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(54) A METHOD OF CONTROLLING THE SOLIDIFICATION PROCESS OF CONTINUOUSLY CAST METALS AND ALLOYS AND A DEVICE FOR IMPLEMENTING THE METHOD

(57) It regards alloys, in particular steel, that are paramagnetic around the liquidus temperature with an aim to support formation of columnar grains, suppression of forming polyhedral grains, refining a primary structure and targeted intervention into formation and distribution of primary and accompanying structural components. The process control is applied in the entire molten metal volume that solidifies under the effect of linear magnetic field having induction of 0.04 to 03 T. The process control of the solidification of continuously cast steel is applied in the entire molten metal volume, magnetically treated molten metal is transported into from the active zone of an electromagnet generating linear magnetic field having induction of 0.04 to 03 T by transportation motion during 5 to 10 seconds with velocity of 0.1 to 0.6 m.s^{-1}, wherein motion of the magnetically treated molten metal may be produced in any manner, in particular by a linear motor or conductively, by interaction of magnetic field of the electromagnet and direct current of 500 to 2200 A separately conducted into a billet by rollers closely below a crystalliser and by rollers below the electromagnet.

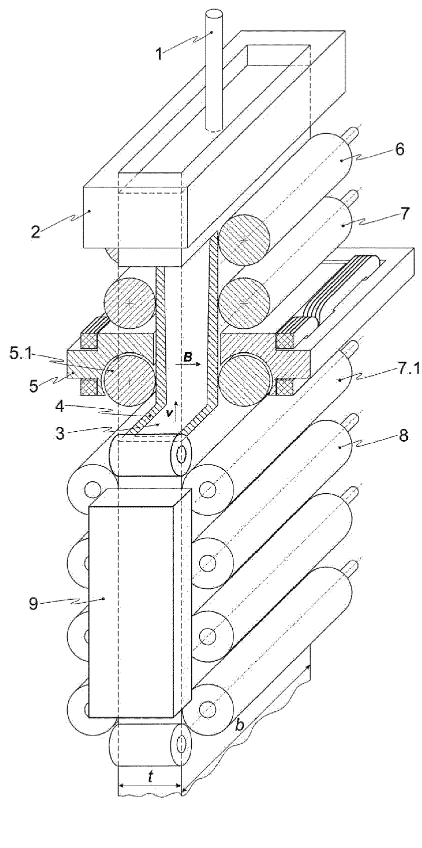

Fig. 2

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Description

Technical field

[0001] The invention relates to a method of controlling the solidification process of continuously cast steel, in particular, or of other metals and alloys that are paramagnetic at the liquidus temperature. The invention is in the field of continuous casting, foundry industry and metallurgy.

State of the art

[0002] Only a thin layer of solidified metal grows on the crystalliser walls at continuous casting of steel and thus developed profile proceeds to the secondary cooling zone together with residual molten metal that solidifies on the length of several metres due to its low thermal conductivity. As a result of the very slow solidification process the steel posses coarse dendritic structure and clumps of inclusions are formed around a longitudinal axis of a billet. There are known methods of structure refinement and partial suppression of axial segregation of continuously cast steel by means of intensive stirring of residual molten metal at the area below a crystalliser in the secondary cooling zone. Induction stirrers, multiphase set of coils produces mostly an advancing magnetic field in, are used for producing molten metal motion. An intensive flow of molten metal having a velocity exceeding 1 m. s^{-1} is a functional factor improving billet material parameters in the known induction devices intended for residual molten metal stirring. As a result of intensive movement of molten metal, solidification zone washing out occurs at a place the stirrer is situated, whilst by stirring motion the loosen fragments of the solid phase and micro-volumes of undercooled molten metal enriched with admixed alloying elements reach the billet central areas, where they serve as crystal nuclei. The solid phase is then primarily formed from the basic melt at the place of a washed out two phase zone resulting in decrease of the content of alloying and accompanying elements. After etching so called white bands in a shape of a frame or ring depending on the billet profile occur on a transverse section of the billet at the place of the stirring activity. As a consequence of reducing overheating of molten metal and by bringing a large amount of crystallisation nuclei a polyhedral grain zone is significantly extended and develops immediately after a pouring shell in the entire remaining cross-section, also in the billets that would solidify transcrystalically without stirring. At present, stirrers with continuous magnetic field known as linear motors are primarily used, they induced linear motion of the molten metal realizing transport of solidification zone products in the direction of the billet axis and returning molten metal stirs up remaining volume of residual molten metal. The motion develops at an interface, where magnetic field of the linear motor enters the residual molten metal through a solidified surface shell. Magnetic field decreases exponentially with increasing depth and hydraulic losses and trajectory motion scattering in space reduce flow velocity of the molten metal. Another disadvantage of induction stirrers is that they generate heat exceeding 1 MJ.s^{-1} on 1 m^2 of the billet surface and therefore they have to be positioned more than 2 m below the crystalliser, where the shell is sufficiently thick and remelting is not imminent. A multi-zone structure and existence of white bands are characteristic features of steel processed by intensive stirring.

[0003] There is also a known a method of induced motion, where forces $\boldsymbol{f}$ (N.m^{-3}) inducing flow of the molten metal are generated by interaction of magnetostatic field $\boldsymbol{B}$ (T) in a direction perpendicular to the billet axis and having direct electric current of current density $\boldsymbol{J}$ (A.m^{-2}) according to patent SK 277974, where $\boldsymbol{f} = \boldsymbol{J} \times \boldsymbol{B}$ applies for the size of generated forces $\boldsymbol{f}$ accounted for the volume unit of the conductor. In operation, the stirrer produces heat volume not exceeding 2 kJ enabling the stirrer to be placed closer to the crystallizer and in comparison with the induced stirrers more favourable spatial distribution of molten metal motion rate is achieved. There is a drawback of an erosion effect of the flowing residual molten metal onto the solidification zone, if the velocity exceeds 1 m.s^{-1} and there is also a need to supply direct electric current into the billet separately.

[0004] There is also a known method of controlled solidification by controlled circulating flow of molten metal in the solidifying ingot according to patent US 3,693,697. The motion of the molten metal induces moving magnetic field progressing downward and entering the ingot around the whole perimeter. Progressing field is formed by a series of helically wound coils around the ingot and magnetic field induced by them enters the ingot radially. The force inducing motion has the highest value at the solid/liquid interface. The deeper penetration of magnetic field the exponentially lowered force is and in the centre is close to zero resulting in a surface layer of flowing molten metal in a lower part of the ingot is pooled into the rising flow extending up to the crystalliser, where it is divided and along the edge of the ingot it returns again downwardly as a moving subsurface layer. A large contact area of the solid/liquid zone guarantees that, even at velocity of 0.25 to 0.5 m.s^{-1} a sufficient amount of fragments of solid phase and admixed molten metal from the solidification zone are released and by stirring motion they are transported into the whole volume of the residual molten metal where they are involved in the solidification process control. Like in case of intense stirring by a conventional linear motor in this case a share of polyhedral grains in the structure also increases. In formal terms, a series of successively connected coils induces a moving magnetic field, which progresses in axial direction, as known from linear motors. A lack of space for coils in the series of withdrawal rollers bring technical difficulties and absence of conventional magnetic circuits greatly reduces effectiveness of magnetic field generation and unsustainably increases energy consumption of the cited method of the solidification process control. Despite significantly lower velocity (0.25 to 0.5 $m.s^{-1}$) than used in conventional stirrers (> 1 $m.s^{-1}$) the energy consumption of the device amounts to several MW. At the process of continuous casting of slabs having ratio of the sectional side lengths greater than 1 : 5 induction of any molten metal stirring with a motion produced by induction, during which washing out of fragments from the solidification zone occurs, is extremely difficult in technical terms.

[0005] The objectives of the invention is a method of controlling the solidification process of continuously cast metals and alloys, in particular steels, that are paramagnetic around the liquidus temperature resulting in support in forming columnar grains, suppression of forming polyhedral grains, refinement of the primary structure and targeted intervention to development and distribution of primary and accompanying structural components.

Subject-matter of the invention

[0006] Said shortcomings are eliminated by a method of controlling the solidification process of continuously cast metals and alloys, in particular steels, that are paramagnetic around the liquidus temperature aiming at support of forming columnar grains, suppression of development of polyhedral grains, refinement of the primary structure and targeted intervention to production and distribution of primary and accompanying structural components based on the solidifying molten metal being processed during solidification by effect of a linear magnetic field of induction 0.04 to 0.3 T produced by at least one electromagnet.

[0007] From an active zone of at least one electromagnet positioned 0.5 to 2 m below a crystalliser the magnetically treated molten metal is transported by velocity 0.1 to 0.6 $m.s^{-1}$ by means of transportation motion produced by any manner, in particular conductively or by induction of at least one linear motor, wherein the control of the solidification process is applied in the entire volume of molten metal, the magnetically treated molten metal is transported into during the period of 5 to 10 seconds.

[0008] Transportation motion of the molten metal is produced by interaction of magnetic field of the electromagnet and direct electric current of intensity 500 to 1000 A separately conducted into the billet by rollers above and below the electromagnet, wherein magnetic field permeates the billet with the molten metal in the direction nearly perpendicular to a longitudinal axis of the billet, and direct current passes the billet longitudinally and may also contain a pulsating component.

[0009] Transportation motion of magnetically treated molten metal in billets of thickness **t** > 0.2 metre and width **b** > 5**t** is produced by interaction of magnetic field of the electromagnet and direct current of intensity 500 to 1000 A conducted into the billet by the rollers above and below the electromagnet, wherein magnetic field permeates the billet with the molten metal in the direction nearly perpendicular to the longitudinal axis of the billet, and direct current passes the billet longitudinally and may also contain a pulsating component.

[0010] Another subject-matter of the present invention is a device for implementation of the method according to the invention consisting of the first electromagnet positioned at the distance of 0.5 to 2 metres below the crystalliser and at least one other electromagnet producing linear magnetic field having induction 0.04 to 0.3 T positioned at the distance of more than 2 metres below the crystalliser and placed between the rollers supplying electric current so that the first rollers supplying electric current are arranged above the first electromagnet and the second rollers supplying current are arranged below the lowermost positioned another electromagnet.

[0011] According to another embodiment, the device consists of electromagnets having a height of the operation area greater than a half of the thickness **t** of the billet.

[0012] According to another embodiment, in the device having width of the billet **b** ≥ **2t** the electromagnet is integrated in a common unit with a withdrawal roller.

[0013] According to a preferred embodiment the device contains at least one roller closely below the crystalliser and at least one other roller located at least 0.5 m below the lowermost electromagnet, all provided with a supply of direct electric current of intensity 500 to 1000 A.

[0014] According to another embodiment, in the device for billets of thickness t > 0.2 m and width b > 5t, the first electromagnet is engaged in order to limit motion of impurities from the crystalliser to the billet containing molten metal with the operation area incorporating two operation zones with mutually opposite vector orientation of magnetic field divided by an area free from the effect of magnetic field having width greater than **t,** wherein at least one roller closely below the crystalliser and at least one other roller located at least 0.5 m below the electromagnet are provided with a supply of direct current of intensity 1000 to 2200 A.

[0015] According to another preferred embodiment of the device, at least one linear motor may be placed below the electromagnet on the narrower side of the transverse section of the billet having size **t** in order to provide transportation motion of the magnetically treated molten metal.

[0016] According to another embodiment, the device for billets having width **b** < 4**t** may contain at least one pair of linear motors attached to the opposite narrower sides of the transverse section **t** of the billet in order to induce mutually opposite direction of the molten metal peripheral flow motion in order to develop perpendicular circulation motion of the molten metal.

[0017] According to another embodiment, the device for billets having width **b** > 4**t** may contain at least one pair of linear motors attached to the opposite narrower sides of the transverse section **t** of the billet in order to induce downwardly directed motion of the molten metal returning as one common flow ascending around the central vertical upward through the operation area of the electromagnet up to the crystalliser.

[0018] A method of controlling the solidification process of the billet based on the molten metal processing by means of magnetic field affecting a certain part of the billet with molten metal. Magnetic field as such is in the analysis of electromagnetic methodology typically considered only as an intermediary necessary to produce electromagnetic forces; however, it has been recently found out that magnetic field is a factor actively and independently affecting the solidification process. The detected level of influence is explained by effect of magnetic field on temperatures and kinetics of phase changes of solidification. The nature of the magnetic field influence on the solidification process is confirmed by the differential thermal analysis (DTA) results based on comparison of cooling curves of technical iron and Al_2O_3 in magnetic field having induction values 0.06 and 0.12 T. In measurements magnetic field had an effect from the moment of Fe sample melting during entire time of its cooling. The DTA results have revealed that magnetic field shifts the temperatures of phase changes of the primary crystallisation of steels toward lower values and has overall influence on their kinetics affecting the thermodynamic conditions of solidification.

[0019] At cooling rate of 50÷100 K/min. close to the conditions of continuous casting magnetic field having induction 0.06 to 0.12 T produces reduction of liquidus equilibrium temperature by 8 to 12 K and avalanche-like development of the phase changes of the primary crystallisation indicates recalescence. Increase in sub-cooling is explained by gain of internal energy brought into the solidifying molten metal by means of external magnetic field due to the presence of unpaired electrons in the atom shell causing rise of an uncompensated spin magnetic moment, like in case of paramagnetic metals and alloys. The detected increase in sub-cooling and avalanche-like development of the phase change of the primary crystallisation is phenomena also observed in the molten metals solidifying after metallurgic processing by means of modification. Processing of molten metal by magnetic field is equally manifested by grain refinement and preferred formation of columnar grains.

[0020] If magnetic field affects during the entire period of solidification it is capable of causing significant changes in the properties of the metal material after solidification. Changes, magnetic field is capable of causing, are generally considered reversible, but effects of molten metal treatment by magnetic field do not cease immediately and the effect of the treatment is maintained for 5 to 10 seconds. The time is sufficient for the molten metal to move from the place of employment of magnetic field to the volume of the surrounding melt by specifically produced transportation motion. In such case the molten metal treated by the effect of magnetic field is mixed with the remaining molten metal in its entire volume, be it in the crystalliser and in the areas above and below the electromagnet. The mixture of the treated and surrounded molten metal subsequently solidifies in the billet under favourable thermodynamic conditions with intense nucleation.

[0021] In case of technologies of electroslag remelting and casting, directed solidification is applied, where the billet solidifies very slowly with a very small liquid metal bath. Consequently, applying transport motion is neither necessary nor reasonably possible. Thus, in order to control the solidification process it is sufficient to expose to magnetic field the part of the crystalliser where there is a solidification zone and the molten metal bath. The crystalliser may not be manufactured from a ferromagnetic material. When casting billets longer than a vertical dimension of the electromagnet operation area the technological equipment has to provide such mutual position of the electromagnet toward the billet that during the entire time of billet making the solidification zone is positioned in the active zone of the electromagnet. The solidification process control by means of magnetic field application in the conventional casts is also possible in principle, but the braking effect of magnetic field is a major obstacle hindering replenishment of the solidification volume losses in the cast.

[0022] In the continuous casting of steel the control of the solidification process is not limited solely to the molten metal volume of the billet directly exposed to the effect of magnetic field, but to the entire volume, the magnetically treated molten metal is transported into during the period of 5 to 10 seconds. In order to reduce transportation requirements the amount of the molten metal exposed to the effect of magnetic field should be as voluminous as possible. For billet thickness **t** and width **b** the measurements of the electromagnet operation area should be at least $b.t^2/2$. The lower rate limit is around 0.1 $m.s^{-1}$ and the upper limit should not exceed 0.6 $m.s^{-1}$ in order to avoid noticeable washing-out of the two phase solidification zone and distribution of solid phase fragments that would serve as crystallisation nuclei causing polyhedral grain production. The lower rate limit 0.1 $m.s^{-1}$ is constrained by inevitable route length of the processed molten metal in the billet itself. The value of magnetic induction should exceed 0.04 T in order to provide sufficient effect on the solidification process and it is not suitable to exceed the value of 0.3 T, at which magnetic field generation becomes unduly demanding in terms of energy consumption. In the continuous casting of bulky billets with the transverse section exceeding 0.3 m^2 the molten metal solidifies in its centre longitudinally up to 10 metres and at a requirement for solidification process control in the entire volume of the billet the multi-stage control of the solidification process shall be applied with use of two or more electromagnets, each having its own system of induction of transportation motion.

[0023] The movement of the molten metal performs solely a transportation role and therefore may be produced by any means, either by induction of a linear motor or conductively by interaction of magnetic field of an electromagnet with direct electric current. Requirements for the motion velocity initially determine transportation requirements given by billet sizes and in order to minimise them, the operation area dimensions of the electromagnet should be maximal. The high energy efficiency of induction is an advantage of the conductive method of the molten metal transportation motion induction, wherein the amount of heat brought into the billet is lower than 2 kJ. A favourable distribution of motion in the molten metal volume contained in the billet is another advantage, since the excited electromagnetic forces produce across the billet a pressure gradient that induces intensive rotation motion above and below the electromagnet along the entire width of the billet. When multiple electromagnets are applied for induction of transportation motion a single common power source, which supplies to the billet are located before the first and after the last electromagnet, is sufficient.

[0024] The value of intensity of direct current passing the billet longitudinally is chosen to correspond to the relation $J.B.b' = p$ (Pa) the product of the current density value J ($A.m^{-2}$) in the molten metal and the lengths of molten metal section b' in the billet subjected to the effect of magnetic *field B* (T) was in the range of 20 to 150 Pa. The required amount of current in the three-dimensional embodiment of Figs. 3 and 4 is 500 to 1000 A. The value of the current density with respect to the transverse section of the entire billet consisting of a solidified surface layer and molten metal in its centre is in the range of 1200 $A.m^{-2}$ to 120 000 $A.m^{-2}$. In the embodiment according to Fig. 5 with respect to the considerably shorter sections of the molten metal the value of direct current passing the billet longitudinally is 1000 to 2200 A. The direct current inducing transportation motion of molten metal in the billet can have a pulsating component.

[0025] In addition to inducing transportation motion in interaction with magnetic field of the electromagnet, direct current as such also participate in the solidification process control. Current flow I along the billet induces circular magnetic field $\nabla\times\boldsymbol{B} = \mu(\nabla\times\boldsymbol{H})$ around the symmetry axis of the billet having effect around as well as in the billet. The mutual interaction of electric current I having density **J** with circular magnetic field $\nabla \text{x}\boldsymbol{B}$ induces concentrically operating pressure p in radius r in the molten metal having permeability $\mu = \mu_0\mu_r$. The value of the concentrically operating pressure in radius r shall be $p = \mu J^2 r^2/4$. Electrically poorly conductive inclusions are subject to inconsiderable forces and are carried away from the current flow axis towards the billet walls. The motion velocity of inclusions in a direction outward the centre is substantially higher than would correspond to the low level of centrifugal forces, as due to the non-potential action of electromagnetic forces around the inclusions micro-whirls orientated in the space arise so that they move away inclusions radially from the centre to the edges.

Brief description of the pictures on the drawings

[0026] A method of controlling the solidification process of continuously cast steel according to the invention will be explained in more details on drawings, where Fig. 1 is the DTA curves of technical Fe. Fig. 2 illustrates induction of molten metal motion by a linear motor and Fig. 3 shows a conductive method of induction of molten metal motion by interaction of magnetic field of an electromagnet with direct current. Fig. 4 illustrates a nature of the conductively induced circulation motion of the molten metal in a billet and Fig. 5 shows a nature of the molten metal motion with two pairs of circulating flows with an opposite sense of rotation above and below the electromagnet.

Exemplary embodiment

[0027] It is understood that various embodiments according to the invention are introduced for illustrational purposes and not as limitations of technical solutions. By using no more than a routine experimentation persons skilled in the art shall find or will be able to find out many equivalents to the specific embodiments of the invention. Such equivalents shall also fall within the scope of the following patent claims. An optimal design of construction cannot cause any problem to persons skilled in the art; therefore these features have not been addressed in detail.

Example 1

[0028] A method of controlling the solidification process according to the invention has been used for controlling the solidification process of a low carbon steel billet having a transverse section 0.2 x 0.2 m continuously cast into a water cooled crystalliser. An electromagnet having an operation area 0.24 x 0.24 m and height 0.12 m placed 0.7 m below the crystalliser was utilised for controlling the solidification process. The mean value of magnetic induction in the operation area of the electromagnet was 0.072 T. The value of magnetic induction in the surroundings of the solidification zone was around 0.1 T. Transportation motion of the processed molten metal was induced by interaction of magnetic field of the electromagnet and separately supplied direct current of intensity 120 to 800 A. The direct current was gained by six-way three phase rectification having approximately 5% pulsating component.

[0029] A nature of the macrostructure, degree of refinement of the primary structure and modifications in distribution of inclusions were the criteria for judging efficiency of the process control. When examining a degree of admixing it was found out that when current of 700 A was applied on a surface and in a geometrical centre of the billet the carbon content was 0.12% and at the junction of the surface and the centre the carbon content was 0.11%. At the current flow of 120 A and the molten metal flowing velocity of approximately 0.07 $m.s^{-1}$ insignificant grain refinement and enlargement of the columnar grain zone by approx. 10% could be observed in a transverse section of the billet. At current values exceeding 300 A a pouring shell border could not be identified. At current 550 A and the molten metal flowing velocity approximately 0.16 $m.s^{-1}$ the grain refinement was more significant and the columnar grain zone was enlarged to 95% of the transverse section. At current 700 A and the molten metal flowing velocity of approximately 0.18 $m.s^{-1}$ the structure consisted of fine columnar grain in almost entire transverse section with only an indistinctive area of polyhedral grains in the centre. During sample preparation for metallographic tests, the lower etchability observable in steel treated by magnetic field and current of 120 A has been found out and the etchability was worsening with increasing current density. At currents of 700 to 800 A the etching time increased by 50 to 100% compared to the steel not treated by magnetic field was necessary to apply for all etching agents. Steel purity tests according to DIN 50602 method indicated that at current of 700 A a significant reduction to 8 to 13% of occurrence of sulphide and oxisulphide inclusions having dimensions below 6 μm in magnetically untreated steel was recorded, which corresponds to the purity level 0 to 1 and represents steel of high metallurgical purity. At current 700 A the current density reached a value of 1.75 $A.cm^{-2}$ with respect to the entire transverse section of the billet or approximately 0.6 $A.cm^{-2}$ in the molten metal in the central part of the billet and such intensity may be regarded an optimum value in terms of manufacture qualities. At values of current 120 to 300 A an occurrence and distribution of inclusions are practically unchanged with respect to the referential magnetically untreated steel, and only at current 800 A and flowing velocity of the molten metal approximately 0.2 $m.s^{-1}$ a decrease in the number of inclusions to the level of 20 to 40% in comparison to the magnetically untreated steel was determined. At current value of 800 A the macrostructure consisted of fine columnar grains insignificantly orientated in the direction of the cooling gradient through the entire transverse section. In the whole range of values of the applied current "white stripes" did not occur in the macrostructure. Total consumption of electric energy of the operation of the device was approximately 9.2 kW. The cited rate values are calculated, as the actual values could not be measured.

Example 2

[0030] A method of controlling the solidification process according to the invention was used for the control of the solidification process of electroslag casting billets of austenitic steel Cr17.7-Ni9.7 - Mn1.2 into a water-cooled copper crystalliser. The following parameters were used for re-melting: diameters of the smelted billet ø 81 x 220 mm, voltage U = 40 V, current I = 1000 A. Dimensions of the operation area of the electromagnet provided for the billet to be exposed to magnetic field in the range of 0.09 to 0.135 T during the whole time of solidification without a need of motion of the crystalliser or transportation motion of the molten metal. The billet material was intended for production of instruments for glass pressing, which determined the scope of the material properties tests. The values of strength and high strain-rate of the smelted steel in a molten state and of corrosion resistance established in two environments, namely by boiling in 65% HNO_3 and in the solution of 30% H_2SO_4 + 1.5% NaCl were determined. The observed increase of corrosion resistance after magnetic field treatment was maintained even after thermal processing that consisted of dissolving and stabilising annealing. The Table indicates the values of corrosion resistance in molten state and the state after thermal processing including a basic malleable material (ZM). The cited values are in good agreement with the results of microstructure tests, where meshing and σ-phase clusters typical for cast steel were absent in the steel solidified under application of magnetic field in the range of 0.09 to 0.135 T, decrease in the content and more favourable distribution of δ-ferrite also occurred. DTA tests also confirmed absence of σ-phase. A small amount of inclusions containing approximately 36% Cr, 57% Fe and 5.7% Ni occurred in the microstructure of steel treated by magnetic field. Sigma phase having a typical composition 50% Cr, 46% Fe and 3.5% Ni responsible for deterioration of mechanical properties and corrosion resistance in steel solidifying under application of magnetic field was not identified, it occurred only in the structure of ET cast steel not treated with magnetic field.

	In molten state		After thermal treatment		
	Magnetic field (T)			Magnetic field (T)	
Corrosion rate ($g.m^{-2}.h^{-1}$)	0	0.115	ZM maleable	0	0.115
Boiling in 65% HNO_3	12.54	1.69	0.942	3	0.6
30% H_2SO_4 + 1.5% NaCl	6.17	2.33	0.362	0.66	0.24
Rm (MPa)	579	530	---	---	---

(continued)

	In molten state		After thermal treatment		
	Magnetic field (T)			Magnetic field (T)	
KCU3 (J.cm^{-2})	131	189	---	---	---

Example 3

[0031] In this example of the embodiment of the invention the execution of the method of controlling the solidification process of the continuous cast steel is described, where the control of the solidification process of a billet having a transverse section in a shape of a circle, square or rectangle is carried out in the entire volume of the molten metal contained in the billet, the molten metal treated by linear magnetic field having induction of 0.04 to 0.3 T in an operation area of electromagnet **5** can be transported during a period of 5 to 10 seconds by speed of 0.1 to 0.6 m.s^{-1}. The nature of influence of magnetic field on the solidification process is indicated on Fig. 1 that clearly shows that magnetic field shifts the phase transitions temperatures of primary crystallisation of steels toward lower values and has overall influence on their kinetics affecting thermodynamic conditions of solidification. A support of development of columnar grains, suppression of formation of polyhedral grains, refining of primary structure and targeted intervention into the forming and distribution of primary and accompanying structural components is an outcome.

[0032] In the embodiment indicated on Fig. 2 the molten metal through tube **1** enters crystalliser **2**, where billet **4** with molten metal **3** in its centre is formed. After proceeding through a pair of guide rollers **6** and **7** the billet enters electromagnet **5** placed 0.5 to 2 m below crystalliser **2**. Movement of the molten metal is produced by induction of linear motor **9**. In order to minimise effects of the flow on a solidified surface layer of the billet linear motor **9** is attached to a narrower side of the billet transverse section having dimension **t** that better withstands the metallostatic pressure strains and is positioned below electromagnet **5**, where thickness of solidified surface layer **4** is greater. An advantage of the solution is that it only requires use of common technical means and methods of installation on continuous casting machine that are tried and tested in practice of continuous casting. A nature of the induced motion reaching the top velocity on interface of the solidified surface layer in molten metal of the billet while downwardly it decreases exponentially is a disadvantage.

[0033] In order to provide effective transport of the processed molten metal from central areas of the operation space of electromagnet **5** into a whole volume of the molten metal in the billet, it is suitable to use linear motor **9** placed both below electromagnet **5** and an opposite shorter side of the billet. At width of the billet $\mathbf{b} < 4\mathbf{t}$ it is desirable that both linear motors produce molten metal motion in a mutually opposite direction forming transverse circulation motion speeding up transport of magnetically treated molten metal from the centre of the electromagnet into the whole volume of molten metal in the central area of the billet. At width of the billet $\mathbf{b} \geq 4\mathbf{t}$ it is desirable that both opposite linear motors produce flow in the same direction and be it downward. Both lateral descending flows shall meet in the centre of the billet and ascend upward as one common flow through the operation area of electromagnet **5** to crystalliser **2**. An advantage of the solution is that the central flow reduces intake of impurities together with molten metal from the area of inlet tube **1** to the developing billet. In order to produce a transverse motion of molten metal special linear motor **9** may also be used, positioned below electromagnet **5** that can be integrated into a common unit with guide roller **8** that has alternative ferromagnetic and non-magnetic sections at the point of poles and gaps, or with the multiple additional guide rollers made of non-magnetic material.

Example 4

[0034] The exemplary embodiment of the invention describes implementation of the method of controlling the solidification process of the continuously cast steel, where the control of the solidification process of a billet having a transverse section shape of a circle, square or rectangle, is carried out in the entire volume of molten metal of a central zone of the billet, molten metal treated by magnetic field having induction of 0.04 to 0.3 T in the operation area of electromagnet **5** is transported during a period of 5 to 10 seconds by speed of 0.1 to 0.6 m.s^{-1}. The embodiment on Fig. 3 illustrates a conductive method of the molten metal motion in the billet induced by interaction of magnetic field **B** of electromagnet **5** and direct current **I** conducted to the billet from indicated source **10** by the first pair of rollers **6** and **7** below crystalliser **2** and by a pair of withdrawal rollers **11** and **12** in the distance of at least 0.5 m below electromagnet **5** positioned 0.5 to 2 metres below crystalliser **2**. Magnetic field **B** permeates the billet in a direction close to perpendicular to the longitudinal axis of the billet and direct current **I** having intensity of 500 to 1000 A passes the billet longitudinally and may have a pulsating compound. Generated electromagnetic forces **f** in the volume of molten metal **3** in the billet develop a linear motion in the plane perpendicular to the direction of lines of magnetic field **B** as well as a pressure gradient inducing two separate circulation flows of molten metal above and below electromagnet **5** as shown on Fig. 4. The trajectory motion of the magnetically treated molten metal in the billet can be modified by incorporating another stage of the solidification process control implemented by supplementing in the distance exceeding 2 metres below the crystalliser at least one additional electromagnet that also generates magnetic field having induction of 0.04 to 0.3 T, wherein at least at the billet area with the operating spaces of the electromagnets direct current flows conducted to the billet by the rollers closely below the crystalliser and by the rollers below the lowermost electromagnet. When applying multiple electromagnets, one common power source, which inlets to the billet are situated before the first and after the last electromagnet, is sufficient for induction of transportation motion. Withdrawal of billets having dimension **b** > 2**t** requires a high number of rollers with small spacings. In case of electromagnet **5** having a height of an operation area greater than 0.5 **t** in order to make the sufficiently large operation area it is suitable to use guide roller **5.1** made of a ferromagnetic material, which would be part of a magnetic circuit. In order to reduce losses caused by scattering of magnetic field into the surroundings adjacent rollers **7** and **7.1** are made of a non-magnetic material, such as austenitic steel. A support of development of columnar grains, suppression of formation of polyhedral grains, refinement of primary structure and targeted intervention into the formation and distribution of primary and accompanying structural components is the outcome.

Example 5

[0035] This exemplary embodiment of the invention describes implementation of a device for controlling the solidification process of the continuously cast steel, where at the solidification process control of massive billets having thickness **t** > 0.2 m and width **b** > 5**t**, be it even at a great distance of electromagnet **5** from crystalliser **2**, a circulating flow of molten metal in the billet would be excessively intense on a surface in crystalliser **2**. Fast motion would disrupt the protection function of the casting powder and sweep the impurities from a surface into a molten metal bath in crystalliser **2**. In such case it is preferred to induce pairs of mutually oppositely directed circulation flows below and above electromagnet **5**, said is achieved in the electromagnet by developing two zones of magnetic field of mutually opposite orientation of magnetic field vector **B** divided by an area lacking magnetic field exertion of a width greater than **t**, as indicated in the embodiment on Fig. 5. Circulation flows above electromagnet **5** are joined in the centre so that the molten metal motion in the centre of the billet proceeds against inlet tube **1** thereby partially limiting entry of impurities from crystalliser **2** into the central area of the solidifying billet. Transportation motion of molten metal in the billet is induced by interaction of magnetic field **B** in both zones of electromagnet **5** and direct current **I** of intensity 1000 to 2200 A supplied between the rollers below crystalliser **2** and below electromagnet **5**.

Industrial applicability

[0036] A method according to the invention may be utilised for controlling the solidification process at continuous casting of technical metal materials, in particular of steels, as well as of metals and metal alloys that are paramagnetic at the liquidus temperature, in order to refine the structure, support development of columnar grains and intervene into formation and distribution of primary and accompanying structural components.

Claims

1. A method of controlling the solidification process of continuously cast metals and alloys, in particular steels, that are paramagnetic around the liquidus temperature aiming at support of forming columnar grains, suppression of forming polyhedral grains, refining a primary structure and targeted intervention into forming and distribution of primary and accompanying structural components, **characterised in that** during the solidification process the solidifying molten metal is treated by an effect of linear magnetic field having induction of 0.04 to 03 T generated by at least one electromagnet, wherein magnetically treated molten metal (3) from the active zone of at least one electromagnet (5) positioned 0.5 metre to 2 metres below a crystalliser (2) is transported with velocity of 0.1 to 0.6 $m.s^{-1}$ by means of transportation motion induced by any manner, in particular conductively or by induction of at least one linear motor (9), wherein the solidification process control is applied in the entire molten metal volume, the magnetically treated molten metal (3) is transported into during 5 to 10 seconds.

2. A method of controlling the solidification process according to Claim 1, **characterised in that** transportation motion of magnetically treated molten metal (3) from the active zone of at least one electromagnet (5) is induced by interaction of linear magnetic field generated by at least one electromagnet and direct electric current of intensity of 500 to 1000 A conducted to a billet (4) by the rollers (6 and 7) above the electromagnet and by the rollers (11 and 12) below the electromagnet, wherein magnetic field pervades the billet with molten metal in a direction close to perpendicular to the longitudinal axis of the billet, and direct electric current passes the billet longitudinally.

3. A method of controlling the solidification process according to Claim 1, for billets having thickness **t** > 0.2 metre and width **b** > 5**t, characterised in that** transportation motion of magnetically treated molten metal (3) from the active zone of at least one electromagnet (5) is induced by interaction of linear magnetic field generated by at least one electromagnet and direct electric current of intensity of 500 to 1000 A conducted to the billet (4) by the rollers (6 and 7) above the electromagnet and by the rollers (11 and 12) below the electromagnet, wherein magnetic field pervades the billet with molten metal in a direction close to perpendicular to the longitudinal axis of the billet, and the direct electric current passes the billet longitudinally.

4. A method of controlling the solidification process according to Claim 2 or 3, **characterised in that** direct electric current passing the billet longitudinally also incorporates a pulsating compound.

5. A device for implementing the method according to any of Claims 1 to 4, **characterised in that** the first electromagnet (5) positioned at a distance of 0.5 to 2 metres below the crystalliser (2) and at least one other electromagnet (5) generating linear magnetic field having induction of 0.04 to 0.3 T positioned at a distance exceeding 2 metres below the crystalliser (2).

6. A device according to Claim 5, **characterised in that** the electromagnet (5) has the height of the operation space greater than a half of thickness t of the billet.

7. A device according to Claim 6, **characterised in that** the electromagnet (5) is integrated with a withdrawal roller (5.1) into a common unit at width of the billet **b** ≥ 2**t.**

8. A device according to any of Claims 5 to 7, **characterised in that** at least one roller (6) positioned above the electromagnet (5) closely below the crystalliser (2) and at least one other roller (12) at a distance of at least 0.5 metre below the lowermost electromagnet (5) are provided with a supply of direct electric current of intensity of 500 to 1000 A.

9. A device according to Claims 5 to 7 for billets of thickness **t >** 0.2 metre and width **b** > 5**t, characterised in that** in order to limit motion of impurities from the crystalliser (2) to the billet (4) including molten metal (3) the first electromagnet (5) is provided with two operation zones having mutually opposite vector orientation of magnetic field divided by an area free from the effect of magnetic field having width greater than the thickness of the billet **t.**

10. A device according to Claim 9, **characterised in that** at least one roller (6) above the electromagnet (5) closely below the crystalliser (2) and at least one other roller (12) at a distance of at least 0.5 metre below the lowermost electromagnet are provided with a supply of direct electric current having intensity of 1000 to 2200 A.

11. A device according to Claims 5-7, **characterised in that** it further comprises at least one linear motor (9) attached to a narrower side of the transverse section **t** of the billet (4) with molten metal (3) is positioned below the electromagnet (5) in order to provide transportation motion of the magnetically treated molten metal (3).

12. A device according to Claim 11 for billets having width **b** < 4**t, characterised in that** at least one pair of linear motors (9) is attached to opposite narrower sides of the transverse section **t** of the billet in order to induce mutually opposite motion direction of lateral flows of molten metal (3) in the billet in order to produce transverse circulation motion of molten metal (3).

13. A device according to Claim 11 for billets having width **b** > 4**t, characterised in that** at least one pair of linear motors (9) is attached to opposite narrower sides of the transverse section **t** of the billet in order to induce downwardly directed motion of lateral flows of molten metal (3) returning as one common flow ascending around the central vertical of the billet upward through the operation area of the electromagnet (5) up to the crystalliser (2).

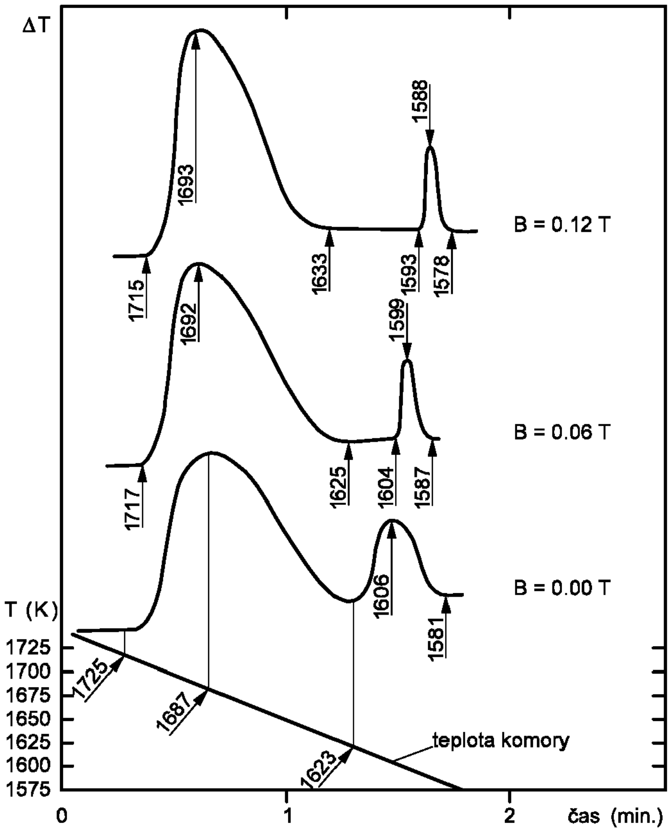
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Fig. 1

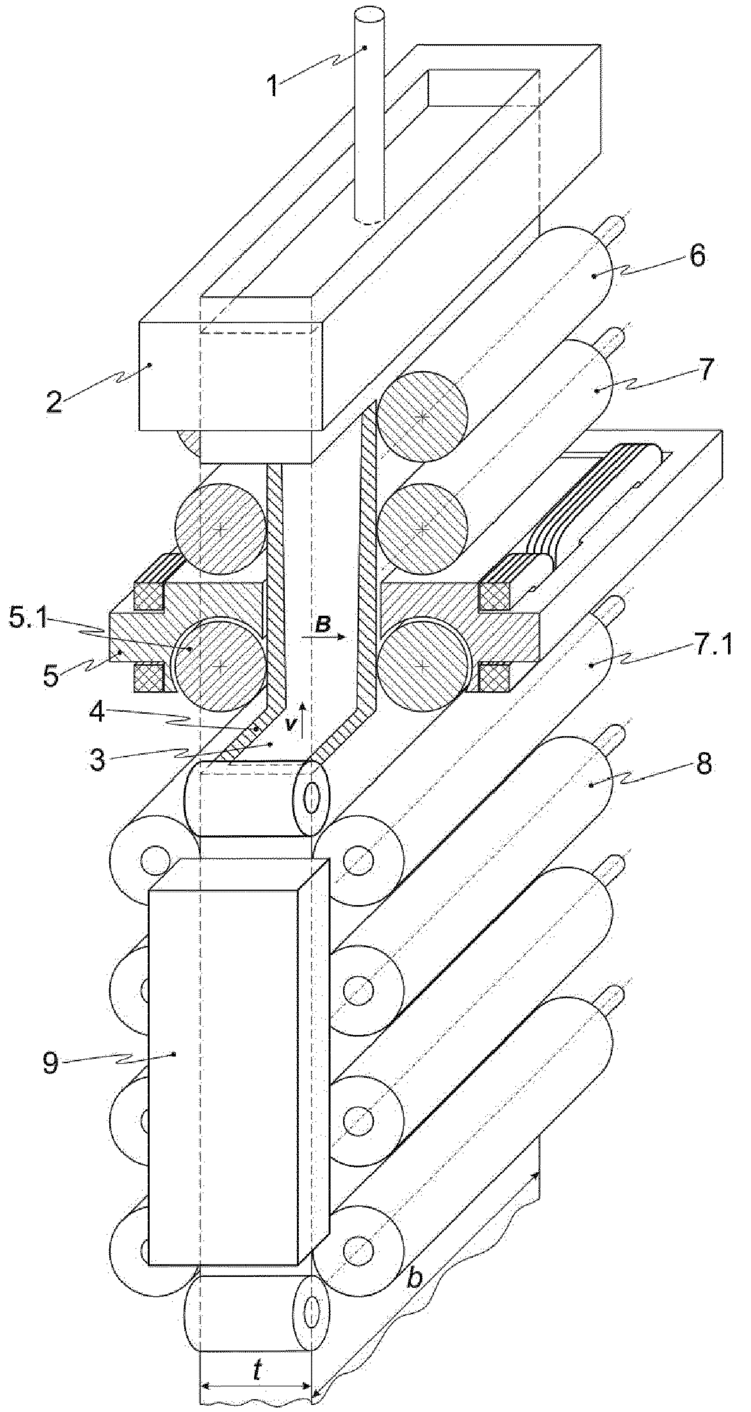

Fig. 2

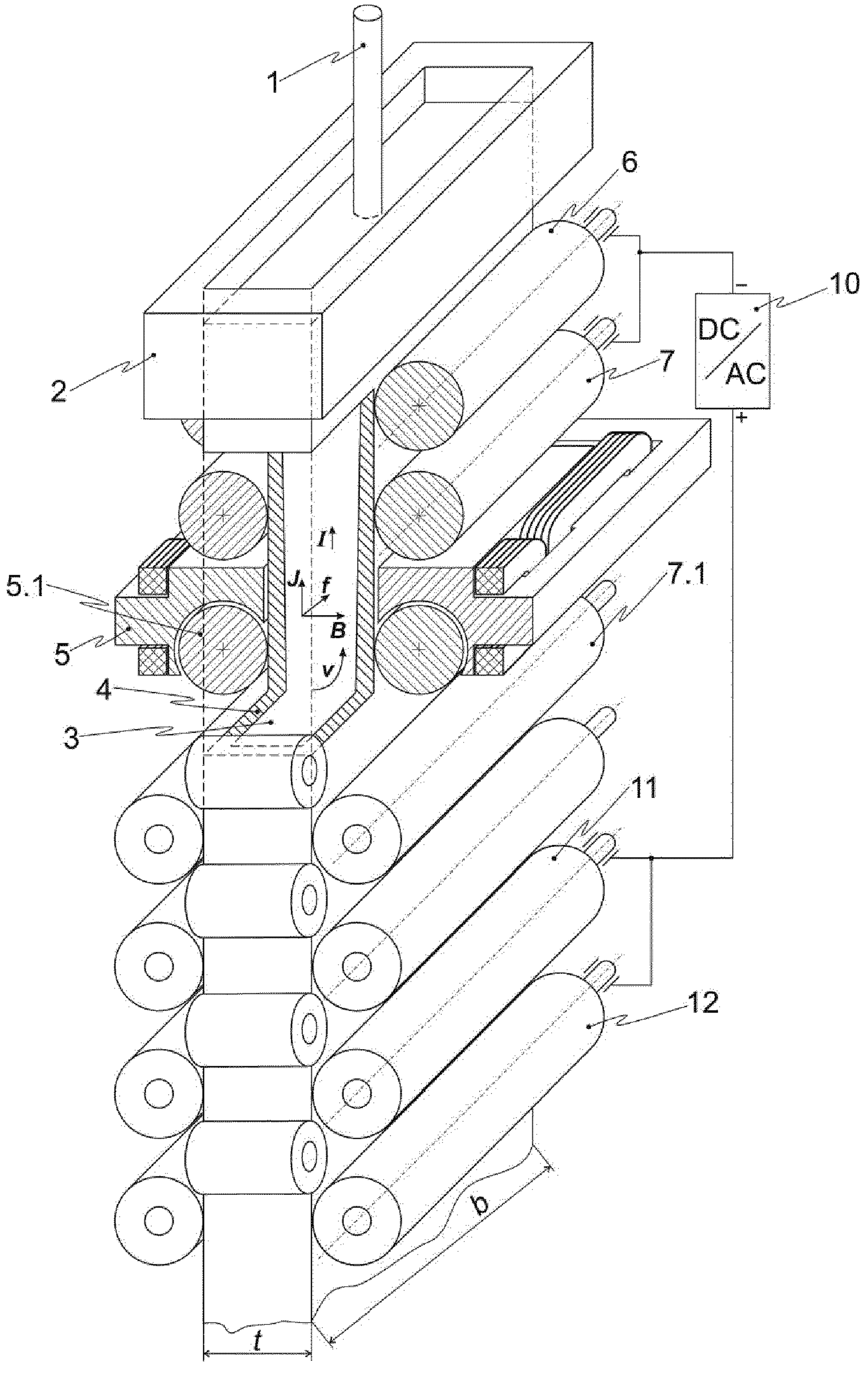

Fig. 3

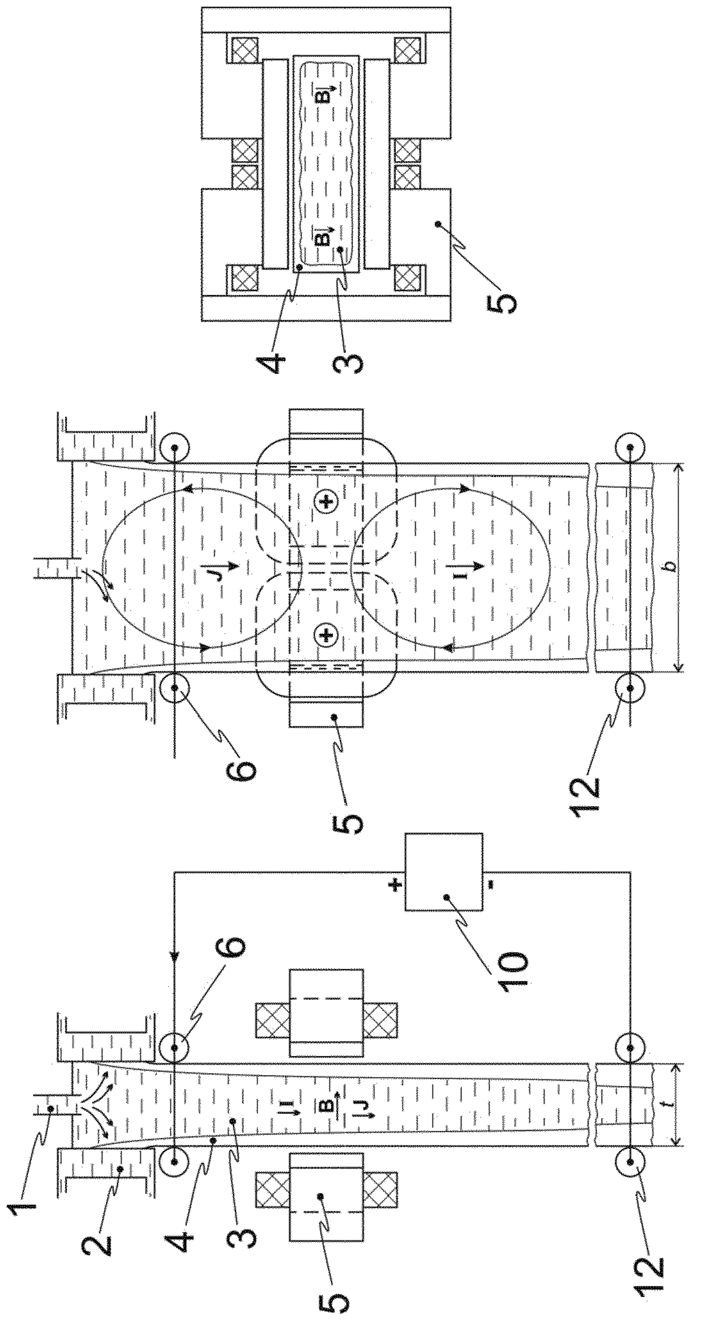

Fig. 4

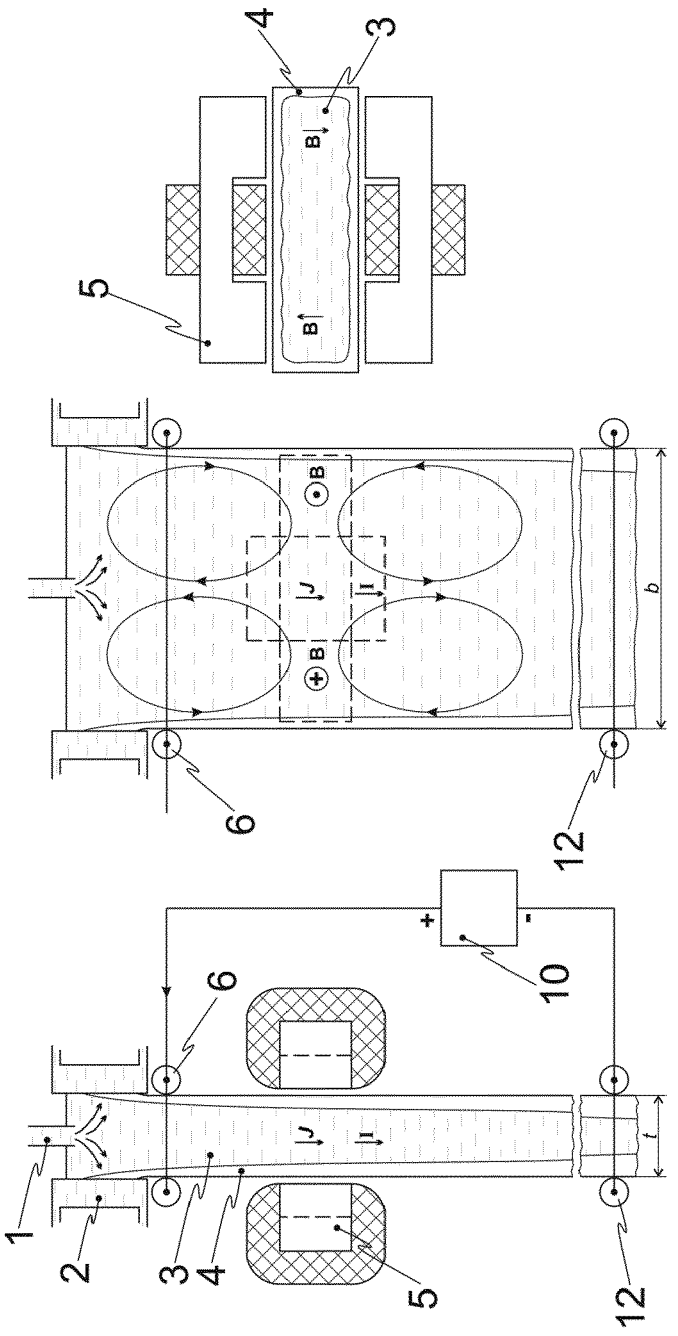

Fig. 5

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EUROPEAN SEARCH REPORT

Application Number
EP 17 16 8423

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X Y	WO 2015/162039 A1 (THYSSENKRUPP STEEL EUROPE AG [DE]; THYSSENKRUPP AG [DE]) 29 October 2015 (2015-10-29) * abstract * * page 14, line 10 - page 16, last line; claims 1, 2, 10, 11, 16, 17, 21, 24; figures * -----	1 2-13	INV. B22D11/115 B22D11/12
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TECHNICAL FIELDS SEARCHED (IPC)

B22D

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
The Hague	7 August 2017	Hodiamont, Susanna

CATEGORY OF CITED DOCUMENTS

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