Analysis of the influence of combined processing on cold resistance of structural steels

E. Yu. Remshev, *Cand. Eng., Associate Prof., E4 Dept.* [1], *e-mail: remshev@mail.ru;*
G. A. Vorobyeva, *Cand. Eng., Associate Prof., A2 Dept.* [1], *e-mail: bgtu@voenmeh.ru;*
M. V. Kostina, *Dr. Eng., Associate Prof., Leading Scientific Researcher, Head of the Laboratory of physical chemistry and mechanics of metallic materials* [2]*;*
A. I. Olekhver, *Cand. Eng., Associate Prof., E4 Dept.* [1], *e-mail: leshicher@mail.ru;*
A. E. Kudryashov, *Junior Scientific Researcher* [2], *e-mail: al.kudriashov@mail.ru*

[1] *Baltic State Technical University "VOENMEKH" named after D. F. Ustinov (St. Petersburg, Russia)*
[2] *A. A. Baikov Institute of Metallurgy and Materials Science of RAS (Moscow, Russia)*

The influence of acoustic fields (aeroacoustic and aerothermoacoustic treatment – AAT and ATAT) on the mechanical properties, structure of structural steels 40Kh and 05Kh21AG15N8MFL, and dependence of the values of the impact strength of these steels on the testing temperature within the range of 20 – (–196) °C has been studied. It was established that possibility of increasing the impact strength of steels and reducing the cold brittleness threshold, which is determined by the temperature corresponding to the KCU (KCV) values, which are 1/2 of the average KCU $(KCV)^{+20}$ – (Txp.) level, by 30 °C for steels of pearlitic and austenitic grades, is achieved via use of ATAT for the steels 45 and 40Kh, and AAT for the steel 05Kh21AG15N8MFL. In this case, tensile strength did not decrease and yield strength displayed a slight increase for austenite steels. As for the steel 40Kh, use of ATAT was characterized by stable tensile strength and rise of yield strength by approximately 100 MPA, accompanied by ductility increase.
Key words: cold resistance, mechanical properties, impact strength, pearlite steels, austenite steels, aerothermoacoustic treatment, aeroacoustic treatment.
DOI: 10.17580/cisisr.2025.01.13

Introduction

Brittle material destruction at the low temperatures is a factor to be taken into account during choice of material for operation in the Arctic regions, because tensile strength increases with temperature lowering, while ductility and impact strength decrease in this case. The working temperature, which characterizes cold resistance of the alloy at the required strength level, is determined by the temperature of tough-brittle transition, when impact strength drops down to the level equal to half of its value at the temperature 20 °C. The temperature T_{50} (when fiber content in a fracture decreases to 50 %) is also used as a cold brittleness criterion. Cold brittleness is inherent to the metals with body-centered cubic (BCC) lattice (high-quality carbon and low-alloy steels of pearlite class), their mechanical properties provide operating possibility at the temperature down to –60 °C, but with Ni content not less than 1–2 % [1]. However, the metals and alloys with face-centered cubic (FCC) lattice (austenite steels with 18 % Cr – 10 % Ni) are not inherent to tough-brittle transition, and their ductility and impact strength decrease monotonously with temperature lowering [1]. In comparison with these steels and alloys, austenite Cr–Ni–Mn–N steels with high nitrogen content are characterized by better corrosion-resistant and mechanical properties, as well as crack propagation resistance and inherence to tough-brittle transition [2–13]. They also have essential prospects for practical use.

The new casting steel 05Kh21AG15N8MFL of austenite class (with ~0.5 % N) is not susceptible to notches and takes precedence of Russian austenite steels in yield strength, impact strength and hardness, what allows to decrease wall thickness of castings [10–13]. Possibility of its use at the negative temperatures is determined by the values T_{DBT} = –75 °C and KCV = 120±10 J/cm² (1/2 from the average KCV^{+20} level 240 J/cm²) [10]. Cold resistance depends on the type of crystal lattice and several factors decreasing T_{DBT} due to varying chemical composition (carbon content, harmful impurities and non-metallic inclusions, increase of nickel content), microstructure (thermal improvement for pearlite steels), as well as decrease of sizes of grains and blocks [1, 2]. The new developed kinds of influence on steels, such as aerothermoacoustic treatment (ATAT) and aeroacoustic treatment (AAT), provide rise of stel ductility and impact strength without lowering of tensile strength [14].

The study of influence of ATAT and AAT on increase of cold resistance of the steels structural pearlite steels 40Kh and austenite steel 05Kh21AG15N8MFL is the aim of this research, which included examination of structure and properties of these steels after ATAT and AAT.

Materials and methods of research

ATAT and AAT as he influence factors

Heating of components (billets) up to definite temperatures to provide quenching (or tempering for quenched steels) and consequent cooling in a gas flow in the acoustic field of the sound range of discrete frequencies, with the level of sound pressure 150–170 dB, are the main operations in ATAT steel technology [14]. Consequently, ATAT includes heating and further cooling in a powerful acoustic field with frequency 60–1,200 Hz with simultaneous gas dynamic effect on gas flow material within the speed range from tens to hundreds m/s (influence of thermal stresses and acoustic fields). Processing of components during ATAT and AAT occurs in a resonator of a gas fluid generator of sound (RGGS). AAT is carried out without heating, at the room temperature. In this case only the effect of acoustic field and has flow in RGGS and near it occurs; the last variant allows to provide processing of the components with dimensions not restricted by RGGS parameters.

Materials

The samples manufactured of steels 40Kh and 45 (hot rolled for the size 25 mm), with chemical composition according to the GOST 1050-88 and GOST 4543-2016 respectively, were subjected to the standard heat treatment (SHT): quenching at 860 °C (in oil for steel 40Kh and in water for steel 45) with consequent tempering at 500–550 °C. The properties of steels were examined during quenching after SHT and SHT+ATAT. The samples for examination of the steel 05Kh21AG15N8MFL, with the following composition, % (mass.): 0.03 C;0.58 N; 0.33 Si; 21.4 Cr; 16 Mn; 7.65 Ni; 0.85 Mo; 0.15 V; 0.07 Nb, were cut from a plate with thickness ~ 40 mm. The properties of this steel were investigated in cast state after SHT (quenching from 1000 °C in water after annealing at 1000 °C during 2 hours) and in initial state after additional AAT.

Processing procedures

ATAT for pearlite steels was carried out via the following procedure: quenching from 860 °C, cooling in air flow and in acoustic field with RGGS (for steel 40Kh); quenching from 860 °C, cooling in water-air mixture flow and in acoustic field with RGGS during 10 min and standard tempering (for steel 45). AAT for the steel 05Kh21AG15N8MFL was conducted via processing in RGGS ("inside" procedure) and near RGGS ("outside" procedure) during 20 min at the room temperature without preliminary heating.

Mechanical properties were determined during testing for static extension of 5-fold samples at the room temperature, using Shimadzu AGX-100кН and Instron 3382 (10 t) machines, in accordance to the GOST 1497-84. Cylinder 5-fold samples with diameter 6 mm were manufactured of the steels 40Kh and 45; the heads of similar samples of the steel 05Kh21AG15N8MFB were fabricated with carving. The error in strength determination does not exceed 10 MPa. Testing for impact bending was carried out using an impact testing machine Amsler RKP-450 (impact energy 450 J), at the temperatures within the range 20–196 °C according to the GOST 9454-84. 40Kh steel samples were manufactured with U-concentrator, and 05Kh21AG15N8MFB steel samples – with V-concentrator. The results of these tests were used for determination of cold brittleness threshold of steels. Conditional temperature of transition in brittle state (cold brittleness threshold of steel) was determined after building the relationships KCU, KCV – *f (t,* °C*)* and % of fiber – *f(t,* °C*)* via two criteria: temperature $T_{DBT} = T_{XP}$.=0.5 KCU^{20}; KCV^{20} and temperature T_{50} for the steel 40Kh. To determine % of a fiber indicator in fracture, the fractures of impact samples were examined via fractographic analysis with small magnifications. Pickling of steels was used for revealing microstructure: in 4 % HNO_3 solution in alcohol (for 40Kh and 45 steels) and in the reactant containing 3 parts of HCl and 2 parts of HNO_3+3H_2O (for 05Kh21AG15N8MFB steel). Steel microstructure was examined using light microscope Olympus GX51.

Results and discussion

Examination of 40Kh and 45 steels

Both steels after SHT have tempering sorbite structure with martensite orientation (**Fig. 1**), for the steel 45 the structure is based on the data [15].

Size of martensite plates is determined both by size of grains and by austenite blocks. Steel structure after quenching in an air flow (ATAT) is characterized by martensite plates with rather smaller size than after standard quenching in oil from the same temperature; it determines also larger degree of sorbite structure dispersity (Fig. 1, *b* and *d*). Size of blocks decreases by 2.0–2.5 times after quenching with ATAT in comparison with standard quenching [14, 16].

Mechanical properties of steels after SHT and ATAT are presented in the **Table 1**; properties of the steel 40Kh (SHT) are higher based on the self testing, comparing with the reference data [15]. When comparing the properties of steels after SHT and ATAT, strength rise for both steels after ATAT should be noted: $\sigma_{0.2}$ for the steel 40Kh increases by ~ 100 MPa and $\sigma_в$ increases by 10–15 % with saving ductility and larger toughness (based on the self and reference data). Slight rise of $\sigma_в$ for the steel 45 in comparison with the data [15] leads to increase of relative elongation δ (%) and especially toughness. KCU values at the temperature –60 °C (at the boundary of low climatic temperatures) are higher for the both steels than KCU values corresponding to the threshold values of their cold brittleness 60 and 55 J/cm^2 for the steels 40Kh and 45 respectively [1], what is not provided by SHT of the steel 40Kh.

The components made of structural steels are often operated at negative temperatures, close to the lower boundary of climatic coldness (–60 °C) [1]. In this connection, taking into account the established positive ATAT effect on the level of impact strength for the steels 45 and 40Kh at the temperature –60 °C, ATAT influence on the threshold of cold brittleness of the steel 40Kh was examined in this research. The results of impact bending testing at the temperatures within the range from +20 tp –140 °C are presented in the **Fig. 2:** the steel 40Kh after ATAT is characterized by higher KCU values. Respectively, as soon as KCU = 110 J/cm^2 after SHT

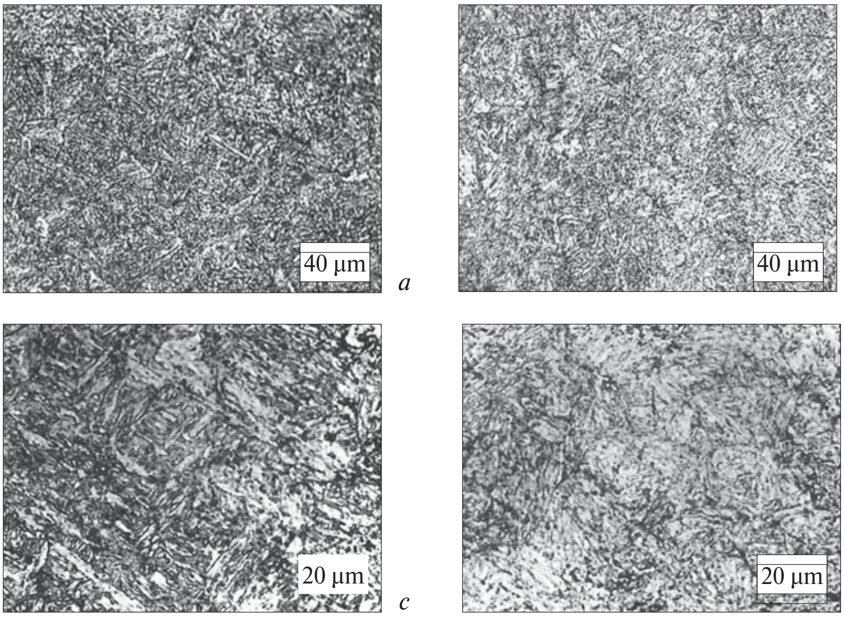


Fig. 1. Microstructure of the steel 40Kh (quenching, temper-ing at 530 °C during 1.5 hours): *a, c* – SHT; *b, d* – ATAT during quenching

Table 1. Mechanical properties of the steels 40Kh and 45 after SHT and ATAT during quenching

Steel grade	Processing procedure	Additional processsing	$\sigma_{0.2}$,	$\sigma_в$	δ	ψ	KCU	$KCU^{-60\,°C}$	HRC
			MPa		%		J/cm^2		
40Kh	Quenching from 860 °C + tempering at 550 °C, 1.5 h	–	1,030	1,120	12	56	110	40	31
	Quenching from 850 °C in water + tempering at 500 °C [1] / GOST 4543/2016	–	910/ 785	1,150/ 980	11/ 10	49/ 45	69/ 59	–	33
	Quenching + tempering at 500 °C, 1.5 h	ATAT	1,140	1200	13	57	120	75	35
Steel 45	Quenching from 850 °C in water + tempering at 500 °C [16], samples with dia. 5 mm	–	730	830	12	45	78	30	18
	Quenching + tempering at 530 °C	ATAT	780	850	16	70	110	59	25

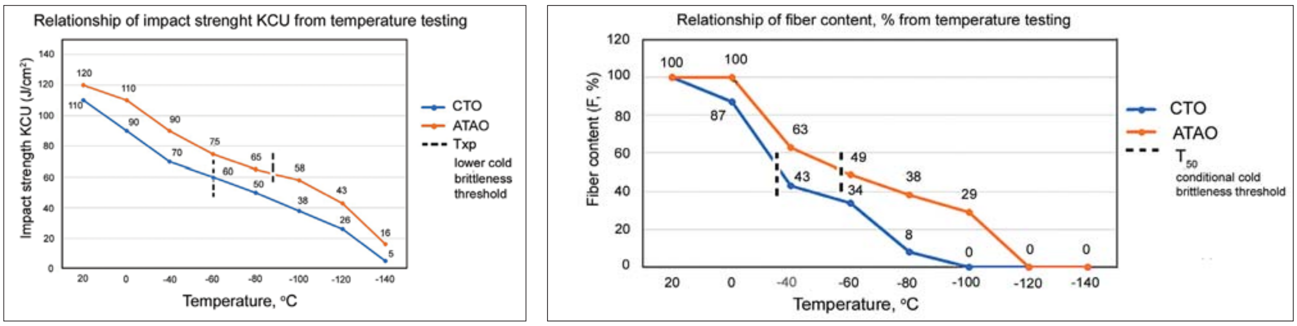


Fig. 2. Relationship of impact strength KCU (*a*) and amount of a tough component in fracture (*b*) for the steel 40Kh from the testing temperature after standard heat treatment and aero-thermoacoustic treatment (ATAT)

at the temperature 20 °C, the KCU = 55 J/cm² corresponds to the temperature $T_{DBT} = T_{XP}$, while after ATAT higher level of KCU equal to 60 J/cm² corresponds to this temperature. Using KCU relationship from the temperature (Fig. 2, *a*), it was determined that the cold brittleness threshold for the steel 40Kh corresponds to T_{XP} = –60 °C after SHT, and T_{XP} = –90 °C (i.e. lower by ~ 30 °C after SHT+ATAT).

Analysis of fiber content in fractures after two processing variants confirmed that the samples after ATAT are characterized by higher fiber content in fracture in the area of negative temperatures. According to the Fig. 2, *b*, T_{50} = –35 °C after SHT, while after ATAT it makes –60 °C. Owing to higher error in fiber determination in fracture, the testing data on KCU level determination seem more reliable; however, it should be noted, that cold brittleness threshold after ATAT is lower by ~30 °C than this after SHT when using both criteria.

Impact strength of the steel samples according to the GOST 9454-78 with allowable KCU value ≥ 30 J/cm² [1] is the accepted criterion of steel workability, and the range of working temperatures expands substantially for this criterion. Micro-fractographs of surface fractures for the steel 40Kh samples, which were tested at the temperature –40 °C (lower than the temperature T_{50} = –35 °C for the samples after SHT) are presented in the **Fig. 3**. After SHT, steel toughness becomes lower: destruction with forming of small pits is observed in fracture micro-relief, together with facets of shear distortions, quasi-shear distortions and steps, which are forming during joining of destruction surfaces located in different levels. This appearance testifies on smaller energy intensity of steel destruction in this area (Fig. 3, *a*). Local instability areas (facets) and crack propagation areas, which look like brittle fracture, are observed in fractures of the samples, which were tested at the temperature –40 °C after ATAT together with pits, their depth characterizes steel ability to local plastic deformation (Fig. 3, *a*, *b*) [13]. Presence of stress concentrators in steel is connected with appearance of crack propagation areas in the form of outlet-like paths. Destruction propagates quickly in these paths, but material is able to retard further crack propagation, as soon as these areas border on the areas with high toughness and new energy input is required for further crack enlargement (Fig. 3, *b*, *c*). Increased values of impact strength after ATAT for the steels 40Kh and 45 (see Table 1) are reached due to varying of steel structure – decrease of sizes of grains and blocks in steels during ATAT [14, 15, 17], what provides increase of steel impact strength (because it is known that decrease of grain sizes is accompanied by increase of strength and toughness) [1].

Destruction works during impact bending consists of origination work KC_o and crack propagation work KC_p. Crack propagation work value better characterizes presence or absence of metal inclination to brittle destruction, because the alloys which are rather ductile and tough at the temperature –20 °C can display brittle destruction [1]. Defects are especially widely presented in cast alloys, they are considered as stress concentrators and can be accompanied by micro-cracks. In these conditions cold resistance of an alloy is mainly determined by the value of crack propagation work KC_p.

Influence of AAT processing at the room temperature on mechanical properties of the cast steel 05Kh21AG15N8MFL was studied; this process is characterized by essential dispersion of mechanical properties in the initial state due to heterogeneity of chemical composition. To eliminate this dispersion, quenching with 2 hour holding at the heating (SHT) temperature was conducted after annealing with 2 hour holding [10]. Mechanical properties of cast steel, which are presented in the **Table 2**, were determined for the samples subjected to the following processing: annealing; quenching at the temperature 1000 °C with 2 hour holding (if no annealing was applied, holding time is 4 hours); cooling in water. The cast steel samples were also processed after AAT during 20 min.

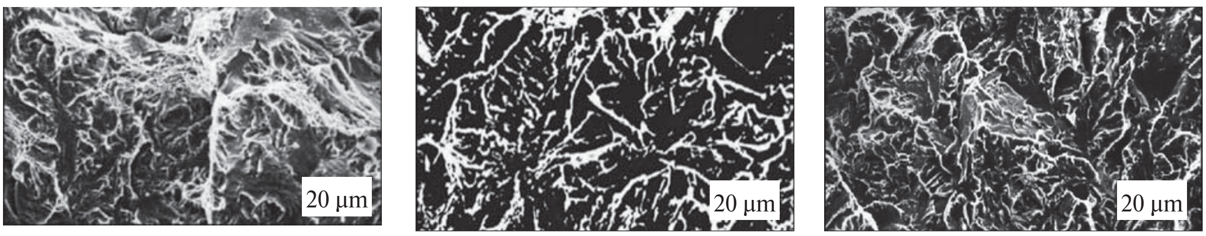
Additional quenching of cast steel after annealing of AAT provides more stable mechanical properties in comparison with initial cast state. Strength and toughness at the temperature 20 °C are slightly higher after AAT in comparison with SHT with practically equal ductility. The properties of cast austenite steel 10Kh18N10TL, which does not contain nitrogen, and of deformed steel according to AISI 316LN, with nitrogen content 0.1 %, are also presented in the Table 2. Both steels have rather lower mechanical properties in strength and toughness at the temperature 20 °C in comparison with the properties of the steel 05Kh21AG15N8MFL.

To provide examination of microstructure, oblique cuts of working parts in tensile samples were used. Cast steel structure both after quenching and after AAT is more homogenous (**Fig. 4**) and has similar grain sizes.

Typical general view of steel microstructure includes austenite, extractions of nitrides, second phase and non-metallic inclusions. Microstructure of the samples after quenching and (more clearly) after ATAT seems more homogenous: non-metallic inclusions decrease their size, grain boundaries are refined, what ensures larger stability of steel properties after heat treatment and AAT.

Table 2. Mechanical properties of the steels 05Kh21AG15N8MFL, 10Kh18N10TL (3)* and AISI 316LN(4*)

No.	Initial billet state	Additional processing	$\sigma_в$	$\sigma_{0,2}$	δ	HB	KCV
			MPa		%		J/cm²
1	Casting, quenching	–	710	415	46	229	225
2	Casting	AAT	721	450	45	241	240
3* [15]	Casting, quenching	–	441	196	25	–	59
4* [USA standard A240/ A240M – 11]	Deformed steel, annealing	–	520	220	45	–	200



a *b* *c*

Fig.3. Micro-fractographs of surface fractures for the steel 40Kh impact samples, which (testing temperature –40 °C: quenching from 860 °C in oil, tempering at 550 °C (*a*); quenching ATAT, tempering at 500 °C (*b*, *c*)

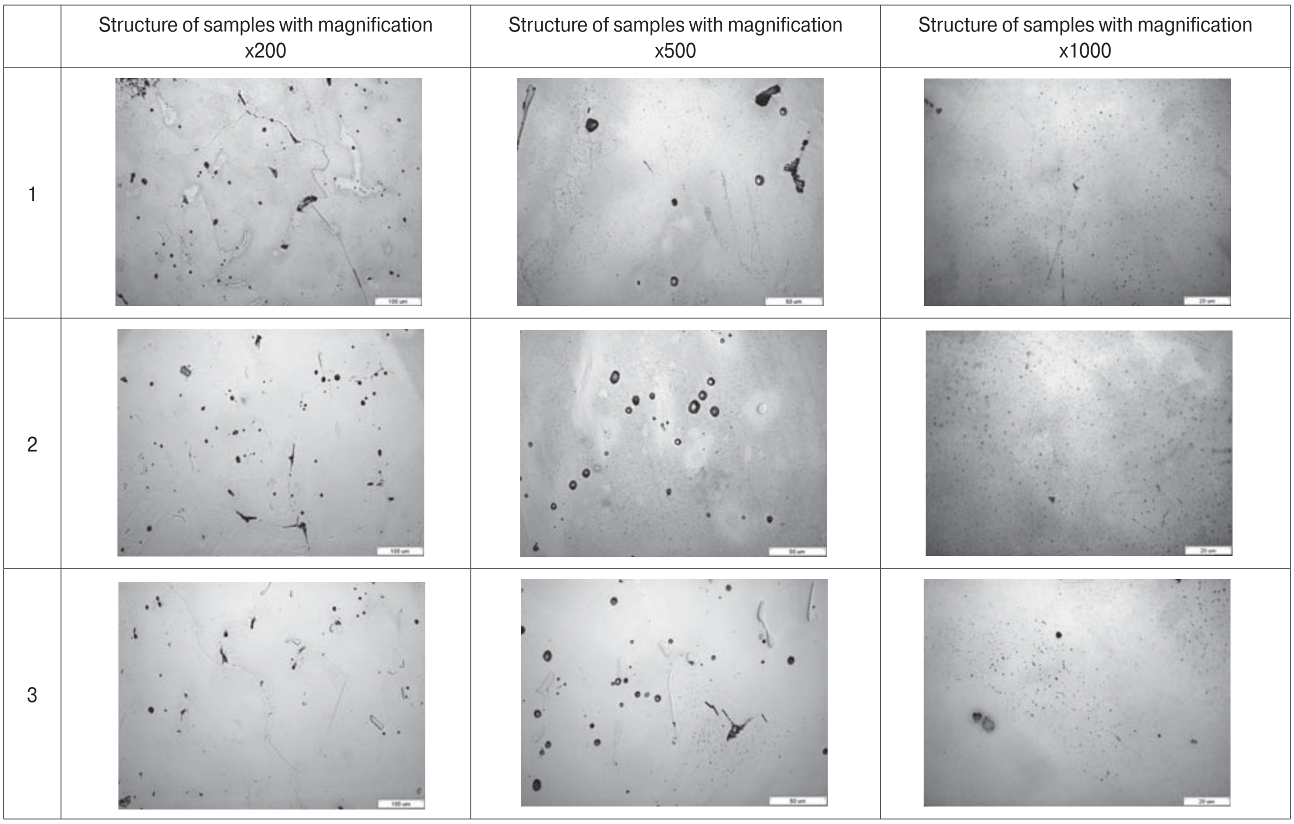
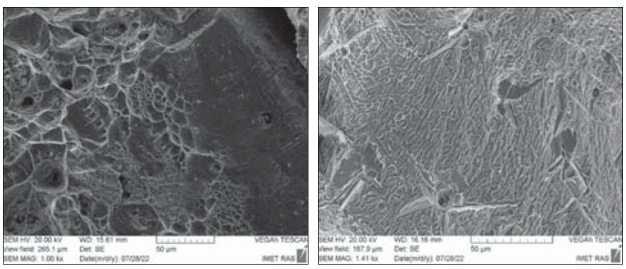


Fig. 4. Steel microstructure for 3 states: *1* – initial (cast); *2* – initial + quenching from 1000 °C; *3* – initial + AAT

Fractographs of surface fracture for the steel 05Kh21AG15N8MFL are presented in the **Fig. 5**. Destruction features of this steel after quenching are tough and brittle, the brittle destruction areas appear in the zones with non-metallic inclusions or pores (Fig. 5, *a*). After AAT the grains are more fragmented, the crack propagation areas are in the form of outlet-like paths, they are not numerous, because the areas with increased material toughness are able to retard further crack propagation (Fig. 5, *b*).

The results of impact strength determination in the area of negative temperatures are presented in the **Table 3**. Larger values of steel KSV were obtained after AAT at the temperature 20 °C, difference in KCV values increases with lowering of a testing temperature. Cold brittleness threshold for the steel with 0.47 % N (which is very close in its composition to the examined steel 05Kh21AG15N8MFL) is revealed at the temperature –75 °C [10, 11], i.e. the temperature when KCV = 115 J/cm^2.



a *b*

Fig. 5. Fractographs of surface fracture for the steel 05Kh21AG15N8MFL: initial state (casting) after quenching (*a*); initial state (casting) after AAT (*b*)

The value of KCV = 115 J/cm^2 for the examined steel after quenching will be also achieved at the temperature –85 °C, taking into account the similar rate of KCV lowering in the area of negative temperatures (see Table 3). Intensity of impact strength lowering during temperature decrease from –40 to –70 °C after AAT corresponds to 32 J/cm^2 and after SHT – to 47 J/cm^2; intensity of impact strength lowering after SHT with consequent temperature decrease to –100 °C makes 30 J/cm^2. Respectively, after ATAT, with the same intensity of KCV lowering as during the previous stage (–32 J/cm^2), approximate value of KCV$^{-100\,°C}$ = 140 J/cm^2. Taking into account ATAT influence on the cold brittleness threshold for the steel 40Kh, we can predict that critical temperature of brit-tleness for the steel 05Kh21AG15N8MFL after AAT for KCV = 120 J/cm^2 will be also lower, ~ (–100 °C). Respectively, AAT also increases impact strength at negative temperatures for a austenite steel. Mechanical properties of this steel during RGGS processing and without it are practically equal.

Cold resistance of steels and alloys depends on the kind of crystal lattice, what is connected also with its packing density. High ductility of metals with dense-packed structures (face-centered cubic structure, hexagonal dense package) is connected with large number of structural states, which can be easily rebuilt one in other in local areas; it demonstrate in slight origination and large mobility of dislocations as elements of a new structure in the initial lattice. These elements move in anisotropic mode and cause localization of plastic shift. It leads to appearance of vortexes of translating flows and initiates creation of flow of defects, while these flows are responsible for plastic flow [16].

Table 3. Impact strength values for the steel 05Kh21AG15N8MFL						
Billet state	KCV, J/cm², at the temperatures,℃ /decrease of KCV*					
	20	–40	–70	–100	–130	–196
Casting, quenching, Holding 4 h	225	185	138/47	106/32	77/30	19
Casting, AAT, 20 min	240	210	178/32	140/30	–	–

* value of measured KCV during temperature decrease by 30 °C (from –40 to –70 °C and from –70 °C to –100 °C)

When carrying out AAT for the steel 05Kh21AG15N8MFL at the temperature 20 °C, decrease of grain size occurs slightly, but impact strength after AAT is higher than that for this steel after quenching due to decrease of stresses along grain boundaries [16, 18]. More developed dislocation structure is forming after AAT processing: blocks are comminuted and obtaining of higher values of impact strength in the area of negative temperatures is provided. The effect of external physical fields (acoustic or magnetic) on metallic materials with FCC lattice demonstrates that these materials are in non-equilibrium state, which increases their inclination to a structural reconstruction during plastic deformation. In this case grain boundaries and triple joints are considered as the points of stress concentration. The lattice with metal hexagonal dense package and one stable modification can't be rebuilt during loading and crack origination is considered as dissipative process in deforming metal [16]. Difference between the values of impact strength of the steels subjected to heat treatment and ATAT of AAT increases with temperature lowering. In the area of negative temperatures, the work of crack propagation provides more significant effect, not the work of crack origination, because plastic deformation is complicated with strength rise and defects existing in an alloy can lead to destruction at smaller stresses [1, 16]. The values of residual stresses and the degree of blocking dislocations decrease after AAT and ATAT, what ensures higher impact strength values in the area of negative temperatures [14].

Conclusion

The influence of acoustic fields (AAT) and complex processing (ATAT) on mechanical properties and cold resistance of austenite and pearlite steels was examined. ATAT complex processing is accompanied by pearlite steel structure forming with decrease of the size of grains and blocks, what provides lowering of the cold brittleness temperature for the steel 45 by ~ 30 °C with slight increase of strength, ductility and toughness. The complex of mechanical properties of the steel 40Kh is higher in comparison with the properties after RGGS quenching in oil. Respectively, it is expedient to study possibility of quenching in the following media: air flow + acoustic field instead of quenching in oil, what ensures positive effect on ecology and processing cost. Use of AAT for the steel 05Kh21AG15N8MFL provides stability of mechanical properties with their slight increase in comparison with quenching, lowering of cold brittleness temperature, and allows to recommend AAT instead of quenching of austenite steel, what ensures decrease of processing duration and cost as well as improvement of operating steel properties.

The research was carried out under financial support of the Ministry of Science and Higher Education of Russian Federation (Scientific and research work "Study and prediction of metal gradient strength fields and ductile parameters during cold metal forming processesin the conditions of complicated loading", FZWF-2024-0006).

REFERENCES

1. Solntsev Yu. P. Cold-resistant steels and alloys. St. Petersburg: Khimizdat. 2005. 476 p.
2. Poletskov P. P., Koptseva N. V., Kuznetsova A. S. et al. Creation of economically alloyed cold-resistant steels with strength level not less than 950 MPa for heavy-loaded machinery. *MiTOM*. 2024. No. 12. pp. 17–24.
3. Lo K. H., Shek C. H., Lai J. K. L. Recent developments in stainless steels. *Materials Science and Engineering R*. 2009. Vol. 65. pp. 39–104.
4. Timmerhaus K. D., Palmer Reed R. Cryogenic Engineering: Fifty Years of Progress. Springer-Verlag. 2007.
5. Uggowitzer P., Magdowski R., Speidel M. O. Nickel free high nitrogen austenitic steels. *ISIJ International*. 1996. Vol. 36. No. 7. pp. 901–908.
6. Gavriljuk V. G., Berns H. High Nitrogen Steels: Structure, Properties, Manufacture, Applications. Springer–Verlag, Berlin Heidelberg New York. 1999, 379 p.
7. Simmons J. W. Overview: high-nitrogen alloying of stainless steels. *Materials Science and Engineering: A*. 1996 (March 30). Vol. 207. No. 2. pp. 159–169.
8. Vijayalakshmi M., Shankar P., Sudha C. Microstructural aspects and thermodynamic stability of nitrogen bearing stainless steel. *Proc. of Int. Conf. on High Nitrogen Steels of the ASM International "High nitrogen steels and stainless steels- Manufacturing, properties and applications"*. Materials Park, Ohio, 2004. pp. 113–132.
9. Gavriljuk V. G. Nitrogen in iron and steel. *ISIJ International*. 1996. Vol. 36. No. 7. pp. 738–745.
10. Kostina M. V., Polomoshnov P. Yu., Blinov V. V. et al. Cold resistance of the new casting steel with 0.5 % N. *Izvesriya vysshikh uchebnykh zavedeniy. Chernaya metallurgiya*. 2019. Vol. 62. No. 11. pp. 894–906.
11. Kostina M. V., Rigina L. G., Kostina V. S. et al. Calcilated evaluation of nitrogen solubility and phase composition in the steel on the base Fe – 13 % Cr with its additional alloying (Mn, Mo, V, Nb). *Metally*. 2023. No. 2. pp. 64–77.
12. Kostina M. V., Rigina L. G., Muradyan S. O., Krylov S. A., Makarov A. A., Druzhnov M. A., Kostina V. S., Kudryashov A. E. Influence of introduction of nitrogen with super-equilibrium concentration in low-alloy steel on its structure, phase composition and mechanical properties. *Metally*. 2021. No. 5. pp. 23–39.
13. Bannykh O. A., Blinov V. M., Blinov E. V., Kostina M. V., Muradyan S. O., Rigina L. G., Solntsev K. A. High-strength casting non-magnetic corrosion-resistant steel and the article manufactured of it. RF Patent No. 2010125561/02. Approved: 23.06.2010.
14. Vorobyeva G. A., Skladnova E. E., Remshev E. Yu. Structural steels and alloys. St. Petyersburg : Politekhnika. 2023. 440 p.
15. Sorokin V. G. et al. Directore for grades of steels and alloys. Moscow: Intermet Inzhiniring. 2001. 640 p.
16. Panin V. E., Egorushkin V. E., Panin A. V. Deformed solid body as a non-linear hierarchic organized system. *Phys. Mesomech*. 2011. Vol. 14. No. 3. pp. 7–26.
17. Finoshina Yu. V., Kirillova A. V. Study of the structure of carbon steel after different kinds of heat treatment. *Vestnik molodykh uchenykh i spetsialistov Samarskogo universiteta*. 2020. No. 1 (16). pp. 208–213.
18. Vorobyeva G. A., Sizov A. M. Formation of properties of structural and tool materials using pulsed treatment. *Journal of Advanced Materials*. 1995. Vol. 2 (1). pp. 75–81.