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Meta Modelling of Submerged-Arc Welding Design based on Fuzzy Algorithm

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Abstract. Fuzzy algorithm based meta-model is proposed for approximating submerged-arc weld design factors such as weld speed and weld output. Orthogonal array design based on the submerged-arc weld numerical analysis is applied to the proposed approach. The nonlinear finite element analysis is carried out to simulate the submerged-arc weld numerical analysis using thermo-mechanical and temperature-dependent material properties for general mild steel. The proposed meta-model based on fuzzy algorithm design is generated with triangle membership functions and fuzzy if-then rules using training data obtained from the Taguchi orthogonal array design data. The aim of proposed approach is to develop a fuzzy meta-model to effectively approximate the optimized submerged-arc weld factors. To validate the meta-model, the results obtained from the fuzzy meta-model are compared to the best cases from the Taguchi orthogonal array.

1. Introduction

In this study, the new approach combining both Taguchi method and fuzzy logic is proposed for estimating design parameters of the weld process. Fuzzy logic is an intelligent soft computing technique that is able to describe a crisp conclusion using more realistic phenomenon under the environment of uncertainty [1-3]. This method requires a knowledge or training data set that includes not only some quantitative data such as experiment results or engineering database but also some experienced facts or rules. Therefore, a reliable approximate reasoning of fuzzy logic largely depends on what kind of knowledge data set is applied. The Taguchi method is usefully applied to generate knowledge data set because the robustness is considered in S/N (Signal-to-Noise) ratio results used to measure the deviation of the performance characteristics from the object value. Using results obtained from the Taguchi method, control parameters and response are defined as fuzzy membership functions, and then fuzzy rules are derived through the fuzzy reasoning process. Using approximate reasoning suggested fuzzy logic in this paper it is possible to infer some useful information with the consideration of the robustness of knowledge data set and the uncertainty. The finite element analysis of a fine-grain steel plate is first carried out to simulate the submerged-arc welding process using thermo-mechanical and temperature-dependent material properties. Simulation results on thermal-mechanical coupled physical phenomena are compared with experiment. Taguchi method is then applied to evaluate the relationships between parameters and responses in the submerged-arc welding process and to generate some training data for fuzzy application. Fuzzy membership functions and
fuzzy rules are derived from the results of Taguchi method. The results of Taguchi method based fuzzy algorithm design would be usefully applied to approximate optimization that could be an efficient methodology to solve design issue with high computational cost in various engineering design [4-6]. The present study facilitates a quantitative decision of welding parameters such as welding speed and welding output that are generally expressed by qualitative linguistic terms in the welding process.

2. Numerical analysis for weld
The numerical analysis for weld is carried out to provide the Taguchi design to experimental data. The thermal-mechanical characteristics of weld are also reviewed from analysis results, and the numerical analyses are performed out according to the level variation of weld design factors in Taguchi design.

The two plate halves, 25(thickness)x500(transverse width)x1000(longitudinal height) mm, made of mild steel, are butt-welded together, wherein the weld electrode moves along the longitudinal top edge of the steel plate. The plate is mechanically fixed at both ends. The temperature-dependent material properties used in the numerical analysis are referred to the study of Andersson [7]. The symmetry boundary condition along the longitudinal plane is spanned by the seam and through thickness axis. The cross-section of one of the plate halves is assumed to be the generalized 2-dimensional plane strain condition to minimize the computing time. The finite analysis models of base metal and filler are made as shown in Figure 1 [8].

![Figure 1. Finite analysis model of weld simulation [8]](image)

The element type of filler is the heat transfer plane element transferring the thermal-structural stiffness and the thermal energy on the welding area. Melting point temperatures are defined on the nodes of the created filler elements as long as the latter ones remain in the weld pool. In case that the heat source moves on, temperature boundary conditions are eliminated and the filler elements are cooled down. The deformable contact condition is applied to the base metal elements and the filler. The heat transfer coefficient is calculated to transfer the filler heat input to the base metal elements. The weld heat source equation is used from Goldak’s double ellipsoidal shaped model [9] that is generally well known for the deep penetration weld analysis.

The weld temperature is applied to the filler element, and the ambient temperature and the heat transfer coefficient are considered in the base metal. For the weld simulation based on the finite element analysis, MSC.MARC [10], a general nonlinear finite element analysis code, is used. The detailed temperature contour results are presented in Figure 2. Residual stress and deformation contour results are also shown in Figure 3.
Figure 2. Weld temperature results (unit: °C)

Figure 3. Weld stress (left; unit: m) and deformation (right; unit: m) results

3. Taguchi and fuzzy algorithm design

3.1. Taguchi design
In the Taguchi design, weld output (kW) is considered as control factor with 4 levels such as 16, 22, 28, and 34, weld speed (mm/s) is also defined as control factor with 4 levels such as 10, 15, 20, and 25, and the noise factor of 3 levels such as 15, 30, and 45 is defined by ambient temperature (°C). The maximum weld stress is regarded as the response for the ‘smaller-the-better’ in the Taguchi design. The weld simulation is carried out according to the L16 orthogonal array that the weld numerical analyses of 48 times are performed. From the results of Taguchi design, it is found that the combination of the lowest level weld output and the highest weld speed is the best case to minimize the weld stress.

3.2. Fuzzy algorithm design
Using the fuzzy algorithm design, the weld factors could be considered realistically as linguistic term and on the continuous design space. In this study, the Taguchi design results are applied to the fuzzy algorithm design to derive the fuzzy membership functions and inference rule. The procedures deciding membership functions and decision rules consist of the five stages. In the first stage, the Taguchi design results are clustered and fuzzified. In the second and third stages, initial membership functions and decision table are constructed. In the fourth stage, the initial decision table is simplified. Finally the membership functions are rebuilt in the simplification process with the triangle fuzzy membership function shown in Figure 4 [8], and then the decision rules are obtained using the fuzzy if-then rule.

3.3. Comparison of Taguchi design and fuzzy algorithm results
The results of the proposed fuzzy membership functions and fuzzy rules are compared to the Taguchi design as shown Figure 5.

In the Figure 5, the meta-model from fuzzy algorithm design is generated by the defuzzification equation [11]. It is noted that the meta-model from fuzzy algorithm design represents the high accuracy with less computational costs.
4. Conclusion
In this study, the fuzzy algorithm based meta-model was proposed for approximating submerged-arc weld design factors such as weld speed and weld output using the Taguchi design results. The Taguchi orthogonal array design based on the finite element analysis of weld simulation was applied to the proposed approach. The nonlinear finite element analysis was carried out to simulate the weld numerical analysis using the thermo-mechanical and temperature-dependent material properties for the general mild steel. The proposed meta-model based on fuzzy algorithm design was generated with the triangle membership functions and the fuzzy if-then rules using the training data obtained from the Taguchi orthogonal array design data. To validate the meta-model, the results obtained from the fuzzy meta-model are compared to the best cases from the Taguchi orthogonal array. It was found that the meta-model from fuzzy algorithm design represented the high accuracy with less computational costs.

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