Applying Finite Point Method in Solidification Modeling during Continuous Casting Process

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In the present work a meshless method called Finite Point Method (FPM) is developed to simulate the solidification process of continuously cast steel bloom in both primary and secondary cooling region. The method is based on the use of a weighted least-square interpolation procedure. A transverse slice of bloom as it moves with casting speed is considered as computational domain and two dimensional heat transfer equation is solved in the computational domain. The present work is verified by the comparison of the surface temperature simulated by both FPM (as the present method) and finite volume method (FVM) as a usual method. Furthermore the solidified shell thickness simulated by the present FPM is compared with the solidified shell measured on a breakout bloom. In the secondary cooling region, the surface temperatures simulated by the FVM and measured by the thermovision machine are applied to validate the surface temperature simulated by the present FPM. The results reveal that the present FPM could be used successfully for the thermal analysis of the steel bloom to determine the temperature field and solidified shell thickness.

KEY WORDS: numerical simulation; continuous casting; meshless; finite point; solidification.

1. Introduction

Continuous casting process has become the primary method for producing of steel bloom, slab and billet. The quality control of continuous casting is the base of reducing of production costs, processing time, and to assure reproducibility of the casting operation and increase of production. This cannot be achieved without a correct knowledge about 1—the thickness of solidified shell and 2—temperature distribution along the different cooling zones.1–3) Simulation of solidification by solving of heat transfer equation is used to calculate the thickness of solidified shell and strand temperature profile.4–7)

The common methods for simulation of solidification are finite element method (FEM), finite difference method (FDM) and finite volume method (FVM). These methods are mesh-based methods and in these methods, the problem domain, where the partial differential governing equations are defined, is often discretized into meshes. However, mesh distortion will fail the computation when FEM treats the discontinuities, i.e. the deformation of mesh which does not coincide with the original mesh lines. The solution is to remesh in each step of the evolution. But this may leads to degradation of accuracy and complexity in the computer program, and the burden associated with the tedious adaptive and interactive re-meshing. Generally, the mesh generation is not very easy, especially in the complex geometry (in the FEM) and also the complex boundary conditions make some difficult for FDM.8) Comparing the mesh-based methods, meshless method dose not use elements. In meshless method, the approximation is constructed entirely in terms of nodes. In result, the discontinuities can be treated by free adding or deleting nodes whenever and wherever needed to simulate the new deformation.

There are a number of famous meshless methods, such as the element free Galerkin (EFG) method, the meshless local Petrov-Galerkin (MLPG) method, the finite point method (FPM) and smooth particle hydrodynamics (SPH).9) Among the meshless methods, Finite Point Method (FPM) is one of the easiest to implement.9) Although it seems that there exist some similarity between FPM and FEM but a comparison of FPM and FEM for two dimensional problems shows there are several advantages for FPM with respect to FEM. Generally it would be possible to summarize the advantages of the FPM as follows: (1) the manual work for data preparation is reduced because of the meshless feature; (2) the dependent variables and their gradients are continuous in the entire domain; (3) by modifying or refining the nodal distribution the FPM is advantageous, by which a node can be easily moved, removed and added in the domain, while by the FEM a local mesh modification and the corresponding nodal and element renumbering are necessary; (4) it would be possible to couple the thermomechanical calculations to the thermal analysis easily (es-
which is a function of temperature, Where the subscript s is referred to the solid and l is referred to liquid. Usually to consider the liquid flow effect on the thermal field, an effective thermal conductivity is employed in the liquid core and mushy zone.15,16) The effective thermal conductivity depend on the some operational parameters such as electromagnetic mold stirrer conditions, geometrical shape, size of submerged entry nozzle and the amount of superheat. In the present simulation the simple suggestion of Louhenkilpi et al.15,16) was used which is an increase of two times for the conductivity of the liquid for bloom.

Boundary Conditions

The boundary condition for the surface of the strand is written as follows:

\[-k(T) \frac{\partial T}{\partial n} = q_n \]  \hspace{1cm} (5)

Where \( n \) in the normal to the boundary and \( \partial T/\partial n = \partial T/\partial x \) for y=0 and \( \partial T/\partial n = \partial T/\partial y \) for x=0 in Fig. 1. \( q_n \) is the local heat flux density (W/m²) which is zero for the symmetry boundaries and for the bloom surface is calculated as follows:

1) In the Mold Region\(^8\):

\[ q_n = \frac{\sigma \Delta T^4_n \rho \alpha C_w Q}{P_m} \times \frac{e^{-\alpha z}}{1 - e^{-\alpha H_m}} \]  \hspace{1cm} (6)

where \( Q \) is the volume cooling water rate (m³/s), \( \rho \) is density of water (997 kg/m³ at 25°C), \( C_w \) is heat capacity of water (4180 J kg⁻¹ at 25°C), \( H_m \) is mold length (m), \( P_m \) is perimeter of the tube mold (billet and bloom mold), \( z \) is mold length (starting from the meniscus) (m), \( \alpha \) is slope of straight lines in a q–z half-logarithmic plot and its value used in this paper is 1.5 m⁻¹, \( \Delta T^4_n \) is total increase of the cooling water temperature (°C) and the term \( H_m \) is the effective mold length which is in contact with the melt.

2) In the Spray Cooling Region\(^2\):

\[ q_n = h_j(T - T_w) \]  \hspace{1cm} (7)

Where the subscript \( j \) shows the number of spray cooling section. In the present research, the spray cooling zone is divided into 3 sections according to the flow rate of water i.e. foot roll area, mobile section area and fixed section area. \( h_j \) is the convective heat transfer coefficient in the \( j \)th section, which can be calculated as follows\(^3\) (with unit of kW/m²·°C):

\[ h_j = h_{ojj} \cdot w_j + h_{nj} \]  \hspace{1cm} (8)

Where \( h_{oj} \), \( r \) and \( h_{nj} \) are the parameters of nozzle, for air-
mist spray nozzle, \( h_{oj} \) is 0.35, \( r \) is 0.556 and \( h_{ij} \) is 0.13, respectively, and \( w_j \) (with unit of \( \text{L/s m}^2 \)) is the sprayed water density, which is calculated as follows:

\[
 w_j = \frac{Q_{sj}}{A_j} \tag{9} 
\]

Where \( A_j \) is the sprayed area of the \( j \)th section and \( Q_{sj} \) is the spray water flow rate in the \( j \)th section. According to Eq. (8) and Eq. (9) the values of heat transfer coefficient for various cooling zones are \( h_1 = 512 \, \text{W/m}^2 \, \text{K} \), \( h_2 = 373 \, \text{W/m}^2 \, \text{K} \) and \( h_3 = 256 \, \text{W/m}^2 \, \text{K} \).

(3) Radiation Cooling Region\(^{19}\)

\[
 q_u = h_{ru}(T - T_{\text{amb}}) \tag{10} 
\]

\[
 h_{ru} = \frac{\varepsilon \sigma (T^2 + T_{\text{amb}}^2)}{(T + T_{\text{amb}})} \tag{11} 
\]

Where \( \varepsilon \) is the emissivity of bloom surface (0.8), \( \sigma \) is the Stefan–Boltzman constant \( (5.67 \times 10^{-8} \, \text{W/m}^2 \, \text{K}^4) \), and \( T_{\text{amb}} \) is the ambient temperature (K).

The initial temperature of melt in the first step of simulation process is equal to pouring temperature.

\[
 T = T_{\text{pour}} \quad \text{for} \quad t = 0 \tag{12} 
\]

3. Description of Simulation by FPM

3.1. Basic Concepts of Meshless Techniques

Let us assume a scalar problem governed by a differential equation

\[
 A(u) = b \quad \text{in} \quad \Omega \tag{13} 
\]

With Neumann boundary conditions

\[
 B(u) = t \quad \text{in} \quad \Gamma \tag{14} 
\]

And Dirichlet boundary conditions

\[
 u - u_p = 0 \quad \text{in} \quad \Gamma_u \tag{15} 
\]

to be satisfied in a domain \( \Omega \) with boundary \( \Gamma = \Gamma_0 \cup \Gamma_u \). In the above, \( A \) and \( B \) are appropriate differential operators, \( u \) is the unknown function and \( b \) and \( t \) represent external forces or sources acting over the domain \( \Omega \) and along the boundary \( \Gamma_0 \), respectively. Finally, \( u_p \) is the prescribed value of \( u \) over the boundary \( \Gamma_u \).\(^{10}\) In the present work the unknown function \( u \) is temperature, the prescribed \( u_p \) is the pouring temperature and the Neumann boundary value \( t \) is the local heat flux density.

The first step of FPM is to provide the problem domain using sets of nodes scattered in the problem domain and its boundary. Figure 2 depicts a typical domain and scattered nodes. Suppose we want to find the unknown function of \( u(X) \) (the filed variable at any interested point of \( X \)). FPM is used to solve the evolution system by interpolation of the unknown function within a small local domain, which is taken to be a circle centered at a point \( X \) (see Fig. 2). However the small local domain can have different shapes and its dimension and shape can be different for different points of interest \( X \), as shown in Fig. 2. A support domain of a point \( X \) determines the number of nodes to be used to support or approximate the function value at \( X \) so it is termed as the support domain of \( X \).\(^{3} \)

Generally in the FPM the field variable of \( u(X) \) is approximated at any interest point of \( X \) as follows:

\[
 u(X) = \sum_{k=1}^{n} \phi_k(X) u_k = \phi^T u \tag{16} 
\]

Here \( X \) is an arbitrary point in the problem domain and with a circular support domain (e.g. \( X = [x \, y]^T \) in 2D). The term of \( n \) is the number of nodes lied in the support domain of the \( X \), \( u_k \) is the nodal field variable at the kth node in the support domain, \( u \) is the vector of elements \( u_k \), \( \phi(X) \) is the kth element of the shape function vector \( \phi \) (which corresponds to kth node of the support domain).\(^{3} \)

3.2. Shape Function Creation

Creating of the shape functions is the most important issue in FPM methods. The challenge is how to create the shape functions using only nodes scattered arbitrarily in a domain without any predefined mesh to provide connectivity of the nodes. A series of methods are proposed to construct the shape functions.\(^{3} \) In this work the moving least square (MLS) approach is used to construct the shape function. MLS method first approximates the field function by:

\[
 u^h(X) = \sum_{j=1}^{m} p_j(X) a_j(X) = p^T(X) a(X) \tag{17} 
\]

Where \( p_j(X) \) is the jth component of the vector \( p(X) \) which is termed “base interpolating function” and contains \( m \) monomial basis functions. For a 2D problem we can specify

\[
 p(X) = [x \, y]^T \quad \text{for} \quad m = 3 \tag{18} 
\]

and

\[
 p(X) = [x \, y \, x^2 \, y^2]^T \quad \text{for} \quad m = 6 \tag{19} 
\]

In the present work, we use the interpolation function with 3 monomial basis functions \((m = 3)\). Also in Eq. (17) \( a(X) \) is the coefficients vector of elements \( a_j(X) \). Therefore, value of the variable function is approximated at each point like \( X \) as a combination of values of the basis functions at that point each weighted by \( a_j \). The only work to be done is to find suitable values for the coefficients \( a_j \).

Assume \( X_1, X_2, \ldots, X_n \) are nodes located in the support domain of \( X \) and \( u_1, u_2, \ldots, u_n \) are their corresponding nodal values. Figure 3 depicts this support domain. Suppose \( X_k \) to be one of the domain nodes in vicinity of the point \( X \), using Eq. (17) the \( u_i \) can be approximate using value of \( a \) at \( X \):
For each node like $k$ in the support domain, the squared error of the Eq. (20) can be written as a function of $X$:

$$E_k(X)=[p^T(X_k)a(X)-u]_2^2$$

(21)

Apparently, as $X$ gets closer to $X_k$, $E_k(X)$ is expected to be smaller. Thus an appropriate formula for $a(X)$ can be obtained by performing a minimization task in which each of the error functions $E_k(X)$ is minimized to some degree considering degree of nearness of $X_i$ to $X_k$. For this purpose, the following function should be minimized:

$$J(X) = \sum_{k=1}^{n} W(X,X_k)E_k(X) = (P^T a - u)^TW(P^T a - u)$$

(22)

Here $W(X,X_k)$ is called the weight function which should be chosen such that to have larger values when $X$ and $X_k$ are closer together. Here we have chosen the exponential weight function as follows as:

$$W(X,X_k) = \exp\left(\frac{(X - X_k)^T(X - X_k)}{\sigma^2}\right) \begin{cases} 1 & |X - X_k| \leq R \\ 0 & |X - X_k| > R \end{cases}$$

(23)

According to Eq. (23), the weight function would be 0 when the point $X_k$ is located out of support domain of $X$ i.e. $|X - X_k| > R$. The term $R$ is the radius of the support domain and is a function of point step. The value of point step considered in this paper is 0.003 m. Here $\sigma$ is a constant number. The matrices of $P$, $u$, $a$ and $W$ are defined as:

$$P = [p(X_1) \ p(X_2) \ ... \ p(X_n)]$$

(24)

$$a = [a_1 \ a_2 \ ... \ a_n]$$

(25)

$$u^T = [u_1 \ u_2 \ ... \ u_n]$$

(26)

$$W = \begin{bmatrix} W(X,X_1) & 0 & \cdots & 0 \\ 0 & W(X,X_2) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & W(X,X_n) \end{bmatrix}$$

(27)

In MLS approximation, at an arbitrary point $X$, $a(X)$ is chosen to minimize the weighted residual (Eq. (22)). The minimization condition requires:

$$\nabla_a J(X) = 0$$

(28)

$$\nabla_a J(X) = 2PW(P^T a - u) = 0$$

(29)

Equation (29) is written as Eq. (30):

$$PWP^T a(X) = PWu$$

(30)

For simpler notation let us to define new matrixes as follows:

$$A = PWP^T$$

(31)

$$B = PW$$

(32)

Therefore the matrix of coefficients could be written as:

$$a(X) = A^{-1}Bu$$

(33)

To consider the Eqs. (17) and (33) it is possible to write the filed function as follows:

$$u(X) = p^T(X)A^{-1}Bu = \phi^T u$$

(34)

Where the term of $\phi$ the shape function. Please note that in this formulation only the shape function is a function of $X$ and it is very useful point, because for solving of differential equation by FPM, the derivations are considered only on the shape function.\(^\text{11}\) The first derivative of shape function could be written as follows:

$$\phi_x = p_x^T A^{-1} B + p_y^T A^{-1} B_y + p_y^T A^{-1} B_{y}^T$$

(35)

The second derivative of shape function is:

$$\phi_{xx} = p_{xx}^T A^{-1} B + p_{xy}^T A^{-1} B_y + p_{xy}^T A^{-1} B_{y} + p_{yy}^T A^{-1} B_{yy}$$

(36)

Where

$$A^{-1} = A^{-1} A^{-1} A^{-1} A^{-1} + A^{-1} A^{-1} A^{-1} A^{-1} A^{-1}$$

(37)

The term of $(\ )_x$ is the first derivative and the term of $(\ )_{xx}$ is the second derivative.

3.3. Solution of the Governing Equation by FPM

FPM is applied to solve the energy equation with boundary conditions of the continuous casting of bloom in the various cooling area. Figure 4 shows the problem domain of bloom represented by a series of scattered nodes.

Equation (1) is solved for the nodes located in the problem domain; Eq. (5) is Neumann boundary conditions and is solved for the nodes located on the boundary and finally Eq. (12) is Dirichlet boundary condition is considered for all of nodes at the time of zero. For a convection-diffusion problem such as energy equation, a special treatment is needed to stabilize the numerical approximation.\(^\text{10}\) Onate et al. have stabilized the Neumann boundary using "residual stabilization technique".\(^\text{10}\) They submitted Eq. (39) as st-
...where
\[ r = k(T)\nabla^2 T + Q_s = k(T) \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + Q_s \quad \ldots \quad (40) \]

The term of \( Q_s \) is a source term. The term of \( h \) is characteristic length and can be found by using the searching exact nodal values for the simple 1D problem with \( Q_s = 0 \). Application of this concept for FPM by Onate et al. gives

\[ h = \begin{cases} \frac{\alpha h}{4} & \text{for quadratic interpolations} \\ \frac{\alpha h}{2} & \text{for linear interpolations} \end{cases} \quad \ldots \quad (41) \]

Where \( \alpha \) is defined as a function of Peclet number as follows:

\[ \alpha = \frac{1 + \sum_{i=1}^{n} \phi_i}{n} \quad \ldots \quad (42) \]

The term of \( h \) is measured along the streamline between the end points for a particular support domain as shown in Fig. 3.

In the first step let us to discrete the energy equation in the time space of any node of \( k \) in the support domain including the internal nodes (Eq. (1)) as follows:

\[ \rho(T_k') C'(T_k') \frac{T_k' + T_k + T_i'}{\Delta t} = k(T_k') \left[ \left( \frac{\partial^2 T_k'}{\partial x^2} + \frac{\partial^2 T_k'}{\partial y^2} \right) - \frac{T_k + T_i'}{\Delta t} \right] \quad \ldots \quad (43) \]

and for the support domain including the points lied on the boundaries

\[ - k(T_k') \left[ n \sin \theta \frac{\partial T_k'}{\partial x} + n \cos \theta \frac{\partial T_k'}{\partial y} \right] = q_n + \frac{h}{2} \left[ k(T_k') \left( \frac{\partial^2 T_k'}{\partial x^2} + \frac{\partial^2 T_k'}{\partial y^2} \right) \right] \quad \ldots \quad (44) \]

Table 1. The practical conditions and data used for the numerical simulation of bloom–normal conditions.

| Parameter       | Value                  |
|-----------------|------------------------|
| Mold dimensions | 0.23 x 0.25            |
| Mold length     | 0.78                   |
| \( V_c \) - m\ min^{-1} | 0.75                 |
| Mold level - %  | 85                     |
| \( Q \) - lit min^{-1} | 2347               |
| \( T_{\text{surro}} \) - °C | 1530               |
| \( T_{\text{ref}} \) - °C  | 1372                  |
| \( T_{\text{ disgusting}} \) - °C | 1492             |
| \( k_f \) - W/mK | 39                     |
| \( k_i \) - W/mK  | 21.6+8.35x10^3T       |
| \( \rho_f \) - kg/m^3 | 7965.98-0.619T     |
| \( \rho_i \) - kg/m^3 | 8105.91-0.5991T     |
| \( C_f \) - J/kgK | 824.615T              |
| \( C_i \) - J/kgK  | 429.849+0.1498T        |
| \( \Delta T^* \) - °C | 4.9                 |
| \( \Delta H_{\text{melt}} \) - J/kg | 243000         |

Here, the term into the bracket in the left hand is \( \partial T/\partial x \) when \( \theta = 0 \) and is \( \partial T/\partial y \) when \( \theta = 90 \), otherwise is related to \( \partial T/\partial n \) at the corner of problem domain (see Fig. 1). In fact, the terms of unknown temperature and its derivatives presented in the Eqs. (43) and (44) for any node of \( k \) at time \( t \) are calculated by FPM as follows:

\[ T_k' = \phi^T T' \quad \ldots \quad (45) \]

\[ \frac{\partial T_k'}{\partial x} = \phi^T \frac{\partial T'}{\partial x} \quad \ldots \quad (46) \]

\[ \frac{\partial^2 T_k'}{\partial x^2} = \phi^T \frac{\partial^2 T'}{\partial x^2} \quad \ldots \quad (47) \]

Here the derivatives of the shape function are calculated by Eqs. (35)–(38).

4. Results and Validation

Table 1 shows the operational and solidification data during continuous casting of a bloom which has been experienced a breakout in the spray cooling region (almost at the position of 2 m from the meniscus). A long part of this bloom which depicts the solidified shell thickness at the mold and spray cooling regions has been shown in Fig. 5. This breakout bloom is used for measurement of the solidified shell thickness. After that the measured shell thickness would be compared with the data simulated by the present FPM. Figure 6 compares the solidified shell thickness simulated by the present FPM and measured on the breakout shell (according to Fig. 5). As it can be seen from Fig. 6, the shell thickness of breakout section coincide well with the line of \( f_s = 0.5 \) obtained by this analysis.

Except of solidified shell thickness, the surface temperature of bloom predicted by the present FPM would be compared with the both surface temperature predicted by FVM and with the measured data by a thermovision machine (thermography method). Figure 7 shows a thermograph of the surface at the radiation region. This figure de-
The thermograph of the bloom at the distances of 15, 15.25, and 15.5 m from the meniscus (where is close to the unbending point and it was safe for measurement of temperature). Because of existence of high concentration of water vapor at the spray cooling region, it was not easy to measure the surface temperature of bloom at the spray cooling region by the thermovision machine. Figure 8 compares the surface temperature of the bloom simulated by FPM with both FVM and measured data. As it can be seen from Fig. 8, the profile of surface temperature simulated by FPM has a good agreement with the FVM. However, the temperature simulated by FVM is almost 6–13°C higher than the results of FPM. Since these methods (FVM and FPM) are based on two different basic theories, existence of a trivial difference between the results of FVM and FPM could be expected. This result that the FVM shows higher temperatures with respect to FPM could be raised from several reasons such as mesh size, time step etc. The comparison of the simulated results with the measured data shows that FPM is more near to measured data with respect to FVM. However both FPM and FVM lay in the range of standard deviations.

Figure 9 shows the lateral temperature profile at the mold exit simulated by the FPM and FVM. According to this figure, as the distance from chilled surface is increasing, the lateral temperature is increased and this procedure is similar for FPM and FVM. This trace also shows a good agreement between both FPM and FVM.

Another important investigation in the thermal analysis of the continuous casting process is to determine the position of the solidus and liquidus isotherms from the chilled surface. Therefore this parameter also is checked in order to validation of the present thermal analysis by FPM. Figure 10 shows the position of solidus and liquidus temperature from the chilled surface at the length of strand simulated by both FPM and FVM. This figure is plotted at $f_s=1$ for the solidus temperature and $f_s=0$ for the liquidus temperature.

Fig. 5. The breakout bloom representing the solidified shell at the mold region. Foot roll region and mobile section region. The breakout has been happened due to fracture of the shell at the end of mobile section.

Fig. 6. The solidified shell thickness simulated by FPM and measured on the breakout section.

Fig. 7. The thermograph from cooling bloom at the radiation region.

Fig. 8. The surface temperature of bloom at the differerence cooling zones simulated by FPM and FVM and also measured by the thermovision machine.

Fig. 9. The lateral temperature at the mold exit simulated by FPM and FVM.

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Fig. 10. The position of solidus and liquidus temperature from chilled surface at the length of strand simulated by both FPM and FVM.

According to Fig. 10 the solidus and liquidus temperatures simulated by the present FPM are similar to results of FVM. For better comparison the part of curve related to the mold area is plotted at the corner of figure to show real difference between FPM and FVM. However, Fig. 10 depicts that the solidified shell thickness simulated by FVM is slightly thinner with respect to the results of FPM. The reason of this result refers to temperature distribution calculated by these methods. The temperature calculated by FVM is higher, so the shell thickness is slightly thinner.

In fact, this figure shows that the length of mushy zone (the difference between liquidus and solidus isotherms) as important parameters in the hot tearing study simulated by FPM is very close to the result of FVM.

5. Conclusion

To simulate the solidification process of steel during continuous casting process, a FPM was applied and the thermal analysis of a steel bloom was done for the various cooling regions. The thermal analysis results such as the surface temperature, lateral temperature, solidus position and liquidus position simulated by FPM were compared with the same results simulated by FVM. The comparison depicts a good agreement between the results simulated by both FPM and FVM. Also the measurements of the surface temperature of the bloom in the radiation region validate the results of FPM as well as FVM. Furthermore, the solidified shell thickness simulated by FPM (corresponding to $f_s=0.5$) was compared with the measured shell thickness on a breakout shell and a good matching was seen. These investigations depict that FPM is a potential numerical analysis tool and would be valuable for the thermal analysis of continuous casting process.

The advantages of this FPM compared with FEM are to avoid the necessity of mesh generation and compared with FDM is the facility to handle the boundary conditions and the non-structured distribution of points. Furthermore, meshing is not needed, where the non-connectivity concept is involved. It also means that it is not necessary to have relationships between nodes, which helps adding or deleting points, or nodes, whenever and wherever needed. Also FPM would be a useful method when the large scale deformation analysis (such as thermo-mechanical and cracking analysis in the continuous casting process) is required and thermo-mechanical and cracking analysis is not possible without thermal and solidification analysis. The results of the present work show FPM can be used to analysis the heat and solidification during continuous casting process.

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