The dynamic of cooling of cast iron in the crystallizer in condition of the semi-continuous production process bimetallic band “steel-cast iron”

V P Lihoshva1,3, A V Shmatko1,4, V V Savin2,5, L A Savina2,6 and A N Tymoshenko1,7

1Physics-technological institute of metals and alloys of the National academy of science of Ukraine, Vernadsky Avenue, 34/1 03680, Kiev, Ukraine
2Immanuel Kant Baltic Federal University, A Nevsky st, 14 236016, Kaliningrad, Russia
3E-mail: plazer_v@mail.ru
4E-mail: blacknorfolk@gmail.com
5E-mail: VVSavin@kantiana.ru
6E-mail: LSavina@kantiana.ru
7E-mail: Marschal@i.ua

Abstract. The dynamics of hard crust formation is investigated in the liquid melt by contact with the working walls of the copper crystallizer under conditions of continuous production of bimetallic products such as "band" at different speeds of the process. The optimal speed is identifying to achieve maximum performance with the satisfactory quality of the finished products. Recommendations for increase speed of carrying out process are offered.

1. Introduction
The competitiveness of most industrial enterprises is largely determined by the performance and reliability of the equipment used and depends on the number of technological breaks and repairs (scheduled and emergency). Parts, operating in conditions of intense wear, determine the share whose replacement leads to downtime of the production equipment and technology. In particular, an urgent problem is to increase the wear resistance of the working bodies of machines and mechanisms of the mining industry operating in conditions of abrasive and impact abrasive wear. A promising direction for solving the problem of reducing the intensity of wear is the use bimetallic products [1, 2]. The main advantage of double-layer and multi-layer parts is the achievement of a set of properties of the material basis and the working layer, which can’t be achieved by using monolayer products. Thus, the use of working bodies on the basis of bimetallic compounds with the necessary indicators of wear resistance of the deposited metal in conjunction with the specified structural properties of the base metal increases the total resource.

At the moment, there are many ways to obtain multilayer structures. The most widespread were processed of surfacing (plasma, laser, gas-powder, etc.) [3–7]. Despite its advantages, these methods have one common drawback-low it is process productivity. Modern technology requirements this is a high performance production, these include the technology for continuously in-situ blanks. Taking into account the disadvantages and advantages of modern processes of production of bimetallic and multilayer products, a hybrid technology of semi-continuous production of bimetallic construction of
the "band" type was proposed [8, 9]. Its main point is the connection of the liquid of the melt preheated to the temperatures required for the diffusion of their connection with the substrate (workpiece) of a different material in the mold [10]. One of the key points of obtaining products using the above method is the crystallization of the melt.

In continuous casting machines, much attention is paid to optimizing the cooling rate of the melt, since it is an important factor in predicting the quality of products [11]. Copper crystallizers of both vertical and horizontal types are used for the production of continuous cast billets at modern metallurgical plants [12, 13]. With the help of the crystallizer, the finished product is formed by increasing the crust of the solidifying metal on the border of the "wall of the crystallizer – melt". According to [13], the value of the hard crust at the exit of the crystallizer is normalized (depending on the cross-sectional configuration) to avoid breaking the molten metal through the hardened wall under the action of the liquid metal head. The main task of the crystallizer is to provide intensive heat removal from the melt. During operation, the crystallizer removes 15–30% of accumulated heat from the liquid metal [13].

An important influence on the crystallization process has a gas gap, which is formed by metal shrinkage during phase transitions and further cooling. The thickness of the gas gap is unstable and can change along the perimeter and height of the crystallizer.

### 2. Results and Discussion

As part of the development of the foundry-plasma technology for bimetallic products, a numerical simulation of the melt cooling process was carried out to predict the crystallization front, taking into account the influence of a constant gas gap, in order to formulate recommendations on the choice of speed for the practical conduct of the process.

In order to optimize the calculation time, the processes of heat and mass transfer in the filling device were not taken into account in the model. As the material of the workpiece used steel DIN 1.0402 the overall dimensions of which are 70x10 (WxH, mm). As a fill layer took grey cast iron DIN GG35 (WxH=50x20, mm). Since the technology of obtaining bimetal strip is a semi-continuous process, the length of the steel substrate and the filled layer was taken conditionally infinite.

The design of the crystallizer was used for the calculation without taking into account the thermal processes associated with the heat transfer of the cooling liquid.

According to the scheme (figure 1) cooling of molten cast iron was calculated as it progresses in the U-shaped crystallizer taking into account the contact with the steel billet. It was assumed that the preheated workpiece to the minimum temperature necessary for the diffusion compound (800 °C). Calculations were carried out for steel strip feed rates in the range of 2–20 mm/s. The temperature of the walls of the crystallizer, not in contact with the workpiece material and the melt, was set equal to the ambient temperature.

![Figure 1. Schematic formulation of the problem of liquid cast iron cooling in the crystallizer.](image)
The model of calculation of cooling of a bimetallic strip at contact with walls of the crystallizer taking into account processes of heat transfer includes the solution of the following equations

**Continuity equations:**

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]  

(1)

**The Navier-Stokes equation:**

\[
\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot \left( \mu \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) \right) - \frac{2}{3} \mu \nabla \cdot \mathbf{u} + \mathbf{f},
\]

(2)

where \( \rho \) – density (kg/m\(^3\));
\( \mathbf{u} \) – velocity vector (m/s);
\( p \) – pressure (Pa);
\( \mu \) – dynamic viscosity (Pa\cdot s);
\( \mathbf{f} \) – vector of body force (N/m\(^3\)).

**Heat transfer equation for liquid phase:**

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \alpha_p T \left( \frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p_a \right) + \frac{\tau}{s} + \nabla \cdot (k \nabla T) + Q,
\]

(3)

where \( C_p \) – specific heat at constant pressure (J/kg\cdot K);
\( T \) – absolute temperature (K);
\( \tau \) – tensor of viscous stresses (Pa);
\( S \) – tensor of rate of deformation (1/s);
\( Q \) – heat source (W/m\(^3\)).

**Heat transfer equation for the solid phase:**

\[
\rho C_p \frac{\partial T}{\partial t} = -\nabla \cdot \mathbf{q} - T \frac{\partial E}{\partial T} + Q,
\]

(4)

where \( E \) – elastic component of the entropy (J/(m\(^3\)\cdot K)).

The following dependence of the liquid phase fraction on the temperature was used to determine the crystallization front:

\[
B = \frac{(T - T_{m,av} + \partial T')a b}{\partial T'} + c,
\]

(5)

where \( B \) – proportion of the liquid phase;
\( T_{m,av} \) – average temperature interval of crystallization: \( T_{m,av} = \frac{T_l + T_s}{2} \);
\( T_l \) – liquidus temperature, °C;
\( T_s \) – solidus temperature, °C;
\( \partial T' \) – crystallization half-interval, °C: \( \partial T' = \frac{T_l - T_s}{2} \);
\( a, b, c \) – logical variable:
if \( T \leq T_{m,av} + \partial T' \) then \( a = 1 \);
if \( T > T_{m,av} + \partial T' \) then \( a = 0 \);
if \( T \geq T_{\text{m.av.}} - \partial T' \) then \( b = 1; \)
if \( T < T_{\text{m.av.}} - \partial T' \) then \( b = 0; \)
if \( T > T_{\text{m.av.}} + \partial T' \) then \( c = 1; \)
if \( T \leq T_{\text{m.av.}} + \partial T' \) then \( c = 0. \)

The calculations took into account the maximum gas gap, which was determined from the equation:

\[
\delta = \gamma (1-B) l \varepsilon,
\]

where \( l \) – value of the linear size, mm;
\( \varepsilon \) – linear shrinkage of cast iron, %.

Since we assume that there is no gas gap at the interface between the steel substrate and the cast iron layer, given the presence of a diffusion connection between the steel workpiece and the cast iron layer, the \( \gamma \) coefficient is introduced into the equation, which determines the proportion of linear shrinkage at the boundaries of the cast-iron layer. Thus, the gas gap on the surfaces contacting with the crystallizer was taken 0.25 mm and 0.4 mm on the vertical and horizontal borders, respectively.

The heat flux through the air gap can be determined from the equation:

\[
q_{\text{air}} = (\lambda_{\text{air}} \delta)(T_{\text{surf}} - T_{\text{cr}}) + \varepsilon \sigma_0 (T_{\text{surf}} - T_{\text{cr}}),
\]

where \( \lambda_{\text{air}} \) – thermal conductivity of air in the gap;
\( \delta \) – value of the gas gap;
\( T_{\text{surf}} \) – temperature of the contact surface of the melt;
\( T_{\text{cr}} \) – surface temperature of crystallizer;
\( \varepsilon \) – reduced emissivity factor of contact surfaces;
\( \sigma_0 \) – Stefan-Boltzmann constant.

The choice of the optimal speed was carried out for the following reasons:
- formation of a hard crust of the required value to exclude the possibility of breakthrough and spilling liquid cast iron at the exit of the crystallizer;
- ensure maximum productivity process;
- ensuring satisfactory quality of finished products.

Based on the analysis of the results obtained, the speed interval was divided into three groups, taking into account the recommendations of applicability in the practical conduct of the process (table 1).

The feed rates of the workpiece 2–8 mm/s are characterized by complete cooling of the melt supplied to solidus temperatures at the time of exit from the crystallizer. Since there is no liquid phase at the crystallizer outlet inside the cast iron layer volume, the risk of shrinkage defects is reduced due to liquid metal feeding. It should be noted that the smaller the length of the liquid hole, the less likely the product shrinkage porosity and shrink holes. For figure 2 the values of the liquid phase in the longitudinal section at the center of the bimetal structure are presented, which give an idea of the crystallization front for velocities up to 8 mm/s. The necessary heat sink, which provides the values of the hardened crust (figure 2), provided by increasing the contact time of the supplied liquid metal with the working walls of the crystallizer. Since productivity is an important factor in industrial applications, results are preferred when choosing the optimal speed is preferable \( V_{\text{cast}} \approx 8 \) mm/s (table 1, gr. II).

With a further increase in the feed rate of the strip, and as a consequence, and the melt flow rate in the crystallizer, incomplete crystallization of the cast iron layer is observed at the time of exit from crystallization (figure 3). Moreover, the higher the speed, the greater the proportion of liquid and liquid-solid phase in the volume, which in turn can lead to a breakthrough of the metal and the appearance of shrinkage defects due to the inability to compensate for shrinkage of the liquid metal. Thus, speeds \( V_{\text{cast}} > 10 \) mm/s are unsatisfactory when the length of the mold is 150 mm.
Table 1. The fraction of the liquid phase in the cross section at the exit of the crystallizer for the velocity range.

| №  | V, mm/s | I      | II     | III    | liquid phase drier, B |
|----|---------|--------|--------|--------|----------------------|
| 2  |         | ![Image](image1) | ![Image](image2) | ![Image](image3) | ![Image](image4) |
| 4  |         | ![Image](image5) | ![Image](image6) | ![Image](image7) | ![Image](image8) |
| 6  |         | ![Image](image9) | ![Image](image10) | ![Image](image11) | ![Image](image12) |
| 8  |         | ![Image](image13) | ![Image](image14) | ![Image](image15) | ![Image](image16) |
| 10 |         | ![Image](image17) | ![Image](image18) | ![Image](image19) | ![Image](image20) |
| 12 |         | ![Image](image21) | ![Image](image22) | ![Image](image23) | ![Image](image24) |
| 14 |         | ![Image](image25) | ![Image](image26) | ![Image](image27) | ![Image](image28) |
| 16 |         | ![Image](image29) | ![Image](image30) | ![Image](image31) | ![Image](image32) |
| 18 |         | ![Image](image33) | ![Image](image34) | ![Image](image35) | ![Image](image36) |
| 20 |         | ![Image](image37) | ![Image](image38) | ![Image](image39) | ![Image](image40) |

where I – satisfactory result; II – optimal result; III – unsatisfactory result.

If it is necessary to increase the productivity, it is necessary to increase the length of the crystallizer or take measures to reduce the effect of the gas gap on the heat transfer processes from the melt to the walls of the crystallizer. To do this, in the crystallizers of modern CCM, a change in the flow section in the direction of reduction is applied to neutralize the effect of shrinkage processes as cooling and advancement in the crystallizer [14]. In the case of a horizontal semi-continuous casting machine, the situation is complicated by the difference in cooling conditions at the boundaries of the heat exchange "cast iron-wall crystallizer" and "cast iron – steel substrate."

Figure 2. Volume fraction of the liquid phase in the longitudinal section for feed rates of the workpiece 4 mm/s and 8 mm/s, respectively.
3. Conclusions

Taking into account the results of numerical simulation of the cooling process of cast iron in a semi-continuous process of obtaining bimetallic structure "band" formulated recommendations for the choice of speed.

Mass-flow rate $V_{\text{cast}} = 2\ldots6$ mm/s is undesirable because of the poor performance of the process. The optimal value is $V_{\text{cast}} \approx 8$ mm/s. If it is necessary to increase the speed, it is necessary to increase the contact time of the cast iron layer with the wall of the crystallizer by increasing its length, or take measures to reduce the influence of the air gap on the heat transfer processes from the melt by changing the flow section to compensate for the shrinkage processes.

Acknowledgments

Research was supported by the Ministry of science and higher education of the Russian Federation, unique project identification number RFMEFI57817X0252.

Reference

[1] Wrobel T 2011 Bimetallic layered castings alloy steel – gray cast iron Science and engineering 2 118–125
[2] Posypajko I Ju and Socenko O V 2011 Povyshenie iznosostojkosti smennyh detalej promyshlennyh smesitelej [Increasing the wear resistance of replaceable parts of industrial mixers] Metall i lit'e Ukrainy – Metal and casting in Ukraine 1 32–35
[3] Hasui A and Morigaki O 1985 Naplavka i napylenie [Surfacing and spraying] ed V N Popova (Moscow: Mashinostroenie) p 240
[4] Gologoskij E G 1998 Mehanizirovannye sposoby naplavki i napylenija detalej stroitel'nuyh, dorochnyih i kommunal'nuyh mashin [Mechanized methods of surfacing and spraying parts of construction, road and municipal machines] (Moscow: MIKHiS)
[5] Tkachev V N, Fishtejn B M, Kazincev N V and Aldyrev V A 1970 Indukcionnaya naplavka tverdyh splavov [Induction hardfacing of hard alloys] (Moscow: Mashinostroenie)
[6] Steen W M and Watkins K G 1993 Coating by laser surface treatment Journal de Physique 3 581–590
[7] Pauleau Y 2006 Material Surface Processing by Directed Energy Techniques (London: Elsevier) Retrieved from https://www.elsevier.com/books/materials-surface-processing-by-directed-
Lihoshva V P, Najdek V L, Karichkovs'kij P M, Pelikan O A, Glushkov D A and Nadashkevich R S 2010 Ukrainian Patent UA №54486 (Kiev: Derdavne pidpriemstvo "Ukrains'kij institut intelektual'noi vlasnosti")

Lihoshva V P, Aftandiljanc E G, Pelikan O A, Timoshenko A M, Nadashkevich R S and Rejntal' O O 2012 Ukrainian Patent UA №74270 (Kiev: Derdavne pidpriemstvo "Ukrains'kij institut intelektual'noi vlasnosti")

Lihoshva V P and Shmatko O V 2017 Bezperervnij livarno- plazmovij metod otrimannja bimetallevih ta bagatosharovih konstrukcij [Continuous casting-plasma method of obtaining bimetallic and multilayer structures] XIII Mezhdunarodnaja nauchno-prakticheskaja konferencija «LIT''E. Metallurgija. 2017» [XIII Internat. Scien.-pract. conf. "Casting, Metallurgy. 2017"] (Zaporozhe: Nacional'naja metallurgicheskaja akademija Ukrainy) pp 166–167

Allazadeh M R 2012 Cooling rate optimization of as-cast consciously cast steel Iranian J. of Material Science and Engineering Vol 9 (3) p 16

Brovman M O 2004 Perspektivah razvitija nepreryvnogo lit'ja metallov [About the perspectives for the development of continuous casting of metals] Nacional'naja metallurgija - National metallurgy 5 66-70

Bulanov L V, Korzunin L G and Parfenov E P 2003 Mashiny nepreryvnogo lit'ja zagotovok Teorija i raschet [Machines for continuous casting of blanks Theory and calculation] (Ekaterinburg: Ural'skij centr PR i reklamy)

Kozyrev N A, Gizatulin R A and Valuev D V 2014 Nepreryvnaja razlivka stali i splavov: ucheboe posobie [Continuous casting of steel and alloys: a tutorial] (Tomsk: Izdatel'stvo Tomskogo politehnicheskogo universiteta)