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Bond Graph Modelling and Simulation of Static Recrystallization Kinetics in Multipass Hot Steel Rolling

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Abstract: In hot rolling, the final thickness of the strip is achieved through plastic deformation of the original stock by a series of counter-rotating rollers. In this work, static recrystallization kinetics in between two stages of steel rolling has been modelled, and simulation studies have also been performed to find out the effect of entry temperature on the recrystallization kinetics. A viable bond graph model has been developed to study the kinetics of the process. Low-carbon steel has been considered for this purpose.

keyword: Pseudo bond graph, static recrystallization, multipass steel rolling, modelling and simulation.

List of notations

Δx	Length of a space-reticule
d_o	Initial grain size
ε	Average strain within the material
i, j	Index of space-reticulation numbering
k, b	Parameters
R_{gas}	Universal gas constant
t	Time
$t_{0.5}$	Half-recrystallized time
T	Absolute temperature of the material
v_s	Velocity of the strip inter-pass zone
V_{ri}	Volume of the recrystallized amount
$\dot{V}_{ri}$	Volume rate of growth of recrystallized amount
V_{total}	Total volume of the space-reticule
X	Volumetric fraction of recrystallized amount

Bond graph elements

0	Common effort junction
1	Common flow junction
C	Energy storing element
Q	Charge of a C element
R	Dissipative element
SE	Source of effort
SF	Source of flow of heat

1 Introduction

In a hot rolling process on metal, the material is given its final shape by plastically deforming the original stock. In this process, the job is drawn by means of friction through a regulated opening between two power-driven rolls. It is seldom possible to achieve the final cross-section in one pass. Therefore, rolling is performed through a number of passes, using different rolling equipment, in a continuous manner. As a result, the thickness of the material gets reduced gradually. In this present work, the thermal phenomena occurring inside and at the surface of the slab in-between two stages of rolling, along with the static recrystallization have been presented. The modelling is done for low-carbon steel.

The main contributions, which have greatly contributed to the promotion of the development of mathematical models for predicting microstructural evolution and final mechanical properties are Irvine and Pickering (1957), Sellars and Whiteman (1979), and Sellars (1980). Sellars proposed the first mathematical model for the prediction of microstructure evolution during multi-pass rolling and suggested the usefulness and the wide possibility of computer technology.

Temperature has a dominating influence on the microstructure and, hence, thermal analysis during rolling is an important aspect. Hollander (1970) first developed the temperature model of hot rolling of flat products by a finite difference technique, and later Harding (1976) produced a more detailed thermal analysis which forms the basis of the finite difference model of SLIM-

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MER [Beynon and Sellars (1992)]. Granda and Shaoqing (1989), Granda and Kong (1993a, 1993b) have developed the bond graph models for the heat transfer phenomena in a stationary material. In previous works, Pal and Linkens (2001a, 2001b, 2001c, 2002) have described the implementation of bond graph methodology for temperature analysis for a single pass in hot steel rolling, and studied the effect of roll gap and roll rotation on temperature during the process. In this present work, a bond graph model of static recrystallization has been done on low-carbon steel, and simulation studies have also been performed to find out the effect of entry temperature on the recrystallization kinetics. The present, and the previous research by Pal and Linkens (2001a, 2001b, 2001c, 2002), have the potential to be integrated with the microstructure model at the runout table cooling, already developed by Pal, Mukherjee and Karmakar (1999, 2002a, 2002b, 2002c), to achieve the final desired microstructure and, thereby, the mechanical properties.

During deformation, dynamic events such as work hardening, dynamic recovery, and dynamic recrystallization occur. Dynamic recrystallization is very important for determining flow stresses within the material, and thereby the rolling loads. In between two passes, the material undergoes the process of static recrystalization and grain growth. Static recovery or recrystallization depends on the microstructure, which emerges from the deformation process of the previous stages [Beynon and Sellars (1992)].

The aim of the present work is to model the static recrystallization process. Bond graph methodology has been used to model the above mentioned kinetics.

2 Bond graph modelling of static recrystallization

The kinetics of static recrystallization in hot steel rolling can be described by the Avrami equation [Beynon and Sellars (1992)]:

$$X = 1 - \exp\left[-0.693\left(t/t_{0.5}\right)^k\right], \tag{1}$$

where X is the volume fraction recrystallized after time t. The exponent k, varies from 1 to 2, is not very much sensitive to deformation parameters, whereas, time for half recrystallized, $t_{0.5}$ changes much. The half-recrystallization time for low-carbon steel is expressed as:

$$t_{0.5} = 2.5 * 10^{-19} d_o^2 \varepsilon^{-4} \exp\left(300000/R_{gas}T\right), \tag{2}$$

where $d_o$is the initial grain size expressed in μm and time is in seconds. ε is the average strain in the previous stage of rolling. The through-thickness temperature of the slab at the exit of the previous stage of rolling would be used as input temperature to the inter-pass zone.

The above Avrami equation for the static recrystallization can be written as :

$$X = 1 - \exp\left(-bt^k\right), \tag{3}$$

where, $b = 0.693/t_{0.5}^k$.

The bond graph model for the above equation is shown in Fig. 1.

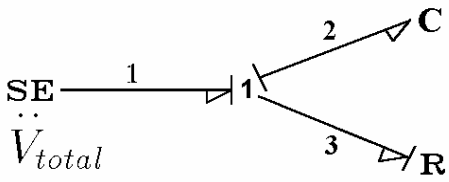

Figure 1 : Bond graph model of Avrami recrystallization process

The value of $K2 = 1$, $R3 = 1/\left(kbt^{k-1}\right)$, and $SE1 = V_{total}$. *SE1* is zero before the start of static recrystallization. The volume rate of recrystallization is obtained from the $Q2$ of the $C2$ element. As $Q2$ increases the effort on bond 3 decreases and hence, the flow returned on bond 3 i.e. the recrystallization rate decreases. Thus, the recrystallization rate depends on the volume of the recrystallized product. The bond graph representation of the static recystallization model is similar to the bond graph structure of Johnson-Mehl-Avrami phase transformation model developed in [Pal, Mukherjee and Karmakar (2002b)].

The space in inter-pass rolling is discretized in several rows and columns along the direction of movement of material and across the thickness of the material (as shown in Fig. 2). During the process of recrystallization, heat loss from the surface of the material takes place because of air-cooling. The bond graph model of temperature variation for the inter-pass rolling is done in a similar way as in temperature distribution in the deformational model [pal and Linkens (2002)]. The Avrami recrystal-

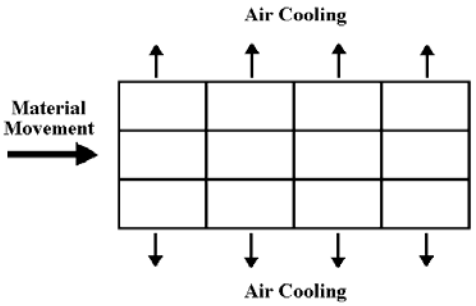

Figure 2 : Discretization for static recrystallization

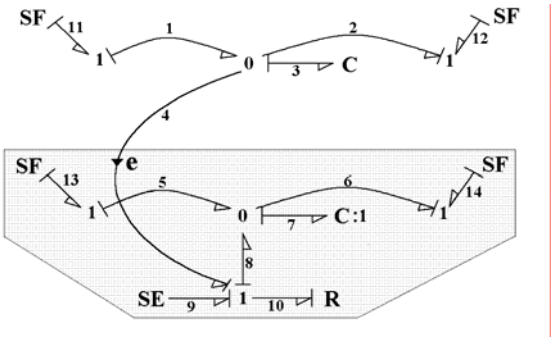

Figure 3 : Bond graph model of recrystallization in a moving continuum

lization kinetics model (as shown in Fig. 1) is for a stationary material and cannot be directly used for a moving continuum. In the case of a moving continuum, the total volume of recrystallized amount is determined by transportation of recrystallized amount across the boundaries of the continuum along the direction of motion and local recrystallization within the control volume.

Accounting for transportation, the volume rate of growth of recrystallized amount in a space-reticule of the $i-$th element can be written as follows:

$$\left(\dot{V}_r\right)_i = \underbrace{\left[\left\{\left(V_{total}\right)_i - \left(V_r\right)_i\right\} \Big/ \left\{1 \Big/ \left(kbt^{k-1}\right)\right\}\right]}_{local-recrystallization} + \underbrace{\left[\left\{\left(V_r\right)_{i-1} v_s/\Delta x_{i-1}\right\}_{in} - \left\{\left(V_r\right)_i v_s/\Delta x_i\right\}_{out}\right]}_{transported-recrystallizd-amount}, \qquad (4)$$

A pseudo bond graph model created from above equation is shown in the shaded part of Fig. 3. This module serves as a building block for modelling recrystallization kinetics in a moving continuum.

The element SE9 and R10 on the 1 junction along with C7 element form the bond graph of the Avrami recrystallization kinetics. However, since the reaction rate of recrystallization depends on the total volume of recrystallized product in a space-reticule, element C7 is attached to a 0 junction along with bond 5 and bond 6 representing inflow and outflow of the recrystallized amount across the boundaries. Element C7, thus, records the total volume of recrystallized amount due to transportation and local recrystallization (coming through bond 8) and develops the effort for proper modulation of the recrystallization.

The amount of recrystallization, which results from the Avrami kinetics, gets depleted from the non-recrystallized amount in the space-reticule at the same rate. This is taken care of by bond 4 with appropriate power direction. Since the bond graph model created to represent the Avrami recrystallization kinetics is independent of volume of non-recrystallization amount, bond 4 is effort activated. If this is not done, the effort due to the amount of non-recrystallized as recorded by the element C3 will cause undesirable enhancement of the reaction rate. In computing the value of SF12 from the above equation, the instantaneous value of Q3 is used for V_{ri}. The values of other three sources of flows are computed in a similar way.

3 Simulation studies

The simulation studies have been performed for low-carbon steel. The model has 25 elements and 8 layers. The total number of system states is 200. The length, width and thickness of the inter-pass zone are considered as 0.3, 0.1, and 0.04 m, respectively. The temperature of the upper two layers of the input to the inter-pass zone is less than the core temperature. This is due to the fact the upper surface is in contact with the roll surface and the temperature of the later is much less than the slab temperature. Bond graph software SYMBOLS (2000) was used to perform the simulation studies. This Windows based software is written on C++ platform. The equation generation and the speed of simulation are remarkably faster than its previous Pascal language based DOS version software.

The surface temperature plot is shown in Fig. 4. The high rise in temperature observed is due to heat conduc-

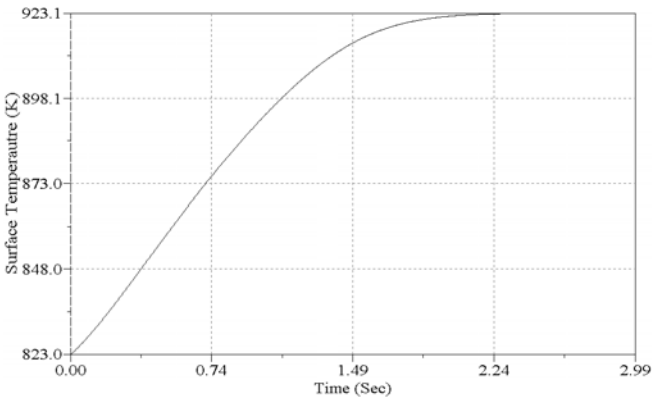

Figure 4 : Surface temperature of a space-reticule at inter-pass rolling zone

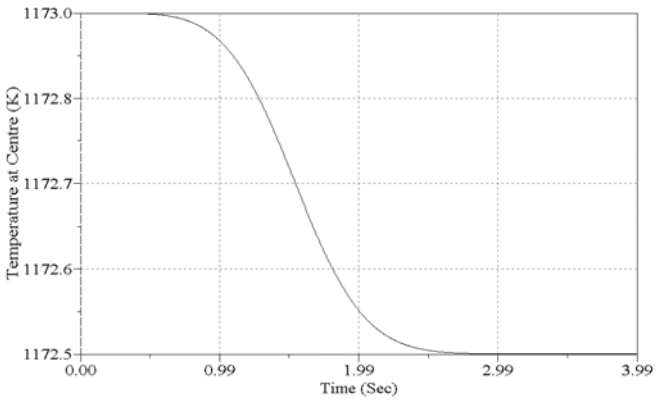

Figure 5 : Centre temperature of a space-reticule at inter-pass rolling zone

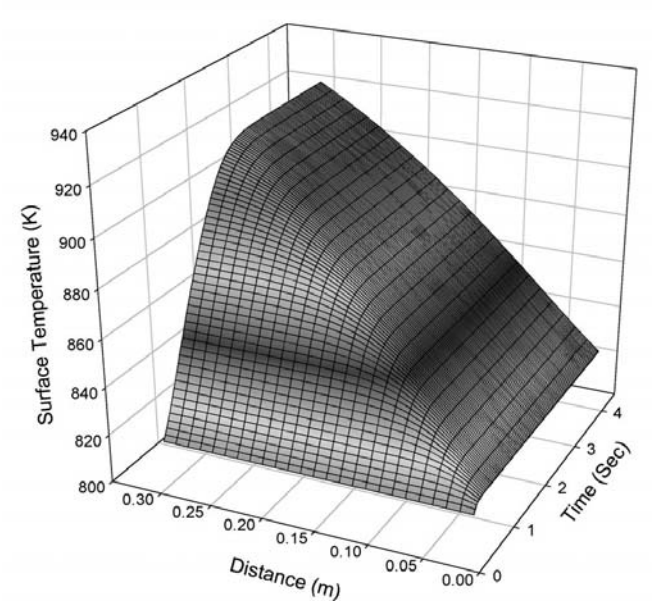

Figure 6 : Surface temperature plot at inter-pass rolling zone

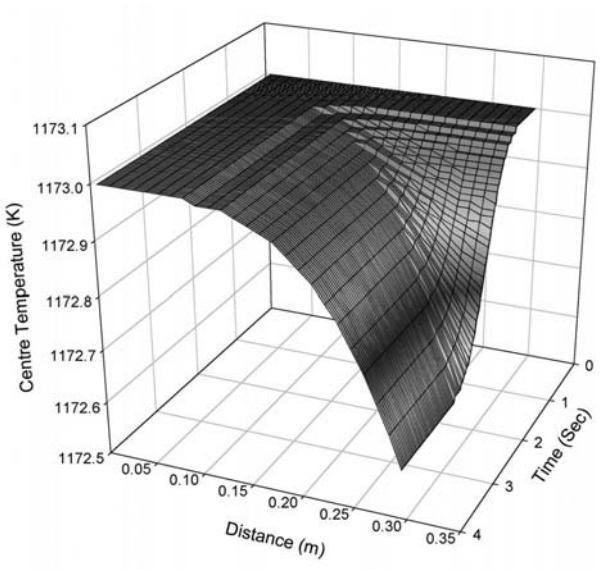

Figure 7 : Centre temperature plot at inter-pass rolling zone

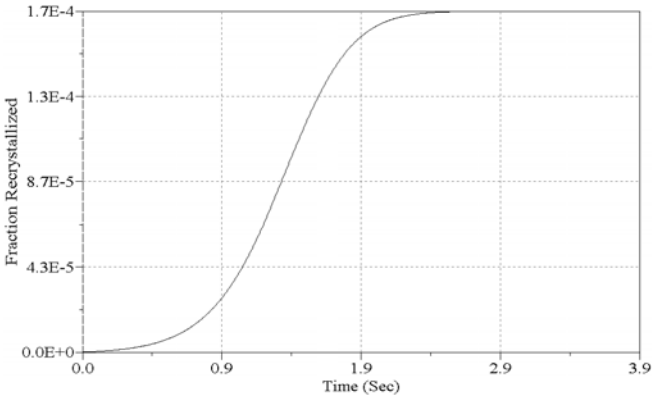

Figure 8 : Recrystallization at the surface space-reticule at inter-pass rolling zone

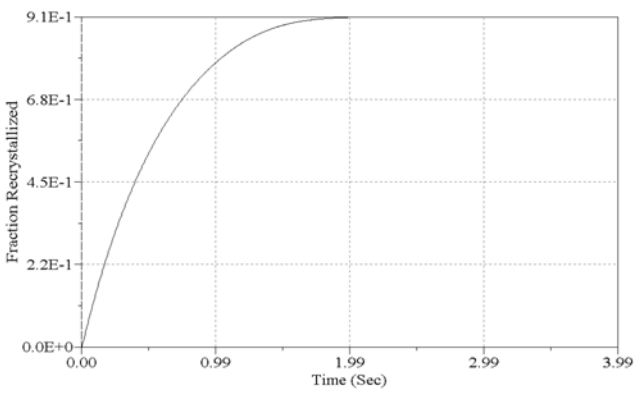

Figure 9 : Recrystallization at the centre space-reticule at inter-pass rolling zone

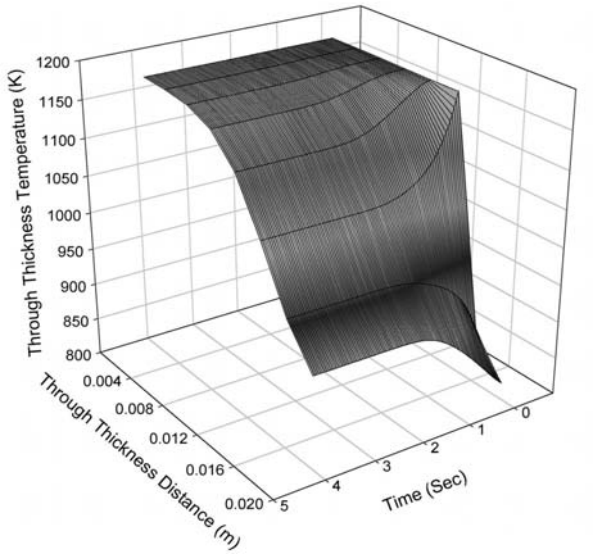

Figure 10 : Through thickness temperature plot at inter-pass rolling zone

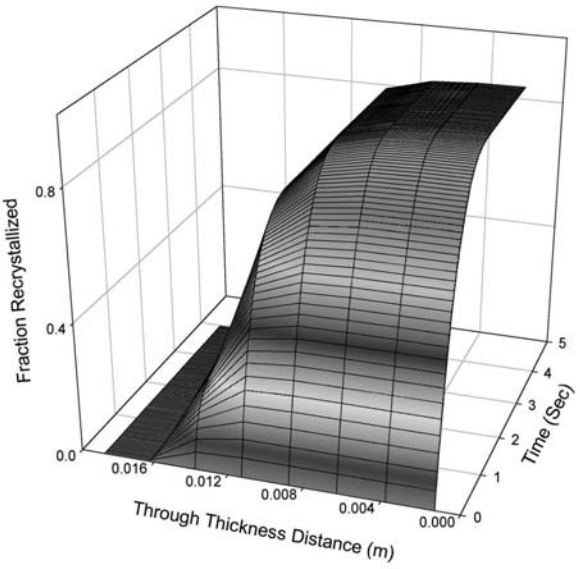

Figure 11 : Through thickness recrystallization kinetics at inter-pass rolling zone

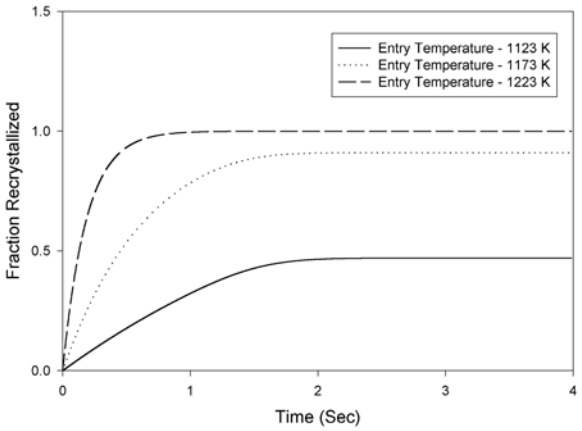

Figure 12 : Recrystallization for three different entry temperatures

tion from inside. The heat loss from the surface to the environment is very low due to the low heat transfer coefficient of convection. The heat convection to air is calculated based on the empirical equation [Beynon and Sellars (1992)]. The temperature of the environment is assumed to be 20^oC. The temperature in the space-reticule at centre decreases with increase in time because of the heat loss to the surrounding space-reticules (as shown in Fig. 5).

Figure 6 shows the surface temperature plot. At the end of the inter-pass zone, the surface temperature is quite high as the heat carried away by the moving material. The centre temperature plot is shown in Fig. 7.

Static recrystallization is very temperature dependent. At lower temperatures at the surface of the material, a very small amount of recystallization occurs (shown in Fig. 8), whereas, at the centre static recrystallization goes up to 91 % (shown in Fig. 9). This is due to the high temperature at the centre.

In the through-thickness direction temperature decreases for the space-reticules near the centre of the material, whereas near the surface temperature increases (as shown in Fig. 10). Recrystallization rate is more at the centre and less at the surface (as shown in Fig. 11).

Recrystallization kinetics has been modelled for three different temperatures. The higher the temperature, the more is the recrystallization rate, as shown in Fig. 12.

4 Conclusion and future work

In this work, static recrystallization kinetics has been modelled for the multipass hot rolling of low-carbon steel using bond graph. Several simulation studies have been performed to analyze the temperature dynamics inside the material for the inter-pass zone. The effect of various entry temperatures on the recrystallization kinetics has been studied. This approach can be extended to

include the runout table cooling effects and metallurgical phase transformation to predict the final microstructure and, thereby, mechanical properties of rolled strip. The present model will be coupled to a reheat process to achieve a bond graph model of through-process of steel processing.

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