Available online at www.sciencedirect.com
ScienceDirect
Surface & Coatings Technology 201 (2006) 2717–2723
SURFACE & COATINGS TECHNOLOGY
www.elsevier.com/locate/surfcoat

Use of fuzzy logic for modeling the growth of Fe_2B boride layers during boronizing

I. Campos [a,*], M. Islas [b], E. González [b], P. Ponce [b], G. Ramírez [a]

[a] Instituto Politécnico Nacional, SEPI-ESIME, U.P. Adolfo López Mateos, Zacatenco, México D.F. 07738, México
[b] Tecnológico de Monterrey, Campus Ciudad de México, Calle del Puente 222 Col. Ejidos de Huipulco, México D.F. 14380, México

Received 16 November 2005; accepted in revised form 16 May 2006
Available online 30 June 2006

Abstract

In this study, the evaluation of the phase Fe_2B growth in AISI 1045 steel during paste boronizing was carried out. Fuzzy logic Mamdani and Takagi–Sugeno methods were used as the technical model. The experimental procedure was performed in a solid paste medium, at temperatures range of 1193–1273 K; for 2, 4 and 6 h; and modifying the boron potential (paste thickness) at the metal surface. Membership functions were proposed for fuzzification and defuzzification of the input and output values. The system structure utilized was based on two membership functions for the input (time and paste thickness), and one for the output (layer growth). Comparing the results, given by the fuzzy logic system with experimental data, the medium error generated from the Mamdani method was 2.61%, and from the Takagi–Sugeno was 3.62%. It is concluded that the technique of fuzzy logic is an alternative for modeling the growth of borided phases.

Keywords: Artificial intelligence; Fuzzy logic; Boron diffusion; Growth kinetics; Boronizing

1. Introduction

Artificial intelligence technologies, including neural network, have already been used in the field of surface engineering, especially in nitriding, carbonitriding and powder boronizing [1,2], in recent years. Paste boronizing is an alternative method of powder boronizing. This method has been employed for more than 20 years [3–5]. Paste boronizing process is used in high work volumes and selective boronizing processes. The treatment must be done in a controlled atmosphere. The atmosphere, and the paste thickness, will determine the growth of the boride layer, impregnated in the substrate [6]. As the boron paste is thicker at the material surface, more compact and continuous layers will be generated. This is because of the increase in the boron mobility found in the formed phases, which decreases the activation energy needed for the boron diffusion [6,7]. During the process, monophase and polyphase layers can be generated. Usually, a monophase layer (Fe_2B) is more desirable for practical applications than a polyphase one (FeB and Fe_2B). The phase FeB, found at the external material surface, is more fragile, due its orthorhombic crystalline structure, and its boron content, approximately 16 wt.% The inner phase, Fe_2B, has 8.33 wt.% of boron, and its crystalline structure is tetrahedral [5]. Depending on the process parameters (temperature, time, boron potential and chemical composition of the substrate), the polyphase layer formation is inhibited. For carbon steel cases, the presence of the monophase iron boride layer, Fe_2B, is often seen, while the boron potential is controlled (between 3–5 mm of paste thickness), while the treatment times are no more than 6 h, and while there is a temperatures range of 1193–1273 K [7].

Artificial Neural Networks (ANN) and Fuzzy Systems (FS) are two different methods for working with the uncertainty due to the variable fluctuations measured in a process. This is seen in a complex linear, or non-linear system [8,9]. On one hand, the ANN approximates the model representation using precise inputs and outputs for training a generic model. This model has enough free grades that formulate a good approximation to the complex relationship among the variables [10]. On the other hand, in the FS, the input and output variables are codified in a

* Corresponding author. Tel.: +52 55 57296000x54768.
E-mail address: icampos@ipn.mx (I. Campos).

0257-8972/$ - see front matter
doi:10.1016/j.surfcoat.2006.05.016

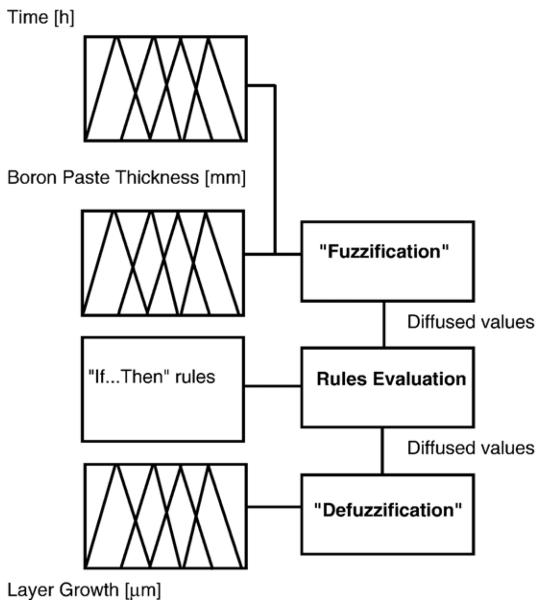

Fig. 1. Mamdani diagram for the paste boronizing process.

fuzzy representation, while its relationships are ruled by "if… then…" laws. Zadeh [11] observed that the two values of the boolean logic are not representative of many cases in the real world. For representing the many divisions between the true and false values, Zadeh developed the idea of a *fuzzy set*. The element has infinitely different property degree between one set and other, instead of belonging 100% to only one of them.

Fuzzy logic eliminates vagueness when it gives specific values to an infinite division between true and false. Even though it sounds contradictory, fuzzy logic is a very precise method for obtaining crisp and clear decisions [8–11]. A FS is based on the way human being quantifies variables. A variable can lie within a certain range, instead of having a specific value. This allows the FS to obtain attenuated transactions between one value and other, must especially in the sets borders. Each set of the ranged values is described by a membership function.

This study evaluates the growth kinetics of the boride layer Fe_2B, in AISI 1045 steel, through a paste boronizing process, using fuzzy logic technique, with the Mamdani and Takagi–Sugeno methods.

2. Fuzzy logic models

2.1. Mamdani method

During the first stage of this method, fuzzification, the crisp values of a system becomes fuzzy values. For example, in the boronizing process, the crisp input of 6 h of treatment will become *high time*, in fuzzy form. For this, the membership functions, μ_s, need to be defined for the inputs. These membership functions are mappings of the crisp value sets, established as follows:

$$\mu_s \rightarrow [0, 1] \tag{1}$$

$$\mu_s(x) = 1,\ x \in S \tag{2}$$

$$\mu_s(x) = 0,\ x \notin S \tag{3}$$

$$0 < \mu_s(x) < 1,\ x \in \text{partially to } S \tag{4}$$

The property degrees, ranking from 0 to 1, depend on the given crisp values. These values are projected towards the membership functions during the fuzzification process. This is why the property degrees represent a quantification of to what extent a crisp value is part of each defined membership function.

In the second stage, the linguistic rules, "if… then…", are determined. These rules command the system behavior. Finally, in the last stage, defuzzification, the output crisp values are obtained with the min–max[1] composition method. Eq. (5) is used to generate the crisp result for the system. The gravity center technique is used to obtain this crisp value, based on the combination of all significant fuzzy outputs.

$$\text{real output} = \frac{\sum_{x=a}^{b} \mu(x)x}{\sum_{x=a}^{b} \mu(x)} \tag{5}$$

Where $\mu(x)$ is the property degree and x is the value inside the rank of the affected membership functions. Triangular membership functions were used for the inputs and the outputs of the Mamdani method. Fig. 1 presents the Mamdani diagram for the paste boronizing process.

2.2. Takagi–Sugeno method

The variation that exists between the Mamdani method and the Takagi–Sugeno method falls on the output. This is observed directly in the rule's evaluation: if A is N and B is M, then C is $X1+X2$. Therefore, instead of getting a defined value inside an output membership function, an equation is evaluated for certain values to obtain the output crisp value using the following:

$$\text{real output} = \frac{\Sigma|y = y^i|y^i}{\Sigma|y = y^i|} \tag{6}$$

Where $y=y^i$ is the degree of membership of the minimum antecedents of each activated rules, and y^i is the evaluated result of the polynomial equations for each of the activated rules. Likewise, the gravity center technique is used to obtain the

[1] The method evaluates each of the rules, taking the minimum value of the antecedents. Later it takes the maximum value of the consequences of the same rule. The consequence that has the higher true value is the one that will dominate the output.