Safety protection of blast-furnace jackets when in operation

Belodedenko S.V.

National metallurgical academy of Ukraine

Chechenev V.A.

IC «STEELPROM»

Abstract
The analysis of the safety status of blast furnace production is given. It was shown that the safety of blast-furnace jackets depends on functioning of the system of their technical condition control. Its efficiency is determined by the capabilities for forecasting the residual resource. For this purpose a diagnostic algorithm based on safety index monitoring - a universal and comprehensive quantitative characterization of technical condition was developed. The algorithm is used to forecast the residual life of the blast-furnace stack casing assembled from large-sized cooling modules.

Blast process stage is the most accidental metallurgical production. It accounts for 20-30% of accidents and 10-20% of deaths among the 28 metallurgical production (here included also nonferrous metallurgy) [1]. Blast furnace (BF) is a high-risk facility, where the jacket elements failures are associated with significant consequential damage. For example, jacket repair of BF with volume of 1386 m^3 of Dneprovsky Integrated Iron&Steel Works (DIISW) after the appearance of the vertical crack from the hearth block before to tuyere zone led to the furnace 195.3 hours outage and the iron loss of 10968 tons. The loss in money terms amounted to 395.4 thousand UAH (without the cost of the accident liquidation, in prices of year 2002). At the same plant in the summer of 2015 there was an accident on the new BF №1m (volume 1513 m^3), when because of the taphole cooler burnout for 18 coolers were out of service, which led to a flood of 15 tons of iron on the area of 100 m^2. The fire, which had been extinguished for more than 5 hours, destroyed the hydraulic drive system of bed mechanization. Dealing with the consequences of the accident has taken 10 days. From 6% to 20% of unplanned BF downtime occur for reasons of jacket elements failures [5,6].

Reliability and diagnostics of jackets

Issues of blast-furnace (BF) jackets resistance are always in the area of special attention of blast-furnace operators, mechanics and builders of industrial buildings. Since the second half of the 20th cent. the works were actively carried out to improve walls constructions and the blast furnaces coolers, as well as to select the optimum steel grades and their jacket thickness. At the same time the nature of the stress-strain state of the jackete elements under conditions of collaborative work of line - compensation layer - jacket system under the influence of internal pressure and temperature on them was studied [1]. It was assumed that due to the advanced technical solutions and support in the calculation of static strength adequate supply, a reliable and accident-free BF operation is possible.

Since the BF wall is a complex technical system, functioning of which is under the influence of many factors, its working ability is poorly predictable for a long period. It became obvious the conclusion that a sufficient reliability of the construction laid in the design, can not be realized when operating without proper support [6]. In this regard, the BF jackets is in fact considered to serve not according to the regular preventative system, and for the actual technical condition for determination of which there is a corresponding "Methodology..." [11]. Such a maintenance system requires the use of technical diagnostics methods [3]. In this regard, since the 70-ies of the 20th cent. in blast furnace production the introduction process of technical diagnostics system is intensified, which allows to control the disign-operational factors. Such systems have a positive impact on the stability of jackets. Thus the "Methodology .." indicates that a high resource of BF jackets in the USA (44 years against 16 years in Russia) is connected with the action of the computer control systems of jacket. This can also be indicated by the developed in 2006 activities to extend to subsequent 12 years the operation of jacket of "Severstal" BF №5 after 20 years of service. One of the prerequisites for such an act, which has the world priority [7], is due to the action in the blast furnace plant of cooling diagnostics system based on SCADA TRACE software system. Thus, the staff has experience in making decisions on the results of the diagnostics and is ready for the service strategy on technical condition.

Of course, only the availability of means of technical diagnostics does not automatically lead to an increase in the resource. The same "Methodology..." gives an average service life of Japan BF jackets, which is 17 years, although it is known that they are well equipped with diagnostic systems. In the above-mentioned complex of BF №5 after the partial reconstruction of jacket (mainly of the dome) in 2008 and 2011, there were two accidents connected with jackets disclosure. The enterprises need to develop a program of repair effects as a result of diagnostics. They should serve not only as the actual values of diagnostic parameters but also as the predicted values of residual resources. Thus, it requieres the individual approach not only for each BF, but also for each jacket element [7].

Currently, most of metallurgical enterprises conduct diagnostics by comparing the recommended and actual values of diagnostic parameters (features). They (depending on BF automation) include jacket temperature at different points, temperature difference of the refrigerant on inlet and outlet, and its flow rate, temperature and thickness of line [5,8]. Thus, the failures and operational conditions states (the 1st and 2nd tasks of diagnostics) are searched.

Often, diagnostic monitoring reveals actual parameters deviation from recommended ones, set at a standard technology. There is no possibility and sense in immediate elimination of such deviations, as practice shows satisfactory further operation. The staff in such cases notes, for example, a "limited operation capability" of the cooling system, although the obtained information is useful for technical condition forecasting (the 3rd task of technical diagnostics). The solution of this problem has a major impact on jackets life.

Methods of *quantitative* forecasting arising from the fault tree (accident scenarios) are well known. Its trunk is as follows: burning (wear) of lining→ coolr failure→ cracking (bulging) jacket area→ jacket rupture (furnace depressurization) [5,7,8]. Each subsequent stage is shorter than the previous by the time [5]. Unfortunately, the lack of scientifically based limit values of diagnostic parameters in real situations makes it difficult to quantify the residual life of jacket. Diagnostics is not brought to the level of technology. In the absence of grounded *quantitative* forecasts the important experience of the staff is of particular importance. Disciplined abidance by maintenance regulations must be supported by educated decisions as to the timing and types of repairs. In this regard the negative role is played by some "education dissonance." It is expressed in the fact that learning structural design is carried out in universities BF building profile, and repair and maintenance operation is made by specialists-mechanics, which educational programs do not have sections devoted to this issue. The designers of furnace structures have a sober understanding of the difficulties of its decision, of the relevance to increase the BF jackets reliability and of the holistic nature to achieve this purpose [9].

The aim of the present work was to develop a complex indicator of the BF jacket technical condition, suitable for *quantitative* forecasting of its operational capability.

Assessment criteria of jacket operational capability

To justify the BF jacket carrying capacity the model traditionally used for metallic structures was accepted: the ability of destruction from a single loading is tested by comparing the equivalent (according to the appropriate strength hypothesis) stresses with calculated resistance for a particular grade of steel.

Current stresses are calculated at the maximum parameters of blast furnace process. Also taken into account the emergency situations, such as breakage of furnace burden after the hang, destructing of scaffold. This leads, consequently, to the jacket vibrations and a dynamic coefficient of between 2 and 3 as well as to the local 2-4 -fold stress excess [2]. This static approach for jackets of metallurgical units is conditional, since the loss of their operational capability relates also to other processes.

Really jacket material, being in a complex stress state, is subjected to cyclic deformations. This is caused by technological needs: changing of iron smelting, tapping modes, if they are accompanied by a pressure drop, etc. There are fluctuations in the value of internal pressure and temperature. Contribution of temperature in the jacket stress state is more significant, because cyclicity is also connected with a change in the lining state and cooling system. There are fatigue phenomena in jacket material, which lead to the emergence and development of cracks. It is considered that the jacket operates in the low cycle fatigue area [2,9]. This is true if start from the daily average frequency of stresses cycle changes equal to 5-6 cycle/day, which determines the required durability of $2 \cdot 10^4 \ldots 5 \cdot 10^4$ cycles per furnace campaign of 12-30 years. Criteria for low-cycle fatigue allow to set up the jacket life time till the appearance of a crack with size of 1-2 mm. For the jacket of BF with average volume from steel Vst.3sp in areas of stresses concentration (with their coefficient of 2.5...3.5) at fixed stresses at rated resistances ranging with a fairly high cycle asymmetry (its coefficient is 0.82), the life time was $8 \cdot 10^4$ cycles. With a relatively rhythmic manufacturing process, creating a loading frequency *f=2 cycle/day*, it is 12 years [2]. The same result (with other loading parameters) is obtained for the jacket of BF with volume of 2700 m^3 [10]. Intensification of the blast furnace process under current conditions is accompanied, as a rule, by an increase in frequency of cycle changes and stress range, as a result of whitch the desired durability, forecasted by these criteria, can not be guaranteed.

Since the end of the 20th cent. for the estimation of the bearing capacity of BF jackets the crack resistance models were used. They allow the casing to insure the jacket from brittle failure with the presence of defects in it. The model of fracture based on energy criteria is most substantiated [12]. It takes into account the stiffness of the stress-strain state and is suitable for all grades of steel. However, the case of a single loading is considered in it, leaving open the question of operating loadings range, which makes it impossible to assess the reliability. In addition, the conclusion about the life time of jacket is making by comparing the current temperature and critical temperature of ductile-brittle transition that is not entirely common for constructures subjected to cyclic loading. Calculations of jackets liveness in deterministic aspect have shown that this period, at least takes 30% of the durability till the occurrence of cracks [2,10].

Using the common models of linear fracture mechanics to determine the critical crack sizes [7, 9] are suitable mainly for jackets made of steel Vst. 3 sp. Jackets from steel of other grades, which are of high crack resistance, need the models of nonlinear fracture mechanics, because a plastic zone of considerable size is formed in front of the crack tip.

The first calculations of jackets reliability are made in the strength setting at the start of operation [2]. The type of the reliability function (its change at operation) for BF jackets has not been investigated.

To assess the current state of jacket the microsamples method is designed, where the degree of the material degradation is set [7] with the forecasting of the technical condition of actual construction is not possible.

Security model of BF jacket

If it is needed to ensure any properties measure of the technical system, so the most rationally is also to control it in the operation. Given this, it is appropriate to make the evaluation of technical state by the security level monitoring [3]. At the service strategy the security index β_R is used as an indicator of technical condition, representing the logarithm of the guaranteed reserve durability with *R* security level. Maintaining the security of operation is carried out by repair actions, and periodic reassessment of residual resources in the identification of loading patterns and jacket material properties during its control.

β_R safety index is defined in the resource statement by comparing the distribution functions of longevity and lifelength. For their research the sample sequence of loadings (load history) of BF stack jacket was formed, which is a block from three pseudo-random processes having the same frequency *f*, but different and interdependent parameters of the stresses cycle (both on ring and meridian ones). All of these characteristics are specified in the probabilistic aspect. Number of loading cycles of each process *i* is determined by the relative volume of its action $c_{i\lambda}$ (λ - year of operation). Damage mainly occurs in areas with faulty cooling elements characterized by magnitude $c_{3\lambda}$. The peculiarity of its determination is that it takes into account not only the relative duration of the BF operation with damaged cooling elements $t_{3\lambda}$, but also the relative area of jacket $z_{3\lambda}$, prone to this process: $c_{3\lambda} = t_{3\lambda} \cdot z_{3\lambda}$ [6].

The advantage of a sample loadings sequence is that having set the parameters of jacket tension in a particular stack place into specific periods of BF operation and lining statuses with coolers, the entire history of loading can be reconstructed. Such a history of BF stack jacket was developed as a result of a considerable amount of experimental and theoretical studies of jacket stress state associated with intensive development since the 80-ies of the 20th cent., collected from large cooling modules (panels) (Fig.1) [6].

With obvious advantages in installing such stack works well in conditions of zinc-containing raw materials, but it requires special attention to be paid to evolution of wall accretion [6]. Around 20 of BFs with the stacks of large size modules were built in Ukraine, Russia, China. The staff appreciated the high maintainability of the cooling system, since the failure of coolant pipes is easily eliminated by the outside dam, thus deteriorating the cooling of a jacket small area. As a result, the value of $c_{3\lambda}$ is less than of the stacks of BF with traditional form.

In practice of the jackets service there occurs a situation when a crack is detected, and the time of its growth should be determined to the critical value. For this purpose it was developed a search algorithm for the distribution function of vitality based on the deformation criteria of nonlinear fracture mechanics and models of damages accumulation [4].

This algorithm was used in justifying the choice of steel for large modules [6]. Collected from similar panels the BF №11 of PJSC Dneprovsky Integrated Iron&Steel Works has served for 20 years instead of planned 12, which shows the viability of design decisions. During the operation there were 3 planned repairs to replace the jacket areas, held after 10 years of operation. On the 16th year of operation, after its examination by technical commission, the run of blast furnace was extended, recommending to limit the cyclical exposure to the jacket metal by eliminating the operation "on slow wind."

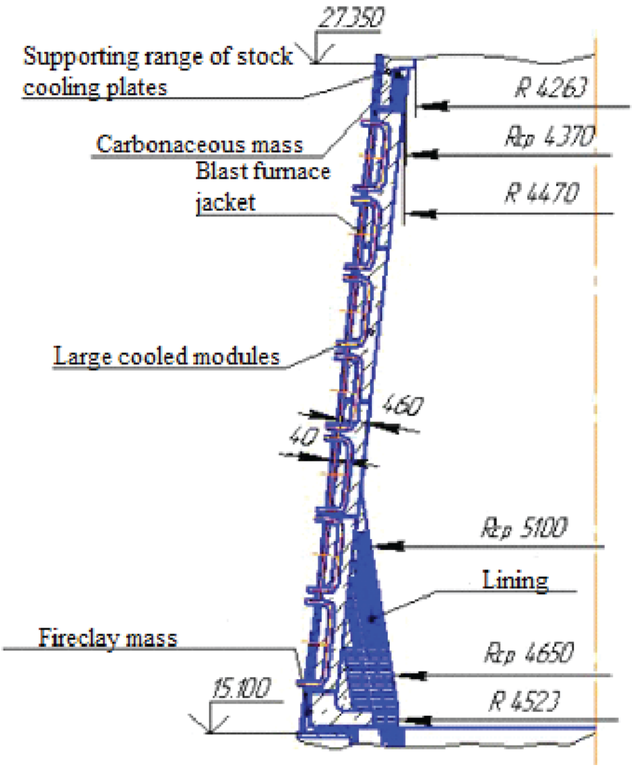

Figure 1. A fragment of the stack wall

With parameters of the survivability distribution function at presence of horizontal surface cracks with initial depth l_0=10 mm (this is 25% of the stack jacket thickness δ=40 mm) [6], it is easy to obtain a safety function $\beta(t)$ for this period of operation. From the determination of safety index, its change in time will look like this:

$$\beta_R(t) = \beta_R^0 - \lg\left[t \cdot f \cdot \left(1 + v_f \cdot u_R\right)\right], \quad (1)$$

where t – time of jacket operation in months;

f=152 cycle/month - the amount of stress cycle changes per month [6];

u_R – quantile of the normal distribution for the probability R;

v_f=0.33 – coefficient of cycle changes frequency variation [6].

Safety index at the time of occurrence of cracks β_R^0 is determined from the survivability distribution function when the crack grows in depth till the critical value l_c, which depends on the steel grade (table). The magnitude l_c is calculated taking into account the maximum stresses during the period of the process $c_{3\lambda}$. Then:

$$\beta_R^0 = \overline{\lg n_0} - u_R \cdot S_{\lg n_0},$$

Table 1. Indicators of the technical condition of the stock jacket of BF №11 of DIISW on stage of survivability in cases of its manufacturing from different steel grades

№	Steel grade	$\overline{\lg n_0}$, cycles	$S_{\lg n_0}$, cycles	l_c/δ	β_{98}^0	t_{98}^0, months
1	Vst.3sp	4.30	0.42	0.55	3.45	11.2
2	09G2S	4.35	0.49	0.68	3.37	9.3
3	16G2AF	4.66	0.41	0.80	3.84	27.4

In this case, the function $\beta_R(t)$ describes the safety of the entire stack jacket assuming the appearance of surface cracks in the vicinity of hole under each of the damaged cooling pipes. In addition, the parameters of loading history have a wide variation, covering all sections of the stack in height. Thus, the magnitude $\beta_R(t)$ has the sense of safety characteristics of elements system. After identifying the crack in its shape, size and location, the parameters of loading process of damaged jacket element should be set more specifically. Due to this the residual life is overrated, the safety index becomes a particular characteristics of the system element, and the risk of jacket exploitation is determined on the basis of a weak link.

Operating time for the security level $R=0.98$ in calendar months will correspond to equality $\beta_{98}(t)=0$ and is a period of survivability:

$$t_{98}^0 = \frac{10^{\beta_{98}^0}}{f \cdot \left(1 + 2 \cdot v_f\right)}. \qquad (2)$$

The equation establishes the connection between major forecast characteristics of diagnostics. There is an algorithm used for its estimation at the early stages of operation (up to cracking), but the durability distribution function is used instead of the survivability distribution function.

Conclusion

Along with the equipping by automated controls of load-bearing structures of blast-furnace complex, the staff development in forecasting algorithms of their technical condition as a result of diagnostics is a prerequisite for increasing the resource and safety of BF jackets.

To forecast the jacket technical condition there is an adapted method of safety index, which, thanks to its resource interpretation, is universal, as it allows to operate with damaging processes of different nature. The safety index in relation to the jackets of BF stack gets the complex character, which allows to evaluate their safety for complex technical systems, without resorting to the usual for such situations procedure of individual elements risk pooling. This is become possible through the use of such a parameter as the relative amount of action in a loading model.

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Influence of operational mode loading on fatigue life with cyclic unstable inelastic materials

Novikov A.I.

PhD in Technical Sciences
Pisarenko G.S. Institute for Problems of Strength, NAS of Ukraine, Kiev, Ukraine

Tsybanev G.V.

D.Sc. in engineering
Pisarenko G.S. Institute for Problems of Strength, NAS of Ukraine, Kiev, Ukraine