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Modeling the properties of TRIP steel using AFIS: A distributed approach

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Abstract

The paper attempts to model the strength of TRIP-assisted steels using fuzzy inference system (FIS). The system is proficient to cope up with the changing environment deterministically due to its inherent modular structure and distributed approach creating a flexible and robust system. The problem domain has been divided into several sub-problems and autonomous agents are employed to execute the tasks and decision making by designing respective FIS. The mechanistic constituents of TRIP process are expressed in modular form using linguistic if–then rules developed from the fundamental physical metallurgy concept. Coordination among the distributed agents in the form of sharing knowledge has been attempted to divide the whole mechanism of TRIP in separate modules to make the system fault tolerant. The model is validated by data collected from published literature and found to be sound enough, considering the limitations of a rule-based model.

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1. Introduction

Zackey et al. [1] introduced the concept of TRIP in C–Mn–Si steels with a composite microstructure of ferrite, bainite, retained austenite and some martensite [2–5]. Gradual transformation of retained austenite to martensite during plastic deformation of TRIP steels results in high work hardening as well as uniform elongation. To achieve tailored microstructure and mechanical properties of TRIP steel it is necessary to have knowledge about the complex role of the composition and the process parameters. For any given chemistry of the steel, the process parameters, viz. amount of cold deformation, intercritical annealing time and temperature, bainitic transformation time and temperature are known to exert appreciable influence on the microstructure and property of the product. The patterns relating the inputs (composition and process parameters) and outputs (mechanical properties) in TRIP steels are qualitatively recognized by the physical metallurgists. Though some attempts have been made to model the TRIP phenomenon from its physical understanding [6,7], but still to date no suitable model exists to predict the mechanical properties of TRIP steel from the independent variables, i.e. the composition and the processing parameters. This is mainly due to the lack of precise knowledge about the role of the independent variables on the microstructure and properties of the steel, which is difficult to gather due to highly complex and non-linear relationship between the variables. On the other hand, efforts have also been

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made to develop data-driven predictive models using tools like artificial neural network for TRIP steel properties [8–10], but these models fail to include the prior knowledge of the system within the model. Barring these two extremes, fuzzy logic is supposed to be the tool, which has the capability to model a system even in presence of imprecise information. It is known to be capable of modeling any non-linear arbitrary relationship for its human like reasoning power, and thus a fuzzy inference system (FIS) is developed to map a set of input–output data. Since fuzzy systems are built by importing the experience of experts for predictive activity, it makes the system highly compatible with the real life situation [11–14]. Several attempts have been made by earlier researchers to model materials properties using fuzzy inference systems [15,16] or adaptive neuro-fuzzy inference system, a hybrid version of the same [17,18].

In the present approach the problem domain has been divided into several sub-problems, each of which is solved by autonomous agents using FIS, called agent-based fuzzy inference system (AFIS). Solutions of complex problems have been achieved using distributed approach [19] where autonomous software agents deal with the fast changing environment, individually or jointly. Coordination among distributed modules in the form of sharing of knowledge, improving the skill of the agents, managing available resources and development of new agent communication protocol are the important research challenges in designing an agent based distributed system. Researchers have proposed various agent-based systems [20–23] for tackling such challenges in different application domain. Pattern recognition [24], RoboCup football tournament [25], Holonic systems [26] and power distributions [27] need special mention here. By and large in these works autonomy and cooperation characteristics of the agents are utilized successfully. Several learning and adaptation techniques of the agents for solving problems in the dynamic environment have been proposed very recently [28] though each of them inherits certain limitations.

The present work proposes a distributed approach to determine the strength of TRIP-assisted steel in presence of incomplete and imprecise knowledge about the problem domain. At the same time, the system deterministically can cope up the changing environment for its modular structure and thus flexible enough. Effort is made to express the whole mechanism of TRIP steel from the fundamental physical metallurgy concept through some linguistically expressed if–then rules. The nature of predictions of the individual agents on the basis of the if–then rules is studied and finally the model capacity for achieving the goal is compared from published data [2–5,29–38].

2. Fuzzy inference system and problem formation

The mechanism used in fuzzy inference system is mapping a given set of inputs to an output space using fuzzy logic. The FIS comprises (a) fuzzy sets and membership functions (b) fuzzy implication operator and (c) linguistic if–then rules. A membership function (MF) is a curve that defines mapping of each point in the input space to a membership value between 0 and 1, called the degree of membership (μ). There are several types of membership functions, viz. triangular, trapezoidal, gaussian, sigmoidal, asymmetrical polynomial, etc., of which the frequently used gaussian function is considered in the present work. If–then rule statements, which are used to formulate the relationship between the inputs and the outputs, generate the system knowledge base. The if–then rule assumes the form:

If X_1 is A and X_2 is B then Y is C

where A, B and C are linguistic variables defined by fuzzy sets on the specific ranges, while X_1, X_2 and Y are measured variables.

The inputs are then fuzzified using the input membership functions. The purpose of fuzzification is to map the inputs to values from 0 to 1 using a set of input membership functions. The input membership functions can represent fuzzy concepts such as "large" or "small", "old" or "young", "hot" or "cold", etc. In making a fuzzy rule, we use the concept of "and", "or", and sometimes "not". Here the concept of "and" has been used and the fuzzy "and" is written as

$$\mu_{\mathrm{A}\cap\mathrm{B}} = T(\mu_{\mathrm{A}}(x), \mu_{\mathrm{B}}(x))$$

where μ_{A} is read as "the membership in class A" and μ_{B} is read as "the membership in class B". There are many ways to compute "and". There are different operators (T) to find $\mu_{\mathrm{A}\cap\mathrm{B}}$, among them the Zadeh technique, named after the inventor of fuzzy set theory, simply computes the "and" by taking the minimum of the two (or more) membership values, and. the most common definition of the fuzzy "and", has been used in this work. The outputs of all of the fuzzy rules are then combined to obtain one fuzzy output distribution. This crisp value of the output is obtained using defuzzification process. In the concept of using center of mass for defuzzification, which has been used in the present study, the center of mass of the output distribution is computed as follows, to get one crisp number:

$$z = \frac{\sum_{j=1}^{q} Z_j \mu_{\mathrm{c}}(Z_j)}{\sum_{j=1}^{q} \mu_{\mathrm{c}}(Z_j)}$$

where z is the centre of mass and μ_{c} is the membership in class c at value Z_j.

Here, the problem has been decomposed into a number of sub-problems. Based on the autonomous agents' specification, the problem has been autonomously formalized into different modules (shown in Fig. 1) from the imprecise problem description. Autonomous agents are software agents that claim to be autonomous, being self-contained and capable of making independent decisions, and taking actions to satisfy internal goals based upon their perceived environment. Since agents are well suited to include their required resources in their description, they can be designed to be very loosely coupled and it becomes easy