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Research Article

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MECHANISM OF FORMATION OF INTERNAL AND SURFACE DEFECTS IN CASTING AND THEIR TRANSFORMATION INTO SURFACE DEFECTS OF SHEET

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Abstract. *This study aimed to elucidate the formation mechanisms of micro-macrostructural heterogeneities in the ingot's cortical zone and their transformation into surface defects during heating, plastic deformation, and rolling processes. The methodology and results of studying the macro- and microstructural and chemical heterogeneities of ingots and finished rolled sheets are presented. A comparative method of structural-concentration analysis of metal at the end-to-end metallurgical processing stage of ingot - slab - rolled sheets was developed. The technique utilizes metallographic methods to study the structure and perform qualitative analysis of non-metallic inclusions. The research findings indicate that the quality of the rolled sheet surface is predominantly determined by the physical heterogeneity of the ingot's crust zone, while the internal defects in thin rolled sheets are largely influenced by the contamination of the metal with non-metallic inclusions. A novel mechanism is proposed for the transformation of defects in the casting cortical zone into surface and internal defects in rolled sheets. This study contributes to a deeper understanding of the formation and transformation of defects during metal processing, enabling the development of strategies for improving the quality of rolled sheets. Additionally, the study highlights the importance of controlling the physical heterogeneity of the ingot's crust zone and minimizing non-metallic inclusion contamination to achieve high-quality rolled sheets.*

Keywords: ingot, macro - and micro-inhomogeneity, slab, rolled sheet metal, defect, structure

1. Introduction

In the competitiveness of thin-sheet rolled products, a special role is given to the radical improvement and stabilization of the quality of the rolled products produced. Its practical solution largely depends on the quality of the steel ingot. During the formation of an ingot, all types of macro-inheterogeneity greatly develop: physical, structural and chemical. This significantly degrades the quality of cast and rolled metal. This problem is especially acute in the production of sheet metal. The waste-free production of thin sheet metal is inextricably linked with the quality of the metal produced, i.e., the presence of "hidden" internal defects in the structure of castings, which in subsequent processing can lead to both direct losses of metal in the form of trim (head or end) and to losses of metal at the final stage of end-to-end technology.

An analysis of the technical literature [1-10] showed that despite a large number of studies on the quality of thin-sheet rolled products, the results are ambiguous and contradictory. There is no consensus on the source and causes of the formation of surface defects in rolled sheet metal. This is because the morphological characteristics of the defects in the steelmaking and rolling origins may be similar since all the defects are elongated in the direction of deformation and have similar characteristics and shapes in the transverse direction. In addition, the metallographic method for determining the causes of the formation of surface defects is applicable for metals that have experienced one high-temperature heating, while in practice, the metal undergoes 2-3 high-temperature heating cycles.

However, there is a proven connection between the structural transformation of macro- and micro inhomogeneity in the ingot and surface defects in the rolled sheets.

2. Research methodology

To study the nature and sources of surface defects in rolled sheets, a comparative method of structural-concentration analysis of metals during the end-to-end metallurgical process of ingot slab-sheet metals was developed based on the metallographic method of studying the structure and qualitative analysis of nonmetallic inclusions. To study chemical heterogeneity and contamination with nonmetallic inclusions, characteristic ingots were isolated. Oxygen cutters were used to cut axial plates parallel to the wide edge 120-150 mm above the axial plane. In the machine shop it was planned to an axial plane, sanded, and then sulfur prints were made on photographic paper after etching the surface of the axial template with a sulfuric acid solution.

The contents of the elements [C], [Mn], [Si], [S], [P], [Al], and [N] were determined by chemical methods. Metal contamination with nonmetallic inclusions was determined by electrolytic deposition and the LT metallographic method. To study the macrostructure of the cortical zone of the ingot, a corner template was cut out at 5 levels along the height of the ingot, corresponding to 5, 25, 50, 75 and 95% of the height from the head of the ingot. The cut templates were planned, polished and etched in a sulfuric acid solution to remove sulfur. To study the causes of defects, samples were taken to determine the presence of nonmetallic inclusions and the chemical composition of the metal along the boundaries of the defects. Thin sections were cut from the selected samples to study the microstructure and contamination of the steel with nonmetallic inclusions, as well as from the samples to determine the number of nonmetallic inclusions. The chemical composition of the phases and structural components was determined by the local microprobe method on a Samesa micro analyzer.

In general, the scheme for determining the nature and origin of surface defects included the following steps:

- study of the topography of defects on the surface of rolled sheets;
- metallographic examination of the steel microstructure in the defective areas;

Determination of the composition and nature of nonmetallic inclusions, both in the defect zone and in the volume of "healthy" metal;

- analysis of the technological parameters of smelting out-of-furnace processing, steel casting and metal rolling at the rolling stage;
- Study of the structure of the cortical layer of the ingot and identification of structural heterogeneity using macroanalysis methods.
- Study of the influence of high-temperature heating on the behavior of inclusions and gas bubbles located in the crustal layer of the ingot.

3. Research results

Metallographic analysis of the microstructure of samples of cold-rolled steel sheets in areas where surface defects appear allows us to identify 3 main types of characteristic structures:

1 – coarse films (Fig.1, a), affecting a significant area of metal in the subsurface layers with a specific type of nonmetallic inclusion in the form of globules of iron oxides (wustite) and pinpoint oxide rash (Fig.1, b)

2 – areas of bubbles filled with iron oxides such as wustite (Fig. 1, c), which often form films on the surface of the sheet during rolling (Fig. 1, d);

3 – Group accumulation of oxide nonmetallic inclusions with complex compositions (Fig. 2, a, b).

Figure 1 shows a point chemical analysis of nonmetallic inclusions from the clusters, where it is clear that the inclusions correspond to oxides of the SiO_2–MnO–FeO system. The nonmetallic inclusions identified in places with defects in cold-rolled sheets are brittlely destroyed manganese silicates and have the following chemical composition: 12-18% SiO_2 up to 58% MnO, and up to 10% FeO.

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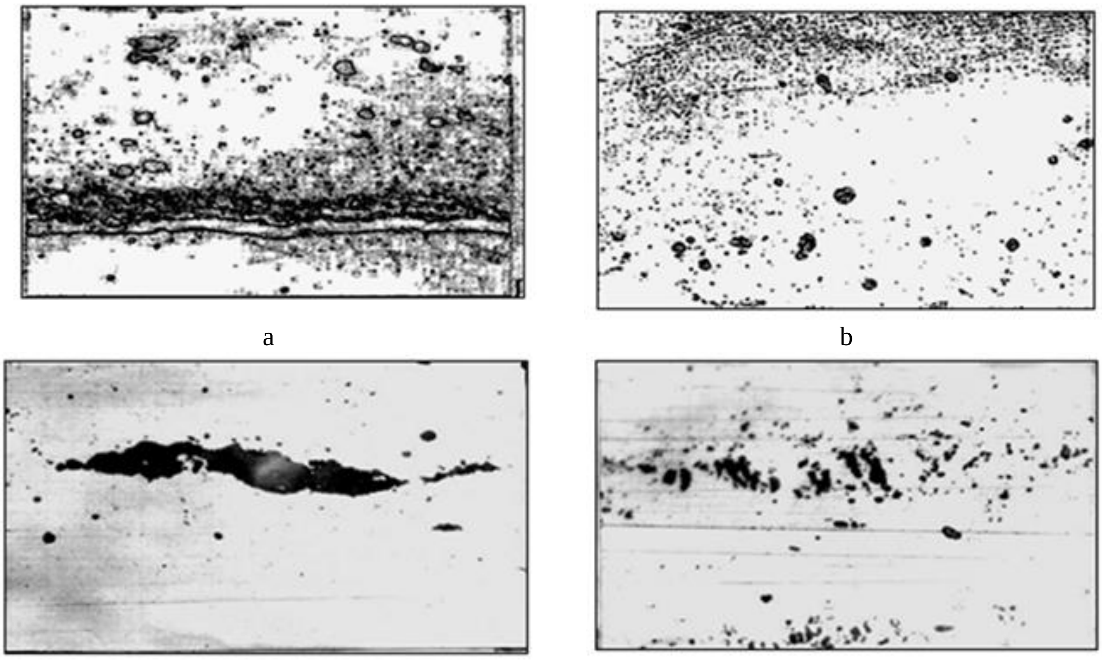
Another type of characteristic steel microstructure in areas with surface defects is revealed by the accumulation of iron oxides of the wustite type (Fig. 3 a, b) between the cavities of pores and discontinuities (gray in the microphotograph: wustite inclusions, dark pores and discontinuities).

Table 1. Chemical composition of the inclusions

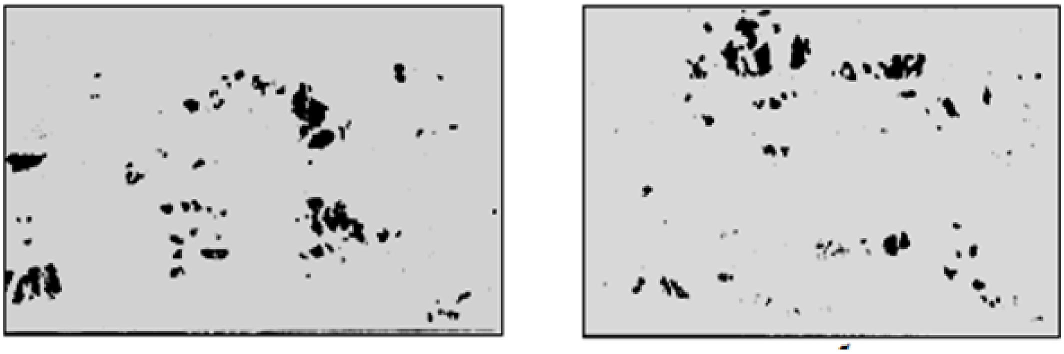
Oxides content,% by weight					
SiO_2	MпO	FeO	Al_2O_3	CaO	MgO
11.52	58.20	19.15	0.68	0.32	0.11



a b

c d

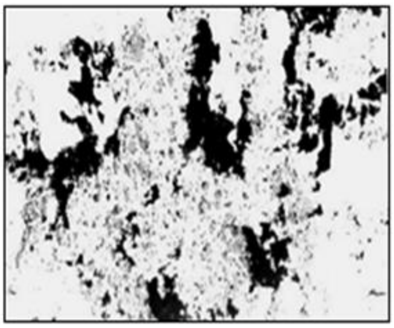
Fig.1. Microstructure of cold-rolled steel 08 KPs in place manifestations of the defect:
a), b) inclusions of iron oxides near the film defect **(**x400); c **-** rolled out bubble, sq. section along the thickness of the sheet (x 630); g - the same, grinding along the surface of the sheet (x 500)



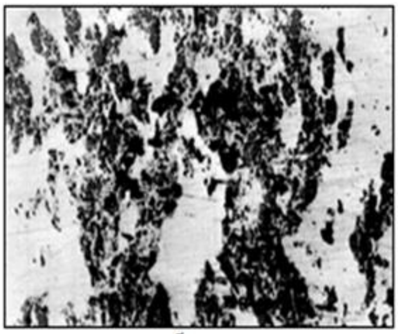
a b

Fig.2. Microstructure of steel at the location of the defect:
a, b - nonmetallic inclusions in a cold-rolled sheet along the surface of the sheet (x 400);

Microprobe point analysis of areas of nonmetallic inclusions confirmed the presence of 91.61% FeO and 2.50% MnO. The analysis revealed that the following types of surface defects formed in the cold-rolled sheets: 1is large films; 2 is a small captivity; 3 are a rolled out oxidized bubbles; and 4 are coarse nonmetallic inclusions. In almost 1-3 groups of defects, the main nonmetallic phase is iron oxides, the content of which is 90% or more.



a

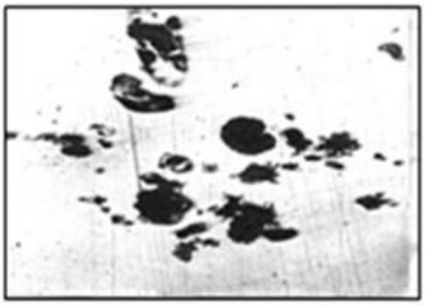


b

Fig.3. Accumulation of iron oxides at defects on the surface cold-rolled steel sheets grade 08 PS:
a) an increase 125 times; b) an increase of 80 times.

A comparative structural-concentration analysis of metal in cold-rolled steel at the site of a defect in the base metal and the cortical zone of the ingot before and after high-temperature heating revealed the morphological signs of structural heterogeneity (Fig. 4). The differences are only in terms of shape, distribution of inclusions and concentration of FeO in wüstite. An increase in the FeO content from 80-85% to 87-93% indicates the oxidation of subcortical bubbles and micropores during the oxidative heating of ingots in the cells of heating wells.

a



b

Fig.4. Microstructure of a gas bubble in a cold-rolled product (a) and the cortical zone of the ingot (b)

To determine the moment of formation of these defects, the macro- and microstructure of the near-surface zones of the ingot and slab were studied. A detailed macro- and microstructural analysis of the structure of the surface zones of the ingots indicated unsatisfactory conditions in the crustal layer of the ingot surface. The steel crust zone has an increased content of gas bubbles (subcortical, pores, and shells), which are often oxidized along the inner walls of bubbles or bubbles filled with metal but with an oxide shell composed of ~ 85% FeO and up to 7% MnO (Fig. 5). The surface crust of the metal is loose, porous and contaminated with nonmetallic inclusions in the form of iron oxides such as wüstite, products of secondary oxidation during casting, and slag particles (Fig. 6).

4. Discussion of the research results

Figure 1 shows SEM images of synthesized ceramics depending on the annealing temperature, which reflect the kinetics of changes in the morphological features of the samples under study. during low-temperature annealing indicates the presence of several phases in the structure of ceramics.

A comparative analysis of defects in cold-rolled steel showed that defects originating from steelmaking accounted for 62 to 84% of all surface defects (Table 2). The results of metallographic studies show that 90% of the surface defects in cold-rolled sheets are represented by a nonmetallic oxide phase consisting of iron and manganese oxides.

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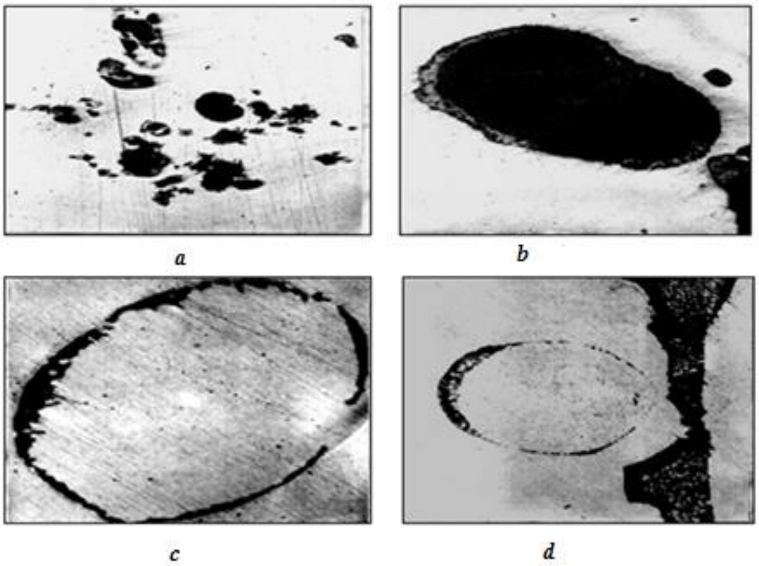

Fig.5. Microstructure of the ingot corner templates: a) x 50; b) x100; c) x 500; g) x200;
a), b) are gas bubbles in the cortical zone of the ingot; c), d) are bubbles filled with metal with an oxide shell.

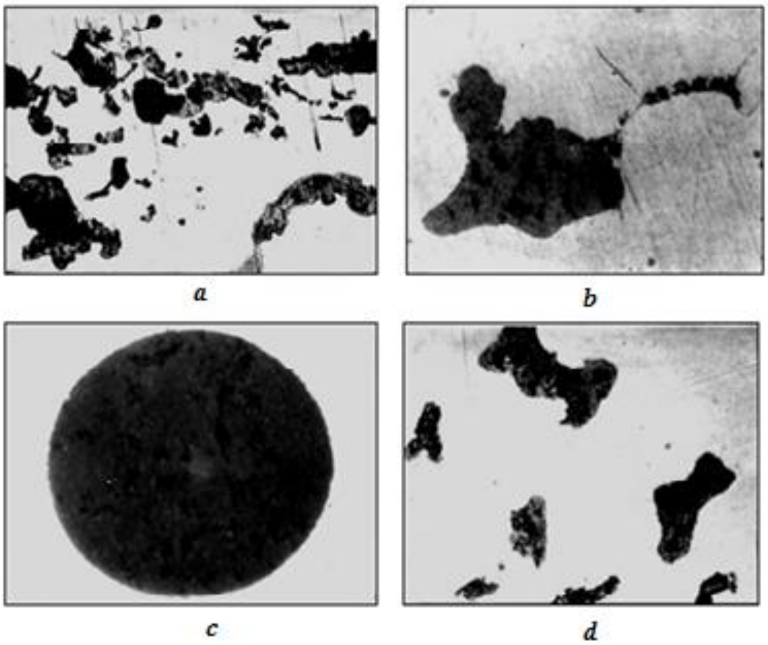

Fig.6. Accumulation of nonmetallic inclusions in a boiling crust: a) x100; b) x630; c), d) x400;
a) oxidized pores; b) slag inclusions in the interaxial sections of the square 3; c) 50% of the top of the ingot, iron oxides in the interaxial areas of the film type; d) slag inclusions.

Table 2. Classification of defects in cold-rolled sheets

Classification defects	pl. No. 380520 08KP	pl. No. 180521 08 KP	pl. No. 0180654 08 PS	Average values
peal bubble, %	48.3	45.8	66.0	56.6
captivity from n/inclusions, %	37. 9	45.8	22.6	32.1
ingot film, %	10.3	-	1.9	3.8
other, %	3.4	8.3	9.4	7.5

A high proportion of surface defects in the film from oxide nonmetallic inclusions (33–38%) and a rolled bubble filled with the oxide phase FeO-MnO indicate their nucleation at the crystallization front in a two-phase zone enriched in manganese, oxygen, carbon, sulfur and phosphorus. Oxidation of manganese occurs at all horizons of the forming ingot, including in the zone of predominant gas release, and the formation of the oxide phase from FeO and MnO occurs both at the crystallization front in the interdendritic sections of the liquid-steel solid surface phase boundary and on the forming outer surface of the bubble CO.

The oxide liquid phase of FeO and MnO, which envelops the CO bubble upon separation, is carried away from the crystallization zone to the head part of the ingot, as evidenced by the appearance of slag foam (ingot slag) on the metal mirror in the mold during boiling. As a result of the movement of bubbles, a specific circulation of the melt occurs at the crystallization front, which promotes the drawing of liquids and their oxidation products after the bubbles and the formation of micro-discontinuous materials and channels filled with an oxide slag phase, mainly FeO and MnO, or metal however, an oxide rim is present along the inner surface of the discontinuity, which was recorded during metallographic analysis. The presence of pores filled with oxides is explained by the much lower values of interfacial tension at the oxide phase-metal boundary than at the gas-metal boundary; therefore, it is easier for an oxide phase nucleus (inclusion of oxides - FeO and MnO) to arise in a liquid metal than a gas nucleus.

The contamination of the cortical zone of the ingot with oxide nonmetallic inclusions formed both on the surface of the CO bubbles and in the interdendritic space was influenced by the intensity of the metal boiling in the mold. With increasing boiling time, first, the thickness of the two-phase zone, which is enriched in liquates and the products of their interaction with oxygen, decreases, and second, intensive leaching of the resulting slag oxide phases into the head part of the ingot occurs.

The intensity of gas formation is determined by the degree of oxidation of the steel by the time it enters the mold, the liquid mobility of the metal, the solidification rate and casting temperature, as well as the chemical composition (oxygen, carbon, manganese content). The main reason for the deterioration of the bottom part of the ingot was boiling (“swelling”) of the metal due to the formation of numerous small CO bubbles covered with a ferromanganese oxide film. The viscous oxide film prevents the free release of CO from the metal, which leads to foaming of the metal. The foamed slag-metal layer rises up wards and, due to the large cooling effect of the cold walls of the mold, settles on its walls to form a frozen “shirt”. The high oxidative potential of the atmosphere in the cavity of the mold, due to the injection of air by a jet of metal, leads to oxidation of the surface of the “splash” frozen on the walls of the mold.

The main share of defects is of steelmaking origin and is determined by three factors:

a - small thickness, porosity and low gas density of the crust layer of the ingot;

b - the formation of internal (hidden) films from splashes (splashes) of metal in the mold during casting;

c - Contamination of the metal in the cortical zone of the ingot with oxide nonmetallic inclusions.

In rolled sheets, this manifests itself in the presence of nonmetallic inclusions of iron and manganese oxides or complex ferromanganese silicates in defective areas of the surface and subsurface layers of the sheets.

The following mechanism is proposed for the transformation of microdefects in the ingot into continuity defects in rolled sheets. When boiling steel ingots with microdefects in the structure of the crustal zone in the cells of heating wells are heated, further oxidation of the “hidden” film, subcrustal bubbles, and microporosity occurs, which leads to a change in the quantitative composition of oxide inclusions, i.e., to increase the FeO content from 34-85% to 91-94%. In addition, diffusion nucleation of oxide satellite inclusions in the form of an oxide rash occurs and the area of the defective metal increases (Fig. 7).

The source of oxygen for the diffusion oxidation of macro- and micro-discontinuities and the nucleation of new satellite oxide phases in the crust zone of the ingot are the oxidizing furnace atmosphere, as well as the oxide phase in the form of a “hidden” film, oxide nonmetallic inclusions, and scale on the surface of the heating ingot. Point quantitative analysis showed that the content of total oxygen in the “hidden” film is 23-31%, which may well serve as an additional oxidizing agent for internal diffusion oxidation of the metal.

When rolling an ingot, the shape changes, and the distribution of microdefects increases. In the surface zones of the steel ingot, accumulations of inclusions are found in the form of films along the interaxial areas of the dendrites (Fig. 8, a).

Coarse defects in the ingot located close to the surface, already at the first rolling stage, roll out onto the surface of the slab and give rise to defects in the form of honeycomb tears and films or after a fire cleaning machine, where a 4-6 mm layer of the metal surface is removed, revealing internal defects in the ingot (Fig. 9 a, b).

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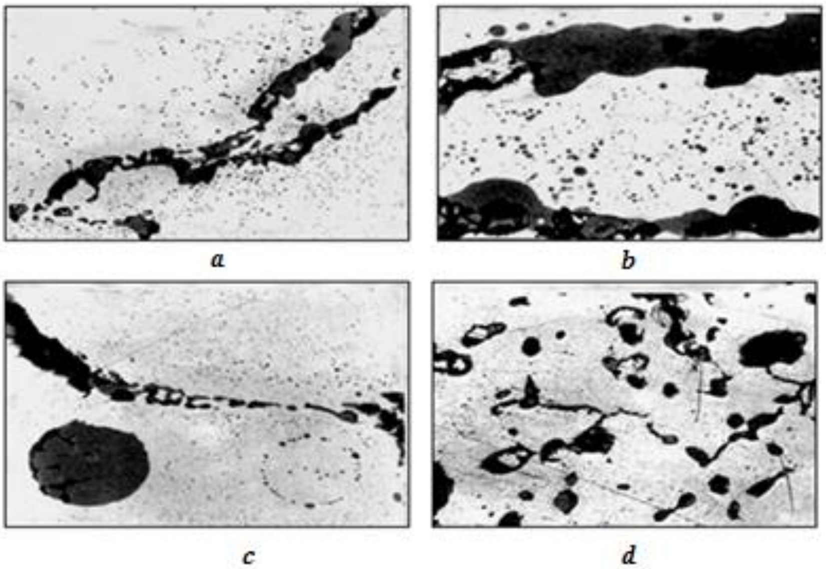

Fig.7. The nature of the distribution of nonmetallic phases after high-temperature heating of steel grade 08 KP: a) general view of the area of the hidden oxide film in the bottom part of the ingot (95% level from the top), heating time 2 hours; b) the same, the nature of the distribution of secondary (diffusion) oxides; c) oxidation around a slag inclusion and a bubble filled with scrap metal at the metal-oxide film interface (holding time during heating for 2 hours); d) oxidation of the cortical zone of the ingot through the tubules and micropores with a holding time of 4 hours (75% of the top).

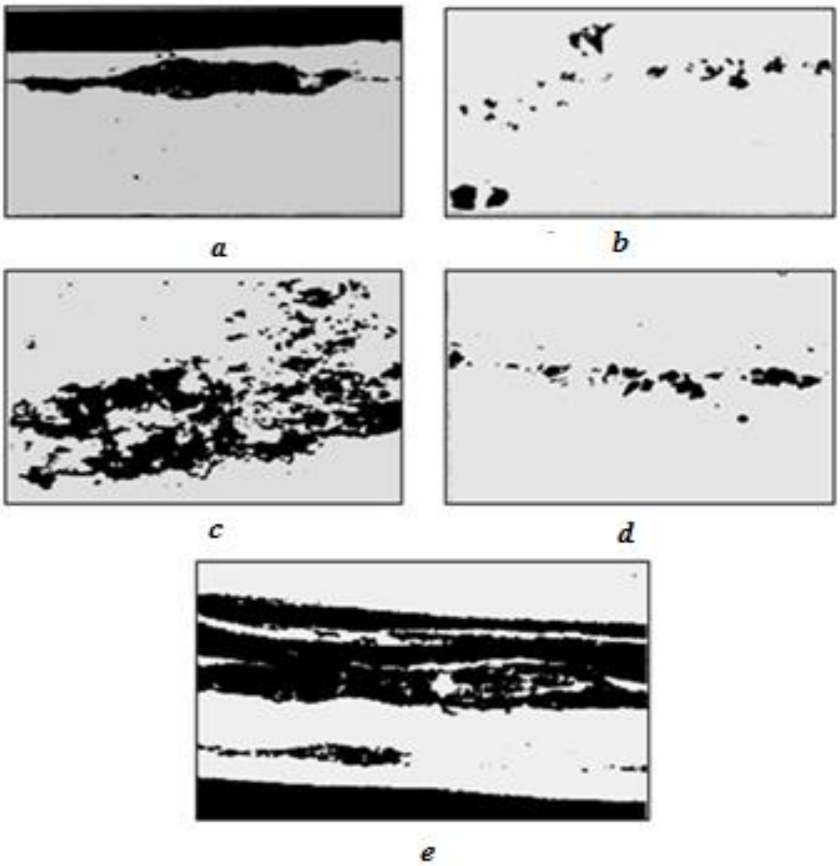

Fig.8. Microstructure of steel at the site of surface defects in cold-rolled sheets: a)rolled out of an oxidized bubble in the surface layer (along the thickness of the sheet) (x 630); b) the same, polished section on the surface of the sheet (x630); c) and d) films in the surface layer of the sheet, 08 KP (x 500); e) coarse inclusions and delamination in the surface layer of the sheet, 08 KP (x125).

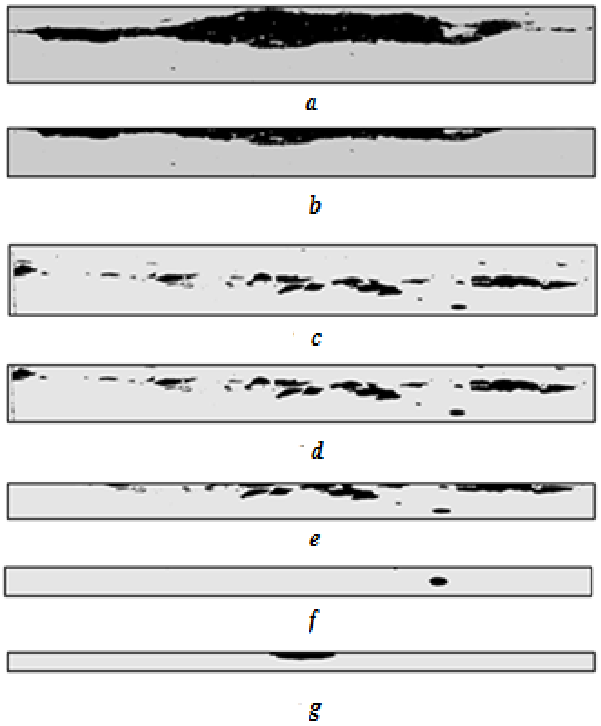

Fig.9. Mechanism of transformation of ingot defects into surface defects in sheet metal:
a), b) formation of captivity and rags in the first stage; c), d), e) formation of a film and a rolled bubble on a hot-rolled product; f), g) formation of a rolled bubble and film on cold-rolled sheet metal

As the layer of healthy metal above the defect thins during subsequent rolling stages, due to the unequal plasticity of the steel matrix and inclusions, the layers reach the surface of the strip and form defects such as rolled bubbles and films; for example, when the slab is heated in methodical furnaces and rolled in a hot mill line (Fig. 9 c, d, e) or during cold-rolled rolling and temper training (Fig. 9 f, g). Large inclusions in the form of oxide films, which are formed mainly in the bottom part of the ingot, form rough defects on the surface of the sheets, usually with peeling or scanlines.

Thus, the results of the experiments make it possible to reveal the nature of nonmetallic inclusions contaminating the surface zones of the ingot to clarify the sources and causes of the formation of the main types of defects in rolled sheets:

1 The main share of surface defects in thin-sheet cold-rolled steel is of steelmaking origin (62-84%) and is determined by three factors:

a – the presence of a thin and loose outer cortical layer on the ingot, damaged by subcortical bubbles, pores, and tubules due to the high oxidation potential of the steel;

b - the presence of an internal (“hidden”) film from boiling of the metal in the mold during casting. In rolled sheets, this manifests itself in the presence of nonmetallic inclusions of iron and manganese oxides or complex ferromanganese silicates at places with defects in the surface and subsurface layers of the sheets;

c – Contamination of the cortical zone of the ingot with oxide nonmetallic inclusions.

2 The identity of the morphological signs of structural heterogeneity in the cortical zone of the ingot and in the location of the defect in cold-rolled steel was established. The differences lie in the shape and distribution of inclusions and the concentration of FeO in wustite.

3 An increase in the concentration of FeO in wustite from 80-85% in the cortical zone of the ingot to 87-93% at the site of the defect indicates that a significant part of the defects are formed during the process of oxidative heating and subsequent hot deformation. During the heating process, oxidation of the internal cavities of microdefects occurs, as does the formation of additional satellite oxide inclusions in the form of dispersed oxide rashes and globules of diffusion wustite oxides near areas of large nonmetallic inclusions, increasing the area affected by defects.

4 The surface defects of cold-rolled sheets are 90% represented by a nonmetallic oxide phase consisting of iron and manganese oxides. A high proportion of surface defects in the film from oxide nonmetallic

inclusions (33–38%) and a rolled bubble filled with the oxide phase FeO-MnO indicate their nucleation at the crystallization front in a two-phase zone enriched in manganese, oxygen, carbon, sulfur and phosphorus.

5 The formation of structural heterogeneity in the form of a "hidden" film in the bottom part of the ingot is associated with the boiling of the first portions of steel and its crystallization on the surface of the mold. The boiling of steel is associated with the formation of a large number of small bubbles of CO, which are covered with a thin slag film of viscous ferromanganese oxides, preventing rupture of the film and the release of CO from the metal.

6 Coarse defects in the ingot located close to the surface are rolled out onto the surface of the slab in the form of honeycomb waste and film at the first rolling stage. As the layer of healthy metal above the defect thins during subsequent rolling stages, due to the unequal ductility of the steel matrix and inclusions, the metal particles reach the surface of the sheets and form defects such as rolled bubbles and films. Large inclusions, in the form of oxide films, which are formed mainly in the bottom part of the ingot, form rough films on the surface of the sheets, usually with peeling or scaliness.

5. Conclusion

Structural-concentration analysis of the metal at the end-to-end process of ingot — rolled steel has established the identity of the morphological signs of structural heterogeneity in the crustal zone of the ingot and in the place where the defect of cold-rolled steel appears. The difference lies in the shape, distribution of inclusions and concentration of FeO in wüstite.

The reasons for microstructural heterogeneity and increased contamination of the cortical zone of the ingot have been established. 90% of surface defects in cold-rolled sheets are represented by a non-metallic oxide phase consisting of iron and manganese oxides. A high proportion of surface defects in the film from oxide non-metallic inclusions and a rolled bubble indicates their origin at the crystallization front in a two-phase zone enriched in manganese, oxygen, carbon, sulfur and phosphorus.

The heating mode of the metal before hot rolling has a significant influence on the development of surface defects in rolled sheet metal. During the heating process, oxidation of the internal cavities of microdefects occurs and the formation of additional oxide inclusions in the form of a dispersed oxide rash.

The nature of the relationship between the type of structure of the cortical zone of the ingot and the development of defects on the rolled surface and the mechanism of transformation of structural inhomogeneity of the cortical zone of the ingot into defects on the surface of rolled sheets have been established. The established patterns made it possible to develop methods for controlling structural and chemical heterogeneity in the end-to-end steel-rolled process.

Conflict of interest statement
The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement:
Ibraev I.K.: Conceptualization, Methodology, Software, Investigation; **Ibraeva O.T.**: Data curation, Writing- Original draft preparation, Visualization; **Zhakupov T.M.:** Supervision, Validation, Writing- Reviewing and Editing.
The final manuscript was read and approved by all authors.

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