THERMO-MECHANICAL MODELLING OF HOT STRIP ROLLING USING FINITE ELEMENT TECHNIQUE

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ABSTRACT

This paper presents a new model based on an Eulerian finite element technique for the analysis of hot strip rolling process. The advantage of this model comes from using the Eulerian fixed mesh technique with an imaginary friction layer at the interface which makes it easier to model the heat transfer and the temperature distribution in the roll. An iterative scheme is developed to deal with strong correlation between metal flow characteristics and temperature distribution in the strip. This model is capable of predicting accurately the velocity and stress fields in the strip and temperature field in both the strip and the roll. The effects of rolling speed, interface heat transfer coefficient and reduction ratio on the thermal behaviour of the strip/roll system are investigated. The predictive capability of the presented model is validated by comparing the results obtained with those available in the literature with which good agreement is found.

***Keywords* :** Hot strip rolling, Finite element modelling, Themo-mechanical modelling, Eulerian fixed mesh technique.

INTRODUCTION

The metal rolling process involves large deformation and high roll pressure which generate a large amount of heat from plastic deformation and interfacial friction. Metal flow characteristics and flow stress are influenced by temperatrue distribution. Also, information on metal flow in the rolling process is vital for the quality improvement of the rolled product. On the other hand, studying the temperature distribution in the roll is necessary since the induced thermal stresses have great effect on roll life, cracking and spalls. Several investigations of thermo-mechanical modelling of rolling processes have been already made. Their scope ranges from highly simplified closed-form solution to recent sophisticated numerical methods giving more accurate solutions. Two numerical techniques were used: finite difference and finite element. Tseng [1] and Tseng *et al* [2] presented a complex model describing the thermal behaviour of the strip and the roll simultaneously based on the Eulerian finite difference method. Their model assumed that the surface temperatures of the strip and the roll approach the same value. A more elaborate solution was presented by Laasraoui and Jonas [3] based on an explicit finite difference method for the on-line predictions of the temperature distribution during hot rolling.

Recently, the finite element technique based on computer simulation has been proven to be an effective tool for accurate modelling of hot rolling process. Updated Lagrangian based finite element formulation has been widely and probably the most common one used for strip rolling processes. However, employing the updated Lagrangian requires complex remeshing and many iterations of stepping through the process [4,5]. Zienkiewicz *et al.* [6] presented the first attempt for a coupled analysis of heat transfer and plastic flow. However, their proposed model considered either the strip or the roll alone. Hwang *et al.*[7] developed two finite element computer simulation programs, one for the strip and the other for the roll. Beynon *et al.* [8], Ponter *et al.* [9] and Silvonen *et al.* [10] studied coupled thermo-mechanical behaviour of hot strip rolling. However. their analyses lack information about roll modelling. Montmitonnet *et al.* [11] neglected the heat conductivity through the roll and assumed that the effect of contact with the strip is applied only to the surface nodes of the roll. Lenard and his coworker [12-16] studied thoroughly the thermal behaviour of the strip in hot rolling using the finite element technique. In their analysis, however, they assumed sticking friction between the strip and the roll and detailed informations about roll modelling are not given. A similar approach was presented by Dawson [17] in which sticking friction between the strip and the roll is assumed. Micari [18] assumed that the roll has infinite stiffness and heat capacity and the roll temperature remains constant at 200°C. A more sophisticated finite element model was recently presented by Lin and Shen [19] in which they considered the strip curvature caused by the difference in the heat transfer coefficient as well as the rotation speed between the upper and the lower roll. The forgoing models differ in their assumption of boundary conditions varying principally with regard to whether the roll/strip contact is assumed perfect or not. Despite this unquestionable progress, there are still some insufficiently explored areas such as accurate modelling of the heat transfer at the interface as well as the heat distribution through roll.

In the present work, a new model for analyzing the coupled thermo-mechanical behaviour of the strip/roll system is introduced. This model based on the Eulerian finite element technique is capable of dealing with the coupled problem of metal flow, temperature field in the strip and the heat transfer to the roll. An iterative scheme is developed for dealing with the strong correlation between the metal flow characteristics and the temperature distribution in the strip. The material behaviour at high temperature is assumed to be governed by Shida equations [12]. The accuracy of the developed iterative scheme and the developed computer program is validated by comparing the temperature distribution with other numerical solutions and experimental data found in the literature. The effects of rolling speed, interface heat transfer coefficient and reduction ratio on the thermal behaviour of the strip/roll system are investigated

PROBLEM FORMULATION

Finite Element Formulation for Metal Flow

Since the detailed features of the Eulerian finite element technique for cold strip rolling and the derivation of the basic equations have been given in earlier publications [4,5], only the important formulae will be repeated here for completeness.

The velocity field is determined based on the virtual power principle as follows:

$$\int_V \sigma_{ij}\,\delta\dot{d}v_{ij}\,dV = \int_A S_i\,\delta v_i\,dA \tag{1}$$

with

$$\dot{d}_{ij} = \frac{1}{2}\left(v_{i,j} + v_{j,i}\right),\ v_{i,j} = \frac{\partial v_i}{\partial x_j} \tag{2}$$

The final incremental equilibrium equation is obtained in the following form:

$$K_{\alpha\beta}\Delta U_\beta = \Delta R_\alpha \tag{3}$$

with

$$k_{\alpha\beta} = \int_V 1/4D_{ijkl}(\Psi_{i\beta,j} + \Psi_{j\beta,i})(\Psi_{k\alpha,l} + \Psi_{l\alpha.k})dV \tag{4}$$

$$\Delta R_\alpha = \int_A S_i\Psi_{i\alpha}dA \tag{5}$$

where $K_{\alpha\beta}$ is the finite element incremental stiffness matrix. D_{ijkl} is the fourth order material constitutive behaviour tensor, ΔR_{α} is the increment of the applied load vector and finally $\Psi_{i\alpha}$ are the shape functions.

The material characteristics are assumed to be elasto-plastic obeying von-Mises yield criteria. The material behaviour at high temperature is assumed to be governed by Shida equations [12] in which the flow strength is given in terms of strain, strain rate, temperature and carbon content.

Finite Element Formulation For Temperature Analysis

The governing equations for the temperature field are developed based on the heat balance equation as follows:

$$K\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+Q=\rho\, c_p\frac{\partial T}{\partial t} \qquad (6)$$

or

$$\nabla^T K \nabla T + Q = \rho\, c_p \frac{\partial T}{\delta t} \qquad (7)$$

where Q is the rate of heat generation due to plastic deformation, The rate of heat generation takes into account the plastic work and the energy accumulated in the material due to the increase of dislocation density. It is expressed by the equation proposed by Rebelo and Kobayashi as follows [20]:

$$Q=\int_v\left[\overline{\sigma}\,\dot{\varepsilon}-\upsilon a\varepsilon+\upsilon b\gamma\exp.\left(\frac{D}{kT}\right)\right]dv \qquad (8)$$

where v is the energy per unit width of dislocation, γ is the dislocation density and k is the Boltzman constant.

The heat flux due to friction along the interface can be calculated as follows:

$$q=\int_s \tau_s\|\Delta v\|dS \qquad (9)$$

Where $\tau_s=(m/\sqrt{3})\sigma m$ (10)

where m is the friction factor and σ_m is the flow stress.

Introducing temperature distribution in the form $T = N_k T_k$, and assuming linear temperature variation during increment of time Δt, yields

$$[2H+(3/\Delta t)C]T_{i-1}=[-H+(3/\Delta t)C]T_i-3P \qquad (11)$$

$$H_{kl}=\int_v(\nabla^T N_k)k(\nabla N_k)dV+\int_s hN_k N_l d \qquad (12)$$

$$C_{kl}=\int_v N_k c_p \rho N_l dV \qquad (13)$$

$$P_L=-\int_v QN_l dV-\int_s qN_l TdS \qquad (14)$$

In Equation 11, T_i is the initial temperature field and T_{i+1} is the temperature field after interval of time ΔT.

Concerning the heat transfer coefficient at the interface, many investigators have attempted to estimate its value by various means. The values they derived vary by several orders of magnitudes. Malinowski *et al.* [21] reviewed and discussed this aspect thoroughly and indicated that it is far from being solved.

FINITE ELEMENT DISCRETIZATION

For the finite element modelling, only the upper half of the strip/roll system is considered. A network of 12x8 eight-nodes isoparametric plane strain elements is employed to model the strip in the x and y directions as shown in Figure 1. Concerning the roll modelling, it is assumed that there is no elastic deformation except in the sector which is in contact with the strip as shown in Figure 1. A network of 7x9 elements is used in roll modelling. The friction layer technique developed by Liu *et al.* [22] is employed to model the strip/roll interface friction. In this technique, an extra imaginary layer of elements is added on each surface on which friction acts. It is believed that employing the Eulerian fixed mesh technique with the imaginary friction layer makes it easier to separate the surface nodes of the strip and the roll in the finite element model. Therefore, the heat transfer through the strip/roll interface can be easily modelled. This represents a difficult task if other techniques are employed. It should be noted that there is a large and localized temperature gradient in contact area between the strip and the roll due to friction heat flux and heat transfer to the roll. Therefore, a fine mesh is employed at the contact area to maintain good accuracy in the computations.

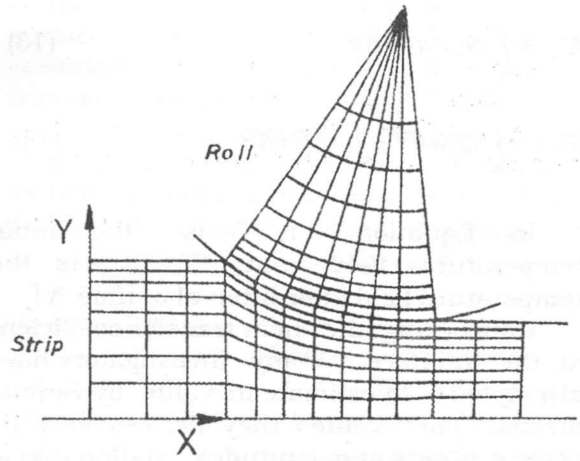

Figure 1 Finite element model used for the strip and the roll

ITERATIVE SOLUTION SCHEME

As stated above, metal flow is influenced by the temperature distribution in the strip since the flow stress strongly depends on it. On the other hand, the temperature distribution is affected by the heat generation due to plastic deformation and friction at the roll/strip interface. In order to model this strong correlation, an iterative scheme is developed.

In the developed finite element simulation program, an increment of time is applied, then the velocity field is computed. The stress, strain and strain-rate fields are calculated. The heat generated due to plastic deformation is computed. The heat flux due to friction is determined knowing the relative velocity and the tangential stresses along the interface. It is assumed that one-half of friction heat flux is absorbed by the strip, with other half absorbed by the roll. The program solves for the temperature distribution in the strip and the roll simultaneously. The temperature field is used to determine the material resistance to deformation in each element. Then, a new time increment is applied. This procedures are continued until the end of contact between the strip and the roll.

As discussed earlier by the author in References 4 and 5, the Eulerian finite element mesh is fixed and the material crosses its boundaries. In each time increment, the field variables in the strip such as: stress, strain, strain rate and temperature are interpolated to obtain those of the material-particles which come to the fixed integration points. For the roll, as discussed above, only the sector which is in contact with the strip is modelled. In each time increment, the temperature field is interpolated to obtain the state of the new material-particles coming to the fixed integration points. For the sake of comparison, it is assumed that the material crosses the left hand boundary of the sector with a constant temperature of 40°C. However, in practice its temperature may have different values due to radiation and convection or water cooling which can be modelled using the heat transfer equations.

RESULTS AND DISCUSSION

The developed computer program has been employed to simulate various processes of hot rolling of low carbon steel strips for which conditions are summarized in Table 1. The data of the first two cases has been chosen so that the obtained results can be compared with those available in the literature [11,12]. The roll radius is 120 mm. The strip temperature is 825 °C in all cases except for the second case equals 870 °C. Thermal properties of the strip and the roll are given in Table 2. The heat transfer coefficient at the interface 4800W/m^{2}K, determined by Pietrzyk and Lenard [23] for hot rolling in laboratory conditions with a constant roll temperature of 40 °C is used. In the analysis k, ρ and C_p

are assumed to be temperature independent, though in fact this is not true.

Table 1 Process conditions used in the simulation

Case Number	Thickness mm	Roll speed rpm	Heat transfer coefficient W/m^{2}k	Reduction ratio
1	38	4	4800	20
2	19	4	4800	21.3
3	38	8	4800	20
4	38	16	4800	20
5	38	4	2400	30
6	38	4	0	20
7	38	4	4800	10
8	38	4	4800	30

Table 2 Thermal properties of the strip and the roll

	Strip	Roll
Material	AISI 1018	1078 Steel
Density ρ (kg/m^3)	7638	7837
Thermal conductivity K (kW/m^2°K)	30	45.2
Heat capacity c_p (kJ/kg.°K)	0.636	0.54

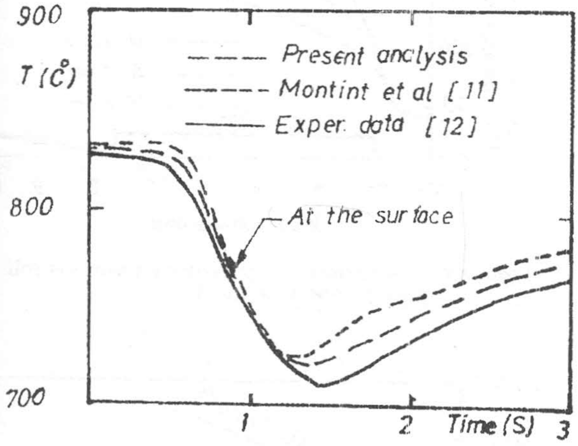

Figure 2 Time-temperature profile at the strip surface in case 1

Figures 2 and 3 show a comparison between the present results, pervious numerical results [11, 12] and experimental data [12] for the first two cases. The comparison is reasonable indicating that the predictive capability of the proposed model is good. In both cases, the amount of heat transferred to the roll exceeded the heat generated at the interface resulting in significant drop in the surface temperature of the strip in the roll-gap. In the second case, there is a small rise in temperature at the center due to plastic deformation. Figure 4 depicts temperature distribution in the strip and the roll in case 1. It is shown that intensive heating of the roll surface has occurred with the maximum temperature of 285 °C at the exit plane. Also, the strip temperature within the roll-gap increases at the centre while at the surface it decreases by about 100 °C.

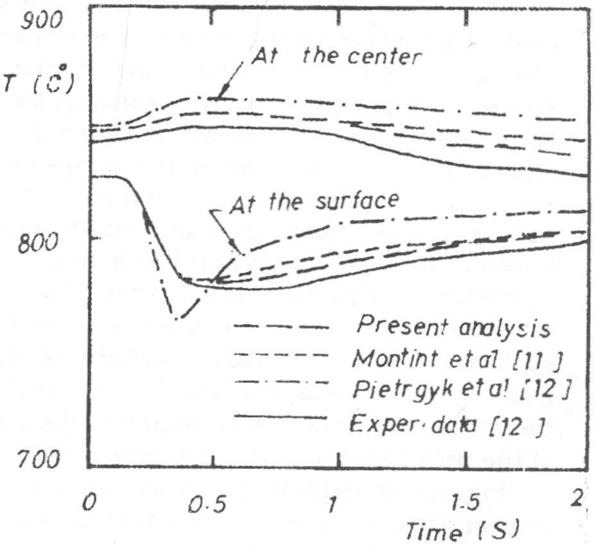

Figure 3 Time-temperature profiles at the strip surface and at the centre in case 2

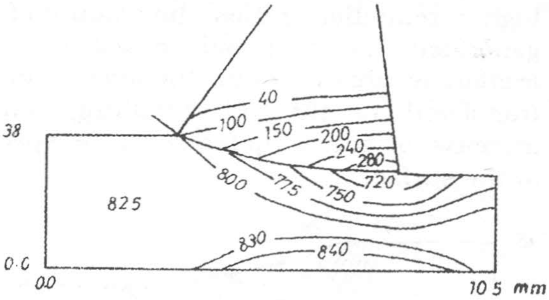

Figure 4 Temperature distribution in the strip and the roll in case 1

The effective strain-rate distribution in case 1 is shown in Figure 5. As expected, it is observed that higher effective strain-rates exist near the initial point of contact between the strip and the roll.

The effect of the rolling speed on the thermal behaviour of strip/roll system is investigated. Figure 6 shows the variation of the temperature at the strip surface and at the centre in the roll-gap in cases 1, 3 and 4. The roll surface temperature decreases as the roll speed is increased due to short time of contact as can be seen from Figure 7 Also, at the beginning of contact the roll surface temperature increases rapidly then the rate of temperature rising decreases.

The effect of variable heat transfer coefficient through the strip/roll interface is also investigated. The variation of the roll surface temperature at the roll-gap for the two cases 1 and 5 is shown in Figure 8. It is shown that the maximum roll temperature decreases by almost 35% when the value of the interface heat transfer coefficient is lowered to one-half. When the heat transfer coefficient equals zero (case 6), the maximum temperature occurred at the strip surface with an average increase of 40°C from the initial temperature. It is shown that the strip/roll system is sensitive to the value of the interface heat transfer coefficient.

Figure 9 depicts the variations of the temperature at the strip surface and at the centre for different reduction ratios, cases 1, 7 and 8. For the case of lower reduction ratio, the strip surface temperature is not much affected due to short time of contact and less expenditure of plastic energy. For higher reduction ratios, the amount of heat generated due to plastic deformation and friction is greater than the amount of heat transfered to the roll resulting in an increase of the strip temperature specially at the surface.

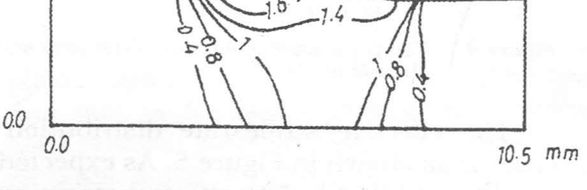

Figure 5 Effective strain rate in the strip during rolling in case 1.

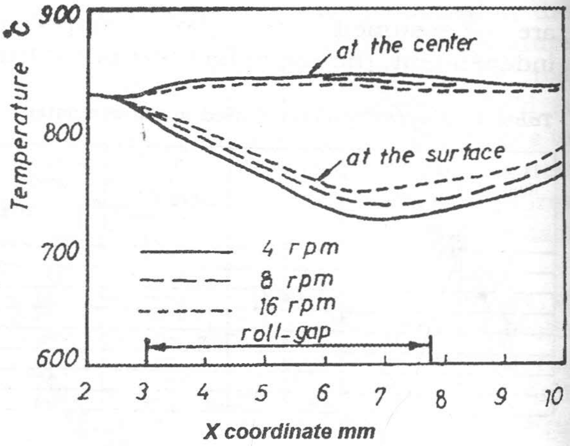

Figure 6 Temperature at the surface and at the centre of the strip for various roll speed, case 1, 3 and 4

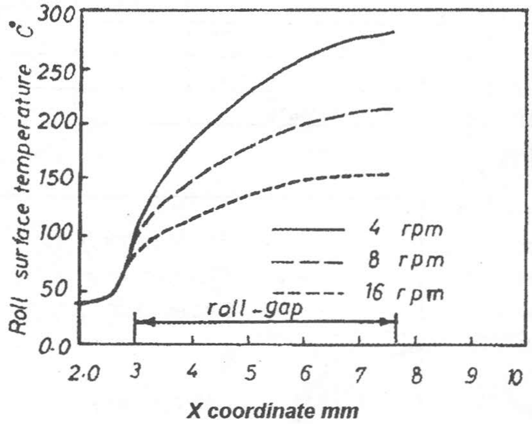

Figure 7 Roll surface temperature for various roll speed, case 1, 3 and 4.

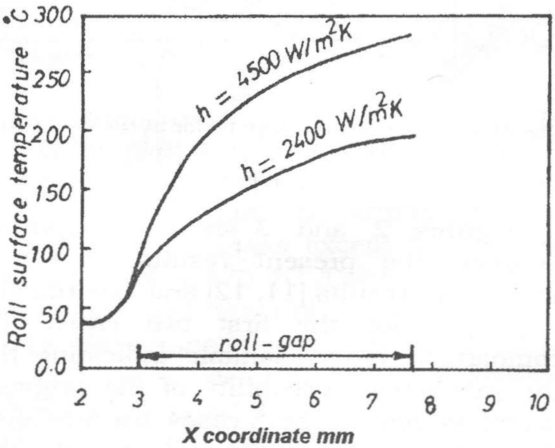

Figure 8 Roll surface temperature for different heat transfer coefficient, case 1 and 5.

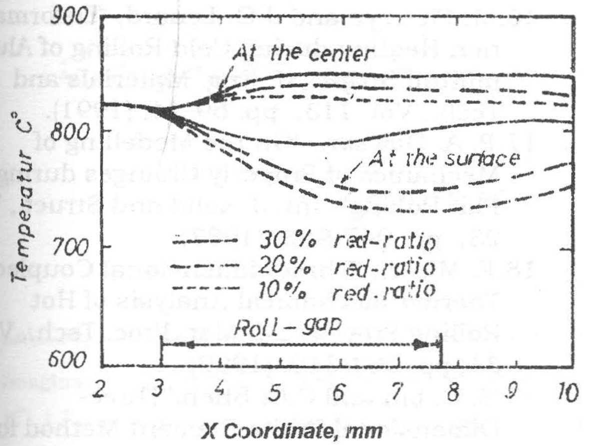

Figure 9 Temperature at the surface and at the centre of the strip for different reduction ratios, cases 1, 7 and 8.

CONCLUSIONS

A new finite element model based on the Eulerian fixed mesh technique is presented which is capable of predicting the metal flow and the temperature distribution in the strip and the roll. An iterative technique is developed to deal with the strong correlation between the metal flow characteristics and the thermal behaviour of the strip/roll system. It is found that employing the Eulerian fixed mesh technique together with the imaginary friction layer makes it easier to model the heat transfer through the strip/roll interface which represents a tedious task if other technique would has been used. The predictive capability of the presented model is validated by comparing the results obtained with those available in the literature. The model has been applied to study the effect of various parameters. It is found that the thermal behaviour of the strip/roll system is significantly affected by roll speed, interface heat transfer coefficient and finally with the reduction ratio. It may be expected that the proposed model will be of great importance in optimizing the process parameters in terms of product quality and roll life

NOMENCLATURE

A	loaded area
a,b	material constants
c_p	specific heat
D	activation energy of diffusion
h	heat transfer coefficient
k	Boltzman constant
K	heat conductivity
m	shear factor
N_i	interpolation functions
S_i	surface traction
T	temperature
T_i	nodal temperature vector
V	current volume
v_i	velocity of material point
x_i	coordinates of material point
$\psi_{i\alpha}$	shape functions
ρ	material density
σ_{ij}	Cauchy stress tensor
$\overline{\sigma}$	effective stress
$\dot{\overline{\varepsilon}}$	effective strain rate

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Received May 21, 1998
Accepted September 7 , 1998

النمذجة الحرو-ميكانيكية لدرفلة الشرائح على الساخن باستخدام طريقة العناصر المحددة

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ملخص البحث

يقدم البحث نموذجا جديدا من طريق التحليل الرقمى لعملية درفلة الشرائح على الساخن مستخدما طريقة أويلر للعناصر المحددة. يمتاز هذا النموذج باستخدام شبكة ثابته للعناصر المحددة (Fixed mesh) مع طبقة من العناصر التحليلية (Imaginary layer) عند سطح التلامس وبهذا يمكن نمذجة انتقال الحرارة من الشريحة للدرافيل وكذلك دراسة توزيع درجات الحرارة فى كل من الشريحة والدرافيل بدقة. تم عمل طريقة تبادلية لدراسة التأثير المتبادل بين خواص معدن الشريحة وتوزيع درجات الحرارة بها. بالنموذج المقترح يمكن التنبؤ بتوزيع المسرعات و الاجهادات ودرجات الحرارة فى الشريحة وكذلك توزيع درجات الحرارة بالدرافيل بدقة عالية. تم دراسة تأثير كل من سرعة الدرفلة ومعامل انتقال الحرارة عند سطح التلامس ونسبة التخفيض فى السمك على السلوك الحرارى للشريحة والدرفيل معا. ولدراسة جدوى النموذج تمت مقارنة النتائج المحسوبة باستخدامه مع النتائج المعملية والرقمية الموجودة بأبحاث سابقة وقد اظهرت المقارنة التوافق التام لنتائج النموذج المقترح بمثيلتها المعملية والرقمية.