1093°C) in air. After the blocks were cut and shaped, they were coated with a thin layer of Kaowool cement. The vessel 25 was shaped to the contour of the wheel and then the U-shaped structure ends were coated with a thin layer of a zirconia cement. A weir of similar composition was used. The casting vessel was then heated with air-acetylene lances. The vessel 18 was about 8.75 30 inches (22.23 cm) long from the receiving end 22 to the exit end 26 and was about 6.5 inches (16.5 cm) wide at the receiving end 22 and about 4 inches (10.16 cm) wide at bottom wall 28 and exit end 26. Molten metal of Type 35 304 alloy was tapped at 1580°C, supplied to the vessel 18 and maintained at a level of about 1.75 inches (4.45 cm) deep in the receiving end 22 and the molten metal was

about 0.75 inches (1.9 cm) deep in the U-shaped structure in the exit end 26 of vessel 18. A casting surface was a copper casting wheel having a width of 7 inches (17.78 cm) and a diameter of about 36 inches (91.44 cm) which provided cooling of the order of less than 2000°C/sec. 05 The casting wheel was rotated at a speed of about 2050 to 300 feet per minute (76.2 to 91.44 metres per minute) past the exit end of vessel 18 and spaced about 40 mils (1.016 mm) therefrom at an angle θ of about 40°. The 10 U-shaped structure of the vessel had diverging or tapered inside surface 31 of sidewalls 30 of exit end 26 opening upwardly. The taper was of the order of about 3° per inside surface. Run 25 of about 100 pounds (45.36 kg) was cast according to the present invention and resulted 15 in successful production of strip having a width of about 4 inches (10.16 cm) and a uniform thickness of from 16 to 18 mils (0.406 to 0.457 mm) having smooth and uniform upper and lower surfaces as-cast and flat edges showing no signs of raggedness or curls.

20 Example II

A casting vessel having a structure generally as shown in Figure 4 was constructed having a Kaowol refractory and alumina bubble refractory insulation 40 in a metal shell 38. The liner 42 was made of Fiberfrax material, 0.5 inch (1.27 cm) thick at eight pounds per cubic foot (128.14 kg/m<sup>3</sup>) which was saturated with a diluted colloidal silica suspension and then dried prior to use. The vessel 18 outside dimensions were about 15 inches (38.1 cm) long and 18 inches (45.72 cm) wide at 25 the exit end and vessel 18 had a slight increasing 3 cross-sectional area to exit end 26. Weir plate 36 was 0 made and positioned similar to Example I and cemented between sidewalls of vessel 18. The inside surfaces 31 of sidewalls 30 were also tapered or diverging of the 35 order of about 3° per surface. The casting vessel was set at a standoff distance of about 35 mils (0.89 mm) at

an angle of about 0° for the free surface of the molten metal was near the crown of the casting wheel. A 500-pound (226.8 kg) Run 84-97 of molten metal of Type 304 was cast according to the present invention on a casting 05 surface of a low carbon steel seamless pipe having a 12.75-inch (32.39 cm) outside diameter, a 0.375-inch (0.95 cm) wall thickness, 48 inches (121.92 cm) wide and internally spray water cooled. The casting wheel was rotated at about 200 FPM (60.96 metres per minute) at the 10 start of the casting for 10-15 seconds to facilitate flushing of the initial metal flow and then slowed to 100 FPM (30.48 metres per minute) for the duration of the Run. The molten metal maintained a depth of about 2 inches (5.08 cm) in the exit end 26 and 2.75 inches (6.98 15 cm) in the receiving end 22.

The vessel 18 also included a cover having a means for radiantly cooling and means for providing a helium atmosphere as shown in Figure 6. The cooling was effected by circulated water at about 3 gallons (13.64 20 litres) per minute through copper tubing having a 0.375-inch (0.95 cm) outside diameter.

The as-cast strip was about 13 inches (33 cm) wide, and having a uniform thickness of about 45 mils (1.143 mm) and having good upper surface quality which was 25 uniform, smooth and crack free. The as-cast strip was then conventionally processed by pickling in a nitric/hypofluoric acid, cold rolling about 50% reduction, annealing at 1950°F (1065°C) for 5 minutes, pickling again in a similar manner, and then cold rolling 30 to 5 mils (0.127 mm) and annealed. The room temperature mechanical properties of the annealed as-cast samples are shown below in comparison to typical properties of conventionally produced Type 304 annealed hot-rolled band.

TABLE

Samples	Tensile Strength (KSI)	Yield Strength (KSI)	0.2% Elongation in 2 inch (5.08cm) (%)
1	104.6	44.6	52.0
2	100.8	40.8	50.0
3	100.8	40.8	49.0
4	100.0	40.0	52.5
7	102.8	42.0	55.0
8	102.0	42.0	57.5
9	103.6	44.0	52.0
10	105.2	44.0	54.5

05        Type 304 alloy conventionally produced may have typical or average room temperature mechanical properties of annealed hot-roll band of 101.1 KSI tensile strength, 43.8 KSI yield strength and 57% elongation in 2 inches (5.08cm).

10        Figure 7 is a photomicrograph of as-cast strip of the present invention showing the typical internal structure from Run 84-52. The Type 304 alloy, shown at 100X magnification, illustrates the typical as-cast structure of small columnar cells oriented in the direction of strip thickness, i.e., top to bottom surfaces. This direction generally conforms to the direction of heat extraction from the strip as it solidifies. The method and apparatus of the present invention controls the growth of the dendritic structure in the strip to produce an as-cast strip which can be conventionally processed into finished strip having properties comparable to or better than conventionally produced strip product.

15        Figure 8 illustrates a typical structure of a conventionally produced hot-roll band of Type 304 alloy at 100X magnification.

20        It is observed that the method and apparatus of the

present invention results in even better strip structure and quality as the gauge of the strip product increases and as the width of the strip increases. The tendency of edge curl in the strip product cast in 4 to 6-inch (10.16 to 15.24 cm) widths appears to no longer be present in the wider widths up to 13 inches (33.02 cm). The method and apparatus of the present invention provides an uncomplicated and direct method for casting crystalline metal strip or sheet from molten metal to continuous strip. The shrinking and cracking problems of finit film solidification are eliminated and a relatively thick strip of quality comparable to or better than conventional production methods is provided.

The method and apparatus appear useful for various metals and alloys, including stainless steel and silicon steels.

CLAIMS:

1. A method of directly casting molten metal to continuous strip of crystalline metal, characterised in comprising:
  1. supplying molten metal (19) to a receiving end (22) of a casting vessel (18) having a receiving end (22) and an exit end (26), the exit end (26) being adjacent to a casting surface (20) and having edges (33) thereof parallel to the casting surface (20);
  2. moving the cooling casting surface (20) generally upwardly past the exit end (26);
  3. feeding molten metal from the receiving end (22) to the exit end (26) to provide a pool of molten metal having a substantially uniform flow and a free upper surface in the exit end (26) of the casting vessel (18);
  4. flowing molten metal from the exit end (26) onto the moving casting surface (20) with a substantially uniform flow across the width of the exit end (26), the surface tension of the flowing metal forming all the surfaces of the strip to be cast, the surface tension of the free surface of the molten metal pool forming the top of the cast strip, the surface tension of the molten metal leaving the bottom of the exit end (26) maintaining a meniscus (35) between an inside surface of the bottom (28) of the exit end (26) and the casting surface (20) to form the bottom of the cast strip; the surface tension of the molten metal leaving two sides (30) of the exit end (26) forming the edges of the cast strip and being substantially as wide as the strip being cast;
  5. controlling the depth of molten metal in the exit end (26) of the vessel (18) and the distance between the exit end (26) and the casting surface (20) to maintain the surface tension of the molten metal on the top, bottom and sides; and
  6. removing cast strip (15) from the moving casting surface (20).

2. A method according to claim 1, wherein the feeding of molten metal (19) from the receiving end (22) to the exit end (26) includes maintaining a substantially uniform cross-sectional area of flow in the exit end (26).

05 3. A method according to claim 1 or 2, wherein the feeding of molten metal (19) includes maintaining a substantially uniform cross-sectional area of flow from the receiving end (22) through the exit end (26).

10 4. A method according to claim 1, 2 or 3, wherein said feeding of molten metal (19) in the casting vessel (18) includes providing molten metal in the receiving end (22) at the same level as in the exit end (26).

15 5. A method according to any one of the preceding claims wherein said feeding the molten metal (19) includes having a gradually increasing width of flow from the receiving end (22) to the exit end (26) while maintaining a substantially uniform cross-sectional area of flow.

20 6. A method according to any one of the preceding claims including baffling the flow of molten metal in the casting vessel (18) to facilitate development of uniform flow at the exit end (26).

25 7. A method according to any one of the preceding claims, including moving the casting surface (20) past a generally U-shaped structure of the exit end (26) of the vessel (18) in a direction generally from the bottom of the U-shaped structure to the top of the exit end (26).

30 8. A method according to any one of the preceding claims, including moving the casting surface (20) in a path from the horizontal and in the direction of the metal flow at an angle of from  $0^\circ$  to  $135^\circ$  as measured between the free surface and the casting surface direction at the exit end (26) of the vessel (18).

35 9. A method according to claim 8, wherein the angle is from  $0^\circ$  to  $45^\circ$  from the horizontal.

10. A method according to any one of the preceding  
claims, including controlling the thickness of the strip  
(15) by the speed of the casting surface (20) and the  
depth of molten metal (19) in the exit end (26) of the  
05 casting vessel (18).

11. A method according to any one of the preceding  
claims, including cooling the molten metal after contact  
with the casting surface (20) at a rate of less than  
2000°C per second to effect solidification of crystalline  
10 metal.

12. A method according to claim 11, wherein the  
cooling is at a rate of less than 1500°C per second.

13. A method according to any one of the preceding  
claims, wherein the casting surface is moved at a speed  
15 of 20 to 500 feet (6.096 to 152.4 metres) per minute.

14. A method according to any one of the preceding  
claims, including providing the casting surface (20)  
parallel to edges (33) of the exit end (26) and at a  
distance of between 0.005 to 0.060 inches (0.127 to 1.524  
20 mm) from the exit end (26).

15. A method according to any one of the preceding  
claims, including removing strip (15) from the casting  
surface (20) having a uniform strip width, which ranges  
from 4 to 48 inches (10.16 to 121.92 cm).

25 16. A method according to any one of the preceding  
claims, including removing strip (15) from the casting  
surface (20) having a uniform thickness which ranges from  
0.010 to 0.100 inch (0.254 to 2.54 mm).

30 17. A method of directly casting molten metal to  
continuous strip of crystalline metal, characterised in  
comprising:

35 supplying molten metal (19) to a receiving end (22)  
of a substantially horizontal casting vessel (18) having  
a receiving end (22) and an exit end (26), the exit end  
(26) being adjacent to a casting surface (20) and having  
a generally U-shaped structure and edges (33) thereof

parallel to the casting surface (20) and spaced therefrom at a distance of between 0.005 to 0.060 inch (0.127 to 1.524 mm);

05 moving the casting surface (20) generally upwardly past the exit end (26) at a speed of 20 to 500 feet (6.096 to 152.4 metres) per minute in a path at an angle of 0° to 135° as measured between the free surface in the direction of metal flow and the direction of the casting surface (20) at the exit end (26) of the casting vessel

10 (18);

feeding molten metal (19) from the receiving end (22) to the exit end (26) while maintaining a substantially uniform cross-sectional area or greater of flow to provide a pool of molten metal having a

15 substantially uniform flow and free upper surface in the exit end (26);

flowing molten metal (19) from the U-shaped structure of the exit end (26) onto the moving casting surface (20) with a substantially uniform flow across the width of the

20 exit end (26), the surface tension of the flowing metal forming the surfaces of the strip (15) being cast, the surface tension of the free surface of the flowing molten metal forming the top of the cast strip, the surface tension of the molten metal leaving two sides (30) of the

25 exit end (26) forming the edges of the cast strip and being substantially as wide as the strip (15) being cast and the surface tension of the molten metal leaving the bottom of the U-shaped structure maintaining a meniscus (35) between an inside surface of the bottom (28) of the

30 exit end (26) and the casting surface (20) to form the bottom of the cast strip (15);

cooling the molten metal upon contact with the casting surface (20) at a rate of less than 2000°C per second to effect solidification of crystalline metal;

35 controlling the depth of molten metal in the exit end (26) of the vessel (18) and the distance between the

exit end (26) and the casting surface (20) to maintain the surface tension of the molten metal on the top, bottom and sides; and

05 removing cast strip (15) from the moving casting surface (20).

18. Apparatus for directly casting molten metal to continuous strip of crystalline material, characterised in comprising:

10 a movable casting surface (20);  
a casting vessel (18) having a receiving end (22), an exit end (26), and an intermediate section (24) therebetween;

means (12) for supplying molten metal (19) to the receiving end (22) of the casting vessel (18);

15 said casting vessel (18) having its exit end (26) having a generally U-shaped structure adjacent the casting surface (20) and edges (33) thereof substantially parallel to the casting surface (20), the intermediate section (24) facilitating a substantially uniform flow of molten metal (19) from the receiving end (22) to the exit end (26), the U-shaped structure of the exit end (26) having a planar bottom wall (28) and diverging inside sidewalls (31) opening upwardly and having a width between the inside surfaces substantially as wide as the strip (15) to be cast, the exit end (26) having fixed width along the bottom wall (28) between the inside surfaces (31) of the sidewalls (30) and a uniform cross-sectional area over a length sufficient to provide a substantially uniform flow of molten metal from the 20 exit end (26);

25 said casting surface (20) being movable generally upwardly past the exit end (26) of the casting vessel (18) at a distance of between 0.005 to 0.060 inches (0.127 to 1.524 mm) therefrom and at a speed of 20 to 500 feet (6.096 to 152.4 metres) per minute.

30 35 19. Apparatus according to claim 18, including a

casting vessel (18) wherein the molten metal level in the receiving end (22) and exit end (26) are at the same level.

20. Apparatus according to claim 18 or 19, wherein  
05 the intermediate section (24) communicating between the receiving end (22) and exit end (26) has a gradually increasing width at the exit end (26) and a gradually decreasing depth so as to maintain a substantially uniform cross-sectional area throughout the length of the  
10 casting vessel (18).

21. Apparatus according to claim 18, 19 or 20, including baffles (36 or 48, 50) in the casting vessel (18) to facilitate development of uniform flow.

22. Apparatus according to any one of the preceding  
15 claims 18 to 21, wherein the casting surface (20) has a direction of movement upwardly from the horizontal and direction of metal flow at the free surface of molten metal at the exit end (26) oriented at an angle of from 0 to  $135^{\circ}$  from the horizontal between the free surface and  
20 the casting surface direction at the exit end (26).

23. Apparatus according to any one of claims 18 to 22, wherein the casting surface (20) comprises the peripheral surface of a rotating casting wheel.

24. Apparatus according to claims 22 and 23, wherein  
25 the exit end (26) of the vessel (18) is adjacent a position on the casting wheel forming an angle of  $0^{\circ}$ - $45^{\circ}$ .

25. Apparatus according to claim 23 or 24, wherein the exit end (26) of the casting vessel (18) is adjacent a position in an upper quadrant of the casting wheel.

30 26. Apparatus for directly casting molten metal to continuous strip of crystalline material, comprising:  
a movable casting surface (20);  
a substantially horizontal casting vessel (18);  
means (12) for supplying molten metal (19) to the  
35 casting vessel (18);  
said casting vessel (18) having a receiving end,

(22), an exit end (26) having a generally U-shaped structure adjacent the casting surface (20) and substantially parallel thereto, and an intermediate section (24) communicating between the receiving end (22) and the exit end (26), the intermediate section (24) having a gradually increasing width to the exit end (26) and a gradually decreasing depth to the exit end (26) so as to maintain at least a substantially uniform cross-sectional area or greater from the receiving end 05 (22) to the exit end (26) of the vessel (18),  
10 the exit end (26) having a bottom wall (28) and sidewalls (30) with diverging inside surfaces (31) opening upwardly and defining the U-shaped structure, the width between the inside surfaces (31) of the sidewalls 15 (30) being substantially as wide as the strip (15) to be cast, the width of the bottom wall (28) between the inside surface (31) of the sidewalls (30) being fixed to provide a substantially uniform cross-sectional area over a length at least equal to the depth of the molten metal 20 (19) therein, the length being sufficient to provide a substantially uniform flow of molten metal from the exit end (26),  
25 said casting surface (20) being movable generally upwardly past the exit end (26) of the casting vessel (18) at a distance of between 0.005 to 0.060 inches (0.127 to 1.524 mm) therefrom and said surface (20) having an upward path forming an angle of 0 to 135° between the direction of metal flow at the free surface and the direction of casting surface movement, the 30 casting surface (20) moving at a speed of 20 to 500 feet (6.096 to 152.4 metres) per minute.

27. A continuous strip (15) of crystalline metal made in accordance with the method of any one of claims 1 to 17.

35 28. A continuous strip according to claim 27 having a uniform as-cast thickness of 0.010 to 0.100 inch (0.254

to 2.54 mm), and the two surfaces thereof being uniform and smooth.

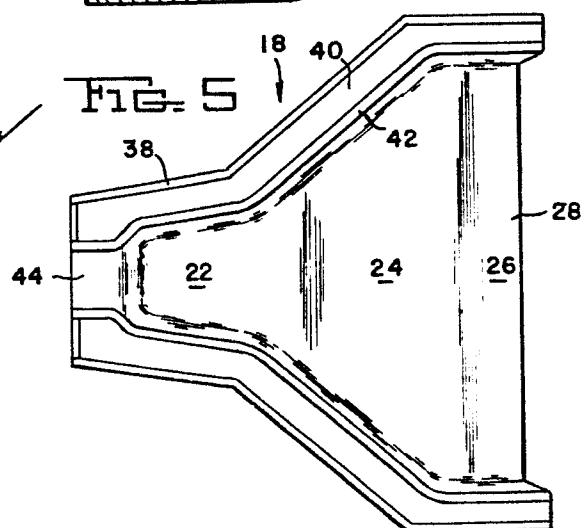
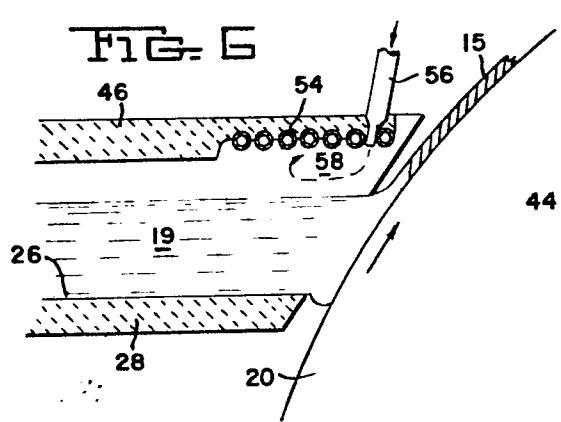
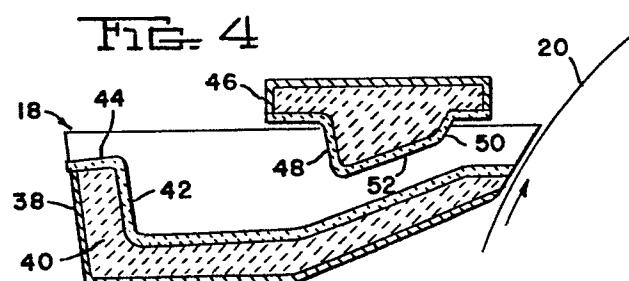
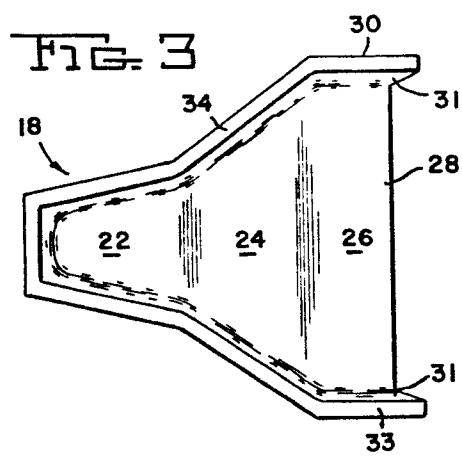
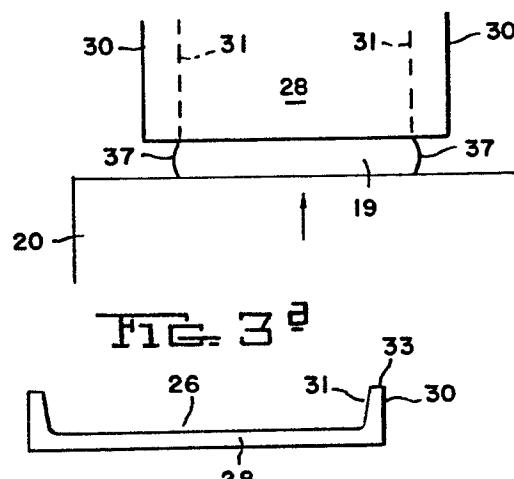
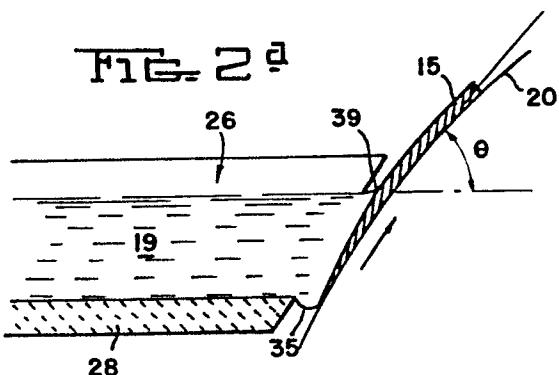
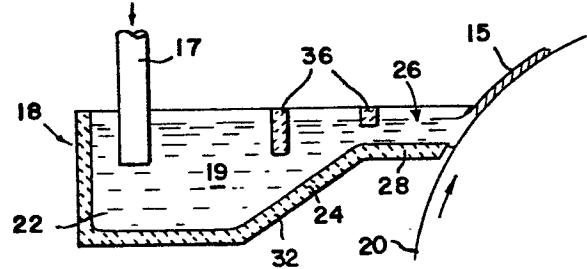
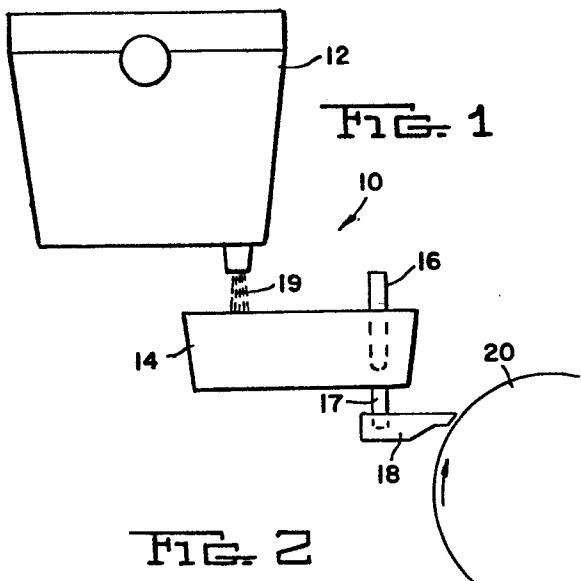
29. A continuous strip according to claim 27 or 28, having an internal structure of relatively small columnar cells oriented in the direction from one surface to the other surface.

30. A continuous strip according to claim 27, 28 or 29, having edges which are substantially flat and smooth.

31. A continuous strip according to any one of claims 27 to 30, which when subsequently pickled, annealed, cold rolled with an intermediate anneal to a final gauge of 0.002 to 0.040 inch (0.0508 to 1.016 mm) and then annealed in a conventional manner, exhibits mechanical properties comparable to or better than conventionally produced strip product.

32. A continuous strip (15) of crystalline metal directly cast from molten metal (19) onto a single moving casting surface (20), the strip (15) comprising an upper surface and a lower surface which contacted the casting surface (20), both the upper and lower surfaces in the as-cast condition being smooth and uniform, edges of the strip being substantially flat and smooth, the as-cast thickness ranging from 0.010 to 0.100 inch (0.254 to 2.54 mm), and the internal structure having relatively small columnar cells oriented in the direction from one strip surface to the other strip surface.

33. A strip according to claim 32, which when pickled, annealed, cold rolled with an intermediate anneal to final gauge of 0.002 to 0.040 inch (0.0508 to 1.016 mm) and then annealed, exhibits mechanical properties at least comparable to conventionally produced strip product.



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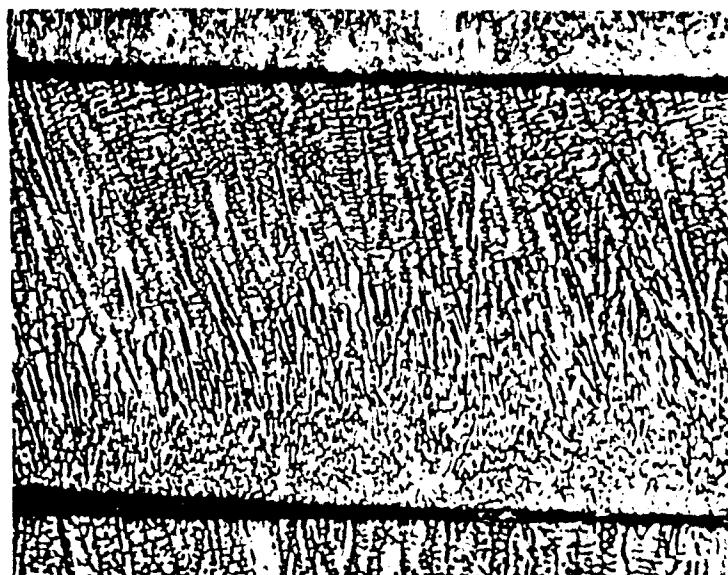


FIG. 7

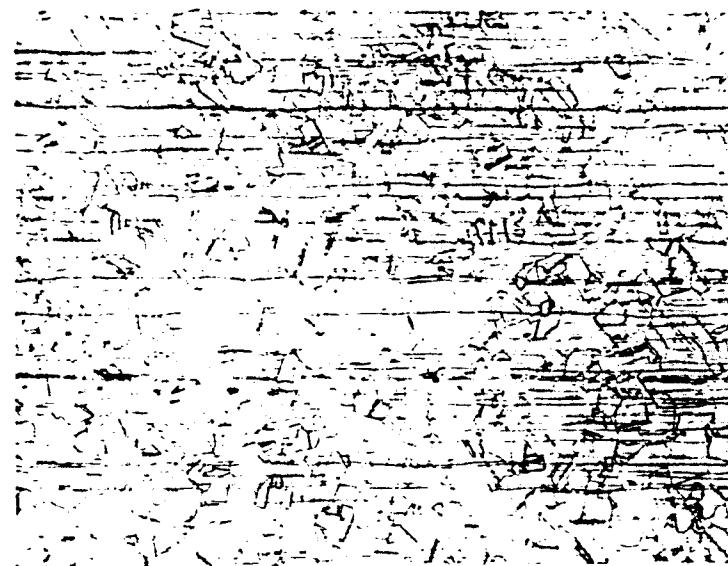


FIG. 8