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Metallurgy

Modeling of Temperature (Thermal) Field during SHS-Electric Rolling

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ABSTRACT. To obtain composite materials, new technology based on the Self-propagating High-temperature Synthesis (SHS) and electric rolling is developed by the authors. Modeling of temperature field during the process of SHS-electric rolling is presented in the paper. Taking into account major thermal and electrical parameters, mathematical model is elaborated, based on which thermal-physical events ongoing in technological process of SHS-electric rolling is considered. Relations for calculations of basic technological parameters are proposed. *© 2018 Bull. Georg. Natl. Acad. Sci.*

Key words: self-propagating high-temperature synthesis, rolling, temperature field

As it is known [1,2], during self-propagating high temperature synthesis (SHS) as a result of thermal impulse an exothermic chemical reaction begins and combustion wave front relocates at a certain speed in the mixture of reagents. As a result of synthesis of reagents going into reaction a solid product is made. Materials produced by such method, especially synthetic, hard tool materials with metastable structure, that are characterized with high chemical purity, perfect monocrystalline grains and high physical-mechanical properties gain more and more interest [3].

SHS is a rapid process. Combustion phase duration varies between 0.5-15 s. This limits the range of heat pressure processing of material. Temperature mode of pressure processing determines strength and hardness of the product. As a result of combustion reaction high temperature gradient is formed between the environment and sample's temperature, causing intense heat losses, especially in pressure compacting conditions during the direct contact with cold instruments.

To obtain compacted and homogeneous materials, immediate compaction of products heated while synthesis is necessary, since materials produced with SHS have finely dispersive, brittle and porous structure.

The continuous progress of the process can be achieved by the suggested innovative, inexpensive, energy saving, combined technological process of self-propagating high temperature synthesis and electric rolling [4, 5], when electric energy is supplied into deformation zone. Produced joule heating combusts the compacted charge in initial section of deformation zone and initiates SHS process (Fig.).

The necessary prerequisite for accomplishing continuous deformation is equality of rolling and combustion's front shifting speeds and compensation of heat losses.

Temperature Field of SHS

SHS is exothermic process. After passing thermal impulse to initiate synthesis, the process runs without external sources of energy. Despite the seeming simplicity in terms of experimental research SHS is a complex process to study empirically. It resembles a combustion process. Thus, to research the SHS process it is important to use method of adequate mathematical modeling based on the fundamental laws of physics and chemistry.

Possibility of SHS is determined by the amount of heat ejection during the exothermal reaction, which warms up the zone of reaction to high temperature and ensures the distribution of combustion front. While considering thermal problem in SHS process, convective movement of reagents is insignificant.

Let us consider adiabatic process of combustion and issue of reagents complete transformation. The equation of enthalpies [2,3] on the initial T_0temperature of reagents and T_{ad} temperature of final products is used as the main condition:

$$\sum_{j=1}^{m}\left[H(T_0)\right]_j = \sum_{j=1}^{n}\left[H(T_{ad})\right]_j . \tag{1}$$

Enthalpy of products on adiabatic temperature of combustion can be written down in the following way:

$$\sum_{j}^{n}[H(T_{ad})]_j = \sum_{j}^{n}[H(T_0)]_j + \int_{T_0}^{T_{ad}} \sum_{j=1}^{n} C_j dT , \tag{2}$$

where C_j is thermal capacity of j -products, which is a function of temperature $C_j = f_j(T)$.

According to the equations (1) and (2) heat produced as a result of exothermic reaction is fully spent on warming up the combustion products from initial T_0 temperature to combustion T_{ad} temperature.

For two component system, taking into account equations (1) and (2), we can write:

$$H_x(T_0) + H_y(T_0) - H_z(T_0) = \int_{T_0}^{T_{ad}} C_z(T)dt . \tag{3}$$

Parameters, included in equations (3), can take averaged values. Thus,

$$H_x + H_y(T_0) - H_z(T_0) = Q = C_{z_{avr}} , \tag{4}$$

from which

$$T_{ad} = T_0 + \frac{Q}{C_{z_{avr}}} . \tag{5}$$

It should be noted that [2] the quantity calculated with this image shows significantly low accuracy in terms of greatness. A relatively accurate result of temperature and products with balanced composition is obtained by using minimum free energy algorithm. This kind of method is included in computer program for calculating SHS process "ISMAN-THERMO".

Thermal Impulse Report of SHS Process Initiation by Resistance Heating

As mentioned above, at the initial stage of SHS-electric rolling container filled with pre-compacted charge is supplied to deformation zone and a slight biting occurs. Rolls stop and heating power passes through rolls and container into deformation zone (Fig.). It is established with many experimental studies [1] that temperature of SHS's initiation of charges of metal-ceramic reagents is 800-850^{0}C.

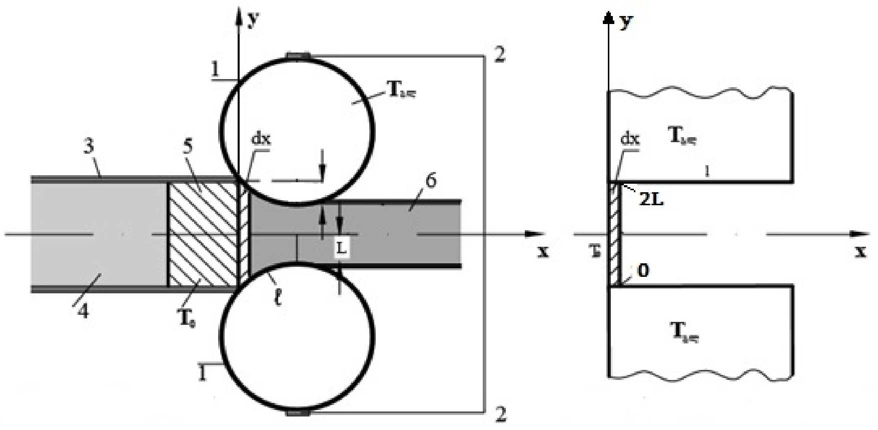

Fig. Diagram of SHS electric rolling.

1.	Rolls;	4.	SHS charge;
2.	Electrical contacts of power supply;	5.	Combustion zone;
3.	Container;	6.	The final product.

Whole energy used from the network of electric contact machine can be calculated with the following formula [6]:

$$W = \frac{cG(T_1 - T_0)}{\eta_0 \tau \cos\phi}, \tag{6}$$

where c-is thermal capacity of hot material; G -is mass of hot material; T_0 and T_1 - initial and final temperature of hot material; η_0-efficiency of heating machine; τ -heating time; $\cos\phi$ -coefficient of equipment force.

Equation (6) determines full power needed for heating the billet with G mass up to T_1 .temperature in τ -time, using averaged values of coefficients of thermal capacity, efficiency and strength.

Power necessary for heating a billet from T_0 to T_1 temperature in τ -time is calculated with the following image [6]:

$$J = \sqrt{\frac{cG(T_1 - T_0)}{\tau \eta_t R}}, \tag{7}$$

where η_t -is thermal efficiency in given time moment; R - average active impedance of hot billet in given range of heating. Characteristic parameters c, η_t and R, included in the image (7) are non-linear functions of temperature, to simplify calculation in given $\Delta T = T_1 - T_0$ temperature range, their averaged values are used.

The magnitude of voltage spread on contacts is equal (Fig.)

$$U_k = U_r + U_{pr} + U_{tr} = (2R_r + R_{pr} + 2R_{tr1} + 2R_{tr2}), \tag{8}$$

where, R_r -is electric impedance of rolls; but R_{pr} -electric resistance of hot billet placed in deformation zone; R_{tr1}, R_{tr2} -are transitional resistances between rolls and contacts and rolls and billet. R_r is electric impedance of compact material of rolls, relative impedance of which is much less than electric impedance of hot, porous, pre-compacted billet, but the section of power transmission is much greater, thus

$$U_r << U_{pr}$$

and it is possible to ignore it with great accuracy.

Transition impedance of contact connection is much bigger than active impedance of power passing other elements of circuit.

In the case of electric rolling (Fig.) contact couples of transitional resistance are contacts placed between cylindrical rolls and graphite-copper contacts fit to it and billet placed in deformation zone.

According to experimental data [3] change in stress from 5 up to 60kN by bulking between the contacts causes reduction of transitional resistance 2-2.5 times. At the same time, the bigger the diameter of rolls, this effect increases even more. Here is empirical image of transitional contact resistance.

$$R_{tr} = \frac{d_2 \phi(P)}{P^{0,4}}, \tag{9}$$

where d_2 - is the diameter of cylinder,(cm); P –strength(N); $\phi(P)$ -is function of P, which in case of clamping force with more than 15kN equals to 0.45-0.48.

Thermal-Physical Problem of Ongoing Process in Deformation Zone

In stationary mode of SHS-electric rolling the process of charge combustion happens in direct closeness to deformation zone (Fig.) As a result the billet heats up to T_1 - temperature and is supplied to rolls of the rolling mill in hot condition. At that moment contact heat transfer occurs to the surrounding environment as well as to cold working surface of rolls from hot charge.

In the process of pressure processing, during plastic deformation, convective moving of mass happens inside the deformation volume. Thus, temperature field of the billet inside the deformation zone depends on convective and diffusional heat transfer. To consider the latter it is necessary to determine speed field of particle flow of the billet in the deformation zone. In this case laws of heat transfer inside deformed volume are going to be written down with Fourier-Kirchhoff differential equation [7]

$$\frac{\partial T}{\partial \tau} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) - \left(S_x \frac{\partial T}{\partial x} + S_y \frac{\partial T}{\partial y} + S_z \frac{\partial T}{\partial z} \right) + \frac{W}{c\rho}, \tag{10}$$

where $T(x, y, z, \tau)$ is function of temperature distribution in the deformed billet volume; S_x, S_y, S_z - components of billet's particle speed along the coordinate axles; $W(x, y, z, \tau)$ – function of thermal source distribution in billet's volume.

In case of hot electric rolling of SHS product, the elemental section of the billet is in touch with rolls for a very short period of time:

$$\tau = \frac{\sqrt{R\Delta h}}{V_r}, \tag{11}$$

where $l = \sqrt{R\Delta h}$ - is biting arc length; R - radius of rolls; Δh quantity of absolute compression; V_r - speed of rolling. In the rolling process temperature field of billet's section is characterized with significant heterogeneity. First of all heterogeneity is caused because an insignificant contact part of rolled section takes part in transferring of heat between the billet and rolls. The rest part of billets' section is unable to take part in thermal transfer because of inertial thermal properties.

Based on fast paced deformation process and high temperature of charge it is permissible to ignore thermal transfer with convective movement as well as influence of thermal components caused by plastic deformation and work of surface friction forces. In case of hot rolling α- coefficient of heat transfer between the billet and rolls can be calculated theoretically. Experimental data for determination of this coefficient exists [8], based on which its value varies in 5x10^3-10^{4}W/m^2.grad range.

Amount of heat received by roll during the contact of its surface from 1m^2 contact surface area to hot product in τ- time [8]:

$$Q = \alpha(T_0 - T_1)\tau f\ , \tag{12}$$

where α – thermal transfer coefficient between the surface of rolls and surface of the billet intended for rolling; T_0 – initial temperature of material intended for rolling; T_r –conditional temperature which would strengthen in case of non-existence of thermal resistance between the touching surfaces; τ - time of contact;

$$f = \frac{2}{\sqrt{h-\alpha\tau}} - \frac{1}{h^2\alpha\tau}(1 - e^{h^2\alpha t} erfch\sqrt{\alpha t})\ , \tag{13}$$

where h - is a relative coefficient of thermal transfer and $h = \frac{\alpha}{\lambda}$; c - specific massive thermal capacity; ρ - density; α - coefficient of temperature conductivity.

Based on the above mentioned, equation (10) reduces to the one-dimensional case:

$$\frac{\partial T}{\partial \tau} = \alpha \frac{\partial^2 T}{\partial y^2}, \qquad \frac{\partial T}{\partial \tau} - \alpha \frac{\partial^2 T}{\partial y^2} = 0\,. \tag{14}$$

In addition, we suppose that the temperature of a roll is fixed and is equal to zero. According to the assumption, homogeneous Dirichlet boundary conditions can be posed on the problem (14). As for the initial condition, we assume that the billet has the temperature of the combustion front, which is uniformly distributed throughout the billet and is denoted by T_0. Schematically reviewed thermal-physical problem is presented (Fig.).

The following is written down:

$$\frac{\partial T}{\partial \tau} - \alpha \frac{\partial^2 T}{\partial y^2} = 0 \qquad 0 < y < 2L, \quad \tau > 0\,.$$

Initial condition: $T(0, y) = T_0 = const$.

Boundary condition: $T(\tau, 0) = 0$ and $T(\tau, 2L) = 0$.

In this case the solution to problem can be found in the following way:

$$T(\tau, y) = \frac{4T_0}{\pi}\sum_{n=1}^{\infty}\frac{e^{-\lambda_n^2\alpha\tau}}{2n-1}\sin(\lambda_n y), \quad \lambda_n = \frac{\pi}{L}\left(n - \frac{1}{2}\right). \tag{15}$$

If we know the $\tau_1 = \frac{l_r}{v_r} = \frac{\sqrt{R\Delta h}}{v_r}$ contact time of rolls with a sample and temperature function $T(\tau, y)$, we can find temperature $\Delta T = T(0, y) - T(\tau_1, y)$ gradient related to heat $Q = C_{pr}m_{pr}\Delta T$, that was lost by billet during the contact with rolls in the deformation zone.

In order to provide isotherm of the deformation process, it is necessary to compensate heat losses. The mentioned can be achieved by production of joule heat amount produced by passing of electricity in deformation zone during the rolling process. The necessary amount of power is determined by image (7) and equals to

$$J = \left[\frac{cG\Delta T}{(R_k + R_{pr})\tau_1}\right]^{1/2},$$

where c and G are heat capacity and mass of the billet placed in deformation zone, and R_k and R_{pr} is an electric resistance transitioning between rolls and the billet.

Conclusion

Thermal-physical events ongoing in technological process of SHS-electric rolling were considered. Mathematical model of the process considering the main thermal and electric parameters is developed. Relations to calculate main technological parameters are suggested.

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მეტალურგია

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**აკადემიის წევრი, ფერდინანდ თავაძის მეტალურგიისა და მასალათმცოდნეობის ინსტიტუტი, თბილისი, საქართველო*
***ფერდინანდ თავაძის მეტალურგიისა და მასალათმცოდნეობის ინსტიტუტი, თბილისი, საქართველო*

დღეისათვის საკმაოდ კარგადაა შესწავლილი თმს და წნევით დამუშავების წყვეტადი, სწრაფმავალი პროცესების (წნეხვა, შტამპვა) შეთავსებით შეზღუდული ზომების ცალობითი პროდუქტის მიღება, თუმცა ამ შემთხვევაშიც, ჰომოგენური თვისებების მასალის მისაღებად, აუცილებელი იზოთერმული რეჟიმის უზრუნველსაყოფად იყენებენ მადეფორმირებელი ინსტრუმენტის თბოიზოლირების სხვადასხვა ხერხს, რაც ართულებს და აძვირებს პროცესს. ამ ტექნოლოგიური სირთულეების დასაძლევად, თვითგავრცელებადი მაღალტემპე-რატურული სინთეზის და ელექტროგლინვის ბაზაზე, ავტორების მიერ შემუშავებულია კომპოზიციური მასალების მიღების ახალი ტექნოლოგიური პროცესი. სტატიაში მოცემულია თმს-ელექტროგლინვის პროცესის ტემპერატურული ველის მოდელირება. ძირითადი თბური და ელექტრული პარამეტრების გათვალისწინებით დამუშავებულია მათემატიკური მოდელი, რომლის საფუძველზე განხილულია ტექნოლოგიურ პროცესში მიმდინარე თბოფიზიკური მოვლენები. შემოთავაზებულია ძირითადი ტექნოლოგიური პარამეტრების გამოსათვლელი გამოსახულებები.

REFERENCES

1. Merzhanov A.R. (1999) Protsesi gardenia i sintez materialov. Chernogolovka publishing house ISMAE (in Russian).
2. Levashov E.A., Rogachev A.S., Kurbatkina V.V., Maksimov U.M., Ukhvid V.I. (2011) Perspektivnye materiali i tekhnologii samarasprostraniushevosia visokotemperaturnogo sinteza. M. (in Russian).
3. Levashov E.A., Rogachev A.S., Yukhvid V.I., Borovitskaya I.P. (1999) Fiziko-khimicheskie i tekhnologicheskie osnovy samarasprostraniushevosia visokotemperaturnogo sinteza. M. (in Russian).
4. Namicheishvili T., Nozadze A. (1993) Electric-contact heating (ekg) electrical system of equipment, *Works of GTU*, **400**, 7.
5. Namicheishvili T., Lortkipanidze J. (2003) Special equipment for the isothermal rolling and the issues of selecting material for its rolls. *Bull. Georg. Acad. Sci.* **168**, 2: 286-288.
6. Romanov D.I. (1981) Elektrokontaktnoe nagrev metallov. M. (in Russian).
7. Isachenko V.P., Osipova V.A., Sukomel A.S. (1975) Teploperedacha. Energy. M. (in Russian).
8. Shilov V.I., Morzeeva G.V. (1965) Isledovanie teplovikh protsesov v protsese prokatki. *Proceedings of the Institute of Metallurgy*, 12: 123-134. Sverdlovsk (in Russian).

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