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IDENTIFICATION OF THE NATURE OF DEFECTS ARISING IN THE PRODUCTION OF CONTINUOUSLY CAST PIPE BILLETS FOR THE OIL AND GAS INDUSTRY

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The paper presents the results of studies of defects that occur in the production of continuously cast pipe blanks for the oil and gas industry. It is shown that the use of the technology of continuous casting of pipe billets in comparison with the traditional methods of pouring liquid steel into a mold has a number of advantages, among which is the high productivity of the technological process. However, it was noted that in many cases, an abnormally high degree of contamination with non-metallic inclusions is observed in the structure of the steel of continuously cast pipe billets.

It was revealed that the largest inclusions are oxides of silicon and manganese. On the surface of the pipes, there are defects in the form of oxide spots, near which there are large non-metallic inclusions. On the surface of the oxide spot, the presence of iron oxides in the form of scale is found, which is a consequence of the secondary oxidation of the metal by air oxygen.

A mechanism for the development of oxide spots and decarburized strips in pipe billets has been determined, which consists in the formation of defects in the form of scratches and cracks on the surface before rolling. These defects during heating for rolling lead to the oxidation of the metal and the formation of scale on the surface of the pipe blanks. The results of experimental studies on the development of recommendations for improving the quality of the initial metal of seamless pipes for the oil and gas industry are presented. The study of the microstructure of steel and the assessment of its contamination with non-metallic inclusions were carried out on optical and electron microscopes, and the mechanical properties of pipe blanks were studied by standard methods

Keywords: pipe steel, non-metallic inclusions, longitudinal cracks, oil and gas industry, continuous casting

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1. Introduction

The quality vector of pipes for the oil and gas industry is the continuously increasing requirements for the steels from which they are made. At the same time, the surface quality of pipes, along with the structure and mechanical properties, is considered a very important indicator of the quality of pipes in general. Consequently, the surface of tubular billets is formed at all stages of the metallurgical process, from steelmaking to the processing of billets by pressure.

As is known, the formation of the structure, mechanical properties and surface quality is carried out at all stages of the production of blanks: in the processes of smelting, out-of-furnace processing, continuous casting, heating for rolling and hot rolling. An analysis of the literature shows that defects that appear on finished pipes can be formed both in the steelmaking process and during pressure treatment, i.e. rolling [1, 2].

The difficulty lies in the fact that it is not possible to practically distinguish the structure and nature of defects that occur during the operation of pipes during drilling of oil wells. Therefore, to determine the structure and type of these diverse defects, more careful control is required, based on methods of fine research. So, for example, it is necessary to find the relationship between the external appearance and nature of a defect with its microstructural features, which can be detected using modern optical and electron microscopes, elemental analysis devices, microanalyses, etc.

It is such an integrated approach for the metallurgical examination of defects in pipe steels that will make it possible to make an objective separation of defects between the processes of steelmaking and rolling production. An integrated approach will allow in advance to prevent the appearance of any defects in technological stages.

2. Literature review and problem statement

The work [3] presents the results of the development and implementation of a defect classifier for seamless hot-rolled pipes, which includes a description of defects, the nature of formation, as well as measures to prevent defects in both pipes and tubular billets. It has been found that the degree of roughness of the oxide spot depends on the size of the accumulations, and the shape of the cavity depends on non-metallic inclusions. However, this work does not provide the causes that give rise to these defects, which makes it difficult to find the relationship and correlation between the operations of the technological chain.

The following work [4] presents the results of a metallographic study of a defect on the outer surface of a hot-rolled seamless pipe. The genetic and morphological features of the defect were determined. A description of the appearance of a microstructure defect in the defect zone is given, a comparative analysis of a defect detected during magnetic particle testing with defects on experimental pipe blanks with applied artificial defects is carried out. Based on the data obtained, the reasons for the formation of a defect are determined, and its classification is given.

The disadvantages of the work [3] can be fully attributed to this work, that is, the reasons that generate these defects in the operations of the technological chain have not been found. At the same time, in [4], studies were carried out on artificial defects that do not reflect the real picture of production.

An analysis of the literature [5] shows that a number of pipe surface defects, for example, a «skin» or a «flaw», can have both a steel-smelting and rolling nature of formation. At the same time, it is not possible to practically distinguish a «rolled crack» from a sunset or a deformation «flaw» from an ingot.

To accurately determine the type and nature of a particular defect, it is necessary to establish criteria by which, along with the external appearance of a defect in pipe blanks, its microstructural features, identified using modern research tools, could be determined. In the literature [6] there is such an attempt, but it is related to reinforcing steels, which cannot be attributed to steels for pipes operating under significantly difficult conditions.

The literature [7] shows the results of improving the machine for continuous casting of tubular blanks. However, it does not provide an analysis of the quality of the obtained seamless tubular blanks for the oil and gas industry.

In the literature [8], under the conditions of Baku Steel Company, work was carried out to set up a continuous casting machine for seamless pipe billets. Practice shows that these blanks do not have stability in quality. Their partial destruction takes place at different stages of the technological process.

Similar results have been obtained in the literature [9] for the quality of continuously cast round billets for pipe production. However, there are no recommendations to improve their quality.

[10] shows the results of the completion of the reconstruction of a continuous casting machine for the production of round tubular billets. However, the plant still cannot establish the stability of the quality of pipes after heat treatment.

In the literature [11], the development of an electromagnetic mixing system for liquid steel in billet and billet molds CCMS has been developed. However, this system has not yet been implemented and, therefore, there is no information about improving the quality of pipes for the oil and gas industry.

In the work [12], the effect of ladle lining on the refining of reinforcing steel during powder blowing was studied. At the same time, the authors have achieved some success in improving the quality of steel for the production of building reinforcement. Such steels, however, do not meet the very stringent requirements for pipe steel.

In [13], the authors investigated the quality of the destroyed casing pipe manufactured by Baku Steel Company. The reasons for their destruction are shown, the main ones being violations of the chemical composition of steel and the presence of non-metallic inclusions in the structure. However, there are no recommendations for their elimination.

In the book [14], the theory and technology of steel production, there are ways to improve the quality of electric steel. However, it lacks specific data on pipe steels for the oil and gas industry.

The paper [15] presents the results of improving the electromagnetic mixing equipment in molds and casting molds. However, these results on the increase of continuously cast billets are still at the stage of laboratory processing.

In this regard, we propose a new approach to solving this problem, which consists in the objective separation of defects in the surface of pipe blanks between steelmaking and rolling production, which will serve as the basis for improving metallurgical and rolling technologies.

The originality of this approach lies in a comprehensive study based on panoramic metallographic analyses of defective areas of pipe steel using an image device on an X-ray micro-spectral analyzer of the composition of «oxide spots» defects and non-metallic inclusions found in the center of the defect neighborhood.

Therefore, an important and insufficiently studied issue is the influence of the purity of the chemical composition of pipe steel on the quality indicators of continuously cast billets, namely, the formation of surface and internal defects associated with insufficient thermoplasticity, a hardened metal crust in the process of continuous casting of tubular blanks [8–11].

It has been found that the loss of thermoplasticity of the metal crust can be associated with the steelmaking nature, that is, the presence of various complex satellite or spinel inclusions in the liquid metal, decarburized areas, or vice versa, the formation of solid structures in the process of hardening.

In this regard, it is necessary to objectively find the causes of the occurrence of defects on pipe blanks according to technological stages. It often happens that the metal seems to be clean, but at subsequent stages of processing, especially during continuous casting and then rolling, many external and internal defects appear.

The practice of pipe production shows that often after rolling and heat treatment (quenching + high tempering), longitudinal surface cracks appear on continuously cast pipe blanks, which are discontinuities in the form of narrow metal ruptures.

Therefore, the study of the nature and identification of the causes of the formation of such defects in pipe blanks and the development of measures to eliminate them is an urgent scientific and practical task aimed at improving the quality and efficiency of production of continuously cast seamless pipes for the oil and gas industry.

3. The aim and objectives of the study

The aim of this study is to identify the nature of defects that occur during the mass production of continuously cast seamless pipe blanks for the oil and gas industry. Knowledge of the nature of the formation of such defects as «oxide spots», «flaw», «rolling crack», etc. will make it possible to develop recommendations for preventing them from being processed by pressure.

To achieve this aim, the following scientific and technical problems are solved:

– to conduc an analysis of the chemical composition of the outer fragment in different parts of the defective pipe;

– to determine the score of non-metallic inclusions in defective sections of pipes;

– to make a microstructural and chemical analysis of non-metallic inclusions at a distance from surface defects;

– to measure pipe micro hardness in defective areas;

– to determine the mechanical properties of pipe steel in order to assess the effect of defects on the quality of pipes.

4. Materials and methods

The objects of this study are continuously cast pipe blanks obtained from 32G2 steel smelted in an electric arc furnace from a charge consisting mainly of metal waste. Metal waste, as a rule, has an unstable quality from batch to batch, and therefore, when using it, a more creative approach is needed in the selection of charge, steelmaking processes and out-of-furnace processing. To solve these issues, it is necessary to have a powerful laboratory base that allows for more thorough quality control of pipe steel and billets for a technological purpose.

Therefore, laboratory analyses were carried out by the authors and factory teams to compare and determine the accuracy of the data obtained.

It was after such an approach to the analysis of the quality of steels and pipes that assumptions were established to identify the nature of defects in the objects under study.

To reduce the number of experiments, an elemental analysis of only characteristic defective areas, which are the main causes of pipe failure during the operation of oil wells, was carried out.

For the manufacture of continuously cast pipe blanks, low-alloy steel grade 32G2 was used. The results of the analysis of the chemical composition of the metal are presented in Table 1.

The charge from metal waste and metallized pellet was smelted in an electric arc furnace with a capacity of 60 tons. Then, continuous casting of liquid steel was carried out on a universal continuous casting machine, which is equipped with a mold to obtain continuous pipe blanks of various diameters.

The study of the pipe metal microstructure was carried out on longitudinal metallographic sections after etching with the nital reagent (4 % alcohol solution of HNO_3), using an optical microscope at ×200 and ×500 magnifications.

The contamination of steel with non-metallic inclusions was assessed on longitudinal unattached micro sections according to GOST-1778 using an Olympus GX51 optical microscope and Philips XL30 scanning electron microscope, equipped with an EDAX chemical analyzer.

The metal hardness was measured on a Rockwell hardness tester, and the micro hardness of the metal in the areas of segregation and near the caps was determined on a PMT-5 micro hardness tester. The diameter of the investigated pipes was 130 mm, and the wall thickness was 8 mm. To identify the causes of oxide spots, longitudinal sections were made.

Determination of the mechanical properties of pipe blanks was carried out according to standard methods: impact bending test according to GOST-9454 on a KM-30 impact tester; tensile test on cylindrical samples according to GOST-1497 on a tensile testing machine 2054P5.

5. Results of experiments on defects in continuously cast tubular blanks for the oil and gas industry

5. 1. Analysis of the chemical composition of the outer fragment in different sections of pipe steel

Fig. 1, 2 show a view of the outer surface of a pipe fragment. As can be seen, on the outer surface of the pipe samples there are oxide spots with a size in the rolling plane of more than 200 mm.

Measurements have shown that the depth of oxide spots along metallographic sections reaches up to 2 mm. To identify the causes of oxide spots, longitudinal sections were made.

The analysis of the chemical composition of the metal, carried out by the creative team No. EİF-MQM-ETS-2020-1(35)-08/02/1-M-02, revealed significant discrepancies with the data provided by Baku Steel Company LLC. Particularly significant are the discrepancies in the content of aluminum, manganese, silicon, molybdenum and copper. The greatest discrepancy is observed for aluminum – in the certificate 0.029, i.e. typical value for deoxidized aluminum steel, actual – less than 0.005 %, i.e. there is a practical absence of aluminum in steel.

Significant discrepancies in the aluminum content most likely indicate a discrepancy between the certificates and the submitted pipe samples. The chemical composition of the pipes meets the requirements of GOST-633, but does not meet the requirements of clause 6.1 in API Spec 5CT due to the absence of aluminum and other elements (Ti, Nb, V) in the steel, which provide a fine-grained structure of steel.

Table 1

Chemical composition of metal of seamless pipe billets*

Marking	Heat number	Data received by the creative team No. EİF-MQM-ETS-2020-1(35)-08/02/1-M-02										
		C	Mn	Si	P	S	Cr	Ni	Cu	Al/Ti	W/V	Mo/Nb
Rp618	105408	0.37	1.10	0.27	0.008	0.010	0.09	0.13	0.23	$\frac{<0.005}{<0.010}$	$\frac{<0.020}{<0.010}$	$\frac{<0.015}{<0.010}$
Rp619	105170	0.29	1.12	0.25	0.016	0.013	0.09	0.15	0.19	$\frac{<0.005}{<0.010}$	$\frac{<0.025}{<0.010}$	$\frac{<0.022}{<0.010}$
Rp618	105408	Data of Baku Steel Company LLC										
		0.32	1.27	0.30	0.015	0.010	0.08	0.11	0.21	$\frac{<0.029}{<0.002}$	$\frac{<0.001}{<0.001}$	$\frac{<0.002}{<0.001}$
Rp618	105408	0.32	1.34	0.28	0.015	0.01	0.07	0.12	0.23	$\frac{<0.029}{<0.002}$	$\frac{<0.001}{<0.003}$	$\frac{<0.001}{<0.002}$

*Note: * the numerator is Al, W, Mo, and the multiplier is Ti, V, Nb*

a

b

Fig. 1. View of the outer surface of the pipe fragment: marking Rp618: *a* — crack on the workpiece; *b* — oxide spot on the workpiece

Fig. 2. View of the outer surface of the pipe fragment

5. 2. Determination of the score of non-metallic inclusions in defective sections of pipes

It has been found that the microstructure of the metal is uniform over the thickness of the pipe wall and is represented by a fine-grained ferrite-carbide mixture formed as a result of heat treatment according to the regime: quenching+tempering.

In the structure, the boundaries of the former austenite grains are partially preserved, the size of which is 30–40 microns. The proportion of excess ferrite does not exceed 5 %. Ferrite grains have an elongated shape inherited from the hardened state. The carbide component in the steel structure is uniformly distributed over the volume [16–19].

The metal of both pipes is characterized by an abnormally high degree of contamination with non-metallic inclusions for electric steel, reaching 5 points according to GOST-1778 (Table 2).

It has been found that most of the inclusions are elongated along the direction of rolling. The length of non-metallic inclusions in a pipe marked Rp 618 reaches more than 6 mm, and in a pipe marked Rp 619 – about 1 mm. Contamination of steel with inclusions does not meet the requirements for high-quality pipe steel in accordance with GOST-34636-2020 and OST 14-21-77.

5. 3. Microstructural and chemical analysis of non-metallic inclusions at a distance from surface defects

The characteristic appearance and chemical composition of non-metallic inclusions at a distance from surface defects are shown in Fig. 3. It has been found that the chemical composition of non-metallic inclusions in the metal of both pipes is basically similar: the largest inclusions are represented by complex oxides of silicon and manganese; less extended manganese sulfides were revealed, as evidenced by the data in Fig. 4, in regions 2 and 3.

Some large inclusions also contain Ca, K, and Ti compounds, which could get into the metal from slag or a slag-forming mixture. The most likely reason for the formation of significantly large oxides is the ingress of slag into the liquid metal, due to a violation of the technological process of smelting and pouring (Fig. 5). The largest non-metallic inclusions acquire an elongated shape during rolling (Fig. 6) [16, 17].

Obviously, large elongated inclusions are stress concentrators and can lead to brittle fracture of pipe metal during rolling or in operation. Fig. 7 shows a view of the oxide spot on the outer surface of a pipe fragment in a longitudinal section.

To determine the nature and causes of the formation of oxide spots, a number of metallographic studies of thin sections were carried out:

– unattached sections (Fig. 8), which made it possible to determine the presence and composition of non-metallic inclusions near the oxide spot;

– thin sections etched with the nital reagent, which made it possible to reveal microstructure anomalies around the oxide spot;

– sections etched with Obergoffer's reagent, which made it possible to assess the degree of segregation and the location of segregation areas.

Table 2

Contamination of steel with non-metallic inclusions

Marking	Contamination of steel with non-metallic inclusions						
	Point oxides	Linear oxides	Sulfides	Brittle silicates	Lamellar silicates	Non-deformation silicates	Nitride
Rp618	1.5	4.5–5.0	1.5	4.0–5.5	5	4.5–5.0	2.5–5.5
Rp619	1.5	5.0	1	4.0–5.0	5	4.5–5.0	3.5
Requirements GOST-34636-2020, no more							
1к	3	3	3	3	3	3.5	2
1к	4.5	4.5	4.5	4.5	4.5	5	3
Requirements OST 14-21-77, no more							
–	4.5	4.5	4.5	–	4.5	–	–

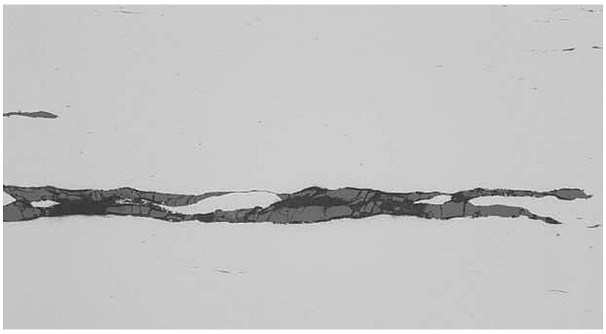
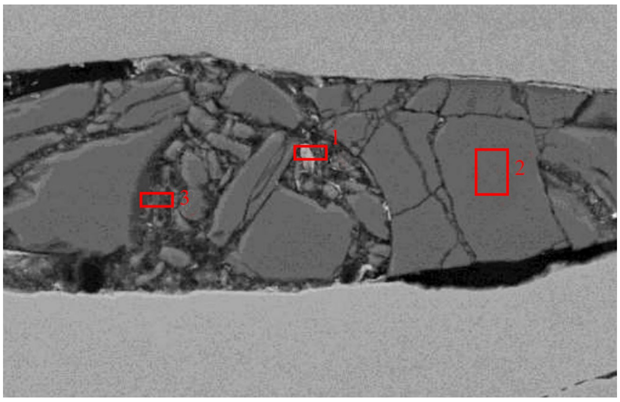


Fig. 3. Characteristic appearance of non-metallic inclusions: marking Rp618

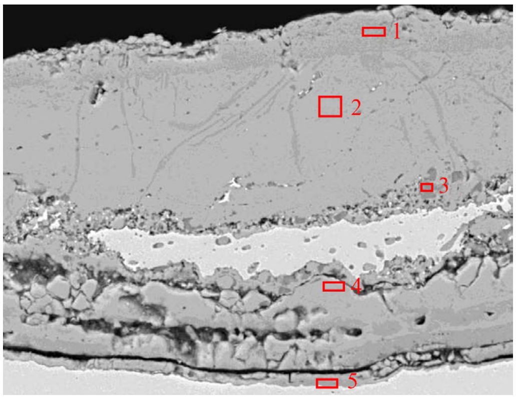


a

Region		C	O	Al	Si	S	Ti	Mn	Fe
Region 1	Wt, %	03.44	–	–	01.24	–	–	03.37	91.95
Region 2		01.78	21.00	00.99	25.53	00.44	00.66	49.59	–
Region 3		14.23	07.52	–	09.36	00.37	00.35	20.87	47.30

b

Fig. 4. Characteristic appearance and chemical composition of non-metallic inclusions: marking Rp618: *a* — defective areas; *b* — chemical composition of defective areas



a

Region		C	O	Si	Mn	Fe
Region 1	Wt, %	0.218	13.59	–	1.12	83.11
Region 2		0.220	11.16	–	1.32	85.31
Region 3		0.357	11.75	0.474	1.66	78.27
Region 4		0.258	10.97	–	1.24	85.21
Region 5		0.222	–	0.58	1.36	95.86

Note: in area 4 found K – 0.18; Ca – 0.57; Ti – 0.21

b

Fig. 5. Type and chemical composition of non-metallic inclusions in the oxide spot: marking Rp618: *a* — defective areas; *b* — chemical composition of defective areas

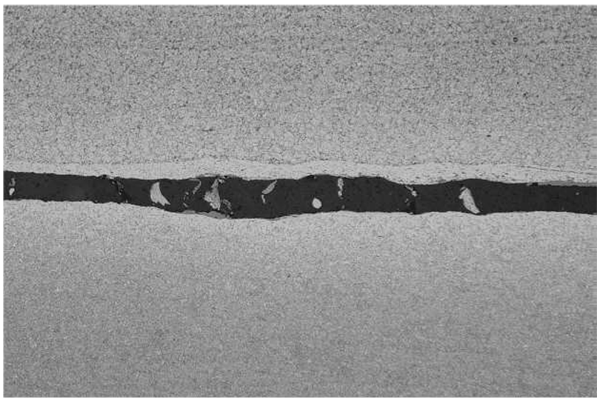
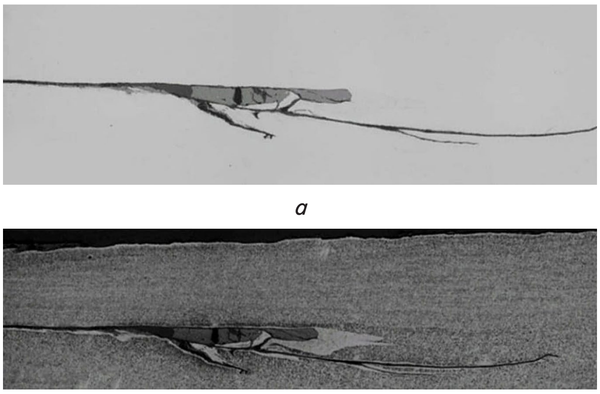


Fig. 6. Type of oxide spot in the longitudinal section: marking Rp618



a

b

Fig. 7. View of the oxide spot on the outer surface of the pipe fragment in the longitudinal section (marking Rp618-2): *a* — before etching, *b* — after etching in Oberhofer's reagent

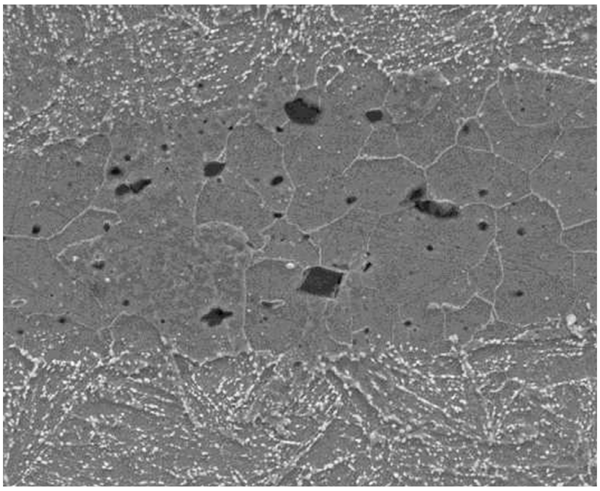


Fig. 8. Type and chemical composition of non-metallic inclusions in the oxide spot: marking Rp619

Additionally, the hardness and microhardness of the metal in the areas of segregation and near the oxide spot were measured. It can be seen on unetched sections that iron oxides, scale, are present on the surface of the oxide spots. The thickness of the scale layer on the surface of oxide spots is non-uniform and varies in the range of 50–200 µm. Small (1–5 µm) rounded oxide inclusions enriched in manganese and silicon were found in the volume of metal under the surface of oxide spots.

It has been found that these inclusions are a consequence of the secondary oxidation of the metal by atmospheric oxygen. The increased concentration of silicon and manganese is due to the fact that these elements have a greater affinity for oxygen than iron and, therefore, replace iron atoms in oxides. These inclusions differ significantly in size and shape from the elongated oxides found in the metal at a distance from the oxide spot. Thus, the formation of oxide spots is not associated with elongated oxide inclusions.

The etched samples show that the surface of oxide spot is decarburized, which is also explained by the oxidation of the metal under the surface of the defect. This indicates that at some stage of production, the exposed surface of the defect at high temperature was in contact with oxygen in the air.

Most likely, this happened at the stage of heating the ingot before rolling it into a circle or before piercing a circle. Etching with Obergoffer's reagent did not reveal significant segregation heterogeneity in oxide spots. This gives grounds to conclude that the development of oxide spots is not associated with segregation processes that occur during the crystallization of liquid steel.

The above features are also characteristic of the Rp619 sample. It should be noted that on this sample, decarburization was detected not only around the opened oxide spots, but also in the form of stripes continuing the direction of the oxide spots. Also, decarburized bands were found far from the opened oxide spots. In this case, small oxide inclusions were revealed in the decarburized band, as well as around the oxide spot.

5. 4. Measurement of pipe micro hardness in defective areas

Also, the results of measuring the micro hardness in decarburized bands, as well as in the segregation band, are presented. It has been found that the hardness of the decarburized metal is significantly lower than the hardness of the metal away from the oxide spot. The hardness of the metal in the segregation band, on the contrary, is higher, which confirms the absence of a connection between oxide spots and segregation processes. The results of hardness measurement by the Rockwell method are presented in Table 3.

Summarizing the above, we can assume the following mechanism for the formation and development of oxide spots and decarburized strips in pipe blanks. The surface of the workpiece before rolling had defects in the form of deep scratches or cracks. When the workpiece was heated for rolling, the surface of defects was oxidized, which led to the formation of scale on the surface, and in the bulk of the metal under the defects, to the formation of a decarburized layer and rounded oxide inclusions.

During subsequent rolling, some of these defects were welded, which led to the formation of decarburized bands in the bulk of the metal. It should be noted that decarburized strips are dangerous pipe defects. The metal in such strips has a significantly lower hardness: 140 HV in the strips, while the hardness of the base metal is 250 HV.

Table 3

Hardness Test Results

Marking	Hardness value, HRB			
	1	2	3	4
Rp618	98.5	94.0	95.0	95.0
	99.0	95.0	95.5	97.5
	98.5	94.0	96.0	97.0
Rp619	96.0	97.0	97.0	99.0
	97.0	97.0	96.5	99.5
	97.0	98.0	97.0	98.5

Based on the hardness, the strength of the metal in strips can be less than 500 MPa. The presence of a weakened layer in the pipe metal saturated with oxides can lead to the formation of cracks during operation. At the same time, these defects cannot be detected by ultrasonic testing, since the metal retains its solidity.

5. 5. Determination of mechanical properties of pipe steel

The results of mechanical tests are given in Table. 4. It has been found that the properties obtained correspond to strength groups E according to GOST-632 and N80 according to APISpec 5CT. It was determined that despite the presence of accumulations of non-metallic inclusions, the metal of the investigated pipes is characterized by high impact strength at a temperature of minus 20 °C. The fracture of the specimens is almost completely ductile, however, it contains multiple delaminations along large inclusions. High values of impact strength are due to high-quality heat treatment of pipes [20].

Thus, it can be noted that despite the rather high mechanical properties of pipe steel, the presence of external and internal defects in it, such as «oxide spots», «flaw», «non-metallic inclusions», etc. are the centers of destruction during the operation of oil and gas wells.

Table 4

Results of mechanical tests of seamless pipes

Marking	No. sample	R_m, MPa	R_t, MPa	R_t/R_m	δ_5, %	KCV – 20 °C, C/sm^2 (C*)	The share of the viscous component in the fracture, %
Rp618	1	790	660	0.84	26.0	91 (73)	100
	2	780	650	0.83	25.0	94 (75)	100
						89 (71)	100
Rp619	1	790	670	0.85	22.5	849 (67)	97
	2	800	690	0.86	23.0	79 (63)	95
						74 (59)	87
Group E requirements	–	≥689	552–758	–	13.0	–	–
Requirements N80Q	–	≥689	552–758	–	13.0	34(27)	–

* – *in terms of a full-size sample*

Therefore, knowledge of the genetics of such defects and their early prevention during production is a very serious task.

6. Discussion of the results of studies of defects arising in the production of continuously cast tubular billets

Analysis of the chemical composition of steel on the outer fragment of pipe steel showed that defective areas have deviations in the chemical composition of 32G2 steel from the standard (Table 1). A particularly large deviation is observed in the aluminum content. So, for example, the content of Al according to the certificate of the plant is 0.029 %, but in fact it is 0.005 %. This indicates poor-quality deoxidation of steel by aluminum.

It was the low-quality out-of-furnace processing of steel that led to the contamination of steel with non-metallic inclusions. So, for example, as shown in Table 2, in the structure of pipe steel there are lamellar silicates, which reach up to 5 points, against 3–4.5 according to the standard, and non-deformable silicates according to the standard are not allowed at all, while they are 4.5–5.0 points.

The study of the microstructure of steel and its elemental analysis (Fig. 4) show that there are large inclusions in the defective areas, which are silicon and manganese oxides, as evidenced by a large amount of Si, Mn, and oxygen. Some large inclusions also contain Ca, K and Ti (Fig. 5). There are also decarburized areas as a result of metal oxidation at the stage of pouring liquid metal into an open ladle.

As the results of hardness tests on decarburized areas (Table 3) show, the hardness in these areas is slightly lower – 140 HV versus 250 HV according to the standard. Such a low hardness of the decarburized sections of the pipes leads to a significant decrease in the strength of the pipe steel as a whole.

Although 37G2 pipe steel meets the standard in terms of strength (Table 4), however, the presence of surface defects on finished pipes leads to multiple delamination along large non-metallic inclusions during operation. As evidenced by the destruction of pipes during operation in oil and gas wells.

The study of the chemical composition of the outer fragment in different sections of the pipe showed that on its outer surface, there are defects of the «oxide spots» type with a size of 200 μm in the rolling plane, their depth reaches up to 2 mm. It has been found that the formation occurred due to poor-quality deoxidation of steel by aluminum, and alloying elements (Ti, Nb, V), which provide a fine-grained structure in steel, were absent at all.

For this reason, the steel structure was contaminated with non-metallic inclusions, reaching up to 5 points. The length of non-metallic inclusions along the rolling direction reaches 1–6 mm. The largest non-metallic inclusions are represented by complex oxides of silicon and manganese, and less extensive manganese sulfides have also been identified. Obviously, these large elongated inclusions are stress concentrators and can lead to brittle fracture of the pipe metal.

The study of the hardness of defective sections showed that they have a significantly lower hardness of –140 HV with a hardness of the base metal of the pipe of 250 HV. The presence of a weakened layer in the pipe metal, saturated with oxides, can lead to the formation of cracks during pipe operation.

The results of the strength properties of the pipes show that they comply with the strength groups E according to GOST-632 and N80 according to ARG Spec 5 CT, despite the presence of accumulations of non-metallic inclusions. However, the presence of the latter in the metal structure of the pipes can lead to their destruction when drilling oil and gas wells.

The studies carried out made it possible to find the causes of the formation of steel-smelting defects, as well as to offer recommendations for their minimization or complete elimination.

It was revealed that some defects, for example, such as «friability», «ingot flaw», which, during hot deformation, are transformed into the defect «internal delamination», «internal cracks» appear mainly due to violation of the pouring modes, then there is an increase in casting speed and temperature.

Consequently, the variety of defects in pipe blanks makes it difficult to determine their nature. Therefore, in order to eliminate many of these defects, it is necessary to consider them in the context of the modes of metallurgical processing and technical characteristics of technological equipment.

It is known that when steel is smelted in an electric arc furnace, the quality of the initial charge plays an important role. Electric arc furnaces operate according to the scrap-process scheme, which is based on metal waste of various composition. Therefore, attention should be paid primarily to the quality of the initial charge materials.

In our opinion, in the production of high-quality products, such as pipes for the oil and gas industry, a special selection of the initial charge is required. It must be free of all dirt and non-metallic inclusions. In other words, a selective selection of the initial charge for electro melting is required.

Only after a careful approach to the quality of the charge can any claims be made to individual operations of the technological chain for the production of continuously cast pipes for the oil and gas industry. Therefore, each defect of metallurgical products must be considered in the complex of the entire technological chain.

It is necessary to introduce physical methods of influencing the metal, such as electromagnetic mixing of liquid metal, vibrational processing during continuous casting of a billet, that is, complex measures are required to improve and maintain the quality of manufactured pipe products.

Thus, our research allowed us to determine the nature and cause of defects in continuously cast pipe billets. It has been found that these defects are of a steelmaking nature, so below we offer recommendations for reducing their level or preventing them. The parametric external and internal microstructural features of defects of steelmaking origin are determined, which include the point location of defects on the surface of the pipe billet.

In addition, it was found that there are non-metallic inclusions of endogenous or exogenous origin in the vicinity of a defect and high-temperature satellite inclusions surrounding defective areas. A large amount of scale and the presence of decarburized areas of a wide band in the defect zone are also observed.

It should be concluded that all these defects are formed as a result of a violation of the electric steelmaking process and are found in the subsequent technological chain in the form of high contamination of the smelted steel.

Metallographic studies of various sections of the object under study with defects showed that cracks and other defects are mainly oriented at an angle to the surface of the sample along the direction of hot deformation, and the inner part of the crack is overfilled with a rather thick layer of scale, while a decarburized section is located along it. It has been found that satellite inclusions are formed as a result of high-temperature metal-scale contact. At the same time, there is a peculiar nature of the placement of satellite inclusions. They practically show the non-uniform nature of the deformation of the metal during rolling and, as a result, hot cracks filled with scale are observed.

Thus, the results of the analysis of the chemical composition of samples of pipe blanks indicate that the technology of smelting and out-of-furnace processing of 32G2 electric steel is based on the scheme of metal deoxidation by manganese and silicon, while aluminum is used in minimum quantities. The results of the analysis of the chemical composition of non-metallic inclusions also testify to this: Al in the metal is less than 0.005 %, and in the composition of non-metallic inclusions it is less than 1.5 % [21, 22].

The metal deoxidation scheme without the use of aluminum is characterized by:

– limited opportunities to achieve low sulfur content in the metal;

– relatively high contamination of the metal with non-metallic inclusions, including large ones, represented by manganese silicates, oxides and sulfides.

Pipe blanks, the metal of which is produced according to the aluminum deoxidation scheme and without reaching the content of 0.02–0.05 % Al, cannot meet the requirements of N80Q standards according to APISpec 5CT, applied to critical pipes, in particular pipes increased corrosion resistance, which are subject to requirements for the content of 0.005 % S in the metal and the purity of non-metallic inclusions at a level of no more than 3.5 points.

Thus, based on the analysis of steel smelting technology and results of the research, it was found that the reason for the formation of oxide spots and other defects in pipe billets is the high contamination of the electric steel with non-metallic inclusions (5 or more points). To eliminate them, the following measures can be recommended [20]:

– to increase the purity of the metal for non-metallic inclusions and sulfur, it is advisable to use a scheme with deep deoxidation of the metal with aluminum;

– transition to the scheme of metal deoxidation with aluminum imposes increased requirements on the technology of out-of-furnace processing and its observance (deoxidation modes, slag guidance of the required composition, purging of metal with argon, modification with silicocalcium, etc.), increasing the information content of melting passports during the process of out-of-furnace processing;

– to control and certify the metal of continuous billets and pipes for contamination with non-metallic inclusions, the development of a special technological instruction is required.

However, the above research is relevant only to pipe steels smelted in an electric arc furnace and blanks obtained in the process of continuous casting. Consequently, the results of these experiments cannot be fully attributed to steels and their blanks obtained by other methods of smelting and casting.

To apply the results of these studies to other industries, it is necessary to find the relationship between the technological operations of various methods of obtaining, at least pipe steels. In other words, numerous experimental works are required on different technological chains for the production of pipe steels and billets, and then a correlation between them should be determined.

7. Conclusions

1. It has been found that the most likely cause of the formation of oxide spots on the surface of pipes is violations of the chemical composition of steel, as a result of poor-quality deoxidation. In turn, the formation of defects on the surface of the workpieces is facilitated by increased local or general contamination of the electric steel with non-metallic inclusions.

2. It has been determined that the metal of pipe blanks is characterized by an abnormally high contamination for electric steel with elongated oxide inclusions (more than 5 points) and a high level of segregation heterogeneity. This indicates a low level of compliance with steel-smelting technology in production. The presence of non-metallic inclusions, reaching a length of 6 mm, are stress concentrators and can cause the development of brittle cracks in the pipe metal. The contamination of steel with inclusions does not meet the requirements of modern standards, for example, GOST-34636-2020.

3. Analysis of the microstructure and chemical composition of non-metallic inclusions indicates that the surface of defects and the volume of metal under defects are subject to high-temperature oxidation. Therefore, primary defects (cracks or marks on the pipe), which later led to the formation of oxide spots on the outer surface of the pipes, were already present during the heating of the billet for rolling; in the process of rolling, some of the primary defects welded together, which led to the formation of decarburized bands in the metal. Thus, oxide spots on the pipe surface are of a metallurgical nature and are due to the influence of the initial quality of the ingot metal.

4. The results of measuring the microhardness in the decarburized and segregated bands showed that it is significantly lower in the decarburized band compared to the hardness of areas away from them. In the segregation band, the microhardness, on the contrary, is higher, which indicates the presence of more brittle silicate inclusions in them.

5. It has been found that despite defects in the form of non-metallic accumulations, the low-alloy steel of the investigated pipe blanks has a sufficiently high impact strength at a temperature of minus 20 °C. Despite the ductile fracture of the samples, they have many delaminations along large defects.

Conflict of interest

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.

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Data availability

The manuscript has no associated data.

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