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REFINING STEEL IN A LADLE BY INERT GAS AND ACOUSTIC BLOW

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Methods are proposed for intensifying mass transfer in blow of steel in a ladle using acoustic vibrations. Industrial tests of blowing metal in a ladle using a lance and imposition of acoustic vibrations generated by an external acoustic radiator are described. An acoustic blow plug (ABP) containing a resonator of jet-acoustic vibrations is proposed for argon blow of steel in the ladle. Model studies and theoretical estimates of factors that contribute to intensification of mixing and decrease in the blow plug erosion are described. The results of industrial testing of blowing steel in a furnace-ladle plant using the ABP at the Severskii Pipe Works are presented.

The blow of metal in a ladle using inert gases significantly improves the quality of steel. Yet the methods for intensifying these processes are constantly being upgraded and the mechanisms of mass transfer processes cannot be regarded as fully investigated.

In order to intensify the mass transfer processes in blowing steel in a ladle, specialists from the Ural State Technical University and the Severskii Pipe Works have proposed a method for acoustic refining of metal. The acoustic treatment can be implemented in blowing either via a gas nozzle, or via a porous plug [1 – 6] inserted in the ladle bottom.

In 2004 the Ural Technical University, the Severskii Pipe Works, and the Dinur JSC designed an acoustic blow plug (ABP) with a resonator positioned inside the plug and developed the corresponding production technology, after which the prototype plugs were tested in the furnace-ladle plants at the Severskii Pipe Works (SPW) [7, 8]. Since then we have been carrying out comparative experimental-industrial testing of the ABP, as well as model test on cold testbenches and theoretical studies to evaluate the mechanism of the processes occurring in acoustic blowing.

Before the ABP was designed, nitrogen blow lances had been tested at the Severskii Pipe Works with superimposed acoustic vibrations generated by an external acoustic radiator (Fig. 1) [1, 4]. The industrial testing of this blow lance exhibited an improved chemical composition and mechanical properties in steel 20A (based on the data of 200 heats), its strength growing by 10.2%, yield point by 21.4%, hardness

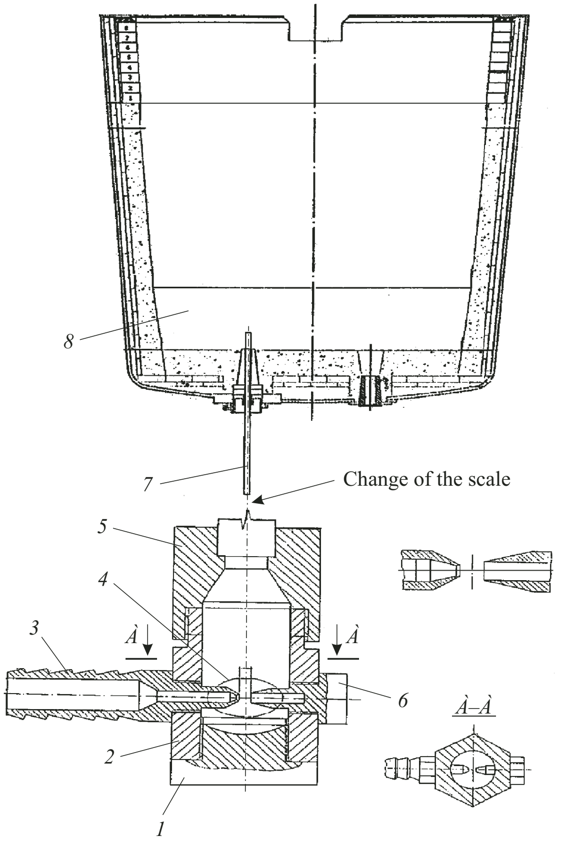

Fig. 1. A device for blowing metal in a ladle with induced acoustic fields: *1*, acoustic radiator body; *2*, cylindrical lateral ring; *3*, nozzle connection; *4*, nozzle, resonator system; *5*, exit cylinder; *6*, resonator nut; *7*, blow lance; *8*, teeming ladle.

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HRB by 6.5%, and shock viscosity at 20°C growing by 12%. The rejection rate for all kinds of defects (inner scabs, cavities, outer scabs on pipes) identified using the DSTAT and STATGRAPH software packages decreased. Analysis of defects in steel demonstrated that the application of a blow lance with an induced acoustic field decreases by 0.35% the number of defects in hot-rolled pipes and increases the yield of acceptable products by 3.6 kg/ton of steel [4].

After the SPW introduced steel refining in a furnace — ladle plant and blowing steel via blow plugs installed in the ladle bottom, it became necessary to develop a plug variant with imposed acoustic fields (Fig. 2) [1, 8]. The model studies of blow processes with imposition of acoustic fields were carried out at the same time [4, 5].

A series of experiments was performed on a ladle model made of organic glass in order to analyze the aerodynamics of gas flows in a solution. The geometric and physical similarity constant was found based on the ratio of steel density at 1650°C to the density of the solution in the ladle at 15°C.

The obtained photo images of static states of the gas bubble flow and its motion have been used to identify the obvious and possible paths and kinds of motion. First and foremost, we have the upward translational motion caused by buoyancy and the lateral motion depending on hydrostatic pressure and the nozzle design. Other possible types are the oscillatory, nearly sinusoidal motion of the bubble cased by nonsymmetrical disruption of the gas flow near the nozzle, as well as rotary motion caused by the disturbance of the gas flow continuity. Presumably the motion of the gaseous medium inside the bubble is possible as well, caused by an independent external source of elastic vibrations in the gaseous medium in front of the nozzle. It is noted that the full opening angle of the bubble flow formed after a preliminary disturbance by acoustic vibrations is more stable and varies from 13 to 25° depending on excessive pressure in front of the nozzle. One can observe a constant increase in the bubble volume and its changing shape, as it moves along the height of the solution. The model studies showed that this process is ambivalent. A certain threshold exists in the efflux regime: before this threshold the bubble flow has a clearly visible boundary with a pinch, in which single bubbles are visible. Past this threshold, the jet breaks into fine bubbles that fill the whole volume, and the gas flow ceases to exist at the length of $(5 - 7)d_0$, where d_0 is the channel diameter.

Besides, acoustic blow devices were tested in submerged conditions (at a depth up to 2 m) estimating the opening angle and the motion of the gas-jet flow both in depth and on the pool surface (Fig. 3). It should be noted that the photos obtained with a small exposure demonstrate a clearly turbulent vortex nature of the two-phase jet during the blow of metal (Fig. 4). Furthermore, a specially designed testbed at the Dinur company was used to determine the flow rate parameters of acoustic plugs, as well as the spectral characteristics of acoustic waves power at the exit from the blow plug using a acoustic analyzer (Fig. 5).

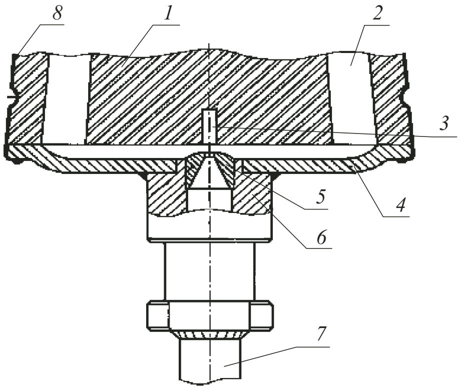

Fig. 2. Diagram of the acoustic blow plug: *1*, refractory plug; *2*, longitudinal though slot-shaped channels; *3*, resonator; *4*, plug bottom, i.e., reflector-adapter; *5*, insert with a nozzle for feeding blow gas; *6*, sleeve; *7*, gas-conduit pipe; *8*, metal case.

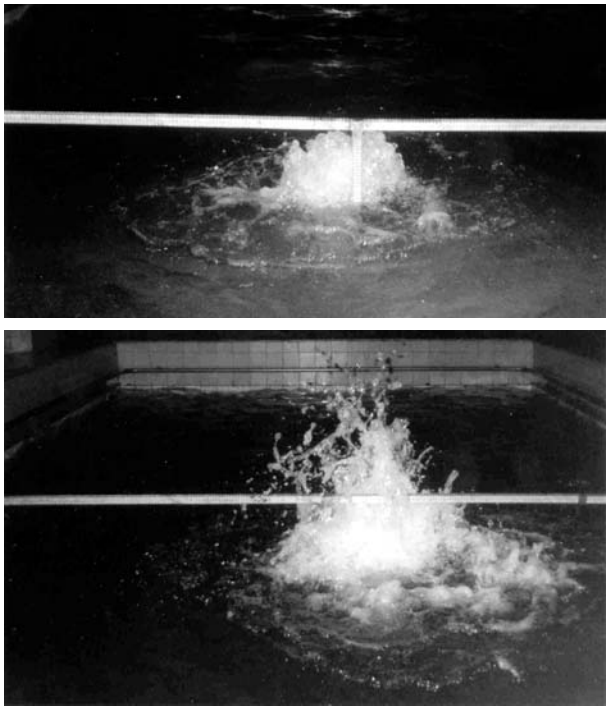

Fig. 3. Images of the outer surface of liquid in the course of blowing using blow plugs and estimate of jet opening angles.

Theoretical aspects of the acoustic field effect on the gas dynamics of a flow provide the following conclusions. It is known that the most significant factor determining the mixing intensity in melting tanks is mixing power. This factor has been particularly studied by M. A. Glinkov [9] when considering the thermal work of steel-melting tanks. Mixing power under jet blowing is determined by the mass flow rate and the square of the jet velocity; the mixing power efficiency in this case is $\eta_j = 0.30 - 0.35$. Additional power in blowing is developed by the bubble column and is due to buoyancy. An approximate estimate of the total mixing power efficiency is $\eta_{tot} = 0.4$.

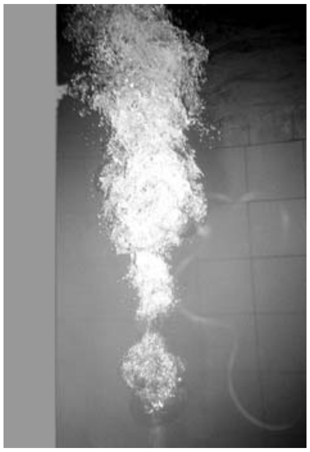

Fig. 4. Structure of acoustic lance jet (instant exposure).

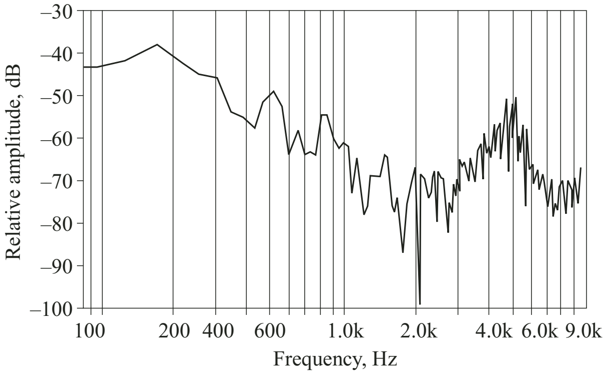

Fig. 5. Frequency spectrum of acoustic vibrations at the exit from the acoustic blow plug. Air pressure 0.3 MPa (k, kilohertz).

It can be expected that when an acoustic field is superimposed on a jet, this field develops additional power. If the acoustic field is generated by gas-jet radiators, in this case the mixing efficiency $\eta_{s.ac}$ is equal to

$$\eta_{s.ac} = \eta_{ac} + \eta_j(1 - \eta_{ac}), \tag{1}$$

where η_{ac} is the jet-acoustic efficiency.

The power of the blow gas jet is calculated using the known formula

$$M_j = 0{,}5\rho V_j w^2, \tag{2}$$

where ρ is the blow gas density (kg/m^3); V_j is the blow gas flow rate (m^3/sec); w is the velocity at the exit from the plug (m/sec), which at $w \approx 50$ m/sec yield the value $M_j \approx 570$ W. Then for $\eta_j = 0.3$ the actual power per square meter of the ladle surface is around 0.1 W/m^2 and around 0.2 W/m^3 of the ladle volume. This power of the blow jets could appear comparable to the maximum power of acoustic waves. For instance, for the power of sound $M_s = 110$ dB its wattage is 0.1 W/m^2. However, the actual measurements at the exit from the acoustic plug using an acoustic analyzer (air blow on a testbed) yield a significantly lower valued of sound power (Fig. 5), moreover, the wattage of the acoustic wave as well is significantly below the above specified values. Presumably such factor as the acoustic wave power can hardly have a perceptible effect on metal mixing in the ladle.

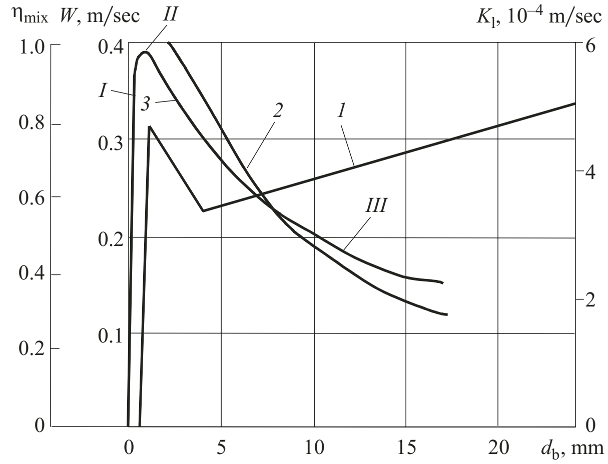

Fig. 6. Dependence of the bubble rise velocity W (*1*), mass transfer coefficient in the liquid phase K_l (*2*) and mixing power efficiency η_{mix} (*3*) on the bubble diameter d_b; the other notations are found in the text.

It should be noted that the diameter of resulting gas bubbles does not enter explicitly in any formula for determining mixing power. However, the available data indicate the effect of the bubble size on the mixing process and, consequently, on mixing power efficiency. In our point of view, the parameters closely related to the mixing efficiency are the bubble float velocity and the mass transfer coefficient. As a bubble rises upward, it experiences the effect of the lift force, the resistance of the liquid layer, and the surface tension. It is established that the rise velocity of a (relatively small) gaseous bubble is proportional to the square of its radius. However, for large flattened bubbles this velocity does not depend on the bubble size [10]. This dependence is obviously seen in Fig. 6 (curve *1*); in curve 1 we can see a maximum in the bubble rise velocity under a certain bubble diameter. The mass transfer coefficient of a bubble rising in a liquid, according to some data, is in inverse proportion to the square root of the bubble diameter [11 – 13] (Fig. 6, curve *2*).

However, a totally opposite dependence is given in [14] for relatively small bubbles ($d_b < 1$ mm): the mass transfer coefficient is proportional to the square root of the bubble diameter. Based on these data, one can assume with a great degree of reliability the presence of a maximum on the curve of the dependence of the mass transfer coefficient on the bubble diameter. This suggests that a maximum has to exist as well on the curve of the dependence on d_b as shown in Fig. 6 (curve *3*). According to this concept, the regimes of power consumed in mixing are divided into three groups: range *I* — mixing efficiency increases with the increasing bubble diameter (for relatively small bubbles), range *III* — the efficiency decreases with an increasing bubble diameter, and range *II* — the maximum efficiency values (Fig. 6).

In this context a hypothesis was put forward [3] that the positive acoustic effect on metal mixing in a ladle is related

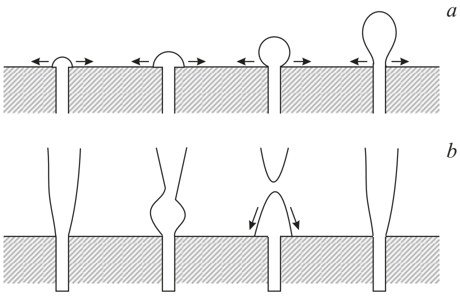

Fig. 7. The scheme of formation of erosion in a blow plug upon the penetration of gas into fluid steel: *a*, bubble area, low erosion (separation of bubbles); *b*, jet area, intense erosion (back blow) [15].

to the possibility of an acoustic field of influencing the size of the forming and rising bubble, to bring this size as near as possible to the mixing efficiency maximum. Furthermore, it has been noted [4] that in this case the opening angle of the two-phase jet increases as well.

One should mention another aspect of the possible role of the bubble diameter of the blow gas discussed in [15]. According to this concept, a gas jet flow generates a so-called "back blow". This phenomenon is related to the instability of the gas flow in the boundary region. The jet flow is deformed and forms a large bubble, whose residue (after it breaks into fine bubbles) is displaced toward the refractory plug surface around the opening. This is accompanied by the formation of a shock wave, which may be the reason of the plug wear (Fig. 7). Indeed, the blow plug exhibits perceptible erosion, which is the consequence of high mechanical stresses. It this context one can assume that acoustic waves, on the one hand, affect the bubble diameter and may increase the stability of the gas flow at the exit from the plug. On the other hand, the acoustic waves may resist the shock wave generated by the bubbles breaking near the plug surface, which decreases the erosion of the plug.

Let us consider some design and technological specifics of making acoustic plugs (Fig. 2). As has been noted, a specific feature of this particular lance is the presence of an acoustic vibration generator. The acoustic vibration generator operates in the frequency range from 100 to 4000 Hz. The required frequency of the generator can be determined based on the particular service conditions of the customer. The generator is located in the lower part of the lance where the gas is fed into the lance channels.

The refractory plug *1* of the lance encased in metal body *8* (Fig. 2) has longitudinal slot-shaped through channels *2*. A thin-wall metallic sleeve *3* (resonator) is installed in the middle part of the refractory plug; the shape and size of the sleeve are determined depending on the required frequency range of the generator. The lower part of the lance contains an adapter *4* for feeding and distributing gas among the lance channels. The adapter of this particular lance differs from the classic design. The disc of adapter *4* is made as a spherical reflector which has an insert with nozzle *5* in its central part. The distance from the critical section of the nozzle to the resonator is calculated depending on the required generator frequency. The nozzle is designed similarly to the Laval's nozzle. The diameter of the nozzle critical section is determined based on the total transmission rate of the lance using the known method. In particular, the critical section diameter d_{cr} of the acoustic radiator nozzle is calculated based on the following formula [5, 6]:

$$d_{\text{cr}} = \sqrt{\frac{4\omega_{\text{cr}}}{\pi}}, \tag{3}$$

$$\omega_{\text{cr}} = \frac{G_{\text{g}}\sqrt{T_{\text{g}}}}{K_{\text{g}}P_{\text{g}}\eta_{\text{loss}}}, \tag{4}$$

where ω_{cr} is the surface area of the critical section of the nozzle, mm^2; G_{g} is the blow gas flow rate, kg/s; T_{g} and P_{g} are the temperature and deceleration pressure of the blow gas in front of the nozzle, K and MN/m^2, respectively; K_{g} is the flow rate coefficient depending on the physical properties of gas; for argon, according to our calculations, $K_{\text{g}} = 0.0404$ $(\text{K}^{0,5}\cdot\text{sec})/\text{m}$; η_{loss} is the coefficient taking into account the resistance loss in the nozzle, $\eta_{\text{loss}} \approx 0.8 - 0.9$.

The other parameters of the acoustic radiator are selected in accordance with the known recommendations [1, 2].

It is obvious that in such design of the acoustic radiator and selection of the size of the nozzle exit section, the excessive pressure of the blow gas, namely argon (up to 1.2 MPa) is used for the effective formation of an acoustic filed and not just throttled, as happens in the traditional plugs. In our case the conditions of the automatic control system controlling the gas flow rate are significantly improved as well: the dynamic deviations of this parameter and the control range decrease, since the flow rate control range becomes more linear.

To ensure the serviceability of the whole unit (the lance) and its reproducibility, the following technology is used. The ceramic part of the unit is cast in a metal mold ensuring the accuracy of its position and surface purity. The lance channels are cast using metal templates (bands) with an accuracy of ±0.01 mm and surface roughness R_a not less that 1.6 μm. The adapter disc is stamped; the inner part of the acoustic lens is polished to achieve roughness R_a not less than 1.6 μm.

The Laval's nozzle is made according to the classical technology and pressed into the central part of the adapter. All parts of the adapter are made of refractory steel 12Kh18N10T or 0.8Kh18N10T. The final assembly of the lance is carried out on a stand ensuring the coaxial assembly of the conical parts of the lance and the adapter, and then seaming and welding.

The SPW in the course of experimental-industrial testing of the plug carried out comparative studies of experimental heats on furnace — ladle plants[2]. We compared the parameters of experimental heats involving acoustic blow and heats

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[2] A report on the study of acoustic blow of pipe steel. Severskii Pipe Works. NITs, No. ML-37/2–2007, 01.02.2007.

using standard plugs (with 36 slots). Between January and October 2006 from 10 to 30% (on the average 20%) of the ladles underwent acoustic blow and the rest of the ladles were blown using standard plugs. This period is determined as the reference one. Between 21.10.2006 and 31.10.2006 all ladles were equipped with acoustic blow plugs (ABP); this period was regarded as experimental. The comparative analysis of experimental heats with acoustic blow shows that with respect to some parameters, such as the quantity of inner and outer scabs on pipes, the contamination of metal with nonmetal inclusions, or nitrogen content in the metal), experimental and standard heats exhibit approximately equal results. The content of nonmetallic inclusions in both experimental and standard ladles satisfied the technological standard. The content of hydrogen in metal under traditional blowing is 9 ppm and under acoustic blow — 6.4 ppm, i.e., under acoustic blow it is 28.8% lower. The specific consumption of argon in acoustic blow is slightly lower and the specific electricity consumption decreases by 7.5%. It has been noted that the blow unit height after 40 heats with standard blowing decreases from 350 to 220 mm, which is equivalent to 37% wear, whereas in acoustic blowing after 40 heats the wear from 350 to 250 mm is 28%, i.e., the wear of the blow plug decreases by 24.3%. Thus, the the plug wear in the case of the ABP is 2.5 mm/heat, which corresponds to the best results in steel melting practice.

Thus, comparative tests have demonstrated certain advantages of ABP, especially significant in the extent of blow plug wear. It should be noted that the above-mentioned comparative wear is especially noticeable in visual observation of waste plugs. The company has decided to continue the use of acoustic blow plugs and accumulation of data and comparative analysis results.

Several companies have shown interest in using ABPs. In particular, preliminary tests have been performed at the Kamastal’ Metallurgical Works; other companies are in the process of ordering ABPs.

CONCLUSION

A domestic acoustic blow plug for fluid metal refining in a furnace-ladle plant has been designed and patented. Experimental and theoretical studies of this acoustic blow plug were carried out revealing the most probable factors of the acoustic effect: gas bubble diameter and the jet opening angle. The experimental-industrial testing of acoustic plugs on furnace-ladle industrial plants have revealed certain advantages of acoustic plugs, especially in their decreased wear (by 24.3%).

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