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Detection and Minimizing of Surface Blistering in Continuously Cast and Hot-Rolled Mild Steel Coils

V. V. Kukhar, O. M. Smirnov*, A. G. Kostryzhev**, K. Ye. Pismarov*,
V. Ye. Ukhin*, O. D. Rud***, M. S. Goryuk*, S. V. Semiriagin*,
Yu. P. Skorobagatko*, and A. Yu. Semenko*

*Department of Metallurgy and Production Organization,
Technical University ‘Metinvest Polytechnic’,
80 Pivdenne Highway,
UA-69008 Zaporizhzhia, Ukraine*

**Physico-Technological Institute of Metals and Alloys, N.A.S. of Ukraine,
34/1 Academician Vernadsky Blvd.,
UA-03142 Kyiv, Ukraine*

***Centre for Microscopy and Microanalysis, The University of Queensland,
75 College Road,
4072 St. Lucia, Australia*

****G. V. Kurdyumov Institute for Metal Physics, N.A.S. of Ukraine,
36 Academician Vernadsky Blvd.,
UA-03142 Kyiv, Ukraine*

This study investigates the root courses of surface blistering and explores methods to minimise it in hot-rolled coil steels containing 0.1–0.2 C, 0.4–1.6 Mn, 0.05 Si (wt.%). Surface voids are believed to form during continuous casting, to develop into surface cracks during hot rolling, and to result in product rejection. These defects are found in the central part of the coils on the side corresponding to the small radius of the continuous casting machine (CCM). Metallographic analysis of samples reveals the defect-proliferation

Corresponding author: Volodymyr Valentynovych Kukhar
E-mail: kvv.mariupol@gmail.ua

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depth ranging from 100 to 300 μm , decarburisation around the defected zones, and grain coarsening of ferrite to ASTM No. 7 (32–45 μm) from ASTM No. 9–10 (11–16 μm) in the non-defected microstructure. In addition to decarburisation, chemical analysis reveals oxidation and presence of non-metallic inclusions in the defected zones. Oxidation indicates moisture ingress during casting, which is linked to a loss of seal integrity at the CCM, particularly, following a leak between the steel and copper water-cooled plate of the mould. Indentation traces observed on the coils' surface indicate the formation of a so-called 'metallic skull' due to the seal damage. The analysis of slag-forming mixtures reveals the maximum allowable limit of moisture content approaching 0.50%, although the moisture content in the coal used for carburisation of steel is ranging from 1% to 1.2% that is well below the limit of 9%. Based on the obtained results, a set of measures is developed to reduce the defect formation; this set includes: strict control of the moisture content in the mould powders, slag-forming mixtures, and ferroalloys; mandatory testing of mould seal integrity before casting; additional monitoring of tundish drying and the prevention of casting without a protective pipe.

Key words: continuous casting, mild steel, surface blister, microstructure characterisation, moisture control, mould powder.

Це дослідження спрямовано на аналізі причин і шляхів усунення дефектів типу «розкатаний газовий пухир» на гарячекатаних рулонах низьковуглецевої криці марок SAE 1008 і S235, що виявився впродовж шістьох днів виробництва на стані 1700 одного з металургійних підприємств групи «Метінвест». Продукція, на якій було виявлено дефекти, складала 3327 тон, з яких 88,3% припадали на сляби, розлиті на машині безперервного лиття заготовок (МНЛЗ) № 3, і лише 11,7% — на сляби з МНЛЗ-2. Особливо дефекти зосереджувалися в центральній частині рулонів з боку, що відповідає малому радіусу МНЛЗ, а також на рулонах, розлитих із застосуванням кристалізатора № 2 упродовж п'ятих днів. Металографічна аналіза зразків показала, що глибина поширення дефектів сягала 100–300 мкм, а структура металу поблизу дефектних зон характеризувалася повним зневуглецюванням і укрупненням зерна фериту до 6–7 номера за шкалою ASTM (32–45 мкм), тоді як нормальне зерно у непошкоджених зонах мало розмір 9–10 номера (11–16 мкм). На основі хемічного складу, визначеного відповідно до стандарту ISO 4967:2013, було підтверджено наявність окиснених зон у вигляді скупчень неметалевих включень в зоні дефектів. Це вказує на окиснення металу через потрапляння вологи у процесі розливання, що було пов'язане з пошкодженням герметичності кристалізатора № 2 на МНЛЗ-3, зокрема внаслідок виявленої течії між крицевою та мідною водоохолоджуваною плитою кристалізатора. У технологічному журналі також було зафіксовано сліди втискувань, які вказують на утворення так званого «металевого королька» як причину пошкодження герметичності. Аналіза складу шлакоутворювальних сумішей показала, що під час розливання вміст вологи у шлакоутворювальних сумішах становив від 0,20% до 0,50%, що відповідає максимально допустимій межі у 0,50%. Контроль також виявив, що вологість вугілля марки АС, яке використовувалося для навуглецювання криці, варіювалася від 1% до 1,2%, що не перевищує граничні 9%. Проте

об'єднання вологих матеріалів і порушення герметичності створювало умови для окиснення металу. На основі одержаних даних було розроблено комплекс заходів для пониження дефектності прокату, включаючи: суворий контроль вологості шлакоутворювальних сумішей і феростопів, обов'язкове тестування герметичності кристалізаторів перед розливом, додатковий контроль просушування проміжних ковшів і недопущення розливу без захисної труби.

Ключові слова: безперервне лиття, низьковуглецева криця, розкатаний газовий пухир, характеристика мікроструктури, контроль вологості, шлакоутворювальна суміш.

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1. INTRODUCTION

Intense commercial competition stimulates metallurgical companies to further improve the technological processes and implement the quality management system [1]. Surface appearance is one of the key quality parameters for many steel grades, such as structural and automotive; therefore, defect monitoring and prevention become a critical part of the whole production process. Various processing factors throughout the production cycle may influence the formation of surface defects, such as rolled-in scale or oxide layers, with processing routes playing a crucial role in determining both surface quality and mechanical properties [2]. In spite of the measures undertaken, the rolled-steel surface may suffer from a number of defects, such as foreign matter (rolled-in scale), roll marks (patches), scratches (long marks), crazing (short multiple marks), pitted surface, and inclusions. These defects are closely related to a steelmaking technology, continuous casting and hot rolling parameters, and the condition of equipment [3, 4].

Surface defects result from multiple causes such as incorrect set-up of the ladle–tundish–mould system, heat transfer within the mould, cooling water sprays, friction between strand and mould, misalignment of the casting machine, straightening strains, and phase transformations [5]. Effective hydrodynamic optimization of tundish flow, including control of turbulence zones and metal receiver design, enhances inclusion removal efficiency, homogenizes the melt, and reduces the risk of gas-bubble entrapment during solidification [6]. Meanwhile, the hydrodynamic conditions in the mould, particularly, the submerged entry nozzle (SEN) design, are essential for maintaining uniform metal flow and minimizing defects during continuous casting [7]. To minimize the defect formation, several measures have been undertaken:

- improvement of the ladle-shroud designs to optimise the molten-metal flow during casting [8, 9];

- correction of the mould oscillation frequency and heat-flux distribution to the slab geometry and steel grade [10–13];
- selection of the casting speed with respect to the high-temperature mechanical properties of a steel grade to minimise temperature fluctuations [14, 15];
- a thorough descaling to prevent rolling of the scale into the surface [16];
- reduction of the sources for formation of non-metallic inclusions and optimisation of the inclusion removal from the liquid steel into the slag before continuous casting [17, 18];
- argon protection of the liquid steel melt during transfer from the ladle to the tundish and to the mould [19, 20];
- optimisation of the caster geometry (nozzle port angle, size, and shape, mould width and thickness), casting speed, argon gas injection, nozzle submergence depth [21];
- improvement of the roll-surface quality and control of their wear [22];
- application of increased cooling rates during strip coiling [23];
- application of various defect detection methods, like electromagnetic sensors, radiography, magnetic particle inspection, and artificial intelligence [24–27].

During ladle treatment and continuous casting, oxygen, nitrogen, and hydrogen can dissolve in the melt. When the melt solidifies, the solubility of gases decreases and CO, H₂, N₂ containing bubbles may form. The addition of aluminium and calcium facilitates steel deoxidation, reducing the risk of gas-bubble formation, while the introduction of yttrium after aluminium may lead to increased losses due to the oxidation and the formation of complex-oxide inclusions [28]. If the steel is pre-oxidized or contains a high oxygen level, this increases the likelihood of reoxidation during casting, negatively affecting the quality of the cast product. The gas-bubble formation depends on the pressure: under low pressure, the gas formation is easier. The lowest pressure in the liquid pool is at the meniscus. Therefore, gas bubbles can form most easily in the mould near the strand surface. The bubbles may be engulfed by the solidifying shell, so, that pores appear near the surface. Nucleation of gases can take place also in the solid strand due to the solubility decrease with temperature or presence of microporosity and cracks [29]. The phase structure influences the bubble formation. For example, the solubility in ferrite is lower than in austenite due to the more close-packed b.c.c. crystal structure (ferrite) compared to the f.c.c. crystal structure (austenite). In medium carbon steel with ferrite–pearlite microstructure, the pearlite colony boundaries and the prior austenite grain boundaries may act as the void nucleation sites [30]. In case of an increased P concentration, Fe(PO) may form around 980°C; then, it will melt and vaporize under high temperature to result

in blistering of scale. Gas holes and cracks can be found in scales at a temperature of $> 1050^{\circ}\text{C}$ due to formation of CO [31]. Subsurface bubbles may develop into surface cracks, especially, in presence of inter-metallic inclusions [32]. Cracks and gas bubbles may close *via* solid-state diffusion, if their surfaces are not oxidised [33–38]. This requires increased compressive strains and stresses. For example, in work [39], during 50% reduction of a 150 mm thick slab, the 10–25 mm diameter voids closed after the fourth pass for a seven-pass rolling schedule and after the second pass for the five-pass rolling schedule. This means that a larger strain per pass provides a stronger void closer. The extent of void closure was observed, increasing toward the slab centre line from the slab edge. During void closure, the local compressive stresses around voids may reach significant values of > 2500 MPa; this drives the void healing process [40]. Effective closure of internal cavities using the shape of the tool and compression modes can reduce the number of subsurface voids, which are potential precursors to surface defects after hot deformation [41].

The reoxidation of liquid steel, that may prevent the void closure, can occur through contact with gaseous atmosphere, slag with high oxygen potential, ferroalloys, refractory phases during secondary steel refinement, cracks in the refractory walls, and during transfer of liquid steel from a ladle to a tundish and to a mould [42–47]. Oxygen pickup increases precipitation of non-metallic inclusions [48, 49] and scale growth, weakens the austenite grain boundaries, and facilitates crack nucleation during hot rolling and cooling [28, 50–52]. Decreasing the oxygen/gas ratio during slab reheating was shown to reduce oxidation and defect formation [53]. If not prevented on the stages of steel making and hot rolling, defects remain on the cold rolled steel [54, 55].

This paper is concerned with investigation and prevention of defects at one of the leading strip mills in Ukraine, namely, 1700 Hot Rolling Mill (HRM) of the Metinvest Group. ‘Rolled-out gas voids’ observed on SAE 1008 and S235 steel coils were believed to originate from continuous casting. These defects were located in the central part of the coils, primarily, on the side corresponding to the small radius of the continuous casting machine. ‘Rolled-out gas void’ defects can be completely removed by surface grinding; however, this slows down the product despatch. As a result of defect removal, the thickness of the finished product may fall below the minimum permissible tolerances, leading to the rejection of the product as scrap and economic losses. The occurrence of such defects not only affects production efficiency, but also introduces significant financial and operational risks, emphasizing the need for predictive modelling and risk assessment in metallurgical enterprises [56, 57]. Investigations conducted in this paper aimed to identify the causes of the ‘rolled-out gas void’ defects on the

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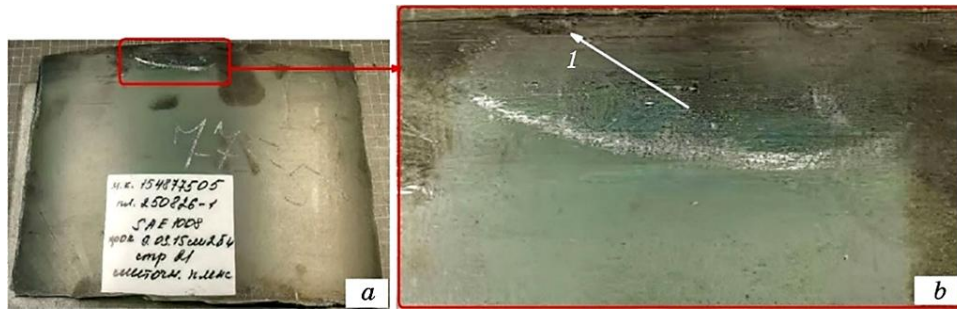


Fig. 1. Photoimage of sample No. 1 (SAE 1008 steel) with a blister (1) defect on the edge (a) and its enlarged view, revealing delamination (b).

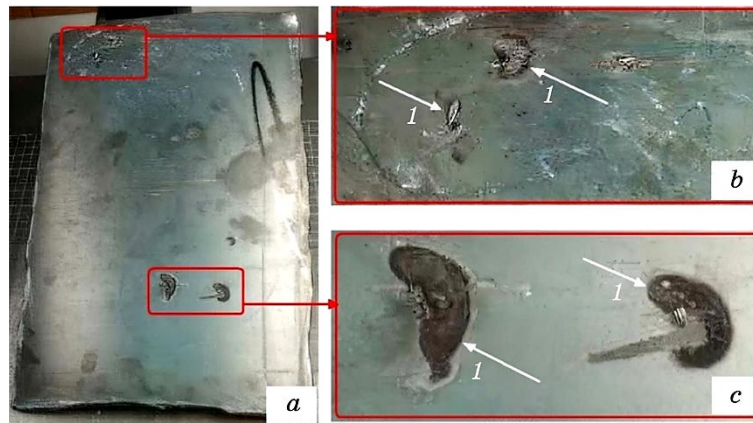


Fig. 2. Photoimage of sample No. 2 (SAE 1008 steel) with blister (1) defects (a), affected area (enlarged) (b), and delamination (enlarged) (c).

ering a 10 mm wide zone (Fig. 1). Directly along the edge, two small 10–15 mm long delamination were found. On sample No. 2 (Fig. 2, a), the entire surface of the rolled product is affected by blisters (Fig. 2, b). Small delamination has also been found extending along the rolling direction up to 20 mm long, accompanied by a dark haze (Fig. 2, c). On sample No. 3, the entire surface is affected by small delamination accompanied by a dark haze (Fig. 3). On this sample, the defects are located on one rolled surface.

Sampling for metallographic investigations was carried out in accordance with the ISO 377:2017 standard ‘Steel and steel products—Location and preparation of samples and test pieces for mechanical testing’. The metallographic study of defect was made in accordance with the ISO 4967:2013 standard ‘Steel—Determination of content of non-metallic inclusions—Micrographic method using standard dia-

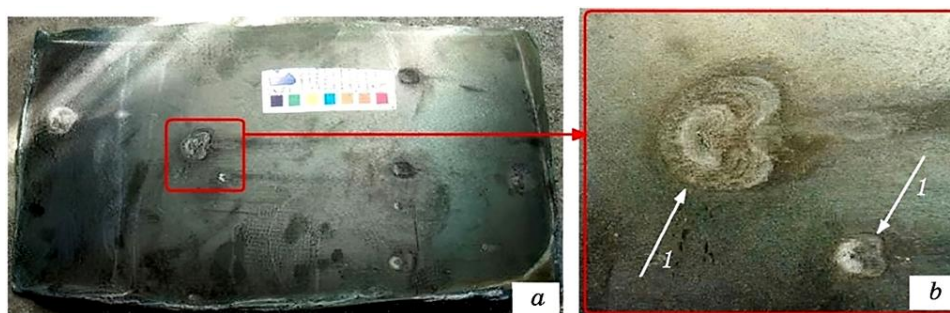


Fig. 3. Photoimage of sample No. 3 (steel S235) with a blister (1) defect (a) and delamination (enlarged) (b).

grams'. The study included determination of the chemical composition of the samples, microstructural analysis of defects, using microsections made in the longitudinal and transverse directions. The microstructure of the rolled products was determined both in the defect areas and for the sound material. The sample etching was carried out using 4% alcohol solution of HNO_3 . The grain size was measured, using optical imaging on a MIM-7 metallographic microscope (optical magnification up to $\times 2000$, bright-field and dark-field observation) following the ASTM E112 'Standard Test Methods for Determining Average Grain Size'.

3. RESULTS AND DISCUSSION

3.1. Structure of the Defects

The macrostructure of a delamination in steel SAE 1008 is shown in Fig. 4, *a*. A coarse cluster of iron oxides was revealed in the delamination cavity. The thickness of delamination was of 80–200 μm . The delaminated metal is diffusively oxidized, completely decarburized; the ferrite grain is enlarged to number 6–7 (32–45 μm). The depth of the decarburized layer at the defect site was measured to be of 100–300 μm (Fig. 4, *b*). The delamination walls with a haze had a thickness of 26–70 μm . The delamination cavity was oxidized, accompanied by oxide accumulations. The exfoliated metal was diffusively oxidized, completely decarburized; the ferrite grain was enlarged to number 6–7 (32–45 μm). The depth of the decarburized layer was of 100–234 μm .

Blisters revealed on samples Nos. 1 and 2 had a structure similar to delamination (Figs. 4 and 5). In line with oxide accumulations, the metal was decarburized in sample No. 1 to a depth of 275 μm , and in sample No. 2—to 296 μm (Fig. 5, *b*). The ferrite-grain size increased to the number 6–7 (32–45 μm). In areas not affected by defects, the de-

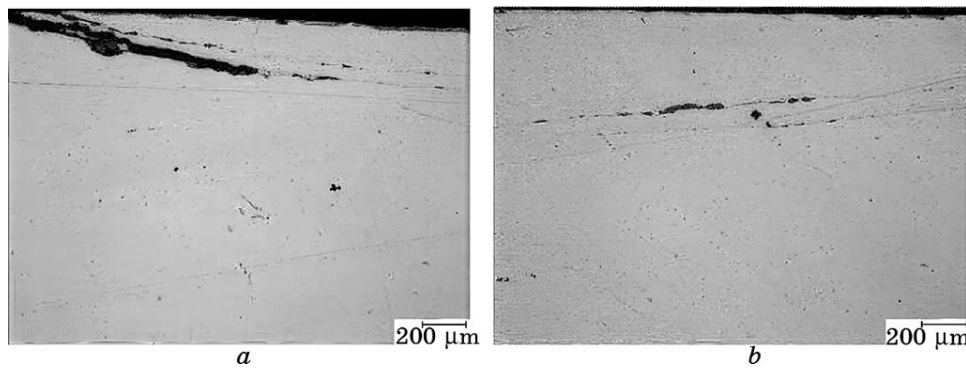


Fig. 4. The macrostructure of the walls of delamination (*a*) and blisters (*b*) in sample No. 1 (magnification $\times 50$).

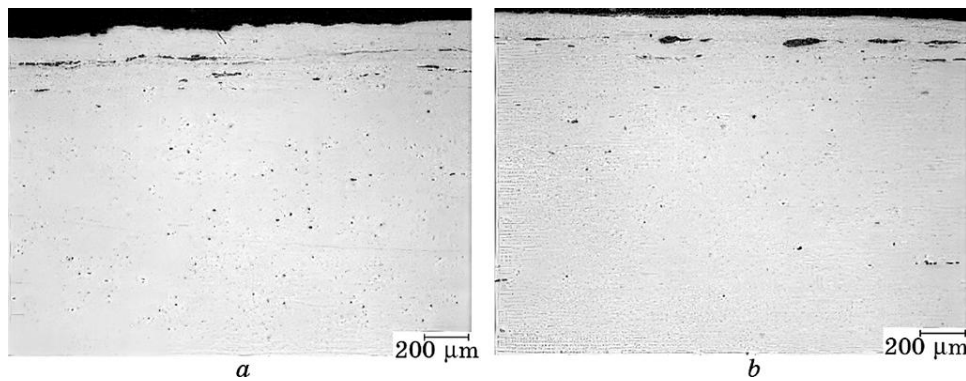


Fig. 5. The macrostructure of the blister walls in sample No. 2 (magnification $\times 50$).

carburized surface of the rolled product was absent on both samples (Figs. 6 and 7). The ferrite-grain number was 9–10 (11–16 μm).

The results of the study indicate that blisters and metal delamination in the rolled products of SAE 1008 steel grade (samples Nos. 1, 2) were associated with defects formed during continuous casting. The absence of decarburization and grain coarsening on the rolled-product surface away from the defects indicates the absence of metal overheating.

The macrostructure of the delamination walls with a haze in steel S235 is shown in Fig. 8. There are no clusters of non-metallic inclusions along the walls of the delamination. Clusters of iron oxides were found in the root of the delamination and along its length. The thickness of the delamination was of 11–50 μm . The delaminated metal was diffusively oxidized, partially decarburized; the ferrite-grain size was

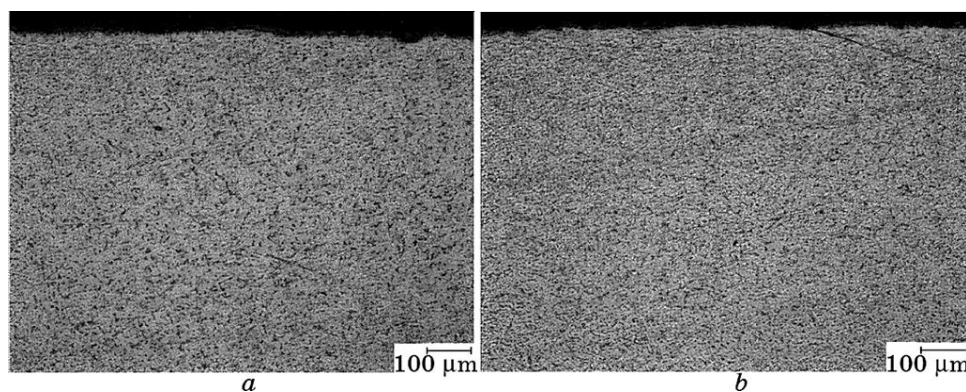


Fig. 6. Microstructure of sample No. 1 through rolled-metal thickness (magnification $\times 100$).

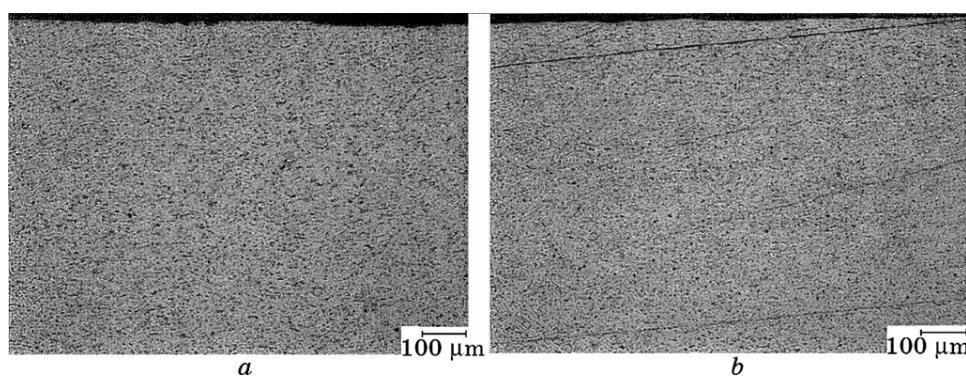


Fig. 7. Microstructure of sample No. 2 through rolled-metal thickness (magnification $\times 100$).

slightly coarsened to the number 8 ($22\text{ }\mu\text{m}$). The depth of the decarburized layer at the defect site was up to $20\text{ }\mu\text{m}$ (Fig. 9). In areas not affected by defects, there is no decarburization of the rolled-product surface. The ferrite-grain size number was of 9–10 ($11\text{--}16\text{ }\mu\text{m}$). The results of the study indicate that defects in the rolled products of steel S235 (sample No. 3) were formed during the rolling of oxidized subcutaneous blowholes in continuously cast slab. As for samples Nos. 1 and 2, the absence of decarburization and grain coarsening on the surface of the rolled products away from the defects indicates the absence of metal overheating.

As a result of metallographic investigation, the following preliminary conclusions can be made: the chemical composition of the samples corresponds to the heat composition and the company regulations for steel grades S235 and SAE 1008; defects on the surface of rolled steels

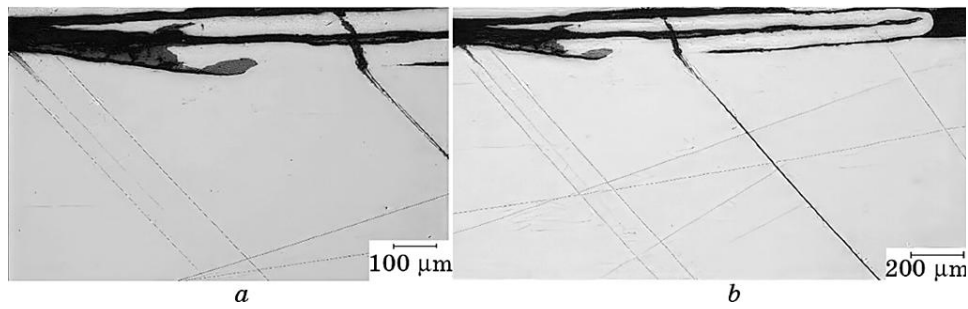


Fig. 8. Microstructure of delamination walls in sample No. 3 (magnification $\times 100$ (a), magnification $\times 200$ (b)).

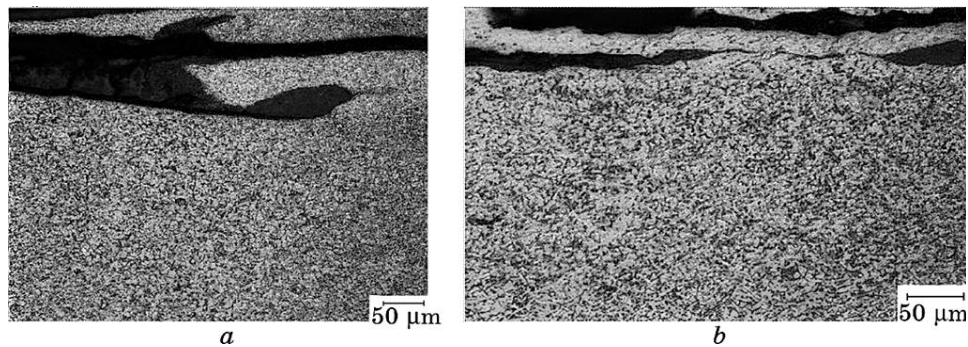


Fig. 9. Microstructure of delamination walls in sample No. 3 (magnification $\times 200$).

S235 and SAE 1008 were formed following opening of oxidized subcutaneous blowholes, which appeared during continuous casting; no signs of metal overheating were detected.

3.2. Root Cause of Blisters

Table 2 summarizes the main known reasons for the formation of subcutaneous blowholes in continuously cast slabs.

The analysis of the process documentation and heats' certificates, performed for those heats, where the blisters were detected, and verification of the processing parameters' correspondence to the required values have shown the following.

(i) Insufficient killing of steel. The average content of total and acid-soluble Al in the steel was of 0.033% and 0.030%, respectively (the standard requirement is at least of 0.02%). The oxygen concentration in the steel before being transported to continuous casting machine (CCM) No. 3 (measured, using an electrochemical oxygen probe, which

TABLE 2. Subcutaneous blowholes, reasons for their formation and methods of prevention.

Key issues	Information on methodology, origins and effects
Detection of the defects	are revealed on sulphur prints (according to Bauman), after etching or peeling, subcutaneous blowholes are clearly visible on the first slabs and usually disappear after the third slab
Key reasons for formation	insufficient steel killing, high gas content in steel (O_2 , N_2 , H_2), wet mould powder metal blow-off by oxygen in the tundish or casting without a ladle shroud,
Additional causes	overheated metal, undried tundish, use of wet ferroalloys
Suggested methods of prevention	improvement of steel killing technology, vacuum treatment of steel, use of dry materials for the tundish lining, use of dry ferroalloys
Impact on the rolled product quality	blowholes and shells can roll out and cause surface cracks during rolling

determines electromotive force proportional to oxygen activity and provides results within 1 minute with accuracy in ppm) is on average of 2.94 ppm, according to the technological instructions of the enterprise, which allow no more than 3 ppm. Thus, no violations of the ‘insufficient metal killing’ criterion were observed.

(ii) Overheated metal. The steel temperature during continuous casting was measured, using an Optris CT Laser pyrometer. This device determines temperature by analysing the infrared radiation emitted by the molten metal. It provides immediate and accurate readings (temperature range: 250–1600°C, accuracy: $\pm 0.75\%$, response time: < 1 second). The measured temperature corresponded to the technological instructions. No ‘hot’ heats were noted. Thus, no violations of the ‘overheated metal’ criterion were observed.

(iii) Wet mould powder. In CCM No. 1 and CCM No. 2, the heats were cast using the mould powder T-4-2(i); in CCM No. 3, the heats were cast using the mould powder ATST-SP627, GS-MC22MA, STSP285-22. The composition of the mould powders is given in Table 3. The actual water content in the mould powder was of 0.20–0.49% (according to the technical instructions, the water content in the mould powder should not exceed 0.5%). Thus, no violations of the ‘wet mould powder’ criterion were observed.

(iv) Metal blow-off by oxygen in the tundish or casting without ladle

shroud. No metal blow-off by oxygen in the tundish was detected; argon consumption in the stopper corresponded to the standardized indicators (the standard for CCM Nos. 1 and 2 is of 0.32–0.51 m³/h, and for CCM No. 3, it is of 0.72 m³/h). During one of the heats, casting a 9 m long slab without a ladle shroud was noted (according to the technical instructions, slabs no longer than 2.5 m can be cast without a ladle shroud). Thus, a local violation of the requirement was detected due to the presence of the reason ‘casting without a ladle shroud’.

(v) Insufficiently dried lining of the tundishes. Drying and heating of tundishes at CCM No. 3 were carried out in accordance with the specified temperature conditions, which were maintained automatically by changing the consumption of natural gas and air. The total drying and preheating time was of 2 hours 45 minutes. Heating to 1100°C took 45 min, after which the temperature was held for 2 hours. During the six-day period under study, six tundishes were dried and heated for CCM No. 3. For all tundishes, the drying and heating time has been increased. Therefore, no inconsistencies were detected for the criterion ‘insufficient drying of lining’.

(vi) Increased gas content (N, H, O) in liquid steel. The steel chemical-composition adjustment, degassing, killing, and reduction of the impurity content in it were performed in the ladle-refining unit (LRU). The hydrogen content in the metal was not measured. Metal oxidation in the LRU before delivery to the continuous casting machine was on average of 2.94 ppm and did not exceed 3 ppm; this is recommended by the technological instructions of the enterprise. At the same time, in Ref. [59], the authors recommended the values of liquid steel oxidation to be within 3–5 ppm. In liquid steel studied in Ref. [45], a fluctuation in the oxygen activity was of 0.6–3.2 ppm, mass fraction of Al was of 0.01–0.1 wt.%, and the CaO/Al₂O₃ ratio was of 60/40–65/35 in the temperature range of 1.520–1.560°C. The average nitrogen content in the steel was of 60 ppm (ranging from 40 to 80 ppm) that also corresponded to the ‘Technological Instruction’ (TI) and is within the known standards [60].

(vii) Leaks in cooling systems. In the heat certificates, a leak in the boiler of BOF No. 2 was noted on the heat dates. During the retraining period, namely, when replacing the mould and the accompanying mandatory inspection of the connection cable and the mould cross-sectional change system, a water leak at CCM No. 3 was discovered in the upper part of mould No. 2 on the narrow wall. No water leaks occurred during the operation. This was noted in the technological casting log, and an inspection report was drawn up for the narrow wall of the mould No. 2 after disassembling and disconnecting the copper working walls from the steel part. The following was revealed during the inspection:

(a) the fastening bolts were tightened according to the instructions (force 60 Nm); they did not have visible defects; their length was main-

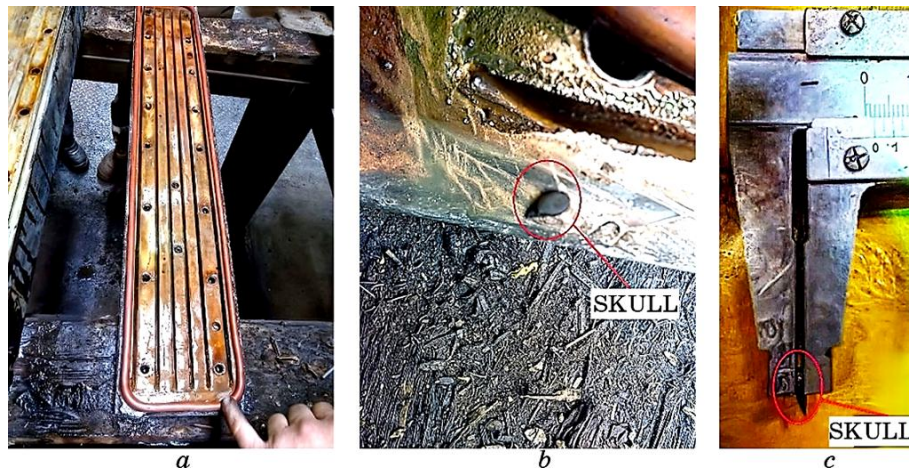


Fig. 10. Photo of the mould wall (*a*) and the skull (*b*, *c*).

tained as required;

(b) on the narrow wall between the steel and water-cooled copper wall on the narrow side (far end), where a water leak was detected, a metal skull was found, and a dent corresponding in shape to the skull was also found (Fig. 10);

(c) on the date of acceptance of mould No. 2, there were no comments about the hydraulic test of the copper plates.

Therefore, it can be concluded that the leak in the cooling system was caused by the presence of a metal skull between the steel and water-cooled copper walls of the mould that led to the damage of the seal. Pressure testing (10 atmospheres, 15 minutes) of the copper plates before commissioning did not reveal any defects, but, during the operation of the mould, this defect appeared. This is confirmed by the detection of a dent and a water leak and corresponds to previously obtained results.

Analysing this case allows us to conclude that leaks or ruptures in the cooling system of the continuous casting mould can lead to the formation of subsurface gas bubbles in the solidified slab. When cooling water accidentally enters the molten metal, it instantly vaporizes, generating high-pressure steam that may become trapped in the solidifying shell and form gas inclusions. Moreover, sudden contact between water and the hot surface of the strand can cause localized uneven cooling, which may lead to microcracks and destabilization of the solidification front. These conditions promote the entrapment of gases and the development of internal voids or blister-like defects in the cast product (slab).

The manuscript [61] states that the cooling systems have a critical

impact on the formation of defects. In CCM steelmaking industry practice, verifying the tightness of mould cooling systems by conducting hydraulic pressure tests is a mandatory procedure. However, excessive pressure during such tests can lead to deformation of copper walls, coating damage, and potential leakage in sealing zones [62]. Reference [62] also notes that failure to adhere to recommended testing parameters may alter the mould geometry and affect the formation of the initial solid shell. Therefore, water leaks such as those described in the carried-out study may be an indirect consequence of improper pre-commissioning pressure-testing procedures. Although the problem of cooling water leakage in continuous casting systems is well known and poses a serious threat to process stability, it remains insufficiently covered in scientific literature. The relevance of this issue is further supported by patent US4182397A [63], which proposed an engineering solution to minimize leakage risks through the use of dovetail-shaped channels and corrosion-resistant fastening elements. Thus, received findings not only confirm the potential link between the cooling water leakage and the formation of subsurface gas bubbles (blisters), but also expand the current scientific knowledge by emphasizing the critical role of mould tightness control as a key factor in preventing defects in continuously cast slabs.

3.3. Root Cause of Gas Saturation

During the study period, scheduled measurements of hydrogen content were undertaken in the tundish, during casting of steel grade S235 on continuous casting machine CCM No. 3. The measurements were taken on five heats, using the Hydris electrochemical probe, in accordance with the plant's standard practice for hydrogen-sensitive grades. The results of hydrogen-content measurements, oxidation values, and comments on the rolling quality of these heats in HRM-1700 are presented in Table 3.

Table 3 shows that the actual hydrogen content in steel at the continuous casting machine was of 3.2–4.9 ppm, while the oxidation of the metal in the ladle-refining unit did not exceed 3 ppm. A number of measures were taken to identify the causes and prevent increased gas saturation of the metal.

(i) CCM No. 3 control sampling was made of argon for water content in the gas. The water content in argon was determined to be of 0.0023% that complies with the required $< 0.0070\%$.

(ii) Three samples of AM-grade coal (used for the carbon-restoration treatment during tapping from the BOF) were taken to determine their water content. The water content in AM-grade coal was within the range of 1–1.2% (with a requirement of no more than 9%).

(iii) The duration of thermostatic treatment of slabs has been in-

TABLE 3. Gas saturation measurements and characteristics of the rolled product quality.

Oxidation and hydrogen content for S235 (1.305) CCM No. 3 for different heats		Notes on the mill	Total, tonnes	Valid, tonnes	Rejected, tonnes
Oxidation on LRU, ppm	Hydrogen at CCM, ppm				
2.9	3.6	–	Heats didn't rolled on HRM-1700		
2.7	3.2	Width divergence (+)	132.3	132.3	0
2.8	4.4	Indentations	141.75	141.75	0
2.8	3.7	–	Heats didn't rolled on HRM-1700		
2.9	4.9	–			

creased for heats cast on CCM No. 2 and CCM No. 3 for orders from HRM-1700 (at least 48 hours in the BOF shop warehouse). Slabs in standby mode were stored in the BOF shop slab warehouse.

(iv) Nine control samples of mould powder were taken, which were used for casting (ATST-SP627, GS-MC22MA, STSP285-22, except for the T-4-2(i), since the entire batch was produced) at all continuous casting machines to determine the water content. The actual water content was of 0.20–0.50%.

(v) In HRM-1700, selective peeling of slabs of current heats of similar grades was carried out. The amount of metal rolled with the blister defect was of 3 312.5 tonnes. From this amount, 42.4 tonnes (1.2%) of rolled steel were additionally rejected due to the defects 'telescope' and 'protruding coils'. These imperfections are not related to the presence of blisters, but depend on the condition and settings of the mechanical equipment of the rolling shop [64].

(vi) The analysis of several heats cast and rolled in the same period did not detect the blister defect. Dependences of the defect formation on the processing parameters (liquid steel treatment, casting, and rolling) in adjacent heats and heats with the defect were not detected.

Considering the sufficient killing of the steel, absence of overheating before rolling and the secondary oxidation in the continuous casting machine, and the nitrogen content being in the required range of 40–80 ppm, the reason for the formation of the largest number of blister defects was the ingress of water from the mould cooling system to the slab surface.

3.4. Development of Methods for Blistering Prevention

The analysis of results obtained in this work suggested the following

methods for prevention of blisters on the rolled steel surface: perform tests of incoming AM- and AF-coals, which are used for carbon-restoration treatment of steel, for water, ash and volatile contents, eliminate the possibility of mixing coals of the AM- and AF-grades with non-coking energy coal during storage, drying and other technological operations, eliminate the possibility of using solid-slag mixtures during steel tapping from the BOF with a shelf life of more than 24 hours, eliminate the production of steel grades, which are going by 'warm' charge to HRM-1700, on BOFs with leaking boiler, use wet ferroalloys only after calcination, conduct mandatory oxidation measurements on the LRU for low-silicon (semi-killed) steel grades cast on continuous casting machines, perform moulds' monitoring for leaks during acceptance and installation on the continuous casting machine, test each batch of mould powder for water content with an increased number of samples (2 or more), conduct weekly monitoring of argon supplied to the continuous casting machine for water content, eliminate using tundishes with violation of the heating and drying schedule.

Following implementation of these measures and prior to publication of this paper, 2.692 tonnes of hot rolled coils have been produced without defects. All this steel was supplied to the electric-resistance welding (ERW) pipe mill that produced pipes fully complying with the standard requirements, demonstrating the effectiveness of the measures undertaken to minimise the defect formation. To further ensure the defect-free production, hot-rolled coils were shipped to the ERW mill with recommendations to maintain a lower manufacturing speed, thereby, eliminating the probability for blister-defects' formation. In addition, the experiments involving etching and galvanizing of hot-rolled steel coils were carried out in the cold-rolling shop. The results confirmed that the galvanized coils met all regulatory quality requirements, showcasing the effectiveness of the implemented measures in mitigating the defects.

4. CONCLUSIONS

The analysis of steel making, casting, and hot-rolling technology at HRM-1700 mill of the Metinvest established the primary cause of the blister defects being the ingress of water during steel casting following a loss of seal integrity in the moulds of continuous casting machines.

The water content in the mould powders was measured to be of 0.20–0.50% that is approaching maximum permissible limit of 0.50%. Therefore, stricter quality control of the mould powders was recommended to prevent formation of defects.

A comprehensive set of preventive methods was developed, including enhanced control of ferroalloy humidity, thorough checks of the

casting machines mould seals, and additional requirements for tundishes' heating. Following implementation of the developed methods, 98.8% of the hot-rolled 2.692 tonnes of steel met quality standards. This confirms the effectiveness of the measures undertaken to reduce the defects' formation.

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AUTHORS' CONTRIBUTIONS

V. V. Kukhar: supervised the research project, validated the effectiveness of preventive methods at the HRM-1700 mill, wrote the paper. O. M. Smirnov: support on the development of the technologies proposed in the paper, details on the technologies, wrote the paper. A. G. Kostryzhev: conducted high-resolution microscopy and micro-analysis of surface defects, interpreted metallographic data regarding grain coarsening and oxide clusters, wrote the paper. K. Ye. Pismarov: coordinated sample preparation and metallographic-investigation procedures, managed the chemical-composition verification according to ISO standards. V. Ye. Ukhin: collected the data, analysis of results and correlation with industrial data, wrote the paper. O. D. Rud: performed physical-metallurgy analysis of the 'metallic skull' and seal damage, investigated the root causes of subsurface gas-bubble formation. M. S. Goryuk: collected industrial production data and monitored casting parameters at CCM No. 3, assisted in the investigation of water leaks in the mould cooling system. S. V. Semiriagin: analysed the moisture content in mould powders and slag-forming mixtures, correlated the defect formation with argon consumption and ladle shroud usage. Yu. P. Skorobagatko: evaluated the gas saturation (hydrogen and oxy-

gen content) in liquid steel, monitored the drying and heating schedules for tundish preparation. A. Yu. Semenko: collected the data, conceived and designed the analysis, wrote the paper.

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