Identifying the causes of metallurgical defects in tube blanks made from 32G2 steel

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This article investigates defects arising during the production of 32G2 steel used for manufacturing pipe blanks intended for oilfield tubing. A comprehensive analysis of two pipe-blank fragments was conducted, including examination of their external appearance, determination of chemical composition, as well as macroanalysis, fractographic study, and metallographic investigation of the metal structure. Particular attention is given to evaluating liquation heterogeneity and the level of contamination by non-metallic inclusions. It was established that the chemical composition of all examined samples fully complies with the requirements for 32G2 steel. Macrostructural analysis revealed that the primary defect of these blanks is pronounced liquation heterogeneity accompanied by the formation of impurity-concentration zones. Fractographic studies identified the presence of pores and cracks within the liquation areas. The fracture surfaces are characterized by transcrystalline brittle cleavage. Metallographic analysis confirmed the presence of regions enriched with low-melting elements—primarily phosphorus and sulfur—indicating non-uniform metal solidification conditions. The investigation of non-metallic inclusions was conducted using optical and electron microscopy, as well as energy-dispersive microanalysis. It was determined that all blanks contain pores (voids) in the central (axial) zone. Metal contamination by non-metallic inclusions was assessed according to scale Sh6. The contents of sulfides and oxides do not exceed 1 point, whereas undeformed silicates reach up to 5 points. Based on the obtained results, it is proposed to improve the current steel-melting technology by placing greater emphasis on the stages of deoxidation and desulfurization. Adjusting these processes will reduce liquation heterogeneity and decrease the amount of non-metallic inclusions, ultimately improving the quality of pipe blanks.

Key words: metallurgical defects, non-metallic inclusions, liquation heterogeneity, oil and gas industry, metallographic analysis.
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Introduction

To ensure the efficient operation of oil and gas companies, it is essential to continuously improve the quality of pipes intended both for drilling and for the transportation of oil and gas. Wear of the outer diameter and thread damage are characteristic defects of drill pipes, casing pipes, and their couplings. These defects arise as a result of inadequate metallurgical processing of the pipe metal and insufficiently controlled heat treatment [1].

In this regard, accurate assessment of the quality of pipes used in the oil and gas industry is a critical challenge for metallurgists and materials scientists. Only after a proper evaluation of the metal quality and the pipes manufactured from it can appropriate innovative approaches be identified for the development of technological operations. At the same time, the technological production chain must be supported by modern laboratory equipment and instruments for metal and product quality control, as well as highly qualified personnel. Moreover, it is necessary to establish correlations between these inter-operational control methods to ensure timely prevention of defects and to avoid their progression during subsequent production stages.

Therefore, the approach to developing a new generation of pipe steels must take into account the technological characteristics of specific production lines, covering the entire chain from steel melting to pipe manufacturing and subsequent heat treatment. Only such an integrated approach, combined with high-quality process control, can improve the efficiency of pipe-blank steel production and,

Table 1. Chemical composition of the metal of pipe blanks

Marking	Steel	Chemical elements, % (mass.)												
		C	Si	Mn	Cr	Ni	Cu	Mo	Ti	V	Al	S	P	Fe
Rp 731 No. 08691	32G2	0.32	0.24	1.26	0.09	0.22	0.24	0.02	<0.005	<0.005	0.01	0.006	0.013	rest
Rp 732 No. 108690		0.33	0.22	1.25	0.15	0.20	0.24	0.02	<0.005	<0.005	0.01	0.019	0.014	rest

consequently, ensure the stability of the quality parameters of the final products [2].

The purpose of this study is to conduct a detailed and in-depth analysis of metallurgical defects in 32G2 steel pipe blanks using various modern laboratory control methods.

Materials and Research Methods

Steel grade 32G2 was produced at Baku Steel Company JSC in a 60-ton electric arc furnace using a scrap-metal charge. The received samples were assigned the conventional identifiers Rp 731 (dimensions 150 × 150 × 11.3 mm) and Rp 732 (dimensions diam. 130 × 13.3 mm). The chemical composition of the pipe-blank metal is presented in **Table 1.**

Macroanalysis of the pipe-blank samples included etching in a 50 % HCl solution and evaluation of defects in accordance with GOST 10243-75.

Fractographic analysis was carried out on fracture surfaces obtained from regions exhibiting central porosity. The purpose of this analysis was to identify the causes of defect formation. From the selected macrotemplates, tensile specimens with a cross section of 10 × 10 mm and a notch located in the area of central porosity were prepared. The procedure for producing metallographic sections and tensile specimens is shown in **Fig. 1,** *a*.

Metallographic analysis of liquation heterogeneity was carried out using a NEOPHOT-21 metallographic microscope (Germany).

The analysis was performed after etching the pipe-blank metal with Oberhoffer's reagent. Etching with this reagent makes it possible to reveal regions enriched with low-melting elements (phosphorus and sulfur). These regions appear as light-colored areas.

The analysis of non-metallic inclusions using optical and electron microscopy, as well as energy-dispersive microanalysis, was performed on metallographic sections cut from the central zone of the blank and near the surface (**Fig. 1**, *b*). Comparative examination enables the assessment of inclusion distribution across the section of the blank.

Conducted Research

The chemical composition of all examined blanks corresponds to the specified steel grades. All steels are characterized by the absence of aluminum, with an Al concentration below 0.01 wt.%. The steelmaking and secondary metallurgy processes are based on deoxidation using manganese and silicon rather than aluminum. The currently applied deoxidation technology without aluminum is characterized by [3]:

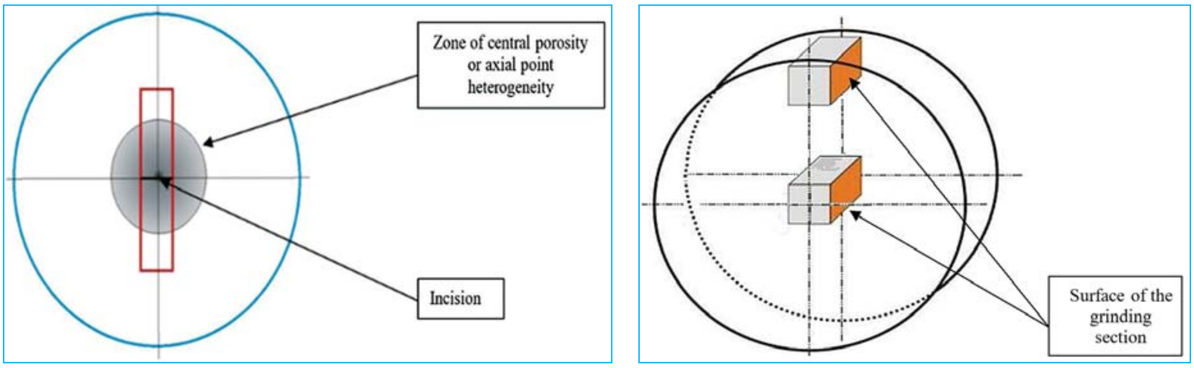
– a relatively high level of contamination by non-metallic inclusions, including large ones represented by silicates and manganese oxysulfides;

– limited ability to achieve low sulfur content in the metal.

Pipe blanks produced from steel not deoxidized with aluminum and lacking 0.02–0.05 % Al do not meet modern requirements and cannot be used for manufacturing pipes in accordance with the following standards: API Spec 5CT, API Spec 5L, GOST 31446-2017, among others.

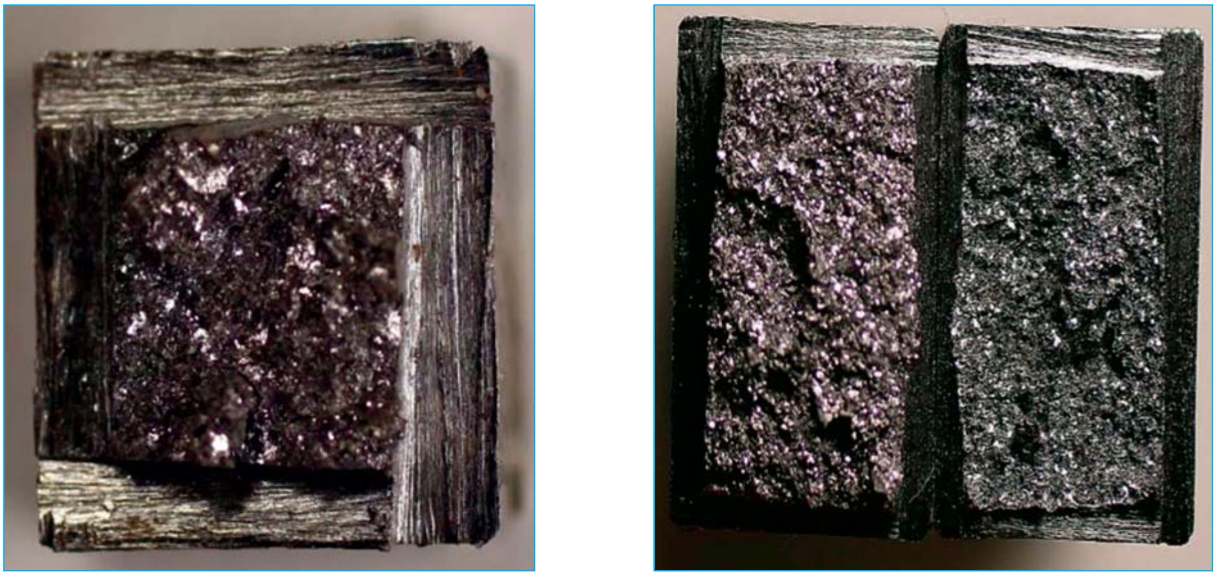
Macroanalysis of the samples showed that the primary defect in the examined blanks is liquation heterogeneity. Liquation in continuously cast pipe blanks is classified into zonal and dendritic types. In the studied blanks, dendritic liquation is most clearly expressed. Dendritic liquation reflects the non-uniform distribution of chemical elements throughout the pipe blank volume.

The investigated blanks also exhibit clearly developed shrinkage-related liquation, which appears as cavities and irregularly shaped voids forming in areas where the metal solidifies last. For the studied blanks, this region corresponds



a *b*

Fig. 1. Schemes for specimen preparation: *a* — tensile specimens taken from the region of central porosity; *b* — metallographic sections prepared from continuously cast blanks



a *b*

Fig. 2. External appearance of fractures made from the central porosity area of pipe blanks: *a*) steel 32G2, No. 108691 (Rp 731); *b*) steel 32G2, No. 108690 (Rp 732)

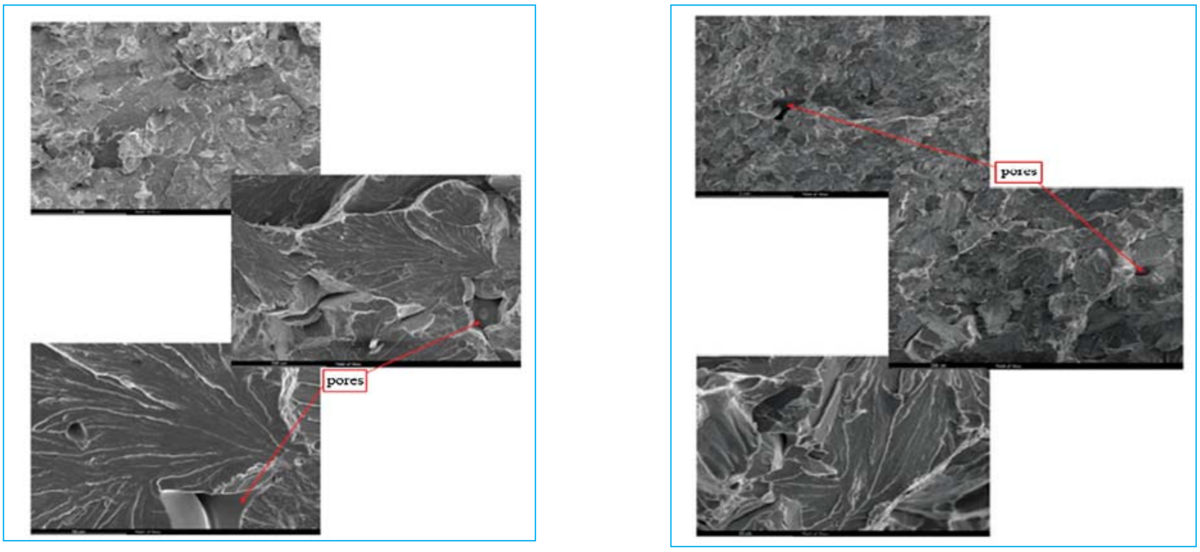
to the axis of the billet. In some cases, instead of concentrated shrinkage cavities, local looseness and porosity are observed. Based on their distribution, shrinkage liquation is classified as concentrated or distributed. In the analyzed 32G2 steel sample, heat number 108691, shrinkage liquation is of the distributed type, while in the remaining samples it is concentrated [4].

For square-section blanks, the presence of sub-surface blowholes up to level 2 according to GOST 10243-75 is typical.

Thus, all examined pipe-blank templates are characterized by increased porosity and liquation heterogeneity. The identified level of defects does not comply with the requirements of GOST 34636-2020. Therefore, the pipe blanks cannot be used for pipe manufacturing.

After specimen failure, a fracture surface with exposed defects – pores and cracks – was formed. **Fig. 2** shows the appearance of the fracture surfaces of the failed specimens. It is evident that both 32G2 steel blanks (Fig. 2, *a*, *b*) fractured by a uniform brittle cleavage.

Fig. 3 shows the fracture surfaces of 32G2 steel at high magnifications. Individual pores up to 70 μm in size are present within the fracture. The fracture itself corresponds to a transcrystalline brittle cleavage. The cleavage facets exhibit a characteristic river-like pattern. The fracture surface of the 150 × 150 mm blank displays coarse faceting, with an average facet size of approximately 200 μm, which is attributed to the coarse-grained structure of the cast metal. In contrast, the average facet size in the diam.130 mm 32G2 steel blank does not exceed 80 μm.



a *b*

Fig. 3. Fracture surface morphology in the region of central porosity: *a*) specimen Rp 731, No. 108691; *b*) specimen Rp 732, No. 108690

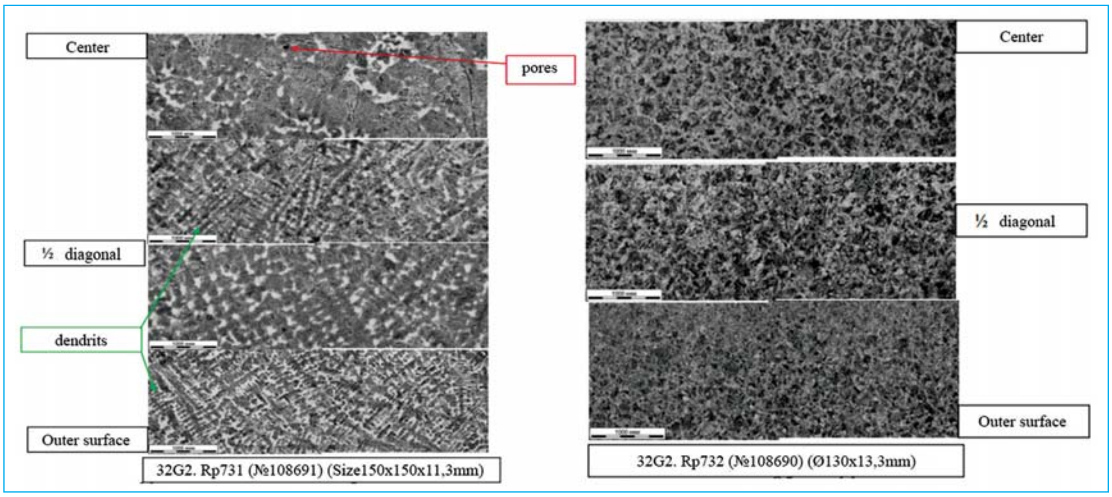


Fig. 4. Microstructure of metal in pipe blanks after etching in Oberhoffer reagent

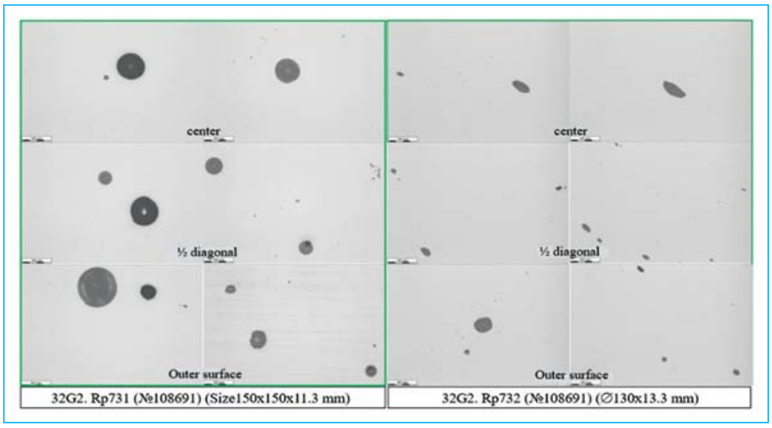


Fig. 5. Characteristic appearance of non-metallic inclusions on tubular blanks made of 32G2 steel

All examined samples exhibit a similar level of liquation heterogeneity. The results indicate that all blanks are characterized exclusively by dendritic liquation. Liquation is most pronounced in the axial zone of the blanks. Upon etching, the interdendritic regions appear light in color. In the axial area, spotting and non-uniformity in the distribution of light-etching regions are more prominent.

Testing Results

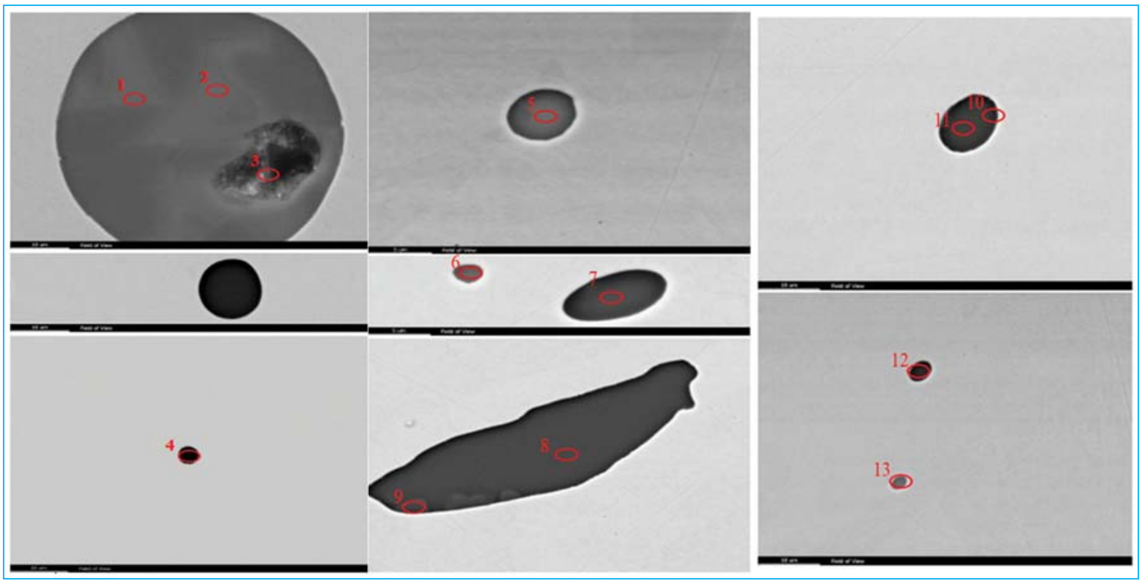
Fig. 4 shows that most pores and defects are located specifically in the interdendritic regions. It is demonstrated that the coarser the dendritic structure, the more pronounced the liquation becomes. Therefore, the casting and cooling technology for billets must be selected to promote refinement of the dendritic structure [5]. **Fig. 5** presents the appearance and distribution of non-metallic inclusions, while **Fig. 6** shows their chemical composition in the pipe-blank metal. It should be noted that the chemical composition of non-metallic inclusions in specimens Rp 731 and Rp 732 was studied at different points; their identification numbers are indicated directly on the micrographs.

These figures show that all non-metallic inclusions have a rounded morphology and contain various contaminating elements, while their Fe content is significantly reduced. This indicates that the inclusions are rich in oxides, sulfides, and complex brittle compounds [6].

The results of the non-metallic inclusion assessment are presented in **Table 2**. Contamination by oxides and sulfides does not exceed level 1, whereas undeformed silicates reach level 5.

Table 2. Results of steel contamination assessment by non-metallic inclusions according to GOST 1778-2022.

Marking	Research location	Contamination of steel by non-metallic inclusions						
		Point oxides	String-like oxides	Sulfides	Brittle silicates	Plastic silicates	Non-deformable silicates	Nitrides
Rp 731	center	1	0	0.5	0	0	5	–
	surface	0.5	0	0	0	0	5	–
Rp 732	center	1	0	1	0	0	2	–
	surface	0.5	0	0.5	0	0	4	–



a

	Mass concentration of elements, %									
	C	O	Mg	Al	Si	K	Ca	Ti	Mn	Fe
Region 1	–	25.85	01.24	07.94	23.58	00.65	12.54	–	28.12	–
Region 2	27.01	13.97	00.57	04.21	12.25	00.39	07.80	–	16.41	17.40
Region 3	–	26.99	02.72	08.89	25.40	–	12.48	00.92	22.60	–
Region 4	02.57	14.09	00.49	05.95	12.91	–	00.33	00.39	21.99	40.92
Region 5	–	–	–	06.10	–	–	–	–	65.45	–
Region 6	04.53	–	–	–	01.44	–	–	–	16.84	71.10
Region 7	04.68	21.69	00.51	05.44	19.83	–	01.35	00.85	36.17	08.55
Region 8	04.50	25.47	00.57	07.54	22.44	01.05	01.39	02.18	34.85	–
Region 9	04.09	25.73	01.07	07.33	22.75	00.62	00.93	02.53	34.95	–
Region 10	03.35	10.68	–	02.93	10.64	–	01.02	01.01	27.26	40.56
Region 11	04.65	24.52	–	06.18	23.40	–	01.79	00.96	37.59	–
Region 12	–	31.43	–	00.21	24.42	–	01.99	–	37.83	–
Region 13	02.96	12.71	–	03.41	12.08	00.16	00.62	00.89	18.83	47.23

b

Fig. 6. Appearance (*a*) and chemical composition (*b*) of non-metallic inclusions in the central region of the 32G2 steel billet. Specimen designation: Rp 732-1 (No. 108690)

The defects identified in 32G2 pipe steel are associated with the presence of harmful impurities in the charge at levels exceeding the permissible limits. Metallurgical practice shows that a number of chemical elements have an adverse effect on both the technological and service properties of metals. These elements include hydrogen, nitrogen, oxygen, sulfur, phosphorus, certain non-ferrous metals, and others. Their sources in steelmaking are diverse; however, several common origins can be distinguished: charge materials, the furnace atmosphere, ferroalloys, refractory materials, and so on. Overall, the total impurity content in steel largely depends on the steelmaking process, secondary metallurgy operations, and casting technology.

Discussion of Results

As noted above, the metallurgical defects found in 32G2 steel produced by smelting in an electric arc furnace from scrap metal, followed by continuous casting into tubular blanks, are due to several factors:

1. The manufacturer failed to select the steelmaking charge selectively. This resulted in defects such as pores and cracks appearing in the steel structure (Fig. 2). Our subsequent studies allowed us to establish that these cracks and pores are of metallurgical origin. At high magnification, fractures of the steel reveal isolated pores up to 7 µm in size (Fig. 3). This type of fracture can be classified as a transcrystalline brittle cleavage. This type of cleavage is caused by the coarse-grained structure of the cast metal.

2. The test samples exhibited liquation heterogeneity. The formation of liquation heterogeneity in the form of dendritic liquation can be explained by a violation of the steel cooling regimes on the continuous casting machine in the secondary cooling zone. However, the defect may be associated with the development of reticular or transverse cracks formed in this zone due to the high drawing speeds and spattering of the tubular blank. Subsequently, secondary oxidation of surface cracks, resulting in the formation of scale and satellite inclusions, is also possible.

Therefore, to prevent the formation of such defects, it is necessary to maintain the temperature and speed parameters of continuous casting. Constant monitoring of the mold surface quality is required. As the dendritic structure becomes finer, the occurrence of liquation increases, as Fig. 4 shows the location of pores and defects in the interdendritic space. Therefore, it is necessary to select a casting and cooling technology that ensures refinement of the steel's dendritic structure [7].

3. Metallographic and energy-dispersive analysis reveal the appearance and chemical composition of non-metallic inclusions in the metal of pipe blanks. When analyzing non-metallic inclusions in the metal structure, their metallurgical origin was established, caused by local accumulations in individual zones. During the pipe rolling process, these non-metallic inclusions can become embedded in the lines and can also migrate to the surface areas of the pipe, causing delamination of the metal surface.

The table in the Fig. 6 shows that non-metallic inclusions contain large amounts of carbon, oxygen, sulfur, even aluminum and other elements. This table identifies two types of inclusions: fayalite ($2FeO{\cdot}SiO_2$) and satellite inclusions based on FeO. Naturally, fayalite inclusions are rounded.

Fayalite inclusions are exogenous; they usually enter the steel as a result of the interaction of the metal with silicon-containing slag-forming mixtures that were used in the tundish to protect the metal from secondary oxidation [8].

The presence of satellite inclusions in the defect zone may be due to high-temperature contact between fayalite and the base metal. Fayalite inclusions act as a source of oxygen, which, through an internal oxidation mechanism, reacts with residual concentrations of deoxidizers and then with iron to form satellite inclusions.

Therefore, to prevent this defect, it is necessary to eliminate the possibility of contamination of the pipe metal with $FeO–SiO_2$ inclusions. To do this, the following measures should be taken: maintain a high metal level in the tundish; control the particle size distribution and moisture content of the slag-forming mixtures used; monitor the condition of the refractories; protect the metal from secondary oxidation during pouring; and pay particular attention to deoxidation technology and secondary steel treatment.

4. Particular attention is paid to the sulfur content in steel.

Sulfur has unlimited solubility in liquid iron and limited solubility in solid iron, therefore, during crystallization of steel, iron sulfides are released along the grain boundaries, forming a low-melting eutectic (988 °C), which causes red brittleness and a tendency to hot cracks during continuous casting [9].The main source of sulfur in steel is pig iron, and an increase in its sulfur content almost inevitably results in higher sulfur levels in steel. Reducing sulfur during melting is accompanied by metal losses and increased lime consumption; therefore, achieving the required sulfur levels (0.015–0.020 % for quality steels) is more efficient through hot-metal desulfurization before steelmaking [8]. The principle of these methods is based on converting sulfur into sulfides that are poorly soluble in the melt. Sulfur activity increases significantly with rising carbon, silicon, and phosphorus contents, which makes direct desulfurization of pig iron particularly effective. Oxygen strongly affects the process: the reaction proceeds rapidly only when its concentration is below 0.01 %. For high-grade steel products, sulfur levels below 0.002–0.003 % are required, which is practically unattainable in primary steelmaking units and therefore necessitates secondary metallurgy treatments [10].

Hydrogen is a harmful impurity that enters the metal primarily from raw materials, the atmosphere, and moisture-containing components. Its solubility changes significantly during the transition from the liquid to the solid state, leading to bubble formation and the development of hydrogen-saturated micropores [11]. At concentrations of 1–2 cm^3 / 100 g, a noticeable deterioration in mechanical properties begins, and at 5–10 cm^3 / 100 g, ductility decreases to a minimum. Hydrogen causes embrittlement in the temperature range from –100 °C to +100 °C and leads to the formation of flake defects (floccules), especially in carbon and alloy steels with large cross-sections.

To prevent flake formation, the hydrogen content must be reduced to 2–2.5 cm^3/100 g, which is unattainable in conventional furnaces and requires vacuum treatment. Additional preventive measures include the use of dry charge materials, minimizing hydrogen in the melting atmosphere, and adding elements capable of binding hydrogen [12].

5. The content of non-ferrous metals is also restricted by steel-grade requirements. For this reason, electric arc furnaces operating on scrap are suitable primarily for the production of long products, since scrap typically contains elevated amounts of copper and other impurities compared to primary materials (DRI, HBI, pig iron).

Transforming electric arc furnaces into chemically active reactors makes it possible to use mixtures of scrap and primary materials, thereby reducing the concentration of non-ferrous metals and expanding technological capabilities [13, 14].

Thus, our analyses allow us to determine the cause of non-metallic defects. Based on these analyses, develop recommendations for minimizing or completely eliminating these defects in the steelmaking process. As a result, characteristic external and microstructural features of metallurgical defects were established, which include pores and cracks, dendritic liquation, the presence of non-metallic inclusions of complex composition, that is, of endogenous or exogenous origin around the defect, the presence of high-temperature satellite inclusions, etc.

Conclusions

The comprehensive metallographic investigation of the pipe-blank steel has shown the following:

1. All examined billets exhibit dendritic liquation heterogeneity and central porosity. During pipe production, the identified defects manifest themselves in the formation of such defects as non-metallic inclusions and heterogeneity of properties across the thickness of the pipe wall.

2. The principal non-metallic inclusions detected in all examined billets are large rounded silicates of manganese

and calcium. Their size reaches up to 200 µm. The contamination level of the pipe-blank metal, according to the “undeformed silicates” scale, is 3–5 points under GOST 1778-2022, which is unacceptable for modern pipe-production requirements. During pipe production, rounded silicates can be drawn out into elongated inclusions that embrittle the metal.

3. In practice, methods of secondary metallurgy do not allow for a reduction in the concentration of non-ferrous metals in steel after smelting, and their permissible concentrations are ensured by the quality of the materials loaded into the electric furnace or by diluting the charge with primary materials during the smelting process.

4. Based on the analysis of fracture surfaces from the central-porosity region of the billets, the morphology of fractures, the microstructure of the metal, the distribution of non-metallic inclusions, and their appearance and chemical composition, the following can be concluded:

– for producing pipe-blank steel intended for the oil and gas industry, selective control of the initial metallic charge is required;

– to improve the quality of pipe-blank metal, the current steelmaking technology must be modified, particularly the stages of deoxidation and desulfurization;

– secondary steel treatment must be performed under vacuum.

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