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Cold resistance of new cast Cr – Mn – Ni – Mo – N steel. Part 2. Studying non-metallic inclusion particles under static and impact loading at low temperatures

M. V. Kostina [1, 2], A. E. Kudryashov [1], L. G. Rigina [1, 3], S. O. Muradyan [1], O. S. Antonova [1], V. S. Kostina [1]

[1] **Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences** (49 Leninskii Ave., Moscow 119991, Russian Federation)
[2] **Moscow Aviation Institute** (National Research University) (4 Volokolamskoe Route, Moscow 125993, Russian Federation)
[3] **JSC Russian State Research Center "CNIITMASH"** (4 Sharikopodshipnikovskaya Str., Moscow 115088, Russian Federation)

Abstract. New cast austenitic Cr – Ni – Mn steel with 0.5 % N (grade 05Kh21AG15N8MF) surpasses cast steel of 18 Cr – 10 Ni type used for comparison in terms of the impact strength in the entire range of climatic temperatures. This part of the paper will pay attention to particles of non-metallic inclusions (NMI) in cast nitrogen-containing steel as a factor which affects mechanical properties under static and impact loading at low temperatures. NMI in laboratory metal consist of globular oxysulfides, with SiO_2 oxides in the central part and an outer layer formed by manganese sulfide MnS, with an average particle size of ~75 % up to 4 μm. During the steel impact bend test at –160 °C, these NMI do not initiate cracking and do not contribute to crack propagation as a fracture in isolated pits. Under tensile conditions at –110 °C, the yield strength of nitrogen-containing steel increases by more than 1.7 times in comparison with the properties at +20 °C. Ductility does not decrease when cooled to –110 °C. In this case, NMI particles are strongly deformed due to the development of cracks in their oxide part. Even when NMI reach the surface of a sample in the working part in the neck zone, they do not initiate cracking. Cracks at the "NMI/deforming metal" interface are not formed. Even with a random arrangement of particles in the form of chains along the axis of application of the tensile load, at a distance of 5 – 20 μm from each other, pores do not form around the particles or merge into a crack nucleus. The results obtained correlate with the literature data that NMI can act as stress relaxers in ductile steels.

Keywords: cast austenitic steel, cold resistance, nitrogen, non-metallic inclusions, fracture, cracks, deformation

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Оригинальная статья

Хладостойкость новой литейной Cr – Mn – Ni – Mo – N стали. Часть 2. Исследование фактора частиц неметаллических включений при статическом и ударном нагружении при пониженных температурах

М. В. Костина [1, 2], А. Э. Кудряшов [1], Л. Г. Ригина [1, 3], С. О. Мурадян [1], О. С. Антонова [1], В. С. Костина [1]

[1] **Институт металлургии и материаловедения им. А.А. Байкова РАН** (Россия, 119991, Москва, Ленинский пр., 49)
[2] **Московский авиационный институт (национальный исследовательский университет)** (Россия, 125993, Москва, Волоколамское шоссе, 4)
[3] **Центральный научно-исследовательский институт технологии машиностроения, ОАО НПО «ЦНИИТМАШ»** (Россия, 115088, Москва, Шарикоподшипниковская ул., 4)

Аннотация. Новая литейная аустенитная Cr – Ni – Mn сталь с 0,5 % N (марка 05Х21АГ15Н8МФЛ) во всем интервале климатических температур превосходит по ударной вязкости литую сталь сравнения типа 18Cr – 10 Ni. В статье уделено внимание частицам неметаллических включений (НВ) в литом металле азотистой стали как фактору, способному влиять на механические свойства при статическом и ударном нагружении при пониженных температурах. Неметаллические включения в лабораторном металле представляют собой глобулярные оксисульфиды с оксидами SiO_2 в центральной части и наружным слоем, сформированным сульфидом марганца MnS, со средним размером ~75 % частиц до 4 мкм. Установлено, что при испытаниях литой стали на ударный изгиб при –160 °C эти НВ не служат источником зарождения трещин и не способствуют их распространению, находясь в изломе в изолированных ямках. В условиях растяжения при –110 °C предел текучести азотистой стали возрастает более, чем в 1,7 раза по сравнению со свойствами при +20 °C, пластичность при охлаждении до –110 °C не снижается. При этом частицы НВ сильно деформируются за счет развития в их оксидной части трещин и даже при выходе на поверхность образца в рабочей части в зоне шейки они не служат источником зарождения трещин. Трещины на границе НВ – деформирующийся металл не образуются. Даже при случайном расположении частиц в виде цепочек вдоль оси приложения растягивающей нагрузки на расстоянии 5 – 20 мкм друг от друга не происходит формирования пор вокруг частиц и их слияния в зародыш трещины. Полученные результаты коррелируют с литературными данными о том, что в пластичных сталях НВ могут действовать как релаксаторы напряжений.

Ключевые слова: литая аустенитная сталь, хладостойкость, азот, неметаллические включения, излом, трещины, деформация

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Introduction

In the first part of this paper, it was demonstrated [1] that new cast austenitic Cr–Ni–Mn steel with 0.5 % N (grade 05Kh21AG15N8MF) surpasses cast steel of 18 Cr – 10 Ni type used for comparison, in terms of the impact strength in the entire range of climatic temperatures. It was shown to be promising as a corrosion-resistant cast material for structures working in the Arctic and Siberia. It was also demonstrated that the presence of dendritic crystals of δ-ferrite in steel 05Kh21AG15N8MF negatively affects its impact strength at –160 °C. This part of the paper considers particles of non-metallic inclusions (NMI) in cast metal as a factor which affects the mechanical properties of steels at low temperatures.

Theoretical and experimental studies of the influence of NMI on fracture during impact bending and other types of tests were reviewed. These include monographs [2 – 4], reviews [5 – 8], and articles [9 – 12]. It was noted that during impact loading at low temperatures, NMI particles can initiate cleavage cracking either due to fracture or due to decoupling of the particle-matrix interface. The effect of NMI on the mechanical properties of steel depends on their composition, morphology, size, number and distribution in the metal, as well as the physical and mechanical properties of the metal matrix material. The type of NMI often plays a more important role than their total number [13]. For example, the impact energy of crack propagation in the metal of low-alloy hardened steel for $35B_2$ + Cr screws does not depend on the total NMI content. At the same time, oxides do not affect it. Sulfides in fibrous form with the axis perpendicular to the notch, as well as nitrides increase it, while large exogenous NMI[1] reduce it [14].

In view of the above, the aim of this work was to identify NMI particles in a new nitrogen-containing cast steel and to analyze their possible impact on the initiation or propagation of cracks during impact bend and tensile tests at low temperatures. Previously [15] it was demonstrated by the transmission electron microscopy method that steel 05Kh21AG15N8MF austenite has nano-sized (~4 nm) particles of CrN nitrides formed by alloying elements. They are not considered as NMI, and in this paper we will examine particles revealed on thin sections and in fractures, caused by the presence of impurities and characterizing the metallurgical quality of steels.

Research materials and methods

Studies of steel 05Kh21AG15N8MF were performed on laboratory casting metal, annealed at 1100 °C and then cooled in water. Steel was smelted in an open induction furnace on pure charge materials and poured into a mold from a cold-hardening mix. The mass of the plate with the gating system was ~70 kg. The chemical composition of the steel is given in *Table 1*.

Tensile tests were carried out in accordance with GOST 1497-84 and GOST 11150-84 in a 10-t Instron 3382 unit. The tensile rate in all cases was 1 mm/min.

Impact bend tests were carried out according to GOST 9454-78 and GOST 22848-77 in an Amsler RKP 450 Zwick/Roell unit with an impact energy of 450 J.

The microstructure was specified using an etchant: 3 parts of HCl + 1 part of HNO_3 + 1 part of glycerol. The microstructure of thin sections was studied using an Olympus GX51 light microscope and a Tescan Vega II SBU scanning electron microscope with an INCA Energy 300 energy dispersive microanalysis add-on. The same microscope was used for the fractographic analysis.

In order to estimate the number, size, and morphology of NMI and their distribution in the cast steel, we analyzed unetched thin sections (60 panoramic images 700×530 μm in size, with a total area of 22.26 mm^2).

[1] These include particles of the charge, exothermic mixes, slag, and damaged lining of units for smelting and casting steel.

Table 1

Chemical composition of 05Kh21AG15N8MF steels (mass. %), Fe – base

Таблица 1. **Химический состав сталей 05Х21АГ15Н8МФЛ, % (по массе), Fe – основа**

Steel	C	Mn	Si	Cr	Ni	Mo	Ti	V	S	P	N
05Kh21AG15N8MF	0.04	14.40	0.24	22.00	7.60	1.12	–	0.22	0.010	0.011	0.47

Research results

Studies of panoramic images of unetched thin sections showed that NMI in cast metal are distributed unevenly. Quite extensive areas are practically free from excretions (Figure 1, *a*), and areas of significantly contaminated metal (Figure 1, *c*). Most of the metal contains NMI in a moderate quantity (Figure 1, *b*). The number of sites of types *a*, *b*, and *c* in Figure 1 can be described by normal Gaussian distribution. Sites of types *a* and *c* are in the descending parts of this curve. The distribution of inclusions by sizes is as follows: the minimum size is ~0.8 μm; and the maximum size (for some rare inclusions) is 20 – 40 μm. Fracture images obtained by scanning electron microscopy were used to specify the dominant size of NMI particles.

Figure 2 shows the results of particle size distribution analysis in a specially selected area of impact specimen fracture. These were obtained as a result of tests at –70 °C, in which there are a lot of NMI particles (Figure 3). For each group, the average particle size is indicated. The arrows mark the percentage of small particles from the total number of particles in the fracture. As can be seen in Figure 2, the percentage of particles with an average size up to 2 μm inclusive is 50 %; and up to 4 μm it is 75 %.

Previously, the fractographic analysis of steel 05Kh21AG15N8MF specimens tested for impact bending at a temperature of –70 °C close to the ductile-brittle transition temperature (T_{DBT} = –75 °C) showed that fractures of this steel remain ductile, while a significant retraction deformation (in comparison with Cr–Ni steel fracture) is observed [1]. As Figure 3, *a*, shows, NMI in such a fracture have an oval or globular shape and are in isolated pits separated by tear ridges. These do not merge into single pores during impact fracture. All non-globular inclusions split under the impact destructive load which should have contributed to stress relaxation. According to data from X-ray spectral microanalysis of the particle composition in the fracture (Figure. 3, *a*) and on the unetched thin section (Figire 3, *b*), their composition includes: manganese; sulfur; silicon; a small amount of aluminum; and oxygen (*Table 2*). Similar data on the chemical composition of particles was obtained during the analysis of NMI in other fields of view on thin sections and fractures. The assumption of the multiphase composition of NMI particles was confirmed by light microscopy of an unetched thin section (Figure 3, *c*, where the largest particles from several microstructure images are collected).

Using the known data on the types and kinds of NMI [4], the structure of the particles and their chemical composi-

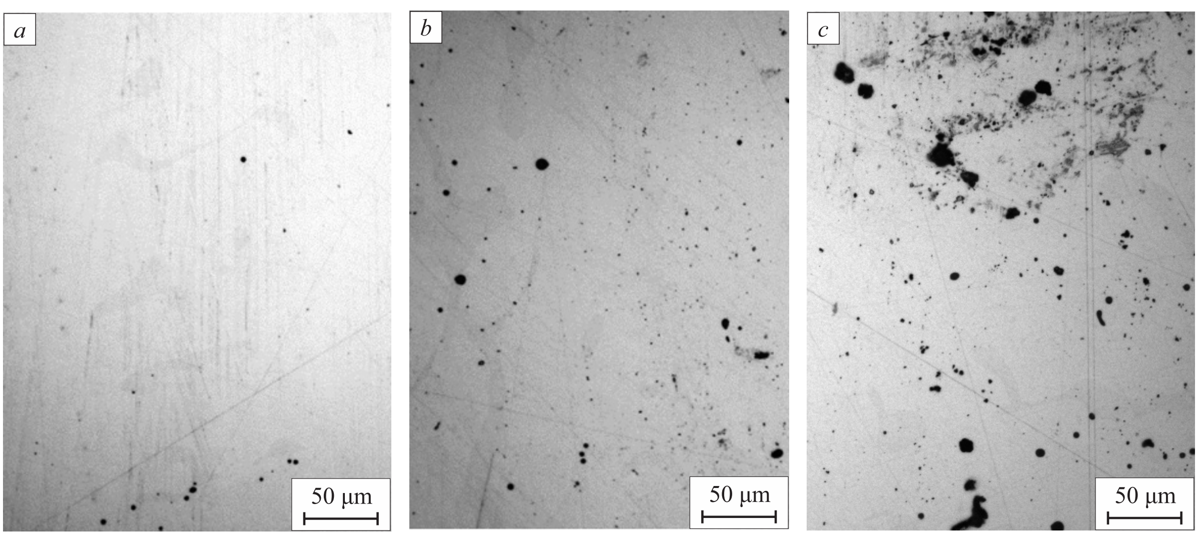

Figure 1. Sites with different types of contamination by non-metallic inclusions:
a – pure metal; *b* and *c* — moderate and high degree of NMI contamination, respectively, characteristic for cast steel 05Kh21AG15N8MF

Рис. 1. Характерные для литой стали 05Х21АГ15Н8МФЛ участки с разным типом загрязненности неметаллическими включениями:
а – чистый металл; *b* и *c* – умеренная и высокая степень загрязненности НВ соответственно

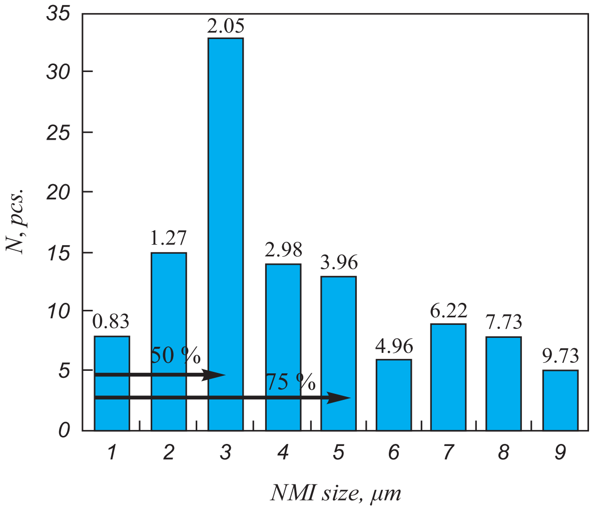

Figure 2. Distribution of particles visible in the fracture in Figure 3, *a*, by size, μm:
1 – <1; *2* – 1 – <1,5; *3* – 1,5 – <2,5; *4* – 2,5 – <3,5; *5* – 3,5 – <4,5; *6* – 4,5 – <5,5; *7* – 5,5 – <6,5; *8* – 6,5 – <8,5; *9* – 8,5 – <12;
N is the number of particles in each of nine size groups

Рис. 2. Распределение частиц, видимых в изломе на рис. 3, *a*, по размерам, мкм:
1 – <1; *2* – 1,0 – 1,5; *3* – 1,5 – 2,5; *4* – 2,5 – 3,5; *5* – 3,5 – 4,5; *6* – 4,5 – 5,5; *7* – 5,5 – 6,5; *8* – 6,5 – 8,5; *9* – 8,5 – 12,0;
N – количество частиц в каждой из девяти групп размеров

tion allow us to conclude that these are oxysulfides with SiO_2 oxides in the central part and the outer layer formed by manganese sulfide MnS (Figure 3, *c*).

It was previously established [1] that the criterial values of KCV for steel 05Kh21AG15N8MF containing up to ~8 % of δ-ferrite are 39 – 49 J/cm^2. The critical ductile-to-brittle transition temperature for this steel (below which the material is not recommended for use, as determined by the criterial method, T_c) was –110 °C. At that temperature, the steel exhibited KCV = 68 – 83 J/cm^2. At –160 °C the steel specimens exhibited impact strength not higher than 0.39 J/cm^2 (Figure 4). Columnar crystals of δ-ferrite (below the cold brittleness threshold at –160 °C) contributed to the embrittlement of the metal to a large extent [1]. We should also take into account the conclusion made in [16] on the basis of studies of the Fe – 18Cr – 15Mn – 2Mo – 0.66 % N steel by transmission electron microscopy.

According to [16], a decrease in the packaging defect energy of high-nitrogen austenitic stainless steel with decreasing temperature can promote twinning and plane slip, thus causing brittle fracture at cryogenic temperatures. The study of fracture after tests at –160 °C (below the critical ductile-to-brittle transition temperature) showed that even in a more brittle state of the austenitic matrix, oxysulfide particles do not initiate cracking and do not contribute to crack propagation (Figure 5). The fracture area with a microcrack in Figure 5, *c* (framed) is the only example of a microcrack associated with a particle, identified for this steel.

Tensile tests of steel 05Kh21AG15N8MF carried out at low temperatures allowed evaluation of the possible influ-

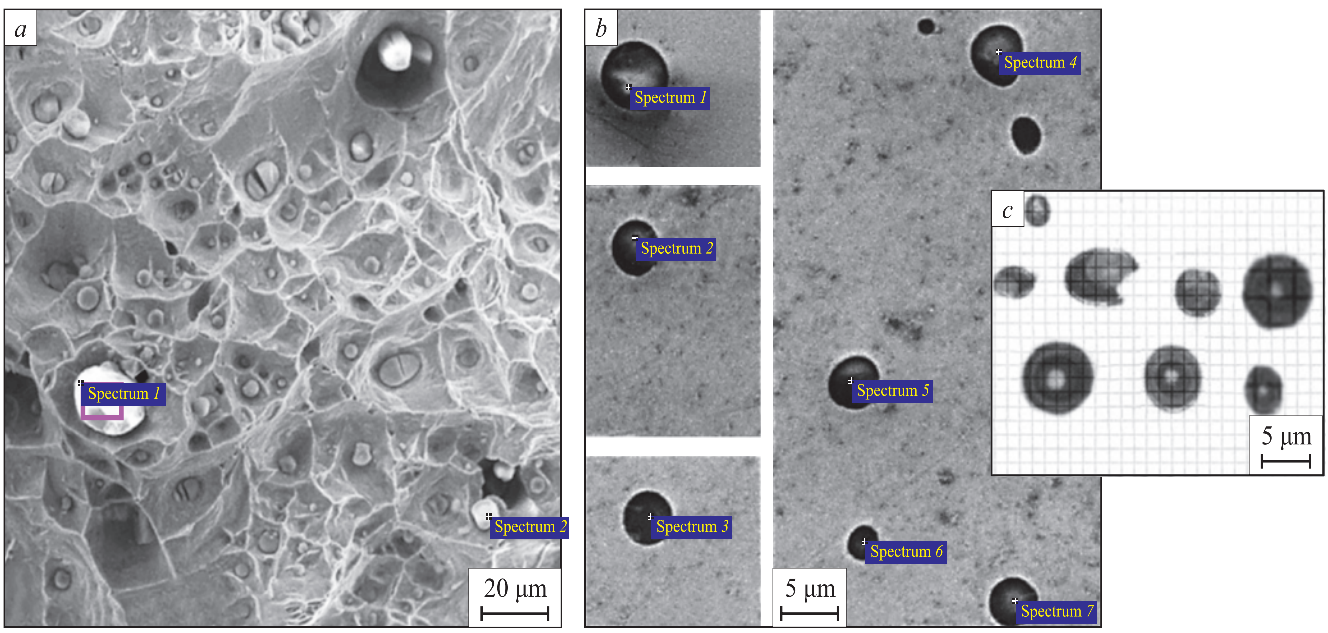

Figure 3. Inclusions in steel 05Kh21AG15N8MF:
a – fracture section with multiple NMI after tests at –70 °C; *b* – NMI particles on an unetched thin section of the same steel;
c – structure of NMI particles (unetched thin section, ×1000, selection of large particles)

Рис. 3. Включения в стали 05Х21АГ15Н8МФЛ:
a – участок излома с большим количеством НВ после испытаний при –70 °C; *b* – частицы НВ на нетравленом шлифе этой же стали;
c – строение частиц НВ (нетравленый шлиф, ×1000, подборка крупных частиц)

Table 2

Concentration of elements, % (at.) in the composition of particles in a fracture and on a thin section of cast steel 05Kh21AG15N8MF

Таблица 2. **Концентрация элементов, % (ат.) в составе частиц в изломе и на шлифе литой стали 05Х21АГ15Н8МФЛ**

Figure	Spectrum	S	O	Si	Mn	Fe	Cr	Other elements
3, *a* (fracture)	*1*	–	61.28	13.82	24.90	–	–	–
	2	2.27	59.53	14.20	23.98	–	–	–
3, *b* (thin section)	*1*	1.44	63.54	9.98	23.24	–	–	0.77 (Ce); 1.04 (Mo)
	2	2.93	56.86	8.96	24.97	3.30	2.14	0.84 (Ce)
	3	3.52	58.17	7.80	23.93	3.37	1.73	1.48 (Al)
	4	2.81	64.10	8.63	24.46	–	–	–
	5	3.88	50.49	12.64	32.03	–	–	0.96 (Ce)
	6	2.41	41.37	5.85	24.77	12.77	11.02	1.81 (Al)
	7	2.60	51.03	6.44	20.81	12.82	6.30	–

ence of NMI particles identified as oxysulfides on the behavior of cast metal under the conditions of static uniaxial deformation. As can be seen from Table 3, steel strengthens appreciably at –110 °C in comparison with the properties at +20 °C. The yield strength increases by more than 1.7 times. The strength limit – increases by more than 1.6 times and plasticity is not reduced at cooling to –110 °C.

Studies of the microstructure of a longitudinally thin section of the working part of a fracture specimen tested at T_c = –110 °C (Figure 6) revealed the following features.

• The inclusions emerging on the surface of a specimen in the working part near the neck zone, as well as in the neck zone, do not initiate cracking (see the surface areas of the working part of the fracture specimen, circled in Figure 6, *a*, *b*).

• NMI particles in the zone of stress localization (neck) are highly deformed. If, in the absence of tensile stresses, the particles visible at the bottom of fracture pits and on a thin section were mainly close to spheroidal in shape (Figure 3, *a*, 5), then in the neck area of the fracture sample the particle width to length ratio was ~1:2 (Figure 6, *a* – *e*).

• Oxysulfide particle elongation occurs due to cracks developing in the oxide part of relatively large NMI at maximum stresses (Figure 6, *d* with images of particles from different parts of the neck area), and the MnS sulfide shell surrounding the oxide is deformed. In this case, no cracks are formed at the NMI – deforming metal interface. This is clearly due to both high plasticity of the matrix austenite and presence of a plastic sulfide shell around the oxide.

• Even if a group of closely located NMI forms a chain inside the metal along the axis of tensile stresses, they do not initiate cracking by the mechanism described also in [4]: "deformations are localized in inclusions. In the matrix near the inclusions, cavities (pores) arise around particles → cavities (pores) stretch to a certain critical size → pores are united into one long cavity – crack nucleation. A crack is propagated from the inclusion to the matrix with the formation of the main crack" (Figure 6, *c*, zoomed image of the area framed in Figure 6, *b*).

• At the stage of the specimen after-breakage, fracture can also occur through cracked particles (Figure 6, *e*), and along the NMI – metal interface (Figure 6, *f*).

Figure 6, *a* also shows that austenite grain boundaries often run along the austenite – ferrite interfaces and that NMI particles play a certain role in restraining these interfaces.

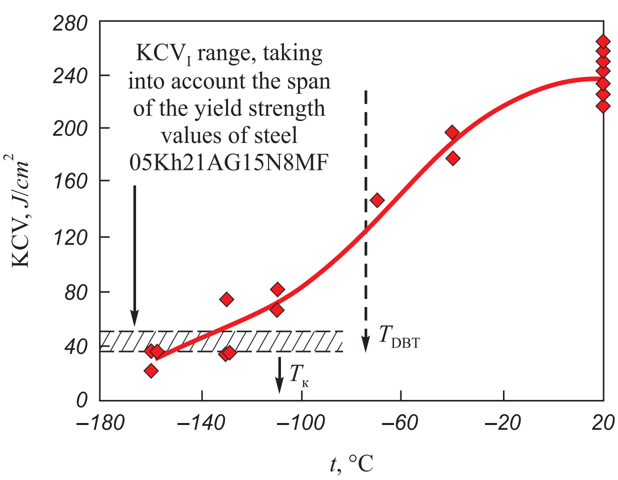

Figure 4. Ductile-to-brittle transition temperature (T_{DBT}) and critical brittle temperature (T_c) of steel 05Kh21AG15N8MF containing up to ~8 % of δ-ferrite

Рис. 4. Температура вязко-хрупкого перехода (T_{DBT}) и критическая температура хрупкости ($T_к$) стали 05Х21АГ15Н8МФЛ, содержащей до ~8 % δ-феррита

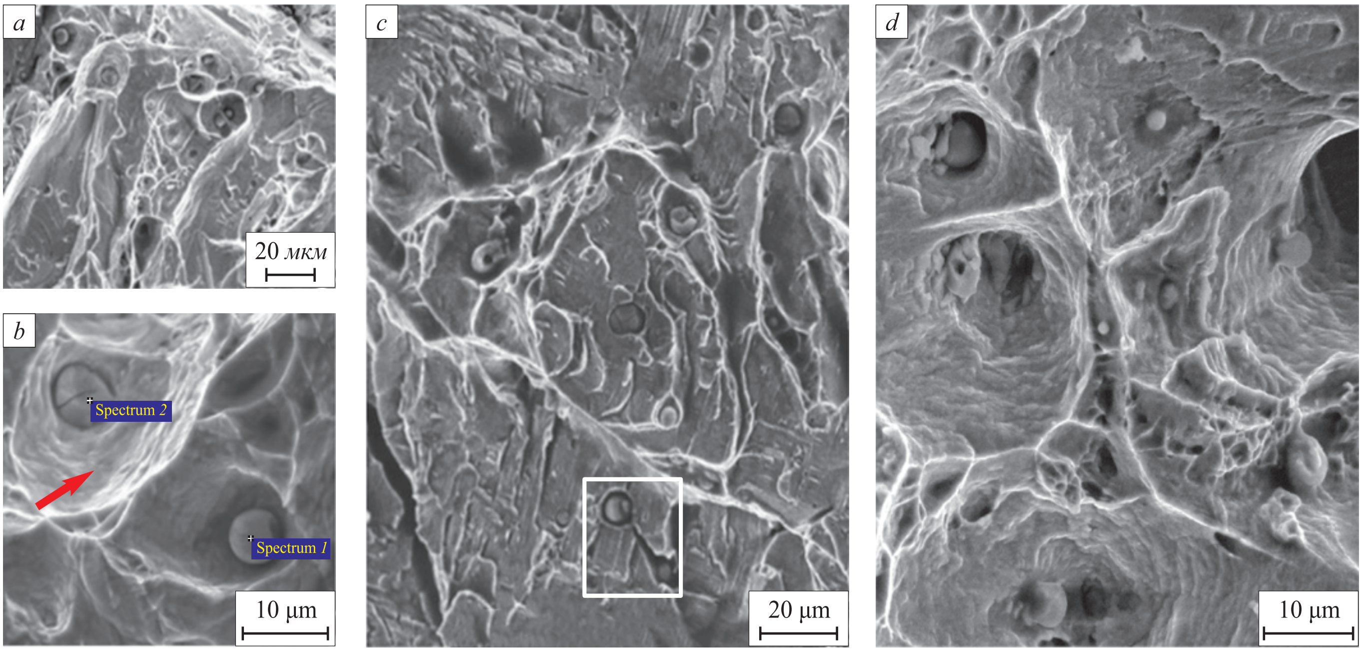

Figure 5. Oxysulfide particles in a fracture of steel 05Kh21AG15N8MF after impact bend test at –160 °C

Рис. 5. Оксисульфидные частицы в изломе стали 05Х21АГ15Н8МФЛ после испытаний на ударный изгиб при –160 °С

Discussion of results obtained on the NMI effect on cold resistance in comparison with literature data for other materials

In ferritic-pearlitic pipe steels of increased strength (material of other structural class) NMI do have a significant impact on cold resistance. Tests of these steels at reduced climatic temperatures show that NMI therein can serve as nucleation points of brittle cracks. This is shown in Figure 5, *a*, where the source of shear was the TiN inclusion [17].

Oxysulfide inclusions in the austenitic matrix of cast steel 05Kh21AG15N8MF do not cause similar consequences during tests at up to –160 °C. In particular, shear centers initiated by NMI particles, similar to those shown in Figure 5, *a*, were not observed. None of the impact bend tests between +20 and –160 °C (Figure 4) showed deviations of more than 30 J/cm^2 in the values of the impact strength from the average value (described by the impact strength curve in this figure). This could be explained by the negative effect of NMI particles.

Table 3

Mechanical properties of cast steel 05Kh21AG15N8MF in tension at +20 ... –110 °C

Таблица 3. **Механические свойства литейной стали 05Х21АГ15Н8МФЛ при растяжении при +20 … –110 °С**

Mechanical properties	Test temperature, °C				
	–110	–90	–70	–40	+20
$\sigma_{0.2}$, МПа	716	–	558	533	402
$\sigma_в$, МПа	1011	–	871	862	684
δ, %	46	–	–	53	41

The data obtained for cast austenitic steel 07Kh13G28N3 with high impact strength at low temperatures can be used in the discussion of these results [12]. When studying this steel, the authors concluded that small fracture pits reduce ductility and plasticity, while large pits are responsible for increasing plastic properties. High impact strength is demonstrated if, in the presence of a large number of small-size pits, the largest area in the fracture is occupied by pits not less than 10 – 15 μm in size, with globular inclusions of no more than 8 μm in size. It was also noted that, in addition to the presence of similar pit relief in the fracture of impact specimens, the plasticity of pits themselves (serpentine character of sliding on their walls, sufficient depth of pits and the absence of fractured pits) is a sign of high metal ductility [18]. The specific signs of a ductile fracture are inherent in cast steel 05Kh21AG15N8MF which is the subject of this study. They include deep pits with traces of serpentine sliding and particles <8 μm (see characteristic images of pits marked by the arrow in Figure 5, *b*). In addition, the results confirm the conclusions [18] based on the fracture analysis:

– "virtually no cases of brittle fracture starting exclusively from inclusions or propagating away from inclusions and further into ductile flow" have been identified;

– "…in ductile steels, unlike high-strength steels, NMI are capable of being stress relaxers due to plastic deformation long before the crack approach. Thus, NMI do not contribute to brittle fracture formation".

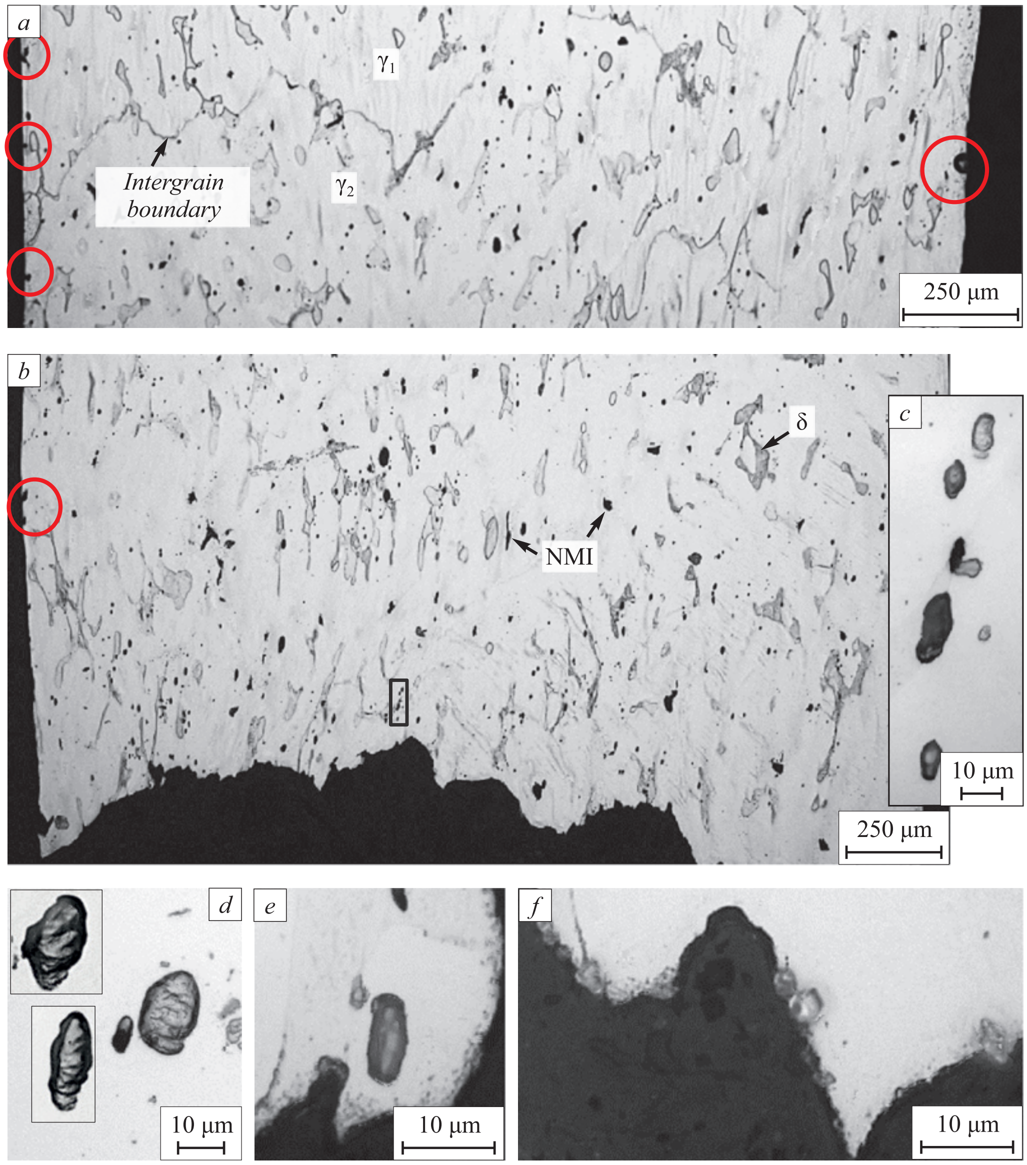

Figure 6. Non-metallic inclusions in the working part of a fracture specimen (tests at –110 °C) near the neck zone (a) and in the neck zone (b – f), including those coming out to the surface of the after-breakage zone (e, f)

Рис. 6. Неметаллические включения в рабочей части разрывного образца (испытания при –110 °С) рядом с зоной шейки (*a*) и в зоне шейки (*b* – *f*), в том числе выходящие на поверхность зоны долома (*e*, *f*)

The second conclusion correlates with the notions stated in [4] that matrix failure near the inclusion is a result of two competing processes: the accumulation during plastic deformation of internal stresses due to the inhibition of the motion of the crystalline structure defects and their plastic relaxation.

Monograph [4] describes different variants of destruction of the inclusion-matrix interfaces during steel deformation, the destruction of NMI during the steel plastic deformation and its possible influence on the crack-to-matrix transition for different types of complex heterophase NMI. For inclusions consisting of refractory phase "ph2" surrounded by sulfide shell "ph-sh1", as in the paper presented by the authors, the formation of cracks at ph-sh1 – ph2 interfaces was noted as a characteristic feature. These boundaries contribute to the localization of the deformation in the inclusion.

When discussing the contribution of NMI to the mechanical behavior of the studied steel, it should be noted that NMI – matrix interfaces, as well as grain boundaries [19, 20] represent sources of lattice dislocations.

The fundamental positive difference of the metal of the mold steel being studied here from metal similar to it in composition, albeit hot-deformed one, is the shape of the majority of NMI close to globular. The difference also lies in the absence of string clusters of NMI. As near globular inclusions the concentration of deformation is lower than that near lamellar inclusions, and is determined by inclusion size [4]. In [21] it was noted that in the case of hot-rolled

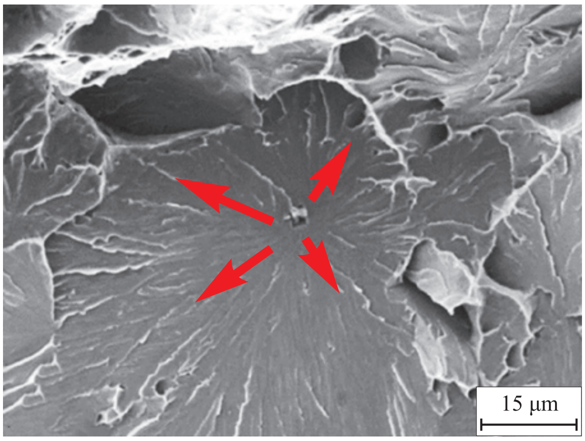

Figure 7. Effect of non-metallic inclusions on cold resistance of pipe steels during impact bend tests: a fracture of specimens of pipe steel K60-A after test at –20 °C with a shear center containing NMI [17]

Рис. 7. Влияние неметаллических включений на хладостойкость трубных сталей при испытаниях на ударный изгиб. Стрелки указывают на излом образцов трубной стали К60-А после испытания при –20 °C с очагом скола, содержащим НВ [17]

metal similar in composition to the 04Kh20N6G11M2AFB steel (the subject of this study) with 0.47 and 0.50 % N, the relatively low plasticity (when compared to other steels of austenitic class) in the Z-direction of rolling:

– may be due to the high strength of the matrix, combined with the presence of adverse-shaped NMI clusters;

– depends both on the total contamination of NMI particles, and on the string morphology of their accumulations.

At the same time, of the three types of detected NMI (complex nitrides containing Nb; aluminum oxides; sulfides), flat clusters of aluminum oxides and specific nitrides most noticeably impaired the metal properties.

Conclusions

In laboratory metal of cast high-strength austenitic steel 05Kh21AG15N8MF containing up to ~8 % ferrite, hardened by nitrogen alloying, the NMI consists of oxysulfides with SiO_2 oxides in the central part, and an outer layer formed by manganese sulfide MnS. Particles of nitrides visible in the fracture or on a thin section, of sub-micron or micron size, were not detected.

The shape of oxysulfide NMI is globular or oval. The share of particles with an average size of up to 2 μm inclusive is ~50 %; and up to 4 μm ~75 %. Individual particles can reach a size of ~20 μm. NMI particles in the cast metal are distributed unevenly. There are quite extensive areas practically free of excretions, and areas of significantly contaminated metal. The bulk of the metal contains NMI in moderate amounts.

In impact bend tests of cast steel at –160 °C, oxysulfide particles:

– do not initiate cracking and do not contribute to crack propagation;

– are in the fracture in isolated pits separated by rupture ridges, and do not merge into single pores under impact fracture.

All non-globular inclusions split under the impact destructive load.

Under the conditions of static uniaxial deformation at –110 °C, yield strength grows by more than 1.7 times when compared to the properties at +20 °C, and plasticity does not fall when cooling to –110 °C. At the same time the NMI particles:

– emerging onto the surface of a specimen in the working part in the neck zone do not initiate cracking;

– located in the neck are strongly deformed with the particle width to length ratio of ~1:2, due to the development of cracks in their oxide part which do not go into the metal of the austenitic matrix.

Cracks at the "NMI / deforming metal" interface are not formed. Even with random particle arrangement in the form of chains along the axis of application of the tensile load, at a distance of 5 – 20 μm from each other, pores do not form around the particles or merge into a crack nucleus.

The results obtained correlate with the literature data showing that NMI can act as a stress relaxer in ductile steels.

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Information about the authors

Mariya V. Kostina*, Dr. Sci. (Eng.), Assist. Prof., Senior Researcher, Head of the Laboratory "Physicochemistry and Mechanics of Metallic Materials",* Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences*; Prof.,* Moscow Aviation Institute (National Research University)
ORCID: 0000-0002-2136-5792
E-mail: mvk@imet.ac.ru

Aleksandr E. Kudryashov*, Research Engineer,* Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences
E-mail: al.kudriashov@mail.ru

Lyudmila G. Rigina*, Cand. Sci. (Eng.), Leading Researcher,* Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences; JSC Russian State Research Center "CNIITMASH"
E-mail: LGRigina@cniitmash.com

Sarkis O. Muradyan*, Cand. Sci. (Eng.), Research Associate of the Laboratory "Physicochemistry and Mechanics of Metallic Materials",* Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences
E-mail: muradianso@gmail.com

Ol'ga S. Antonova*, Junior Researcher,* Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences

Valentina S. Kostina*, Cand. Sci. (Eng.), Junior Researcher of the Laboratory "Physicochemistry and Mechanics of Metallic Materials",* Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences
ORCID: 0000-0001-7956-499X
E-mail: vskostina@yandex.ru

Сведения об авторах

Мария Владимировна Костина*, д.т.н., доцент, ведущий научный сотрудник, заведующий лабораторией физикохимии и механики металлических материалов,* Институт металлургии и материаловедения им. А.А. Байкова РАН*; профессор,* Московский авиационный институт (национальный исследовательский университет)
ORCID: 0000-0002-2136-5792
E-mail: mvk@imet.ac.ru

Александр Эдуардович Кудряшов*, инженер-исследователь,* Институт металлургии и материаловедения им. А.А. Байкова РАН
E-mail: al.kudriashov@mail.ru

Людмила Георгиевна Ригина*, к.т.н., ведущий научный сотрудник,* Институт металлургии и материаловедения им. А.А. Байкова РАН*;* Центральный научно-исследовательский институт технологии машиностроения, ОАО НПО «ЦНИИТМАШ»
E-mail: LGRigina@cniitmash.com

Саркис Ованесович Мурадян*, к.т.н., научный сотрудник лаборатории физикохимии и механики металлических материалов,* Институт металлургии и материаловедения им. А.А. Байкова РАН
E-mail: muradianso@gmail.com

Ольга Станиславовна Антонова*, младший научный сотрудник,* Институт металлургии и материаловедения им. А.А. Байкова РАН

Валентина Сергеевна Костина*, к.т.н., младший научный сотрудник лаборатории физикохимии и механики металлических материалов,* Институт металлургии и материаловедения им. А.А. Байкова РАН
ORCID: 0000-0001-7956-499X
E-mail: vskostina@yandex.ru

Contribution of the authors

M. V. Kostina – scientific guidance and formation of the main concept, goals and objectives of the study, preparation and revision of the text, formation of conclusions.
A. E. Kudryashov – microstructure studies by optical microscopy, incl. development of the etchant composition; processing and analysis of the results of microstructural studies, preparation of the article.

L. G. Rigina – steel smelting, analysis of the results by inclusions.

S. O. Muradyan – mechanical tests for tension and impact bending (incl. at long temperatures) and their analysis.

O. S. Antonova – studies by scanning electron microscopy, incl. fractographic analysis and X-ray microspectral analysis.

V. S. Kostina – selection of literature data for the introduction and the results discussion, preparation of the figures.

Вклад авторов

М. В. Костина – научное руководство и формирование основной концепции, цели и задачи исследования, подготовка и доработка текста, формирование выводов.
А. Э. Кудряшов – выполнение исследований микроструктуры методом оптической микроскопии, в том числе разработка состава травителя, обработка и анализ результатов микроструктурных исследований, оформление статьи по правилам редакции.
Л. Г. Ригина – выплавка стали, анализ результатов по включениям.
С. О. Мурадян – проведение механических испытаний на растяжение и ударный изгиб, в том числе при пониженных температурах, анализ результатов механических испытаний.
О. С. Антонова – проведение исследований методом сканирующей электронной микроскопии, в том числе фрактографический и микрорентгеноспектральный анализ.
В. С. Костина – подбор литературы для вводной части и обсуждения результатов, работа с рисунками.

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