OPTIMAL CONTROL OF THE SINTERING PROCESS

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Abstract: This paper describes the model based control system of the sintering process. The control includes ignition control, sintering control and exhaustion control. The mathematical models are derived from basic models of physical and chemical processes and use directly and indirectly measured quantities from sintering strand. The control system determines the optimal quantity of coke, volume of coke combustion air, preheating gas volume, combustion air for preheating and volume of exhausted gases. Values of these quantities are corrected according to the identified process state. Manipulated variable is the turbo-exhausters operating speed.

Keywords: mathematical model, simulation, dynamic behaviour, optimisation, control

1. INTRODUCTION

For the most blast furnaces sinter is a basic metallic charge, and significantly influences their production rate and quality of the pig iron (Brož, 1988). The sinter strand converts input material to sinter by physical and chemical transformations. The main aim of the sintering process is to effectively produce sinter of desired quality. The ideal output of the sintering process is the sinter with desired properties independent on variations in the properties of the input materials. Mechanical and metallurgical properties of the sinter depend on its composition and on the sintering process (Kyseľová, et al., 1998, Majerčák, et al., 1986).

As all metallurgical production, the sintering is high in energy consumption and has serious environmental consequences. Optimisation of the sintering process is oriented mainly towards sinter quality enhancement, fuel economy improvement and minimisation of environmental impacts. The possibilities to achieve these objectives are in the removing of some limitations given by sinter strand components and by improvements of its operation.

The behaviour of the sintering reaction zone is vitally important in determining the sinter quality. If the temperature becomes too high or the reaction zone progresses too slowly the sinter becomes rich on the glassy phase, which prevents the reaction in the blast furnace. If the temperature in the reacting zone is too low the sintering is not processed sufficiently and the sinter has not the desired mechanical, physical and metallurgical properties. Between these two extreme conditions various grades of sinter can be produced and for given input materials by proper choice of sintering conditions good quality sinter can be gained.

Economy of the sintering process is determined mainly by the coke and ignition furnace fuel consumption. For a given sinter strand they are determined by the requirements on the sinter quality. Increased values are generally influenced by process organization and by some over dimensioning, which creates thermal reserve for the process irregularities. The improvements in both directions can significantly influence the fuel economy. For this purpose were developed theoretical and empirical approaches with the aim to put the system closer to its thermal optimum.

The sintering process control is one of the main contributors to the successful sintering plant operation and belongs to the key factors of its economic efficiency. Present approaches are basically oriented on particular problems with tendency to empirical approaches. Our approach is complex. Simulations determined the optimal ignition, sintering and exhaustion conditions. These results were used for the design of new ignition furnace and for new organisation of the suction process and for the development of adequate control strategy, which was successfully realised (Koštial, et al., 1998, Kwon, et al. 1998, Myllymäki and Poutiainen, 2000, Terpák, et al., 1997, 2002, Vanderheyden and Mathy, 2001).

2. SINTERING PROCESS

Mechanical and metallurgical properties of the sinter depend on its composition and on the sintering process (Majerčák, et al., 1986). Transformation of the sintering material into sinter takes place on the sintering strand (Fig.1). The main components of the sintering strand are the ignition furnace, sintering belt and exhausting system. The sintering material creates a bed on the sintering belt and consists of metallic burden (concentrate, crushed ore), slag (mainly limestone), coke and water (moisture). The sintering process starts by the ignition of the upper surface of the sintering bed with the ignition furnace and the process continues up to the bottom of the sintering bed. The sinter is then discharged on the cooling conveyor and is transported into the blast furnace bunkers.

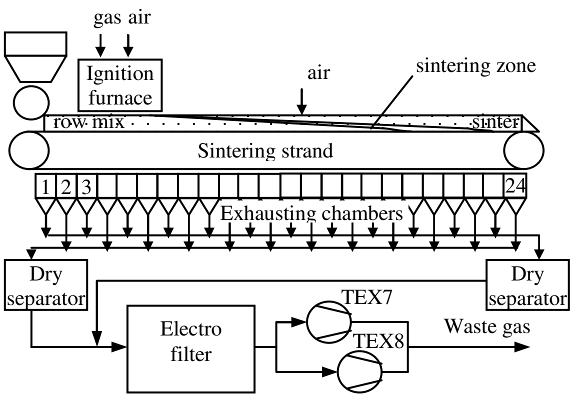

Fig. 1. Sinter plant scheme

Sintering is three-stage process consisting of preheating, sintering, and cooling. The preheating process consists of moisture evaporation, carbonates dissociation ($CaCO_3$, $MgCO_3$, $FeCO_3$), and enthalpy increasing. The sintering process includes heat generation by the coke combustion, melting, and chemical reactions. Sintering temperature determines the level of melting and phase transformations. It is created glassy liquid phase in which solid particles are dissolved.

The cooling period includes sinter solidification, sinter cooling, and sintering air preheating. Solidification intensity determines the proportion of glassy phase to the crystallized phase and their ratio influence mechanical and metallurgical properties of the sinter. The most appropriate structures have crystallized dendrites in the glassy phase.

3. MODELING OF THE SINTERING PROCESS

Purpose of the developed mathematical models is to analyse the influence of the system and process parameters as charging material composition, sinter strand velocity, ignition furnace layout and suction conditions on its behaviour and to predict the process behaviour. The models are constructed on the first principles and include processes in ignition furnace, sintering bed and exhausting system.

3.1 Ignition furnace model

The primary is the model of heat generation in the ignition furnace. The amount and composition of the fuel and air going into the individual burners is the input for this model. According to the amount of air, the combustion calculation is realized with the output of the amount, composition, and calorific temperature of combustion gases. The gas temperature in the ignition furnace is calculated iteratively from the heat balance equation

$$Q_{in} = Q_{rf} + Q_{cf} + Q_{rs} + Q_{cs} + Q_{gi} + Q_{lo}, \quad [W] \quad (1)$$

where Q_{in} is the chemical and physical heat of the fuel and the air, Q_{rf}, Q_{cf}, Q_{rs} and Q_{cs} is the heat transferred by radiation and convection to the ignition furnace and sintering surface, Q_{gi} is the heat of combustion gases, and Q_{lo} represents the heat losses into the surrounding.

3.2 Sintering bed model

Heat transfer is by conduction, convection, and radiation. The conduction is non-stationary heat transfer through the ignition furnace and sintered material described by the one-dimensional Fourier equation

$$\frac{\partial}{\partial t}\left(c(T)\rho(T)T(t,x)\right) = \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T(t,x)}{\partial x}\right), \qquad (2)$$

where t is time $[s]$, $t > 0$, x is the spatial coordinate in the direction of heat conduction $[m]$, $0 \le x \le H$, c is the specific heat capacity $[J.kg^{-1}.K^{-1}]$, ρ is the density $[kg.m^{-3}]$, $T(t,x)$ is the temperature $[K]$ and λ is heat conductivity $[W.m^{-1}.K^{-1}]$, with the initial condition and boundary conditions

For the numerical simulation of the temperature distribution $T(t,x)$ the model was approximated by spatial and temporal discretization with the implicit method, which ensures computation stability for large time steps. In the spatial interval $0 \le x \le H$ the temperature was computed in n points by the iterative solution of tridiagonal system of algebraic equations.

For a non-stationary heat transfer in the sintered material the calculation was realized by the iteration method based on heat balance for the elementary volume

$$Q_{qi} + Q_{rs} + Q_{cs} + Q_{cc} = Q_{go} + Q_{as} + Q_{en}, \quad [W] \quad (3)$$

where Q_{gi} is the heat generated from the combustion gas, Q_{rs} and Q_{cs} is the heat transferred by radiation and convection from the ignition furnace, Q_{cc} is the heat released by coke combustion, Q_{go} is the heat loss by waste gases, Q_{en} is the heat of endothermic reactions and water evaporation and Q_{as} is the accumulated heat in the sintering material.

For the calculation of radiation heat transfer the zone method was used. The total amount of heat transferred to the *i-th* zone is calculated by the approximate formula (Koštial and Dorčák, 1988)

$$Q_i = \frac{\sum_{j=1}^{NC} QE_j}{\sum_{j=1}^{NC} A_j} A_i - QE_i, \quad [W] \quad (4)$$

where $QE_j=\sigma A_j T^4_j$ $[W]$ is the radiation flux of the *j*-th zone, σ is the Stefan-Boltzmann constant, A_i $[m^2]$ is equal to εS for the surface zone with area S and emisivity ε and $4V\alpha$, for volume zones with volume V and absorptivity coefficient α, and T_j $[K]$ is the temperature of the *j*-th zone. NC is total number of zones.

The carbonate dissociation is according to the equation

$$MeCO_3 = MeO + CO_2. \quad (5)$$

Under the assumption that the activities of carbonates and oxides are equal to one, the balance constant of equation (5) is equal to the partial pressure p_{CO2}. The constants A and B of the function $\Delta G=A+BT$ represents the change of the standard free enthalpy in carbonate dissociation. For the dissociation reaction (5) holds

$$\Delta G=A+BT=RT\ ln(p_{CO2}). \quad [J/mol] \quad (6)$$

By the substitution of the numerical values for A, B and p_{CO2} can be calculated for the temperature T, and, therefore, the amount of CO_2 and the amount of the dissociated carbonate can be determined.

The equation (6) can describe ferrous oxide dissociation as well. The difference is only in the expression for the balance constant independent on the oxygen partial pressure. Below 570^oC, the dissociation is governed by equations

$$3\ Fe_2O_3 = 2\ Fe_3O_4 + 1/2\ O_2 \quad (7)$$
$$Fe_3O_4 = 3\ Fe + 2\ O_2 \quad (8)$$

and above 570^oC

$$3\ Fe_2O_3 = 2\ Fe_3O_4 + 1/2\ O_2 \quad (9)$$
$$Fe_3O_4 = 3\ FeO + 1/2\ O_2 \quad (10)$$
$$FeO = Fe + 1/2\ O_2 \quad (11)$$

Modelling of water vaporization or condensation is based on the functional dependence of the partial pressure of the saturated steam on the temperature. The volume of the vaporized steam or condensed steam is determined from the difference of the apparent partial water pressure and the actual partial steam pressure

$$Hm_{H2O} = V\ \rho\ (p_p/p - H_2O/100) \quad (12)$$

where V $[m^3/s]$ is the total volume of the gases, ρ $[kg/m^3]$ is the density of the steam depending on the temperature, p_p $[Pa]$ is the partial pressure of saturated steam, p $[Pa]$ is the total pressure of the gas mixture, and H_2O [%] is the percentage of steam in the mixture.

The carbon combustion is expressed by the following equations

$$C + O_2 = CO_2 - H_1 \quad (13)$$
$$C + 1/2\ O_2 = CO - H_2 \quad (14)$$
$$H_2O + C = H_2 + CO + H_3 \quad (15)$$

The relative proportion of carbon in CO_2 is *0.712*, in *CO 0.178*, and in the reaction with H_2O is *0.11 kg/kg* (Drabina, 1987). Then the carbon combustion heat is

$$Q = H_1\ 0.712 + H_2\ 0.178 - H_3\ 0.11 \quad (16)$$

Carbon combustion takes place under certain conditions. However, if the temperature is above the carbon ignition temperature (750^oC), then the rate of carbon combustion is a function of oxygen content in combustion gas according to the relationship

$$C = \frac{V^{O_2}}{(1-0.11)}\left(\frac{0.712}{O_2^{CO_2}} + \frac{0.178}{O_2^{CO}}\right), \quad [kg/s] \quad (17)$$

where V^{O2} $[m^3/s]$ is the oxygen volume in combustion gas, O_2^{CO2} and O_2^{CO} $[m^3/s]$ is the amount of oxygen needed for the reaction $C + O_2 = CO_2$ and $C + 1/2\ O_2 = CO$.

3.3 Parameters identification and model validation

Because of the model's deterministic nature, only few parameters had to be adjusted empirically, namely heat transfer coefficients in the ignition furnace and sintering bed, excess of suction air and the kinetic terms of chemical reactions. The parameters were adjusted on the sinter strand. Qualitative model validation was by comparison with the results of other models (Muchi and Higuchi, 1972) and with measured data (Wuillaume, et al., 1990). For the quantitative validation the measurements from experimental sintering pot were used. Satisfactory model reliability was demonstrated.

3.4 Exhaustion model

Exhaustion model serves for determination of the volume of exhausted gases. Exhausted gases consists from the ignition furnace combustion gases, gases

from the sintering process, including coke combustion, water evaporation, dissociation of carbonates and gases from other chemical reactions. Third part of exhausted gases is intake air from leakages. Sinter strand gases are calculated from the chemical reactions and balance equations. Intake air volume is calculated from the oxygen content in the exhausted gases.
The determination of the intake air is based on the balance of waste gas volume

$$V_{TWG} = V_{WG} + V_{FA} \tag{18}$$

and on partial balance of oxygen

$$V_{TWG}\,X_{TO2} = V_{WG}\,X_{WO2} + V_{FA}\,X_{AO2} \tag{19}$$

where V_{TWG} is the total volume of exhausted waste gas [$m^{-3}s$], V_{WG} is the volume of waste gas exhausted through the belt [$m^{-3}s$], V_{FA} is the volume of false air [$m^{-3}s$], X_{TO2} is the percentage of O_2 measured in the total waste gas volume [%], X_{WO2} is the percentage of O_2 in waste gas passing through the belt [%], X_{AO2} is the percentage of O_2 in false air [%].
By solving the above equations we obtain the relation for the intake air volume

$$V_{FA} = V_{TWG}(X_{TO2} - X_{WO2})/(X_{AO2} - X_{WO2}) \tag{20}$$

The percentage of oxygen in waste gas under sintering belt is given by the air, which is exhausted through the belt and is given by the relation.

$$X_{WO2} = V_{EA}(m - 1)X_{AO2}/V_{WG} \tag{21}$$

where V_{EA} is the measured exhausted air through the belt [m^3/s], m is the excess of exhausted air [m^3/m^3].

3.5 Process optimisation.

Primary simulation gives the temperature distribution in the sintering bed through the sintering process (Fig.2)

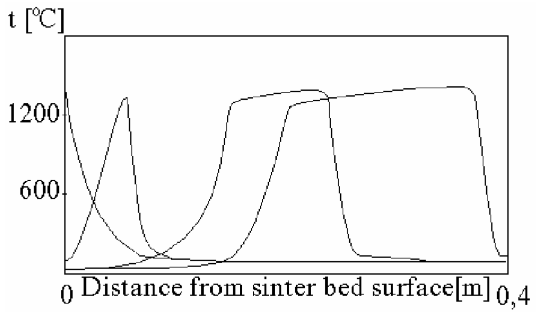

Fig.2. Temperature distribution in the sintering bed

Characteristic is gradual heat accumulation in the sinter influenced by the air-sinter thermal capacity ratio. Because this capacity ratio is less than one, heat accumulated in the sinter cannot be fully utilised for sintering air preheating. Therefore the layer with maximal sinter temperature is gradually growing (Fig.2).
The preheating in the ignition furnace influences the variation of the maximal sintering temperature at the upper bed surface. Sinter quality enhancement requires uniformity of the thermal conditions through the sintering bed, which can be characterised by maximal sintering temperature and by the sintering time which is time delay above lowest sintering temperature (Fig.3).
The sintering temperature and sintering time depends on the coke content in the sintering charge. They are increasing by the increasing of the coke content (Koštial 1998).

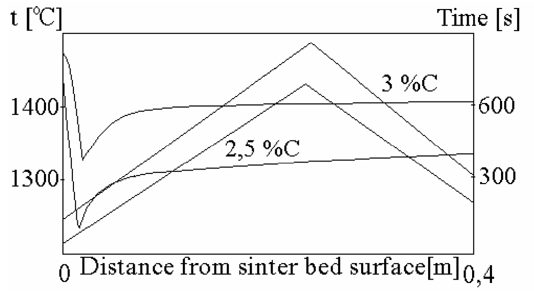

Fig.3. Maximum sintering temperature and time

Sintering temperature optimisation. The ignition process influences homogeneity of the sintering temperature. The surface temperature is generally held near the maximal value (melting temperature) and can be influenced by fuel input and its caloric value. This ignition strategy cannot effectively decrease the temperature non-homogeneity. For this reason a two-stage ignition strategy was proposed which consist from:

- Preheating on ignition temperature,
- Ignition with oxygen rich combustion gases.

In our case in the preheating period blast furnace gas was used, and for the ignition coke oven gas with air surplus $m=1,7$. This strategy enabled significantly improves maximal temperature homogeneity (Fig. 4).

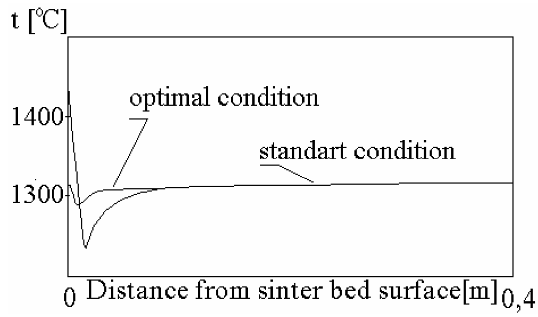

Fig.4. Sintering temperature optimisation

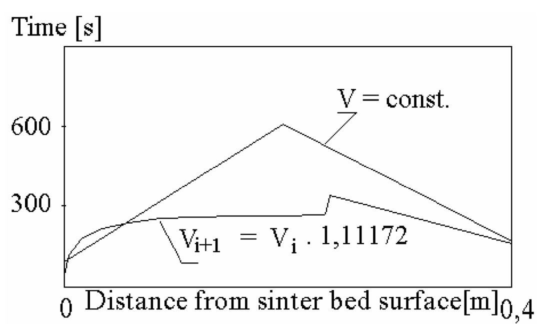

Fig.5. Sintering time optimisation

Sintering time optimisation. The sintering time is increasing from the top surface (Fig. 3). For this reason the high temperature sinter layer is progressively increasing (Fig.2).
Sintering time decreasing at the bottom layers is because of decreased sinter resident time on the sintering belt. Sintering time non-homogeneity can be improved by non-constant sintering intensity, which can be influenced by exhausting intensity through the length of sintering belt (Fig.5). In this case the optimal sintering intensity is

$$V_{i+1} = V_i .1,11172 \qquad (22)$$

where V_i is the sintering air volume

The non-uniformity of the sintering time can be compensated with increased sintering temperature. In such a way, inside some limitations, uniform-sintering conditions can be created. The layer with the minimum of the maximal sinter temperature is critical. Improving the preheating conditions can influence it.

Ignition optimisation. The optimisation of the ignition process has been directed on improving the preheating efficiency and preheating conditions. The preheating efficiency was enhanced by increasing the blast furnace-coke oven gas ratio and by minimizing the preheat heat. The blast furnace-coke oven gas ratio could be increased by their separate combustion. Optimal proportion was found by simulations and proved by practical realization. Required preheating heat can by determined from the temperature profile of the sintering process (Fig.6).

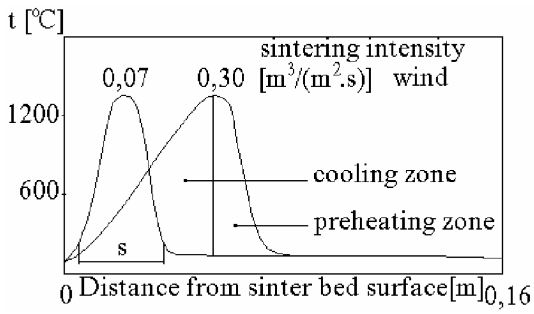

Fig.6. Preheat heat requirements for different sintering intensities

It consists of the sintering material preheating heat (right side) and heat required for air preheating (left side). The amount of this heat depends on the sintering temperature and on the layer thickness *s*, which can be influenced by the sintering intensity (air volume $m^3.m^{-2}.s^{-1}$). Low sintering intensity at the beginning stage has direct influence on the preheat heat requirements. However, preheating is a one-side process with the maximal temperature on the surface. The required heat should be therefore accumulated in the surface layer of the thickness *s/2*. Because of limitations on maximal sinter surface temperature it is not possible to deliver the whole required heat by surface preheating. The heat deficiency can be partly compensated by the air preheating in the subsequent part of the ignition furnace. From the preheating homogeneity requirements the maximal preheating is desirable at the sidewalls parts of the sintering belt. It was achieved by the proper layout of the ignition burners.

Exhausting optimisation. In case of the sintering strand normal operation optimal exhausting is when the sintering process is complete at the determined burn through point and the flue gases volume is according the predetermined sintering intensity. Exhaustion intensity and adequate throttling of exhausting chambers can achieve this.

4. CONTROL SYSTEM

The control of the sintering process has the objective to keep required sinter quality and maximise fuel economy. The control system is divided in the following subsystems:

- Sintering control,
- Ignition control,
- Exhaustion control.

4.1 Sintering control

Sintering control includes determination of the raw mix coke content and sintering air rate with predetermined longitudinal distribution. The sintering temperature and sintering time can influence the sintering. This dependence can be gained from the phase diagrams or empirically.
The sintering temperature and sintering time depends on the coke rate. The required rate of the sintering air is determined from the coke rate, strand performance and raw mix composition by the oxygen balance model.

4.2 Ignition control

Ignition control consists of setting the preheating temperature and the preheating heat, which are in some extend independent. The ignition temperature is, in view of the above considerations, the maximal sintering temperature and it depends on the sinter composition. It is controlled by the air/coke oven gas ratio and is determined by the heat balance model. The determined values have to take into account the process irregularities.
Preheating heat depends on the thickness of the preheating raw mix layer and raw mix composition. The desired thickness of the preheating layer is determined by the initial sintering intensity. Preheating heat is controlled by the amount of the blast furnace gas and the coke oven gas in their predetermined proportion and is determined from the heat balance model.

4.3 Exhaustion control

The main objective of the exhausting control system (Fig. 7) is to secure exhaustion of desired quantity of the waste gas. This value is determined by the feed-forward control and is corrected according to the identified burn-through point. Output from the control system are the required turbo-exhausters operating speed.

The calculated desired waste gas volume for turbo-exhausters is corrected according to difference of the positions of actual and desired burn through point, which is characterised by maximal waste gas temperature. The standard position of this point is in the centre of the 22nd chamber, in some cases in the 21st or 23rd chamber. The real position of this point (Fig. 8) we can identify from the parabolic approximation of the measured temperatures in last three chambers:

$$T(l) = a_2\, l^2 + a_1\, l + a_0 \tag{23}$$

where l is distance from the end of sintering belt [m].

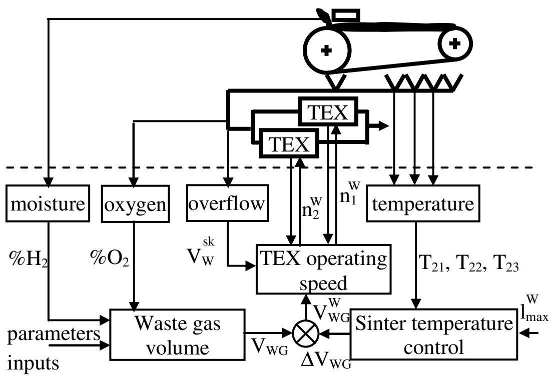

Fig. 7. Exhaustion control system

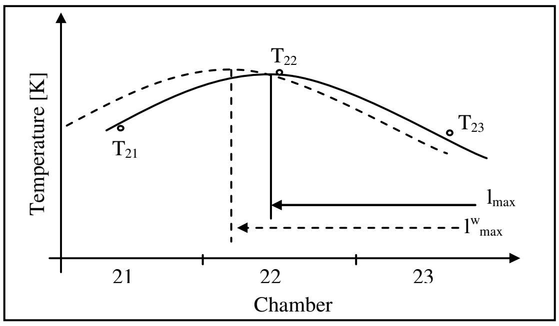

Fig. 8. Burns-through point position

From this parabolic approximation we can also compute the difference between real and desired position of the maximal waste gas temperature

$$e_l = l_{max} - l^W{}_{max} \tag{24}$$

and then we can determine the correction of desired waste gas exhausting volume

$$V_{WG} = V^W{}_{WG}\,(1 + e_l\,/\,(\,l_{max} - l^W{}_{max}\,)) \tag{25}$$

Turbo-exhauster speed has upper and lover limits and is corrected when particle concentration in exhausting gases is above upper limit. Communication with operator is through displays.

5. CONCLUSION

Sinter strand control system is feed forward - feedback type. This structure enables dynamic reaction on input disturbances. The control system has adequate behaviour on changes in sintering belt speed, coke and moisture content, position of the burn through point, etc and secures it optimal course. The industrial implementation of the control system proved its validity and brought significant improvement of the sintering process efficiency and quality.

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