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Optimization of geometric parameters in a welded joint through response surface methodology

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HIGHLIGHTS

- Experimental desing for a GMAW welding process to maximize the amount of information.
- Response surface-based modelling (RSM) to quantify response variables of interest.
- Statistical model selection to obtain the most informative models.
- Statistical model checking for definitive models to ensure inference capabilities.
- Multiobjective optimization to identify the Pareto front of optimal solutions.

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ABSTRACT

This work makes use of experimental design and response surface methodology to model Gas Metal Arc Welding processes. The correlations among three key geometric parameters, ie., penetration, bead width and overthickness, and four technological variables that define the welding process are quantified. Based on experimental data and using model selection techniques, a mathematical model has been deduced for each of the response variables herein presented. Using these models, a multiobjective optimization is carried out to find the space of optimal solutions (i.e., the Pareto front). After a preliminary study of the relationships between independent and response variables, regression models are built. These models capture the data variability reasonably well (e.g., around 70% of the variability). These models are the basis to perform the multiobjective optimization using the ε-constraint approach. Results reveal that the conditions which favour a good balance between maximum penetration and minimum bead width and overthickness, involve a high value for gas flow rate, low values for electrode feed rate and voltage, and an intermediate value for the electrode position. This permits the authors to define the welding conditions that lead to an optimum joint geometry and then to guarantee its properties.

1. Introduction

The mechanical properties of a welded joint depend on the geometry of the bead together with other factors. The study of the geometric factors of the weld bead has an important consideration for the design and manufacturing of welded constructions. The geometry of the bead directly affects the quality of the welding in the building of structures [1]. In order to obtain a correct weld, it is essential that the fusion between the base metal and the material deposited is appropriate. The surface of the base metal which is part of the joint must be completely melted until it forms a sufficiently deep bead. If the drops of metal from the electrode and the heat of the arc are not able to melt the base metal, then the bead will have little penetration. The dimensions which best define the geometry of the bead are its width, its penetration, and its overthickness, Fig. 1 (overthickness is referred to “height” in the figure). This geometry depend on the technological parameters of the specific welding process, in relation with the heat contributed in the process and with the thermal conditions in which it occurs [2]. It is therefore important to establish appropriate welding parameters in order to produce a stable weld bead. In general, the optimization criteria are aimed at maximizing the weld bead’s penetration while maintaining the values of bead width and over-

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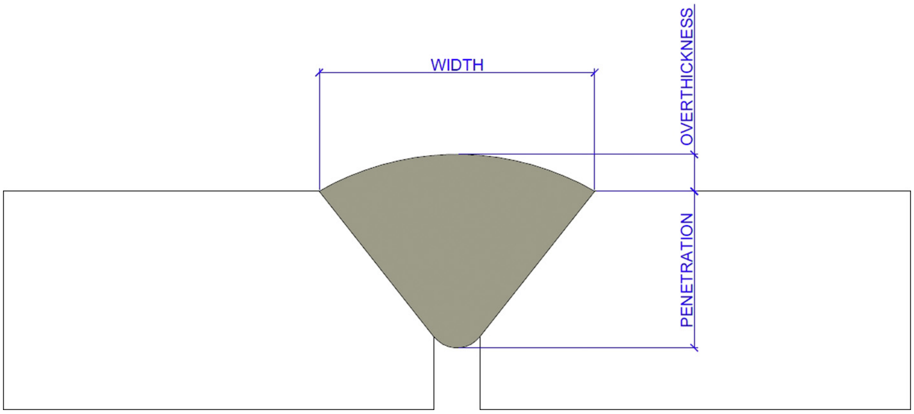

Fig. 1. Parameters which define the transversal geometry of a weld bead.

thickness as low as possible. Thus, for a given passing depth, a lower bead width means a greater thermal efficiency of the process, concentrating the heat more and reducing the heat affected zone [3]. The overthickness is not a determining parameter from the point of view of the mechanical behaviour of the joint, although a lesser thickness means greater metallurgical yield of the weld, that is to say the depositing of metal is carried out more efficiently. Another aspect related to the overthickness is that it can act as a concentrator of tensions, if it is excessive [4], but the effects on structures with non-cyclical loads should not be significantly affected by this.

Different authors have analyzed the relationship which exists between the parameters of the welding process with the geometry of the beads obtained, proposing models in which the functions of the response Y are expressed according to the model proposed by McGlone and Chadwick [5], depending on the process variables $X_1, X_2, \ldots X_n$, as indicated in Eq.1 in which b_1 to b_n are the fitting constants of the model.

$$Y = b_1 X_1^{b_1} X_2^{b_2} \ldots X_n^{b_n} \tag{1}$$

The values of the coefficients b_1 to b_n are calculated by multiple regression. Karadeniz et al. [6] determine a McGlone and Chadwick type model, also known as curvilinear fit, considering as influential variables the voltage and intensity of the electric arc, and the welding speed. They only consider the study of the penetration by MAG welding in steels with a low carbon content and limit themselves to obtaining the variation of that parameter according to the indicated variables. Wahab and Painter [7] consider as process variables the voltage and intensity of the arc, the welding speed, and the gas flow utilized, limiting themselves to obtaining a model similar to that indicated. Kim et al. [8] also base their research on the curvilinear model, obtaining the penetration, overthickness and the bead width as response functions. These authors establish that the accuracy of the models found varies from 0% to 25%. In all the works mentioned thus far, the common denominator is not only the model employed but also that no optimization methodology is established with the response variables.

Kim et al. [9] correlate the penetration of the weld bead with the intensity, voltage, weld speed and angle of welding. They compare the results obtained by means of the curvilinear model with those obtained from a linear correlation with the experimental variables. The authors demonstrate that the linear model offers better behaviour. Specifically, if the results obtained by those authors are analysed it can be seen that the mean error in a linear regression is 16%, whereas the curvilinear model which Eq. (1) represents leads to a mean error of 23%. Both methods present some experimental values which are more than 50% away from the corresponding theoretical value. The welding angle tested varied from 10° to 20°, which is the typical range of application in robotized GMAW welding operations.

Some authors establish optimization methodologies for the welding parameters. Kim et al. [10] employ a genetic algorithm to obtain a range of optimal values for the welding variables. They then optimize the response variables using the surface response methodology in the zone determined by the algorithm. These authors do not consider the flow of shield gas nor the position of the torch as welding variables. Srinivasa Rao et al. [11] apply the Taguchi method for the analysis of each parameter of pulsed arc welding on the geometry of the bead and separately optimize each of the response variables of the bead geometry. Sadowski et al. [12] carried out an analysis of variance (ANOVA) and offered statistical evidence that supports the view that an isotropic treatment may be acceptable for computational analyses and design of spiral welded steel tubes.

In this work, a methodology for the multiobjective analysis of the weld bead geometry applied to a butt welding process without preparation of the edges of the mild steel plate by means of the GMAW procedure is carried out. The technological variables considered are the gas flow, the voltage, the electrode feed rate, and the angle of the torch with regard to the perpendicular of the sheet metal, that is to say, 0°, −45° and 45°. The welding speed has not been considered as a technological variable since it has the same effect, although inverse, as the voltage and the arc intensity. The electrode feed rate is equivalent to considering the arc intensity as a variable. The optimization methodology employed allows to determine different optimal operation conditions and the Pareto frontier when multiple objectives are considered at once.

2. Optimal design for experiments and response surface methodology

Response Surface Methodology (RSM) consists of a set of mathematical and statistical techniques to develop a functional relationship between a response of interest, y, and a number of associated control (or input, or explanatory) variables, $x_1, x_2, \ldots, x_k$. It is useful for applications in which reliable physical mathematical models to establish such a relationship are not available. It is also useful in those cases where obtaining experimental data is costly, in order to attempt to reduce the costs involved. In general, the relationship between y and x_i is unknown but can be approximated by a low-degree polynomial model. This technique was first introduced by Box and Wilson in 1951 [13]. These authors suggested second order degree polynomials to approximate the relationships, although there are other functional forms to apply