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Analysis and development of modern conceptions on the rhomboidity formation nature for continuously cast billets. Part 1

The rhomboidity of the profile being shape defect of continuously cast billets despite advanced technology of their production and improvement of billet continuous casting machines (CCM) design development continues to occupy a significant part among other typical defects. Modern concepts about the nature of this defect remain incomplete and for a number of points – as unconfirmed assumptions. One of the most noticeable “white spots” among them is the vexed question about the reason for increased addiction of mediumcarbon steel to rhomboidity. Research carried out by the authors aimed at circumstantiation and development existing concepts about the regularities and mechanisms of the rhomboidity formation as a multilevel and multifactorial process.

The rhomboidity initiation occurs in the mould meniscus region due to non-uniform heat removal from the billet along the profile perimeter. The reason for the non-uniform heat removal can be considered the local contact conditions between billet and mould that differ along the perimeter. The trigger of the square profile deformation process occurs when the heat removal intensity decreases even in one of its corners. According to the authors the metal level fluctuations in the mould caused by the instability of the turbulent jet from tundish cannot be considered as a dominant and independent factor in the rhomboidity initiation. Specific level fluctuations often observed in the “rhombic” strands of CCM are primarily due to the dynamic interaction of billet with mould.

One of the main reasons for the differing billet with mould contact conditions was offered to consider the billet spatial (three-dimensional) deformation within the CCM casting arc that can be investigated as a multifactorial “Mould – Billet – Secondary Cooling Zone” (M-B-SCZ) system. Proposed approach allows integration to improved concept both the provisions the objectivity of which has been proven in the course of previous research and the data known from practice regarding the influence of many technological, technical and other factors on the rhomboidity. This approach also makes it possible to more objectively and deeply understand the regularities and mechanisms of the rhomboidity formation as a multilevel process. This is a prerequisite for improving the billet quality, developing new technological solutions and optimizing preventive measures aimed at billet rhomboidity reducing.

Keywords: billet CCM, rhomboidity, meniscus region, level fluctuations, non-uniform heat removal and solidification, contact conditions in mould, 3-d deformation.

The rhomboidity of profile (normal cross-section) defined as the difference of its diagonals (Fig. 1) for square continuously cast billets is characteristic and one of the most common shape defects [1]. The part of this defect in their total volume that is often the causes sorting and waste of billets remains significant reaching 30–50 %. This reduces the technical and economic efficiency of not only casting but also rolling process. Rolling process of billets with increased (≥ 4 %) rhomboidity leads to specific problems with both the quality of the rolled products and the productivity of mill. In particular, favorable conditions are created in this case for non-uniform reduction along the profile width. This leads to

non-uniformity of elongation and as a consequence longitudinal twisting of the roll. This excludes the obtaining of high-quality rolled products from it. Moreover, forced rolling process stops lead to loss of mill productivity and energy overconsumption due to the need to reheat the cooled billets [2, 3].

The rhomboidity problem for billet CCM is aggravated by the following circumstances:

1) At present there is no complete understanding of the influence mechanisms for individual factors and the phenomenon regularities as a whole [4]. The existing concepts about the billet rhomboidity formation processes have some mosaicism and incompleteness. A number

Fig. 1. The billet rhomboidity of 15 mm for medium carbon steel (profile 150x150 mm)

of provisions regarding the regularities of the rhomboidity formation due to their inherent inconsistency still remain the subject of scientific discussions. Among the vexed questions that can be considered open the most noticeable is the question of the reasons for the increased addiction of medium-carbon steel to rhomboidity. It is believed that this question is clue to understanding the nature of this undesirable phenomenon.

2) Control of the billet profile geometry is carried out everywhere as a rule selectively and manually on the billet shelves of warehouse at least 4 hours after casting.

This is due to the need to cool the billets to a suitable temperature [3]. The point out time delay does not allow timely to determine the rhomboidity magnitude and to carry out if necessary corrective measures or close the problem strand (when the rhomboidity is higher than the allowable magnitude). This leads to an increase in the sorting and waste of billets. In addition such control requires additional production areas, personnel and standby of the overhead cran at the billets inspection and transfer site. Moreover, the measurement process takes place in unsafe working conditions. The billet rhomboidity measurement at transport or transfer roller tables of CCM that is practiced at some mills creates an increased danger for personnel and is in fact a violation of safety rules.

3) Despite the improvement in the production technology and billet CCM design there are currently no solutions that would guarantee the elimination or reduction (to the allowable magnitude) of rhomboidity directly in the casting process. All known measures foreseen to prevent it are carried out by the technological and maintenance personnel of CCM before the start of serial casting and are of a preventive nature. Few operational measures (change in the intensity of primary and secondary cooling, change in the casting speed, etc.) are not effective. Therefore the strands with an increased billet rhomboidity are usually closed and after serial casting the mould often is replaced, the spray nozzles are cleaned or replaced, the accuracy of alignment of CCM casting arc equipment is checked, etc.

Thus the circumstantiation and development of the known concepts about the nature and regularities of the billet rhomboidity formation during casting process at

a

b

C

Fig. 2. Automated measuring complex of billet CCM introduced at MMZ ISTIL (Ukraine) in 2008 for rhomboidity determination in the casting process: *a* – optical block; *b* – screenshot from the CCM main control desk monitor (the rhomboidity magnitude data are encircled in red); *c* – digital image of hot billet end

billet CCMs to be an urgent research area to increase the technology efficiency.

Taking into account the current trend towards digitalization of production processes it should be noted that control of the billet profile geometry in the casting process using computerized measuring systems based on laser scanners or machine vision systems has not yet gone beyond the frames of experimental industrial samples [3, 5]. Nevertheless we can note the complex created in 2008 at MMZ ISTIL (Ukraine) and successfully passed pilot industrial tests. The optical block of this complex for forming a primary billet end digital image (with billet temperature is above 800 °C) was installed at the beginning of the walking beam cooling (Fig. 2, a). During the step-by-step complex adaptation including software the absolute measurement error including associated with the presence of traces (so-called "beard") on some billets from oxy-cutting was reduced and did not exceed 1.5 mm. Long-term (more than 1 year) operation of the complex in the "Master's Advisor" mode had confirmed its efficiency and reliability by 2010. In real time complex provided information on the actual billet rhomboidity to the CCM main control desk monitors with identification of the ordinal numbers of the strands and billets (Fig. 2, b, c). This allowed the CCM shift supervisor to make the necessary decisions promptly.

From the practice of casting at billet CCMs various factors are known that contribute to the occurrence of billet rhomboidity. They can be conditionally divided into: 1) technological (casting speed, steel overheat, tundish jet alignment, taper of mould tubes, intensity of primary and secondary cooling (SC), uniformity of SC (including due cleaning and changing of spray nozzles, water collectors alignment), pressure and flow rate control and measurement, etc.); 2) factors determined by the chemical composition of steel (the content of carbon, sulfur, phosphorus and some elements that increase the addiction to rhomboidity); 3) technical, including constructive and depending on the quality of CCM casting arc equipment maintenance (wear degree, alignment precision, etc.) including mould assembly, oscillation table, foot and other rolls, withdrawal pressure, etc. Herewith the solutions adopted at one CCM are not always applicable to others because of the specific situations regarding the listed differing conditions and multifactoriality [1, 4].

Since the occurrence and rhomboidity magnitude that are conditioned by action of these factors as well as their combinations are random nature and there is no 100 % clarity in understanding the mechanisms of the influence of many factors on rhomboidity today there is also no gradation of most of them in terms of significance. However it can be assumed that there are such factors and associated conditions that most likely trigger a chain of processes and ultimately lead to the transformation of a square billet profile into a rhombic one.

A lot of research and publications around the world have been devoted to the study of the factors, mechanisms and regularities of the billet rhomboidity formation. At the same time as noted above in a number of details as well as in the integral picture of phenomenon under consideration there is no complete clarity in their under-

standing. It is obvious that the rhomboidity nature is multilevel and multifactorial. For its solving it is required to use new approaches and those key provisions that are objective and serve as the basis for the development of existing concepts.

One can constate that the thermophysical aspects that inherent in the process of rhomboidity formation have been studied in sufficient detail. It is supposed that distortion of the billet profile and the occurrence of accompanying defects such as external near-corner and internal diagonal cracks are caused by the violation of thermal symmetry along the billet profile perimeter. The achieved level of understanding of these aspects allowed to create adequate models of thermophysical processes and the related thermally stressed state of billets for solving by numerical methods. For example in article [6] the analysis of thermal processes, thermal stresses and deformations in the "mould – billet" (M-B) system was carried out. In this case the mathematical formulation of the problem includes equations system of non-linear thermoelasticity and unsteady thermal conductivity during the billet formation. Its numerical solution for various boundary conditions of heat transfer (1 – tight contact between billet and mould in all its corners, 2 – violation of tight contact in a pair of opposite corners) allowed to define the features of cooling, stresses and deformations for crystallizing profile both as a whole and its corner zones that cause cracking.

One should note that the situation when the contact conditions are violated in pairs of opposite billet profile corneres in the most possible in practice cases cannot be considered as some initial condition. Rather they can be considered as the result of processes that occur under certain conditions and lead to distortion of billet profile. Therefore the question of the conditions and factors that trigger these processes as well as the mechanisms of their action is quite well-formed. Unfortunately, questions of this kind were not enunciated in the above-mentioned article [6].

In a number of publications devoted to the billet rhomboidity problem the factors that trigger the mechanism of rhomboidity formation are considered those the probability of which is extremely low at modern billet CCMs. These are in particular low quality of cooling water or casting oil, local water boiling in the mould due to insufficient (less than 8 m/s) velocity of its flow, insufficient (6–9 mm)

Fig. 3. Range of rhomboidity magnitudes measured along the billet length for medium-carbon steel [7]

Fig. 4. The nature and dynamics of the temperature distribution on the working mould surface in the horizon 45 mm below the meniscus: *a* – steel with [C] = 0.32% (rhomboidity up to 15 mm); *b* – steel with [C] = 0.12% (rhomboidity up to 2 mm) [7]

or unequal thickness of mould tubes, the difference in thickness of the adjustable water gap (channel gap) between the tube and mould, non-optimal (for the actual casting speed) magnitudes of the mould tube tapers or its corners radius, non-uniform oil supply around the profile perimeter, excessive wear of the mould tube surface or its profile shape distortion, violation of temperature and casting speed modes and other factors from the M-B system caused by imperfection of the mould design and casting technology, general CCM equipment maintenance and alignment [1, 4, 7]. One should note that many of the views that were formed in the initial period of the casting technology development for billet CCM regarding the mechanisms and factors that determine the rhomboidity formation have not passed the test of time. For this reason the problem of rhomboidity that had retained its topicality at the newest billet CCMs had required new ideas and approaches.

In article [7], where such ideas and approaches were clearly formulated the study of the conditions and factors that lead to the trigger of the rhomboidity formation process as well as the cause of the increased addiction to rhomboidity of medium-carbon steel was considered as a priority goal. In the course of study a series of industrial experiments was carried out at seven CCMs of five North American mini-mills including measurement of the mould tube temperature and billet rhomboidity for different steel grades. Simultaneous control of technological and other parameters, numerical simulation of heat transfer and solidification processes in the mould for various heat removal intensities, etc. were carried out.

Among the factors that have the most noticeable effect on thermal processes in the mould the following ones are highlighted [7]:

- interaction of a crystallizing billet shell with an oscillating mould;
- carbon content in steel;
- magnitude of metal level fluctuations in the mould;
- the physical characteristics of the casting oil as well as the uniformity of its supply;
- the mould taper, etc.

The mould design features, some parameters and settings (upsets) of the casting process also are mentioned. An arbitrary combination of these factors according to the researchers generates random and unpredict-

able distinctions in the billet cooling conditions in mould. These distinctions determine the constant variation disclosed in some cases not only in the magnitude but also in the direction (positive or negative sign) of rhomboidity (Fig. 3).

According to the results of above-mentioned study, the authors assumed that the initiation and subsequent growth of billet rhomboidity are due to the features of the heat transfer and solidification processes in a narrow (up to 50 mm) meniscus region of the mould. This approach is somewhat different from the generally known one, according to which these processes are considered within the entire M-B system. Metal level fluctuations caused by the unstable outflow of turbulent jet from the tundish were named as the root cause of the indicated thermal and temperature non-uniformity occurrence. Herewith a characteristic feature of these fluctuations is increase in the metal level in one place of the profile perimeter and a simultaneous its decrease in opposite place of perimeter. As a result of such fluctuations along the profile perimeter temperature maximum and minimum arise. As a consequence differences in the intensity of heat transfer and the rate of solidification arise (Fig. 4). Increasing of such temperature variations according to results of measurements leads to the billet rhomboidity growth (Fig. 5).

According to researchers, a change in the physical state and as a consequence in the heat-conducting ability of the casting oil used as a lubricant in contact with

Fig. 5. Dependence of billet rhomboidity on the measured temperature variation (the difference between the temperature maximum and minimum) for region located 45 mm below meniscus [7]

the mould surface that have noticeably different temperatures plays a significant role in these processes. This oil depending on local temperatures on the mould surface can be liquid ($< 200\text{--}210\text{ }^{\circ}\text{C}$), boiling (two-phase, $200\text{--}350\text{ }^{\circ}\text{C}$) or subject to pyrolysis ($> 350\text{ }^{\circ}\text{C}$). Increase in temperature on a part of mould perimeter above the boiling and pyrolysis points of oil leads to additional intensification of heat removal and to growth of temperature and solidification non-uniformity in the meniscus region. The oil lack taking place at high temperatures leads to local "sticking" and transverse depression on billet surface that also contribute to growth of the heat removal non-uniformity.

Within the framework of the proposed concept researchers presented an original explanation for the increased medium-carbon steel addiction to rhomboidity. In particular it was assumed that the non-uniformity of solidification taking place under conditions of the metal level fluctuations and as a consequence of heat removal intensity scatters for medium-carbon steel billets is higher than for low- and high-carbon steel. Researchers attributed this feature of medium-carbon steel to increased intensity of heat removal in the mould meniscus region founded out for it (Fig. 6) as well as a relatively narrow interval of its crystallization ($\Delta T \approx 50\text{ }^{\circ}\text{C}$ for $[C] = 0.32\text{ }%$). It is noted that the combination of these factors that determine the conditions in the mould meniscus region for the rhomboidity formation is the most unfavorable for medium-carbon steel in comparison with other grades. Herewith the lower intensity of heat removal in the meniscus region founded out for low-carbon steel was associated by the researchers to the increased roughness of the interface due to steel peritectic transformation. The absence of addiction to rhomboidity for high-carbon steel according to researchers was associated with a wider crystallization interval ($\Delta T \approx 100\text{ }^{\circ}\text{C}$ for $[C] = 0.84\text{ }%$).

Evaluating the above mentioned results [7] it can be noted that the researchers themselves understanding the certain limitations of the proposed approaches made a proviso. In particular they pointed out that not only the factors related to the mould meniscus region but also any other design and production factors that lead to temperature growth on a part of the profile perimeter ("hot mould" operation mode) and temperature differences around the profile perimeter that contribute to the

rhomboidity appearance. Herewith as example the SC is given that being outside the M-B system has although indirect but a noticeable effect on the rhomboidity.

The considered results of the study [7] were an important stage in the development concepts concerning rhomboidity nature. A number of its provisions have received reliable experimental confirmation and can certainly be considered as objective. At the same time some provisions in our opinion are quite controversial and require correcting. Their critical analysis will be carried out below.

In articles [8, 9] devoted to the study of the mechanisms and regularities of the rhomboidity formation and accompanying cracking it is shown that the difference in the solidification rate along the billet profile perimeter in the mould is associated with the difference in the heat removal intensity. This is primarily due to a change in the billet local contact conditions in the mould. The longitudinal and transverse temperature gradients arising as a result of this non-uniformity determine the magnitude and sign of stresses, deformation and cracking intensity in hardened billet profile shell. One should note that the provision on the dependence of the heat removal intensity on the billet contact conditions in the mould differs from the corresponding provision in [7] and despite its obviousness is fundamentally important for understanding and further development of the rhomboidity nature concept.

Study of the thermostressed state and deformations for solidified billet shell in the M-B system carried out using the methods of numerical simulation and physical modeling for various possible variants of the deterioration for billet local contact in the mould showed that the departure of even one of the billet corners is a sufficient condition to trigger the process of square profile transformation into a rhombic one [8, 9]. The heat removal non-uniformity that occurs in this case leads to the loss of stability by the square profile and its transformation process trigger into a rhombic one. It is noted that the situation with the departure of two opposite billet corners can be considered as a result of the dynamic development for solidified billet profile distortion process caused by the violation of contact along one of the profile corners.

According to the simulation and modeling results it is also noted that even in the absence of violations of the contact conditions along the profile perimeter the solidification rates in the corner zones and zones along the center of the profile faces differ by 1.5–2.0 times. This is due to the actual natural differences in the cooling conditions along the profile perimeter [8]. However in this case due to the symmetry and balance of the stress and deformation diagrams in the solidified billet frame the profile is not distorted.

Taking into account the results of [8, 9] let us analyze in more detail those provisions of [7] that in our opinion are debatable. In particular one of these is the provision on the dominant role of metal level fluctuations in the rhomboidity initiation. Researchers supposed that these fluctuations were caused by the hydrodynamic instability of the turbulent metal jet from the tundish. Herewith it is noted in [7] that the relationship between level fluctuations and the tundish jet instability is taken as an as-

Fig. 6. Calculated heat flux profiles in mould for 0.12 pct., 0.32 pct. and 0.84 pct. carbon steels [7]

sumption whereas there are no studies in this direction and the corresponding results are absent.

Above-mentioned characteristic feature of the metal level fluctuations in the mold observed with significant rhomboidity consist in the metal level increasing in one place of the metal mirror and simultaneous its decreasing in another place. In this case in fact there is a periodic change of the metal level in antiphase on opposite profile perimeter sides. Such situation means the presence of lateral waves on the metal mirror with a certain their direction in horizontal plane. One should note that so-called "coincident" waves are formed on the metal mirror in case with optimal mould oscillation alignment. "Coincident" waves do not move along the metal mirror surface in any lateral direction.

Metal level fluctuations caused by the unstable outflow of centered turbulent jet from the tundish have a random character without a certain direction of the generated waves and periodicity of their occurrence. These random hydrodynamic disturbances are superposed on "coincident" waves. As a result of this superposition the waves on the metal mirror will also have a random irregular character and their lateral movement will not have a certain vector of directivity.

In our opinion the lateral horizontal wave formation in the mould is caused by the dynamic interaction between billet and oscillating mould. This interaction is such external source of energy that generates these waves and as a consequence noticeable metal level fluctuations in the mould. One can note that the maximum fluctuations can arise when the lateral waves have diagonal directivity. In this case the mould oscillation marks on the billet surface have inclined orientation (Fig. 7).

The presence of intensive wave formation and as consequence metal level fluctuations is deviation from the nominal casting mode. It can be caused by various reasons that will be discussed in detail in the second part of our article. As practice shows in such case the load on the mould oscillating table (mechanism) drive increases due to growth of frictional forces between billet and mould. This was confirmed by the corresponding trends in the casting e-protocols (different strands for

same heat) when one of two strands had noticeable level fluctuations but no rhomboidity (Fig. 8). Figure 8 shows that growth of level fluctuation magnitude is accompanied by growth of magnitude scatter (difference between maximum and minimum per cycle) and average oscillation current.

One should note that growth of metal level fluctuations magnitude due to the dynamic interaction between billet and mould as practice shows is not always accompanied by an increase in rhomboidity but very often leads to emergency breakouts under the mould. The latter is associated with the formation of splashes on the mould walls and such billet surface defects as "crust curl" and "laps" [10, p. 43]. They significantly increase the breakout probability. One can assume that the rhomboidity initiation in such conditions occurs only when significant differences in the billet contact conditions in the mould arise. These conditions are accompanied by growth of thermal and temperature non-uniformity.

At the same time the indicated non-uniformity can arise without an increase in wave formation and in level fluctuations. For example such situation can arise with significant wear of corner zones of the mould tube. Such wear causes noticeable differences in the contact conditions along the profile perimeter. In this case level fluctuations can arise already in the process of initiation and growth of rhomboidity due to wedging of the rhombic profile in the mould. Growth of frictional forces between billet and mould can lead to mould oscillation mode that with a high probability will be accompanied by jerks. Herewith due to interaction mould with billet lateral waves and as a consequence level fluctuations will be generated.

Thus the metal level fluctuations in the mould cannot be considered as a dominant and independent factor in the rhomboidity initiation as supposed in [7]. These fluctuations can have completely different nature that is not related to the influence of jet from tundish. There are reasons to believe that specific level fluctuations can in some cases be caused by the dynamic interaction between billet and mould.

Regarding the explanation presented in [7] about increased addiction of medium-carbon steel to rhomboidity

Fig. 7. Oscillation marks on the billet surface with inclined orientation due to intense lateral wave formation in the mould

Fig. 8. Casting e-protocols (billet 150x150 mm) from different CCM strands with displaying trends in the speed, oscillation current and the magnitude of the metal level fluctuations: a – presence of remarks on the metal level fluctuations; b – absence of such remarks

Fig. 9. Influence of carbon content in steel on rhomboidity: *a* – according to [1]; *b* – according to [4]

Fig. 10. Fragment of the Fe-C phase diagram

the following arguments should be noted. Firstly, it is unable to explain the well-known local maximum of rhomboidity noted in the range $[C] = 0.30 \dots 0.32 \%$ (Fig. 9). Secondly, evaluating the argumentation of presented explanation it should be noted that the factor of the heat removal intensity in the meniscus region cannot be due to the roughness of the interface. The heat removal intensity in meniscus region of mould is largely conditioned by the features of high-temperature steel shrinkage due to polymorphic transformations according to the "Fe-C" system phase diagram (Fig. 10). It is known that during the solid-phase peritectic transformation $Fe_{\delta} \rightarrow Fe_{\gamma}$ (line HJB) accompanying the process of steel solidification its instantaneous shrinkage takes place. It is due to the lower (by 2.5–3.0 %) specific volume of austenite Fe_{γ} compared to ferrite Fe_{δ} [11]. With growth of the carbon content in the range $[C] = 0.10 \dots 0.51 \%$ the shrinkage magnitude of this type gradually decreases and at $[C] = 0.51 \%$ becomes equal to zero. That is associated with a decrease in the amount of formed ferrite Fe_{δ} to zero [12]. For steel with a carbon content $[C] > 0.51 \%$ solid-phase structural transformations in steel during solidification are absent. For this reason its shrinkage is due only to gradual thermal compression of austenite when it is cooled below the BC (liquidus) and JE (solidus) lines (Fig. 10).

Regarding the noted influence of the "crystallization interval" factor on the rhomboidity the following arguments can be noted. For high-carbon steel a wide

crystallization interval and accordingly an extended two-phase zone cause an increased interface roughness. As a result the thickness of the thermal boundary layer at the phase interface increases and consequently the heat transfer intensity at it decreases. However, neither this decrease nor a decrease in the steel crystallization heat and steel thermal conductivity with growth of steel carbon content (for example growth of steel carbon content from 0.06 to 1.0 % is accompanied its thermal conductivity decrease by 1.4 times [13, p. 225]) does not influence the growth of heat removal intensity in the mould meniscus region with increasing carbon content in steel (Fig. 6). This result is primarily due to the preservation of a tight contact of billet with mould in the meniscus region due to the absence of structural transformation in steel for $[C] > 0.51 \%$ with instantaneous shrinkage during its solidification in the mould meniscus region.

Thus, it is obvious that the contact conditions of billet with mould for casting by open jet determined by the size of the gas gap act as a priority factor influencing the rhomboidity through the intensity and non-uniformity of heat removal in the mould. It is this context in our opinion that should determine the explanation of the increased addition nature for medium-carbon steel to rhomboidity. This approach as will be shown in the second part of the article is productive and allows such an explanation to be presented. But the unfavorable (for medium-carbon steel) combination of such factors as the intensity of heat removal, the crystallization interval and its increased

sensitivity to level fluctuations proposed in [7] as an explanation cannot in our opinion be considered correct.

In favor of the conclusion about the priority role of the contact conditions between billet and mould is evidenced by the well-known fact about the absence of rhomboidity problems for medium-carbon steel if it is cast by protected jet. In [7] a decrease in the magnitude of metal level fluctuations in the mould during casting through a submerged entry nozzle (SEN) is indicated as a priority reason for this well-known fact. Many experts including the authors of this article have a different point of view on this matter.

It is known that a feature of this technology is the presence of slag layer on the billet surface. It is formed in the process of melting the slag-forming mixture supplied to the metal mirror in the mould. The slag layer has significant resistance to heat transfer that greatly exceeds the thermal resistance of the billet hardened shell. It is 60–65 % of the total thermal resistance of heat transfer in the mould [14, p. 51]. Due to this the intensity of heat removal from the billet is simultaneously reduced and straightened. This circumstance despite the presence of various factors contributing to billet rhomboidity formation (carbon content in steel, wear of mould tubes, non-uniform secondary cooling, etc.) provides uniform and somewhat delayed solidification that prevents rhomboidity generation.

One can assume that the contact conditions and the gas gap size are determined beside with the taper and the mould tubes wear, steel shrinkage during solidification and cooling also the features of the billet spatial third-dimensional (3-d) deformation within the CCM casting arc under the influence of technological and technical factors operating within it. This provision will be discussed in detail in the second part of this article. Taking into account this approach it is obvious that when studying the factors and regularities that determine the rhomboidity generation and growth it is necessary to go beyond the above mentioned limited M-B system and to consider a multilevel and multifactorial “Mould – Billet – Secondary cooling zone” system (M-B-SCZ). This system additionally contains structural elements of the CCM casting arc including mould, its oscillation table (mechanism), foot, support and pinch (centering) rolls and also a number of technological factors. In this case one should take into account possible deviations and violations of technological and operational modes, design features and quality of equipment maintenance. As far as we know this approach has been proposed for the first time in the study of the rhomboidity formation.

Elastic forces and reactions from various supports act on the billet in the M-B-SCZ system. One should note that elastic forces by definition are potential and in such system can be considered as active [15]. The billet rhomboidity formation is ultimately determined by elastic-plastic deformations in combination with the solidification process that fixes the distorted profile geometry. Since the deformation of the solidified billet frame under the action of thermoelastic forces during steel shrinkage occurs at temperatures ≥ 1300 °C the phenomenon of metal high-temperature creep and stress relaxation should be taken into account [16].

Conclusions

Modern concepts on the rhomboidity nature of continuously cast billets are incomplete. The mechanisms of the influence of some factors on rhomboidity remain not entirely clear. In the course of circumstantiation and development of these concepts they should integrate both the provisions the objectivity of which has been proven in the course of previous research and the data known from practice regarding the influence of many technological, technical and other factors on the rhomboidity.

In the course of the existing concepts analysis indisputable and debatable provisions were identified and circumstantiated. One can consider an objective fact that the rhomboidity initiation occurs in the mould meniscus region due to non-uniform heat removal from the billet along the profile perimeter. The trigger of the profile distortion process occurs when the heat removal intensity decreases even in one of its corners.

The metal level fluctuations in the mould cannot be considered as a dominant and independent factor in the occurrence of rhomboidity. Having a specific character they obviously are not associated with the effect of the turbulent jet from the tundish and may be due to the dynamic interaction between billet and mould. The reason for the non-uniform heat removal can be considered the contact conditions between billet and mould that differ along the perimeter.

One of the main reasons for the differing contact conditions was proposed to consider the spatial (three-dimensional) deformation of billet within the CCM casting arc under the influence of various technological and technical factors. To determine them it is proposed to study the multifactor M-B-SCZ system. In more detail these and other issues as well as new explanation of increased addition to rhomboidity of medium-carbon steel will be considered in the second part of this article.

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Надійшла 12.04.2021

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Received 12.04.2021

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Аналіз і розвиток сучасних уявлень з природи формування ромбічності безперервнолитих сортових заготовок. Частина 1

Ромбічність профілю, будучи дефектом форми безперервнолитих сортових заготовок, незважаючи на розвиток технології їх виробництва і вдосконалення конструкції сортових машин безперервного лиття заготовок (МБЛЗ), продовжує займати помітну частку серед інших типових дефектів. Сучасні уявлення про природу цього дефекту досі залишаються неповними, а по ряду моментів – на рівні непідтверджених припущень. Однією з найбільш помітних «білих плям» в них залишається питання про причини підвищеної схильності до ромбічності заготовок з середньо-вуглецевих марок сталі. Виконані авторами дослідження спрямовані на уточнення і розвиток існуючих уявлень про закономірності і механізми формування ромбічності як багаторівневого і багатофакторного процесу.

Зародження ромбічності відбувається в області меніска кристалізатора через нерівномірне по периметру профілю тепловідведення від заготовки. Причиною цієї нерівномірності можна вважати неоднакові по периметру умови контакту заготовки і кристалізатора. Запуск процесу деформації квадратного профілю відбувається при зниженні інтенсивності тепловідведення навіть в одному з його кутів. Флуктуації рівня металу в кристалізаторі, обумовлені нестабільністю турбулентного струменя з проковша, на думку авторів, не можна розглядати як домінуючий і незалежний фактор виникнення ромбічності. Специфічні флуктуації рівня, що часто спостерігаються на «ромбічних» струмках МБЛЗ, обумовлені насамперед динамічною взаємодією заготовки з кристалізатором.

Однією з основних причин відмінностей в умовах контакту заготовки з кристалізатором запропоновано вважати просторову (тривимірну) деформацію заготовки в межах розливної дуги МБЛЗ, яку можна розглядати як багатофакторну систему «Кристалізатор – Заготовка – Зона вторинного охолодження» (К-З-ЗВО). Запропонований підхід дозволяє інтегрувати в уточнені уявлення з природи ромбічності як положення, об'єктивність яких доведено в ході попередніх досліджень, так і відомі з практики дані про вплив на ромбічність різних факторів технологічного, технічного і іншого порядку. Такий підхід дозволяє також більш об'єктивно і глибоко зрозуміти закономірності і механізми зародження і зростання ромбічності як багаторівневого процесу. Це є необхідною умовою для підвищення якості заготовок, розробки нових технологічних рішень і оптимізації профілактичних заходів, спрямованих на зменшення ромбічності сортових заготовок.

Ключові слова

Сортова МБЛЗ, ромбічність, применіска область, флуктуації рівня, нерівномірність тепловідведення і затвердіння, умови контакту в кристалізаторі, тривимірна деформація.