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Analysis and development of modern concepts on the rhomboidity formation nature for continuously cast billets. Part 2

Concepts on the rhomboidity formation nature for continuously cast billets were developed and detailed within the framework of the approach proposed earlier. At the same time, the practical orientation of the research results was a priority goal. The adduced regularities and mechanisms of the rhomboidity initiation and growth processes are based on the provisions known from technical mechanics and strength of materials. Operation and maintenance experience for billet continuous casting machines was also taken into account. The achieved level of understanding of these regularities allowed to explain the increased addiction for medium carbon steel billets to rhomboidity. Moreover, the mechanism of occurrence for the extremely undesirable so-called "autocatalytic" character of the rhomboidity formation process was explained. Based on the research results, new solutions to reduce the billet rhomboidity were also proved and proposed. A noticeable improvement in the rhomboidity billet quality was achieved during the implementation of technical, technological and organizational measures, both known and new. The average annual sorting index on the rhomboidity for medium carbon steel billets 125x125 mm was reduced from 1.79 to 0.08 % for 5 years after the start of research and measures implementation. Those measures that, due to objective reasons, were not implemented, including for operational (during casting) reduction of rhomboidity, can be transferred to interested structures.

Key words: rhomboidity, spatial deformation, thermoelastic stresses, coefficient of linear thermal expansion (compression), complex strength, bending and torsion strains, stability, linear and angular displacements, tolerances.

Understanding of the nature and regularities of various phenomena that reduce the technological processes efficiency in metallurgy, including steel continuous casting (SCC), is a necessary condition for their improvement. The phenomenon of spontaneous (in the casting process) transformation of a square profile of continuously cast billets (CCB) into a rhombic one, studied in this article, reduces not only the productivity of billet continuously cast machines (CCM), but also the yield index. The need for increased attention to adjustment and maintenance of the CCM's casting arc equipment, including mould, its oscillation mechanism, monitoring the mould copper tubes state, foot and support guiding rolls, branch pipes and water sprayers of secondary cooling (SC), water quality, etc. complicates the CCM's operation, requires highly qualified personnel.

"Starvation" over the past decades of the rhomboidity problem for billet CCMs is largely due to the lack of a clear understanding of the regularities of the rhomboidity formation process activation, the influence mechanisms for a variety of factors, as well as the available opportunities for active counteraction to them. The current situation, in our opinion, is partly due to the fact that the SCC technology is located at the junction of various fields of knowledge, including those that are quite far from those that form the foundation of metallurgical science. To this we can add the obvious fact that the peak of interest to the applied research in metallurgy is in the past. Considering that now this research is carried out mainly at technical universities, one can note that the lack of researcher's production experience, unfortunately, cannot be compensated by the high theoretical level of their

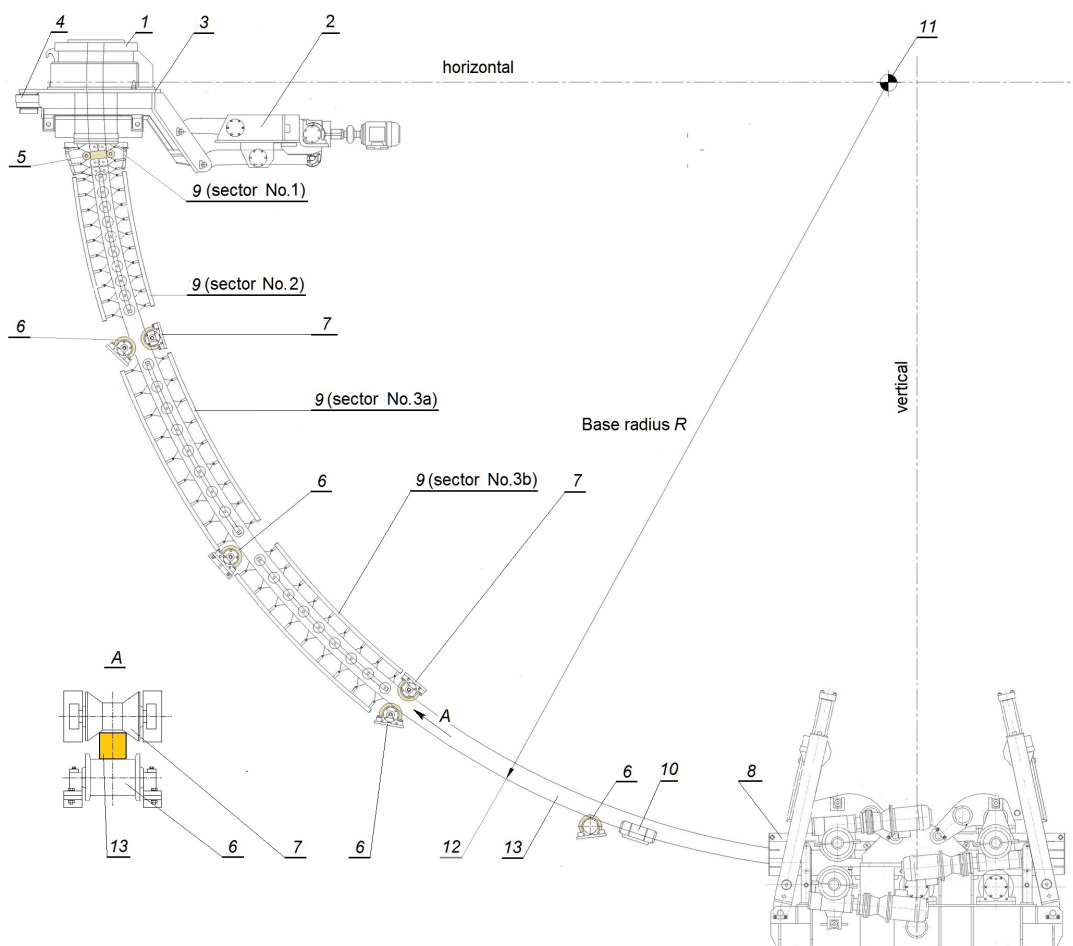


Fig. 1. M-B-SCZ system on the example of DANIELI billet CCM (type 3BLC08/06), put into operation at MMZ ISTIL UKRAINE in 1999 (1 – mould; 2 – lever type mould oscillation unit (MOU) with electromechanical drive; 3 – oscillating supporting table; 4 – pneumatic springs to balance the oscillating masses; 5 – set of foot rolls; 6 – support guiding rolls; 7 – centering pinch rolls; 8 – withdrawal and straightening unit (WSU); 9 – SCZ with water sprayers sets installed on stainless steel branch pipes arranged on the 4 sides of the billet; 10 – guiding delimiters of billet lateral deviation; 11 – base curvature center; 12 – strand base radius R ; 13 – billet)

training. Meanwhile, production experience, as will be shown below, is an important condition for the developing objective concepts about the nature of this undesirable phenomenon (rhomboidity of CCB).

Let us consider in detail those provisions that follow from the approach proposed in the first part of this article [1]. Remind, that the violation of the uniform contact conditions for the billet and mould, that triggers the profile distortion process, should be considered, first of all, as a result of the billet three-dimensional elastic deformation within CCM's casting arc. To determine this deformation, it is necessary to study "Mould – Billet – Secondary Cooling Zone" (M-B-SCZ) system (Fig. 1). In this case, various technical (design features of the M-B-SCZ system elements, level of their maintenance and condition, precision of their positioning and adjustment, etc.) and technological (temperature-speed mode of casting, cooling parameters, steel chemical composition, etc.) factors, that, as practice shows, greatly affect both the occurrence probability and rhomboidity magnitude, are easily integrated into concepts in question. The billet deviation from the nominal position (technological axis of the strand) is a consequence of its spatial deformation. This deviation violates the concentric position of the

formed billet profile relatively to the mould tube and, as a result, triggers its distortion process.

In the general case, the profile deviation can be adduced as a result of its linear displacements in the transverse direction (in the YOX plane) and angular rotation (relatively to the longitudinal Z axis) (Fig. 2). As evidence indicating the presence of such deviations, one can cite facts well known from the practice of billet CCM. For example, this is indicated by such a fact as the unequal lunule depths on the mould tube outward surfaces from the centering screws along the perimeter. This is observed at "rhombic" strands. The lunule depths from the centering screws indentation on some faces can reach 1–2 mm, while on another faces they may be absent. In addition, the fact of extremely uneven (along the profile perimeter) wear of the inward working surface of some mould tubes is well known.

Precision tube positioning in the mould is performed using two or three rows of centering screws spaced apart in height (Fig. 3). It is necessary both to ensure tube concentricity with the strand longitudinal axis, and to equalize the conditions for its cooling (primary cooling circuit). The thermal gaps adjustment differing somewhat according to the screw rows is provided (during the mould

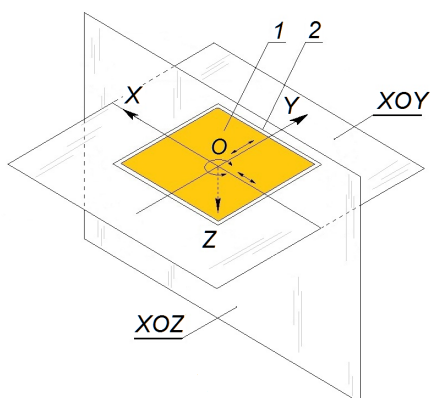


Fig. 2. Possible linear and angular deviations for the billet profile (normal cross section) in the mould (1 – billet profile; 2 – working (contact) perimeter of the mould tube; XOZ – vertical plane, in which the axis of the strand is located; XOY – plane of normal cross section (transverse); double-edged arrows show possible billet profile displacements in the XOY plane)

assembly) under the manual in order to compensate the tube thermal expansion. In general, used mould design solutions provide the possibility of some tube position correction (so-called "self-alignment") during the casting process. Billet rhomboidity during the casting of several heats series, as a rule, gradually decreases and stabilizes for this reason. This circumstance explains such fact, well known from practice, that for CCMs, where only one billet profilesize is cast, the rhomboidity problem sharpness is practically absent. At MMZ ISTIL UKRAINE

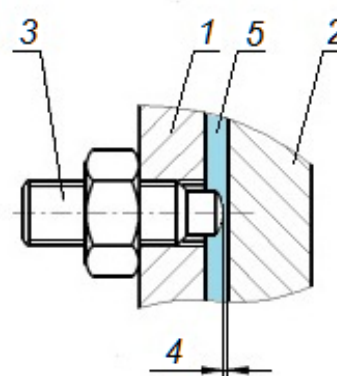


Fig. 3. Centering tube in the billet CCM mould (1 – stainless steel "jacket" of the mould; 2 – mould tube; 3 – centering screw with a lock nut; 4 – adjustable thermal gap with thickness of 0.3–0.4 mm; 5 – water "jacket" with thickness of 3–4 mm)

100 % of CCB was produced for sale, the portfolio of orders included 5 square profilesizes and 5 round profilesizes. Change of profilesizes under this circumstance was carried out up to 5–6 times a month, so the rhomboidity problem was topical.

The results from the measurement protocols performed using the VATRON MoldChecker laser measuring device were analyzed at MMZ ISTIL UKRAINE to identify the features of the mould tubes wear character. This device provides both 3-d picture of the billet working surface wear relatively to billet initial profile (at the time of supply), and the foot rolls actual position (Fig. 4).

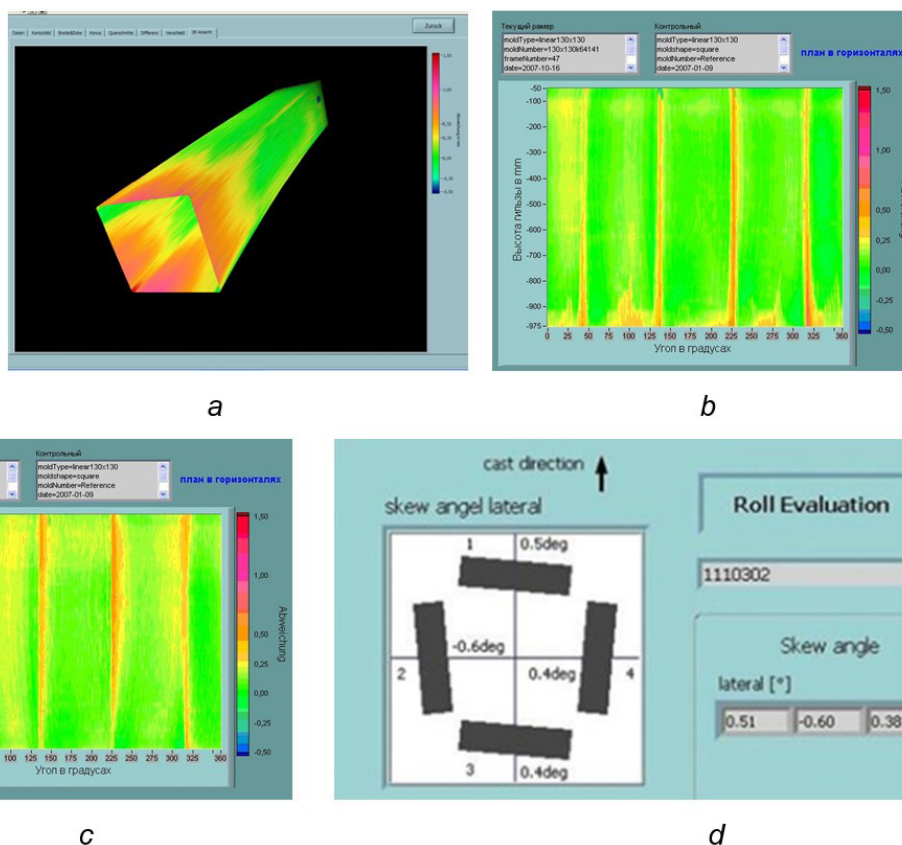


Fig. 4. Graphic files from the measurement protocols of the VATRON MoldChecker for the mould tubes wear and the foot rolls position on "rhombic" strands: a – isometry of the tube working surface wear; b and c – the tube surface involutes for intense wear of the near-corner zones; d – foot rolls position

In the course of this analysis, it was found that the simultaneous wear of all four near-corner tube zones at all operation stages is a fairly typical phenomenon (Fig. 4 b, c). Significant wear of the tube near-corner zones with a cast tonnage of less than 1000 tons is shown in Fig. 4 b. Tubes with high wear of the near-corner zones are usually decommissioned ahead of schedule despite a small operation life (steel cast tonnage), since the use of such tubes significantly increases the billet rhomboidity probability, especially from medium carbon steel. The use of such tubes for casting of high-carbon steel can also lead to the formation of both near-corner cracks and longitudinal compression on the billet surface.

Obviously, that this wear type can be caused, first of all, by the angular deviation (rotation) of the billet profile relatively to the longitudinal Z axis through the billet's torsion. This moment deserves special attention when studying the features of stresses and strains in the billet under the action of various factors. *Active*¹ and *passive forces* act on the billet in the M-B-SCZ system. Active are the *potential forces of thermoelasticity*, gravity, as well as the forces acting from the pinch centering rolls. Passive forces are the so-called *reactions* from various type *supports*. The following assumptions can be used when preparing the *calculation scheme* for the M-B-SCZ system.

A billet formed within the billet CCM casting arc can, in the first approximation, be considered as a tubular bar with a curved axis and a changeable (along the length) rigidity seeing its changeable shell (wall) thickness. The longitudinal bar axis is a plane curve lying in the vertical XOZ plane. It should nominally coincide with the strand technological axis. Billet parts located in the mould and WSU can in the first approximation be considered, respectively, as having a *slide* and *rigidly fixed supports*. Support guiding rolls No. 2, 4 in the calculation scheme for the M-B-SCZ system shown in Fig. 1 can be defined as *hinged movable supports*, and No. 1, 3 (depending on the upper pinch rolls design) – as *slide* or *bi-slide supports*. The described M-B-SCZ system is *statically indeterminate*. A detailed analysis of the calculation scheme for this system and the solution methods known from the strength of materials are far beyond the frame of this study. So we will restrict ourselves to considering only those provisions that are necessary to understand the mechanisms and regularities of billet spatial deformation.

The stresses that arise in the formed billet and cause its spatial deformation can be created by two groups of factors. The first group includes factors caused by deviations of various elements of the M-B-SCZ system (mould tube; foot, centering pinch and support guiding rolls; WSU) relatively to their nominal position and uneven wear of their surfaces contacting with billet. The second group includes factors that influence the billet thermal state. For the second group factors the billet spatial deformation takes place only if its formation process is accompanied by the appearance of an asymmetric temperature distribution in billet normal cross section. The following factors can be attributed to the second group: violation

of the tundish metal jet concentricity with the longitudinal axis of the mould or features of the natural convection development in the billet liquid core at radial CCM. These factors are responsible for uneven heat transfer along the billet profile perimeter and heat fluxes at the solidification front. It, in turn, leads to thermal asymmetry of billet profile, that amplifies with an increasing in the casting speed and cast steel overheat. Thermal asymmetry is also caused by factors that result in non-uniform heat removal from the billet both in the mould and in the SCZ. These factors include uneven mould tube wear and tube misalignment in the mould, clogging and misalignment of the SC water sprayers, unstable casting speed and forced short-term stops during casting, for example, due to steel castability deterioration [2], etc.

It is important to note that the spatial deformation that triggers the billet profile distortion process can be caused by factors of both the first and second groups. At the same time, some factors of the second group can arise both independently and as result of the first group factors action, i. e. be secondary or induced. Therefore, the rhomboidity formation process can have a various and multifactor character. If, as shown in [3], it is accompanied by a constant change in the rhomboidity magnitude and direction (sign), then it is obviously that periodically there is both some growth and subsequent weakening of the profile distortion process. It is also obviously that the conditions necessary for the appearance of such rhomboidity "evolution" mode should differ from the conditions under which the profile distortion process is able to take, according to the some researchers, the so-called "autocatalytic", i. e. self-supporting character of the process with the end result in the form of nonchanging direction (sign) high rhomboidity [4].

Fig. 5 shows a noticeable transverse displacement (up to the prop against the roll flange) of the billet contact track on the 4th support guiding roll of the SCZ, disclosed at the "rhombic" strand. Such noticeable billet displacement from the strand axis is accompanied by



Fig. 5. Transverse displacement of the billet contact track on the 4th support guiding roll

¹Here and further in the text, the terms used in the relevant chapters of technical mechanics and strength of materials are in italics

uneven SC of the billet, since the SC water sprayers are aligned strictly relatively to this axis. Such displacement creates guaranteed conditions for the billet spatial deformation and the rhomboidity generation. It is important to emphasize that the billet spatial deformation process activation and subsequent profile distortion in the mould can be due to the factors of both groups indicated above, but achieving a self-supporting character for the profile distortion process requires specific conditions, that will be discussed below.

An explanation of increased addition for billets from medium carbon steel to rhomboidity that fully fits into the proposed approach framework and the provisions formulated on its basis seems to be as following. So, it is logically to assume that the reason for such addition can be associated with the intensity of spatial deformation, primarily due to the uneven billet cooling. The elementary volumes of an unevenly cooled elastic body cannot freely shrink, that leads to the appearance of thermoelastic stresses in it. In this case for isotropic material Hooke's law be generalized to include thermal effects. The total strain ε of each elementary volume in this case is the sum of its thermal $\varepsilon^{(T)}$ and mechanical $\varepsilon^{(M)}$ strains: $\varepsilon = \varepsilon^{(M)} + \varepsilon^{(T)}$ [5, p. 405]. Then, for the projection of the total strain on the X axis will be equal to:

$$\varepsilon_x = \varepsilon_x^{(M)} + \varepsilon_x^{(T)} = [\sigma_x - \nu(\sigma_y + \sigma_z)]/E + \alpha_l \Delta T.$$

Here α_l – CLTE(C) – coefficient of linear thermal expansion (compression), $^{\circ}\text{C}^{-1}$; ΔT – temperature change, $^{\circ}\text{C}$; $\sigma_x, \sigma_y, \sigma_z$ – projections of normal stresses along the X, Y, Z axes; ν – Poisson's ratio for steel; E – modulus of elasticity, MPa.

Considering that $\varepsilon_x^{(T)} = \varepsilon_y^{(T)} = \varepsilon_z^{(T)} = \alpha_l \Delta T$, the formulas for determining the projections of the total deformation of elementary volume ε_y and ε_z on the Y and Z axes will be similar for ε_x , but differ only in the part that defines $\varepsilon_y^{(M)}$ and $\varepsilon_z^{(M)}$.

It can be seen from the above formulas that CLTE(C) α_l is a physical characteristic that determines the deformation magnitude of an elastic body due to thermoelastic stresses. One can assume that this physical characteristic of the material is precisely the link that indicates the cause for the increased addition for medium carbon steel billets to rhomboidity. Indeed, a check on the known data [6, 7] confirmed the presence of the supposed nonlinear dependence of CTE(C) for carbon steel on the carbon content $\alpha_l = f([C])$. Fig. 6 shows that this dependence has an explicit local maximum in the range of contents $[C] = 0.30\text{--}0.32\%$. Disclosed local maximum coincides with the maximum in the graph of the rhomboidity dependence on the carbon content in steel [1]. Considering the fact that the phase transition $\text{Fe}_\gamma \rightarrow \text{Fe}_\alpha$ in steel occurs in the temperature range $T \approx (700\text{--}900)^{\circ}\text{C}$ with the steel volumetric expansion, this interval was excluded from consideration when plotting graphical dependences $\alpha_l = f([C])$. It can also be assumed that the dependence $\alpha_l = f([C])$ retains an extreme character with a local maximum in the indicated carbon contents region at temperatures above 1000°C . One can note that the CLTE(C) α_l values during steel cooling are higher than during its heating.

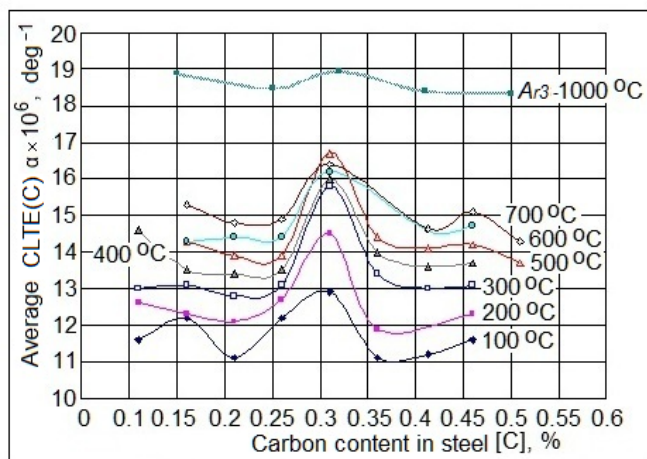


Fig. 6. Dependence of the CLTE(C) on the [C] and temperature for carbon steels according to [6, 7] (Ar_3 is the polymorphic transformation ($\text{Fe}_\gamma \rightarrow \text{Fe}_\alpha$) beginning temperature during steel cooling)

We cannot exclude that, along with the proposed, also additional mechanisms may be for the influence of other chemical elements in steel on its addition to rhomboidity. For example, for boron and manganese steels, such addition, in our opinion, can be associated with the fact that with an increasing in the content of Mn and B in steel, its elastic limit increases. This ultimately leads to an increase in steel deformation due to thermoelastic stresses.

Let us mention the main provisions that must be taken into account for the considered M-B-SCZ system without going deeply into the determining stresses and strains methods known from strength of materials and technical mechanics. So, the assumption about the strain smallness (compared with the dimensions of the body itself) is used for the body subjected to loading that do not go beyond the elastic region [5]. Further, the following analogy with the action of external forces is used when formulating problems of thermoelasticity in strains (displacements): displacements and strains in a heated body arise the same as in an unheated one (from the same material and the same shape), if equivalent external forces (volumetric and superficial) are applied to it. In the general case, these forces are determined by known formulas and they take into account the thermophysical characteristics of the material, including CLTE(C), modulus of elasticity, thermal conditions, etc. [5, p. 407].

The main regularities that cause billet spatial deformation within the CCM casting arc, including the mould, are following. It is known [8, p. 345; 9] that the bending of a curved bar in the case when the forces acting on it do not lie in the principal plane of inertia (that in our case coincides with the bar longitudinal axis plane or, in other words, with the plane of its initial curvature), leads to the complex strength appearance. Complex strength is characterized by the presence of more than two force factors in bar normal cross-sections. In the general case, loading of the small curvature bar by an arbitrary load leads to the simultaneous occurrence in its cross-sections of all six internal force factors, namely: normal force N , shear forces Q_y, Q_x , torque M_z and bending moments $M_x,$

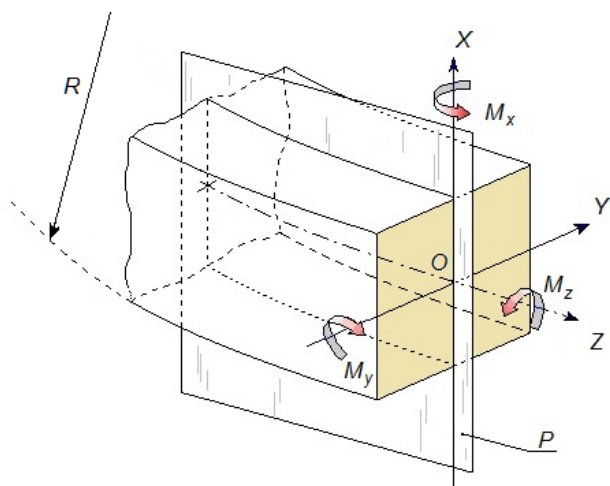


Fig. 7. Scheme of force factors acting in the normal cross-section of a curved bar when it is loaded with an arbitrary load without taking into account the shearing Q and normal N forces (P – principal plane of inertia; OX and OY – principal central axes of inertia for normal cross section; M_z – torque; M_x , M_y – bending moments)

M_y . Normal (from bending) and shear (from bending and torsion) stresses arise under the action of the indicated force factors. Since shear stresses from shear forces Q and due to bar bending are in most cases significantly less than shear stresses from torsion, they are usually disregarded. For the same reason, normal stresses from the bar compression-tension forces N are often disregarded. Therefore, the combination of torsion with pure bending is actually considered in the calculations. The displacement of the cross section center along the X and Y axes is determined by the *Mohr's method*. With regard to the problem under consideration, the view of the force factors acting in certain normal sections of the billet can be as shown in Fig. 7.

The bar axis curvature has some effect on the stress distribution in its cross sections, but its influence becomes significant only for a large curvature bar, when the ratio of the axis curvature radius to the height of its profile (cross section) is less than 5. The influence of the axis curvature on the stresses and strains in the bar of small curvature is insignificant; therefore, the calculation of such bars for bending with sufficient accuracy can be performed using the formulas for a rectilinear bar [9].

If the external acting forces plane (*force plane*) coincides with the bar curvilinear axis plane then the planar bend for such bar is unstable under certain conditions. In particular, the stability loss for a curved bar is possible when small deviations of the acting force from the principle plane of inertia lead to lateral deflection and torsion of the curved bar. Bar bending in this case also occurs in a plane that is perpendicular to the force plane, with its cross-section rotating by a certain angle. Instead of a planar bend, a bend in two planes with simultaneous torsion of the bar cross section takes place. Bar axis deviation from the nominal position in this case can lead to the *tilting moment* appearance. The loss of bar stability occurs when the tilting moment becomes higher than the *moment of stability*. When the body loses stability, it

tends to take a position with minimal potential energy. All existing restrictions on possible linear (in the transverse direction) and angular (relatively to the longitudinal axis) billet displacements for the investigated M-B-SCZ system should be taken into account.

As an example of such a loss of stability for a curved bar we can give the following from everyday life. So, when you try to unbend a curved bar because of the action in its normal cross-sections along with the bending moment also arising torque, its position becomes extremely unstable. One can assume that this kind of instability is one of the main reasons for the "autocatalytic" mode of the rhomboidity formation process. Its result is high and difficult to eliminate rhomboidity of nonchanging direction (sign). It is obvious that such situation is possible under certain conditions. According to our estimates, it is possible, for example, if the deformations under the action of the bending moment M_y in the vertical XOZ plane tend to reduce the bar curvature. Both technological and technical factors can lead to the appearance of such situation.

It is obvious that the ranking of various factors affecting the billet rhomboidity and the optimization of measures foreseen to reduce the probability of its occurrence and subsequent steady growth should be carried out taking into account the presented theoretic provisions. Priority can be considered those measures, the implementation of which reduces the probability of an "autocatalytic" mode of the rhomboidity formation. It is also obvious that the number of factors that can provoke the transition to the indicated mode are less than those that contribute the rhomboidity initiation.

Complex strength may also arise in a rectilinear bar with the so-called *planar* and *spatial unsymmetric bending* [5, p. 237]. In the first case, the force plane does not coincide with its principal planes of inertia. In the second, external forces act in different planes. The bar curved axis for these cases is, respectively, planar or spatial curve. Consequently, the considered mechanisms and regularities of spatial deformation of curved and rectilinear bars are applicable to billets cast at CCMs of both radial and rectilinear types. The latter were built in the last century and they were also characterized by the billet rhomboidity problem. Thus, the presented provisions from the field of technical mechanics and strength of materials for stresses and strains in rectilinear and curved bars are clue in understanding the causes of the billet spatial deformation that initiates its profile distortion process and can, under certain conditions, go into an undesirable "autocatalytic" mode.

According to the analysis results of theoretical and practical aspects for the rhomboidity problem there is reason to believe that:

- 1) the rhomboidity initiation can be due to both factors that cause some initial uneven cooling (for example, due to linear or angular deviation of the tube relatively to the strand axis, clogging of water sprayers, etc.), and factors that cause billet initial spatial deformation (for example due to various kinds of deviations and inconsistencies in the M-B-SCZ system elements position) and, as a result, complex strength in the solidified billet with its subsequent additional spatial deformation;

2) depending on the actual conditions determined by a combination of acting factors, some initial rhomboidity can both steady grow and spontaneously weaken with change of direction (sign);

3) the factor of uneven cooling (both primary and secondary) plays a determining role in the noticeable (exceeding the permissible limits) rhomboidity formation. Such unevenness can be both a consequence of various violations in the operation of cooling systems and a consequence of the billet spatial deformation due to complex strength because of the reasons noted above and associated with tolerance violations for the M-B-SCZ system elements positioning. This provision correlates with the above proposed explanation of the nature of the increased addition to rhomboidity for medium-carbon steel billets;

4) the rhomboidity formation process gets an extremely undesirable "autocatalytic" mode in the presence of factors that provoke the loss of billet static stability.

Since the rhomboidity initiation can be provoked by even a slight deviation of any M-B-SCZ system element from the nominal position, the relevant design and technological documentation establishes fairly tight tolerances for all dimensions, including linear and angular, that determine their position relatively to the base radius arc. Support guiding and pinch centering rolls, located along the base radius arc are mounted on roller bearings. They ensure the billet positioning strictly in the required location. The upper rolls pinch the billet to the lower rolls using a pneumatic system. A spatial system of datum marks, relevant geodetic equipment, a special template, a measuring tool are used for precise mounting and alignment of support guiding rolls. These procedures, including the actual position periodic checks of the M-B-SCZ system elements and their adjustments, are quite laborious, require the qualified personnel involvement, reduce the productivity of the CCM and increase the billet cost.

Since the mould is structurally an assembly unit, and the billet in the mould is in contact with the copper tube and foot rolls, their precise positioning is a responsible procedure performed in accordance with a special manual. The tube position error relatively to the CCM strand base radius arc is determined by the total error of the corresponding dimensional chains. The foot rolls block is mounted on the mould lower flange. Individual adjustment of each roll is made relatively to the previously centered (in the mould body frame) tube by adjusting the angular position of their eccentric axes. In this case the special template is applied. For this procedure steel shrinkage is taken into account.

Tolerances for mounting dimensions that determine the position of the MOU and the mould itself on the MOU are ± 0.15 mm. Tolerances for the mating dimensions of the mould parts (upper and lower flanges, "jacket", etc.), that determine the position of the tube in the mould body frame, are set according to the eighth tolerance grade IT8 (quality class). For comparison, we note that the tolerance for the deviation of the tube actual profile from the specified one (determined by the value of steel shrinkage) is ± 0.1 mm, and the tolerances for various shape deviations in the tube internal profile (convexity, concavity, non-parallelism, misalignment or skewness, etc.) are 0.15–0.25 mm per side. The angular deviation tolerances for the various SCZ rolls are: for foot rolls – 0.1 mm per roll length (or 0.04–0.05 degrees), for support guiding rolls – 0.2 and 0.5 mm per 1000 mm (or 0.01 and 0.03 degrees) respectively in the longitudinal and transverse planes (Fig. 8 a). Practice shows (Fig. 4 d) that the actual angular deviations of the foot rolls on "rhombic" strands can significantly exceed the specified tolerance (respectively 0.4–0.6 degrees versus 0.04–0.05 degrees). The foot rolls with such deviations cannot ensure the concentric position of the billet top relatively to the tube in case of the billet spatial deformation. The linear deviation tolerances for the M-B-SCZ system elements rela-

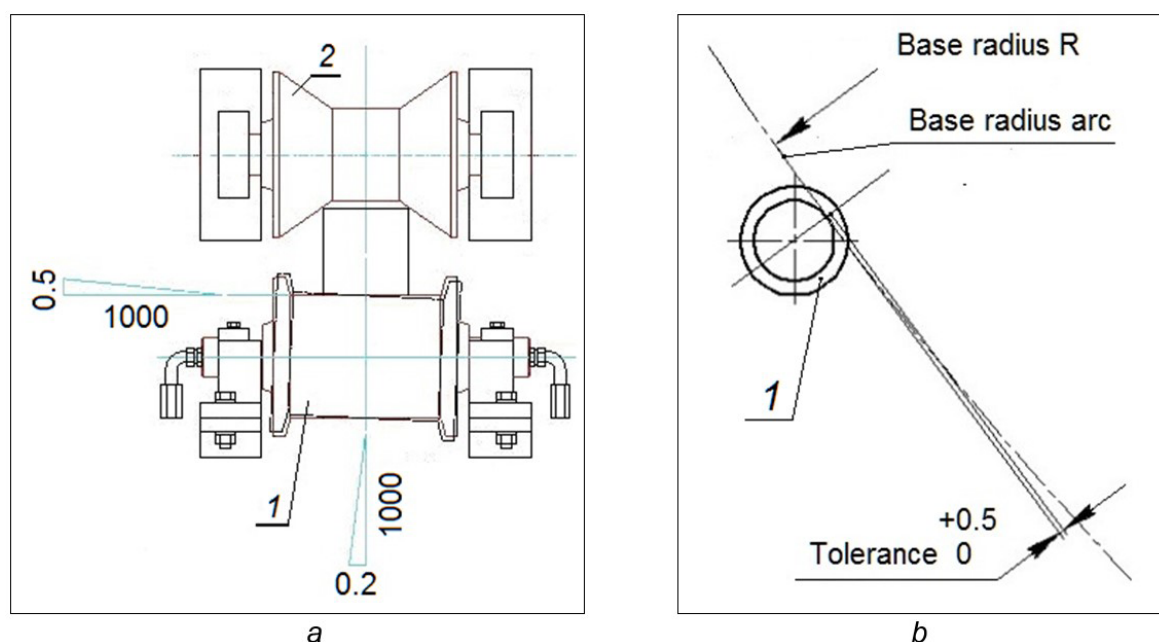


Fig. 8. Tolerances for angular (a) and linear (b) deviations of the support guiding rolls for DANIELI typical billet CCM with base radius $R = 8$ m (1 – lower support guiding roll; 2 – upper pinch centering roll)

tively to the CCM base radius arc during their mounting and alignment are: for the tube – ± 0.25 mm, for support guiding rolls No. 1–3 and the WSU rolls – $0 \dots +0.5$ mm (Fig. 8 a), for support guiding roll No. 4 – ± 0.25 mm.

In practice, the enterprise's mechanical service for various reasons, for example, through the lack of a special template, may not abide by these requirements or recommendations, simplify the design of units or procedures for checking and positioning, replace alloyed steel grades with usual carbon grades, etc. Such actions can negatively affect the rhomboidity situation. One can note that the factors associated with the unsatisfactory maintenance and adjustment of the casting arc equipment at many enterprises are considered as priorities in obtaining rhomboidity. Therefore, the main responsibility for the loss of billet quality indicators by rhomboidity in the absence of obvious violations in steel production technology, including continuous casting (increased sulfur and phosphorus content, violation of the temperature and speed casting condition, violation of the SC parameters, etc.) is laid on the mechanical services of the shop and CCMs.

One can note that the mould deviation, as a dynamic element of the M-B-SCZ system, from the nominal position can have not only a constant (like for all other elements), but also a variable (changing during the oscillation cycle) components. Primarily the MOU technical state and the results of foreseen balancing procedure (by means of pressure change in the MOU pneumatic springs) influence the variable component value. The conditions for transverse wave formation on the metal mirror in the mould and, as a result, a noticeable increase in the magnitude of metal level fluctuations are created

under a significant magnitude of the variable component for transverse deviation (the so-called vibration displacement) along the X and Y axes due to the dynamic interaction of mould with billet. As noted earlier [1], such wave formation under certain conditions can also contribute to the rhomboidity occurrence.

Various methods of vibrodiagnostics are used to estimate the MOU technical condition. Vibrodiagnostics using a specialized Oscillation.Checker device from the Austrian company VATRON, in our opinion, is the most informative and visual (Fig. 9 a). This device provides continuous measurement of movement parameters in three planes, visualization and recording of results. It allows to determine the actual oscillation parameters (for example, the NST parameter, the mould lead, etc.), as well as the vibrodisplacement magnitudes, vibrovelocity, vibroaccelerationes in 3 axes, to identify the presence of phase distortion and mould torsional oscillations around the longitudinal Z axis.

Fig. 9 b, c, d shows the mould vibrodisplacement graphs in the transverse XOY plane, taken from the MOU vibrodiagnostic protocols for the lever type MOU. The presented results were obtained using simultaneously two sensors installed on the oscillation supporting table on the right and left (along the Y axis) of the mould. The vibrodisplacement of the mould cross section geometric center along the X and Y axes is determined as the arithmetic mean of the corresponding displacements for the two sensors along these axes. Fig. 9 e, f shows the vibrodisplacement graphs along the Y axis for the oscillation cycle, corresponding to the graphs of Fig. 9 c, d. They demonstrate the complex spatial movement of the oscillating mould. The presented graphs show that

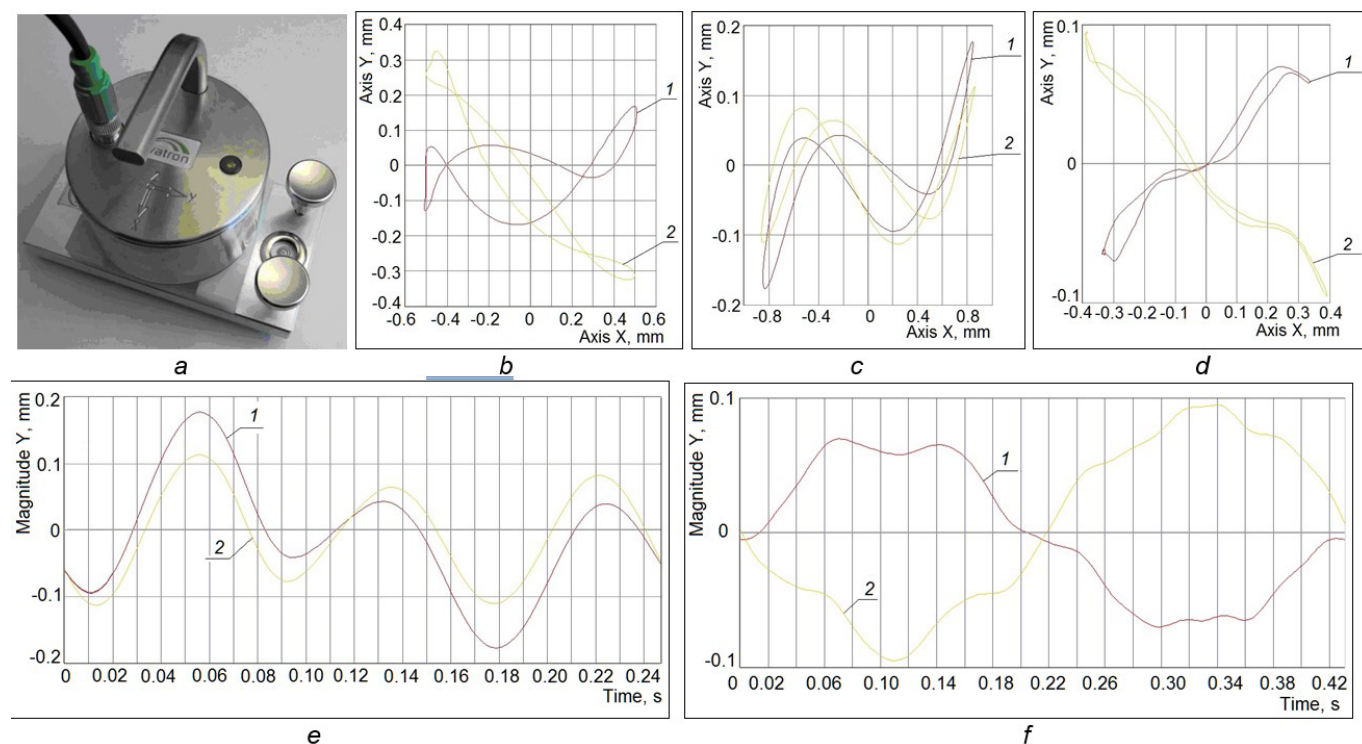


Fig. 9. Oscillation.Checker sensor (a); the mould vibrodisplacements in the transverse XOY plane on strands Nos. 1, 2, 5 (b, c, d); the mould vibrodisplacement along the Y axis for the oscillation cycle (graphs in the e, f-figures correspond to graphs in the c, d-figures). Graphs notation: 1, 2 – graphs of the left and right Oscillation.Checker sensors

the mould during the oscillation process can move in the Y axis direction (close to plane-parallel movement), and also can perform torsional oscillations concerning the longitudinal Z axis. Such torsional oscillations can, along with the billet torsion, contribute to accelerated wear of the mould tube near-corner zones and thereby contribute to the rhomboidity generation.

Vibrodisplacement along the X axis consists of two components: 1) due to the mould movement along the base radius arc and 2) due to the presence of gaps in the MOU kinematic chain. The first component can be determined by knowing the base radius R and the oscillation stroke. The resulting vibrodisplacement in the XOY transverse plane can be defined as the vector sum of vibrodisplacements along the X and Y axes.

As for the critical value of the mould transverse (in the XOY plane) vibrodisplacements, according to the experience of billet CCM operation at MMZ ISTIL UKRAINE, it was determined at the level of 0.7–1.0 mm. With these values the probability of casting stability violation as well as the billet rhomboidity appearance increases sharply. Casting at strand with such results of vibrodiagnostics can be allowed after maintenance (rebalancing of the MOU, replacement of the mould) or replacement of a life-expired MOU. In order to reduce the mould vibrodisplacement magnitude, to reduce the dynamic loads on the MOU and to increase its resource at MMZ ISTIL UKRAINE in 2008 we began to use the amplitude-frequency mode of mould oscillation with the lowest possible oscillation frequencies, that was unified for square profilesizes of 120, 125, 130 and 150 mm. This measure eliminated the need to perform the laborious procedure of the oscillation amplitude changing when changing the billet profilesize, provided a reduction of labor costs and time for changing the billet profilesize, provided maintenance simplification and the MOU technical condition improvement, the CCM productivity increasing, and also billet rhomboidity reduction.

Thanks to advanced theoretical concepts about the billet rhomboidity nature it became possible to explain the influence of various factors and production situations on this typical shape defect, and most importantly, to give certain recommendations on the priority of various measures foreseen to reduce the billet rhomboidity. Let us consider, for example, such a typical situation for billet CCM as the start of a reserve strand or restart of a working strand during serial casting. As practice shows, in this situation, the billet rhomboidity is observed quite often. Deviations of the actual flow characteristics $Q = f(P)$ from the nominal ones are detected in these situations very often and mainly in the lower sectors of the SC. One should note that each SC sector, equipped with a certain number of water sprayers of a certain type-size, has a known dependence of water flow Q on its pressure P . Deviations from the nominal characteristics indicate various kinds of violations. In particular, if at a nominal water flow its pressure in the system is higher than the nominal one, then clogging of the water sprayers takes place (mainly on the side of a small radius r). This situation leads to insufficient billet cooling on the r side and overcooling on the R side. This leads to the

thermoelastic stresses appearance that aspire to reduce the billet curvature. Such deformation, as shown earlier, contributes to the most severe "autocatalytic" mode of the rhomboidity formation process.

The alignment of support guiding rolls Nos. 1–3 (Fig. 1) relatively to the base radius arc not in the positive tolerance limit, as required by the technical documentation (Fig. 8 b), but in the minus zone will lead to a similar negative result. In this case, the billet is affected by forces from the pinch rolls (supports Nos. 1, 3 in Fig. 1) and billet weight itself, that causes stresses and strains from bending in some billet cross sections. They aspire to reduce the billet curvature and provoke the loss of its stability. The stability loss can also be provoked by a number of other factors that directly or indirectly (through complex strength) cause torsional deformation. One such factor, for example, could be the imperfect design of the upper centering pinch rolls.

Such rolls, for example, at DANIELI billet CCMs are traditionally made conical (Fig. 8 a). In addition to centering the billet, they must perform pinch function. Seeing that billets of 5 square typesizes were cast at MMZ ISTIL UKRAINE, centering pinch rolls of DANIELI design had uneven and stepped wear of conical surfaces. The pinch force for such rolls with wear may often not coincide with the billet initial curvature plane, that leads to complex strength and, as a result, billet torsion strain relatively to its longitudinal axis Z. In fact, a wear roll of this design can provoke the rhomboidity generation. That is why we at one time recommended for MMZ ISTIL UKRAINE to transfer to the use of pinch rolls with smooth barrels and flanges. Pinch rolls of this design are successfully used by a number of companies, such as CONCAST et al. Comparative tests on part of the CCM strands confirmed the effectiveness of this solution. After that the replacement of conical pinch rolls was performed on all CCM strands.

Also, as an example of technological measures that were proposed taking into account advanced concepts, one can advert the SC corrected mode. One should note that for the SCZ lower sectors of the radial type billet CCMs, the point of view on the need for a uniform (along the perimeter) SC to a certain extent contradicts the physical regularities for the natural convection development in the liquid core of the billet and convective heat transfer at the solidification boundary. The displacement of the cross section thermal center relatively to the geometrical one towards the small radius r side indicates a lower solidification rate along the upper billet facet and, as a result, the presence of a profile thermal asymmetry [10]. Considering this, as well as the fact that the water sprayers of the lower SC sectors on the small radius r side are most addicted to clogging, we also proposed to install water sprayers with increased flow characteristics on the two lower SC sectors on the small radius r side. This solution reduces the clogging probability and provides more intensive cooling of the upper billet facet. As a result, conditions are created that reduce the probability of billet static stability loss during its spatial deformation due to the complex strength appearance in it. Tests of this extraordinary technological solution fully confirmed its effectiveness. It was introduced in 2010 with the en-

Dynamics of rhomboidity sorting for billet 125x125 mm from steel Grade St5sp ([C] = 0.28–0.37 %)

Profilegrade of steel	Billet rhomboidity sorting, %*				
	2007	2008	2009	2010	2011
125x125 mm St5sp	1.79	1.48	0.82	0.33	0.08

* – from the annual production volume of this steel profilegrade

tering of appropriate changes to the CCM technological instruction.

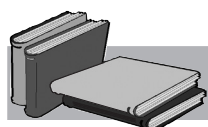
In general, the work begun in 2007 at MMZ ISTIL UKRAINE aimed at reducing losses associated with obtaining rhombic billets included both theoretical studies and the implementation of various measures of an organizational, technical and technological character, including known and proposed according to new concepts. Implementation of most measures was carried out only after positive results at the preliminary tests stage. As a result, it was gradually possible to significantly reduce the billet sorting on the "rhomboidity" defect. The table shows the dynamics of rhomboidity sorting for billet 125x125 mm from medium carbon steel Grade St5sp ([C] = 0.28–0.37 %) according to DSTU 2651:2005/GOST 380-2005 for the period 2007–2011. This billet profilegrade was the most wholesale in production. To compare the achieved indicators and their dynamics, as an example, we can present the data from [11] on similar indicators of one of the US plants before and after the implementation of new mould tube type (WAVE MOULD). The KME Company, that developed and manufactures such mould tubes, positions them as an innovative product. At the same time, the reduction in the billet rhomboidity is highlighted by the company's specialists as the most noticeable among other advantages of such mould tubes [12]. So, if before the implementation of WAVE MOULD the sorting level on rhomboidity for billet 178x178 mm from steel AISI 4130 ([C] = 0.28–0.33 %) according to the ASTM A29 standard was 2.12 % (2012), then after of their implementation, it decreased to 1.62 % (2013).

Since it was not possible to implement a number of measures, primarily requiring funding, due to the general deterioration in the enterprise working conditions after 2011, the authors are ready to consider transferring these and other solutions to interested structures. Among these solutions, for example, the technological

know-how to quickly reduce the rhomboidity in the casting process is present. It was assumed that this solution would be integrated with the automated system for billet rhomboidity measuring during casting, developed at MMZ ISTIL UKRAINE and presented earlier [1]. One should note that such solutions could become an integral part of the smart technology for billet CCMs. Their effectiveness, according to our estimates, is beyond doubt. Their implementation will minimize economic losses from the CCB rhomboidity, will simplify the maintenance of CCMs, and will reduce the personnel qualification requirements.

CONCLUSIONS

The development of theoretical concepts on the CCB rhomboidity nature is carried out using the provisions known from technical mechanics and strength of materials. Results in studies of the mechanisms and regularities of the rhomboidity initiation and growth processes made it possible to explain the reason for the increased addiction for medium carbon steel billets to rhomboidity. The proposed mechanism of appearance for the extremely undesirable so-called "autocatalytic" mode of the rhomboidity formation process, that contributes to the formation of a noticeable nonchanging direction (sign) rhomboidity, makes it possible to distinguish among the various types of "antirhombic" measures those that are able to prevent its appearance. An in-depth understanding of the billet rhomboidity nature made it possible also to propose new effective technical and technological solutions aimed at reducing rhomboidity. Achieved during the research and implementation of various measures period the rhomboidity sorting reduction for the medium carbon steel billet confirms the effectiveness of both proposed concepts and the implemented "antirhombic" measures.

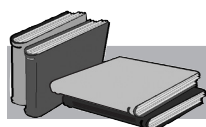


ЛІТЕРАТУРА

1. Pisarskyi S.M., Smirnov O.M. Analysis and development of modern concepts on the rhomboidity formation nature for continuously cast billets. Part 1. *Метал та лиття України*. 2021. Т. 29. № 2 (325). С. 31–40. DOI: <https://doi.org/10.15407/steelcast2021.02.031>
2. Писарский С.Н., Смирнов А.Н., Лавренко Д.А., Рябый Д.В. Оценка технологических возможностей стабилизации скорости разливки открытой струей на современной сортовой МНЛЗ. Сообщение 1. *Металл и литье Украины*. 2018. № 3–4 (298–299). С. 28–33. URL: <https://steelcast.com.ua/en/article/estimation-technological-possibilities-speed-stabilization-casting-open-jet-modern-billet>

3. Kumar S., Samarasekera I.V., Brimacombe J.K. Mold thermal response and formation of defects in the continuous casting of steel billets. Part 2: Rhomboidity. *Iron and Steelmaker*. 1998. 25 (12). P. 51–66.
4. Ботников С.А. Современный атлас дефектов непрерывнолитой заготовки и причины возникновения прорывов кристаллизующейся корочки металла. Волгоград, 2011. 97 с. URL: <https://www.twirpx.com/file/636390/>
5. Варданян Г.С., Андреев В.И., Атаров Н.М., Горшков А.А. Сопротивление материалов с основами теории упругости и пластичности. Москва: АСВ, 1995. 568 с. URL: <https://dwg.ru/dnl/11130>
6. Температурный коэффициент линейного расширения стали. URL: <http://thermalinfo.ru/svoystva-materialov/metally-i-splavy/temperaturnyj-koeffitsient-linejnogo-rasshireniya-stali#tab1>
7. Шатов А.Я., Бойков Д.А., Ступак А.А. Линейная усадка стальных отливок, ее связь с диаграммой состояния Fe-Fe₃C. *Вестник Брянского государственного технического университета*. 2007. № 2 (14). С. 20–26. URL: <http://www.docme.su/doc/1380690/4217>
8. Тимошенко С.П. Сопротивление материалов. Т. 1. Элементарная теория и задачи. Перевод с англ., 3-го изд. Москва: Наука, 1965. 364 с. URL: <https://cloud.mail.ru/public/EKfb/4KhPcN7zL>
9. Перемещения в пространственном брусе малой кривизны при произвольной нагрузке. URL: http://mysopromat.ru/uchebnye_kursy/sopromat/peremescheniya_v_prostranstvennom_bruse/
10. Сладкошteeв В.Т., Потанин Р.В., Суладзе О.Н. и др. Непрерывная разливка стали на радиальных установках. Москва: Металлургия, 1974. 288 с. URL: <https://ua1lib.org/book/2987791/4ff8ef>
11. Bakshi I.A., Piwowar H.-D. (2014). WAVE Mould for Improved Billet Shape and Quality. URL: https://hobbydocbox.com/Jewelry_Making/109538469-Wave-mould-for-improved-billet-shape-and-quality.html
12. URL: <https://www.kme.com/en/specialdivision/melting-casting/innovation-products/mould-tubes>

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REFERENCES

1. Pisarskyi, S.M., Smirnov, O.M. (2021). Analysis and development of modern concepts on the rhomboidity formation nature for continuously cast billets. Part 1. *Metal and Casting of Ukraine*, vol. 29, no. 2 (325), pp. 31–40, doi: <https://doi.org/10.15407/steelcast2021.02.031>
2. Pisarskyi, S.N., Smirnov, A.N., Lavrenko, D.A., Riabiy, D.V. (2018). Estimation of technological possibilities of the speed stabilization of casting by open jet on modern billet CCM. Report 1. *Metal and Casting of Ukraine*, no. 3–4 (298–299), pp. 28–33. URL: <https://steelcast.com.ua/en/article/estimation-technological-possibilities-speed-stabilization-casting-open-jet-modern-billet> [in Russian].
3. Kumar, S., Samarasekera, I.V., Brimacombe, J.K. (1998). Mold thermal response and formation of defects in the continuous casting of steel billets. Part 2: Rhomboidity. *Iron and Steelmaker*, 25 (12), pp. 51–66.
4. Botnikov, S.A. (2011). Modern atlas of continuously cast billet defects and the causes of breakouts in a crystallizing metal shell. Volgograd, 97 p. URL: <https://www.twirpx.com/file/636390/> [in Russian].
5. Vardanyan, G.S., Andreev, V.I., Atarov, N.M., Gorshkov, A.A. (1995). Strength of materials with the basics of the elasticity and plasticity theory. Moscow: ASV, 568 p. <https://dwg.ru/dnl/11130> [in Russian].
6. Temperature coefficient of linear expansion of steel. URL: <http://thermalinfo.ru/svoystva-materialov/metally-i-splavy/temperaturnyj-koeffitsient-linejnogo-rasshireniya-stali#tab1> [in Russian].
7. Shatov, A.Ya., Boykov, D.A., Stupak, A.A. (2007). Linear shrinkage of steel castings, its relationship with the state diagram of Fe-Fe₃C. *Vestnik Brianskogo gosudarstvennogo tekhnicheskogo universiteta*, no. 2 (14), pp. 20–26. URL: <http://www.docme.su/doc/1380690/4217> [in Russian].
8. Timoshenko, S.P. (1965). Strength of materials. Vol. 1. Elementary Theory and Problems. Transl. from English, 3rd edition. Moscow: Nauka, 364 p. URL: <https://cloud.mail.ru/public/EKfb/4KhPcN7zL> [in Russian].
9. Movements in a spatial beam of small curvature under arbitrary load. URL: http://mysopromat.ru/uchebnye_kursy/sopromat/peremescheniya_v_prostranstvennom_bruse/ [in Russian].
10. Sladkoshteev, V.T., Potanin, R.V., Suladze, O.N. et al. (1974). Continuous casting of steel at radial machines. Moscow: Metallurgiya, 288 p. URL: <https://ua1lib.org/book/2987791/4ff8ef> [in Russian].
11. Bakshi, I.A., Piwowar, H.-D. (2014). WAVE Mould for Improved Billet Shape and Quality. URL: https://hobbydocbox.com/Jewelry_Making/109538469-Wave-mould-for-improved-billet-shape-and-quality.html
12. URL: <https://www.kme.com/en/specialdivision/melting-casting/innovation-products/mould-tubes>

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Аналіз і розвиток сучасних уявлень з природи формування ромбічності безперервнолитих сортових заготовок. Частина 2

У ході розвитку та деталізації уявлень відносно природи ромбічності в рамках запропонованого в частині 1 цієї публікації підходу акцент зроблено на практичній спрямованості проведених досліджень. Запропоновані закономірності та механізми процесів зародження та зростання ромбічності спираються на відомі з технічної механіки та опору матеріалів положення, а також на результати та факти з досвіду експлуатації та обслуговування сортових машин безперервного лиття заготовок (МБЛЗ). На основі цих положень вперше запропоновано пояснення природи підвищеної схильності до ромбічності заготовок із середньовуглецевої сталі, а також механізму виникнення так званого «автокаталітичного» характеру процесу формування ромбічності, який є вкрай небажаним. За результатами досліджень запропоновано нові рішення для зниження ромбічності заготовок. У ході реалізації технічних, технологічних та організаційних заходів, як відомих, так і вперше запропонованих, досягнуто помітне покращення якості заготовок з ромбічності. Середньорічний показник відсортуння по ромбічності заготовок 125x125 мм із середньовуглецевої сталі протягом п'яти років з початку досліджень та реалізації заходів був знижений з 1,79 до 0,08 %. Ті заходи, які з об'єктивних причин не були реалізовані, зокрема з оперативного (по ходу розливання) зниження ромбічності, можуть бути передані зацікавленим структурам.

Ключові слова

Ромбічність, просторова деформація, термopужні напруги, коефіцієнт лінійного теплового розширення (стиснення), складний опір, деформації згинання та кручення, стійкість, лінійні та кутові переміщення, допуски.