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Welding process selection through a double criteria: Operational costs and non-quality costs

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Abstract

This paper presents a methodology to compare two welding processes, namely SAW (submerged arc welding) and GMAW (gas metal arc welding) and to select the best one for a given application. The selection was based on double criteria: operational costs and non-quality costs. The former is related to the normal costs evaluated in such kind of decision, like consumable cost, labor cost, etc. The latter is the financial loss suffered by the client every time response variable drifts away from its target value or presents variability. The non-quality costs reduction is fulfilled through the proper adjustment of the process variables, in such a way that deviations from the target are minimized while robustness to noise and to process variable fluctuations is maximized. Since this a multi-response, multi-objective problem, the optimum solution is a compromise. Prior to comparison, the two welding processes were optimized. The results indicated that the non-quality costs for the SAW process are slightly higher, but these are compensated by its lower operational costs. Therefore, the SAW process has the lowest total cost and, consequently, it is the best process for the given application.

Keywords: Experimental optimization; Quality; Response modeling; Submerged arc; GMAW

1. Introduction

The quality of a welded material can be evaluated by many characteristics (or responses), such as bead geometric (penetration, width and height) or mechanical properties. These characteristics are controlled by a number of welding variables, and, therefore, to attain good quality, it is important to set up the proper welding process variables. But the underlying mechanism connecting them (welding variables and quality characteristics) is usually not known.

In the optimization of a given welding process, the quality engineer is generally interested in the achievement of the three objectives below [1]:

1. minimize target deviations;
2. maximize process robustness to noise factors (minimize variability);
3. maximize process robustness to process variables oscillations.

The targets are the ideal values for each response. To minimize target deviations means to produce units with their responses as close as possible to the ideal values. The noise (variability) is caused by the effect of non-controllable factors, such as weather condition. To maximize robustness to noise means to produce units relatively insensitive to these non-controllable factors.

The process variables are the controllable factors, i.e., product or process variables that can be controlled. In the welding process under investigation, typical variables are welding voltage, wire feed speed, welding speed, etc. The process variables should be adjusted in order to achieve objectives 1–3. However, during the production phase, changes in setup, operators, raw material supply, etc., may compromise holding the levels of some (or all) process variables at fixed levels. Therefore, it is also desirable to develop robustness to process variables fluctuations. This means that when the process variables experience small variations from their optimal setting, the quality responses will not degrade.

To achieve these three, sometimes conflicting, objectives, Ribeiro and Elsayed [2] proposed the following five steps optimization methodology:

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(1) Problem identification: list process variables and quality characteristics of interest (and for the latter, define target and priorities). Defining the proper targets is crucial. Engineer must be sure that the chosen targets are in harmony with the customer requirements.
(2) Experimental design: study the problem and choose the proper experimental design to collect data concerning mean and variability. The levels of the process variables must be chosen carefully in order to properly investigate the region of interest. Also, it is important to collect enough data to allow variability modeling.
(3) Response modeling: build mean and variance models for each response. To perform step 3 the engineer must be familiar with model building techniques. Building models for each response separately, the engineer has the opportunity to learn important facts about the process under study. Barbetta [3] proposed an iterative technique for building models of mean and variance. At first, the variance model is built with a statistic made from the calculated variance and from the quadratic error (taken from the mean model). Then the mean model is recalculated using the variance statistic values as weights when finding the new mean regression parameters, in a technique known as generalized least-squares (GLS). This technique is a variation of the common ordinary least-squares (OLS). The procedure is repeated at least twice or is finished by visual analysis of residual error and R^2 index.
(4) Objective function definition: the gradient loss function is based on the function proposed by Taguchi to quantify the non-quality costs [4]. These costs may be defined as the financial loss suffered by the client every time response variable drifts away from its target value or presents variability. Eq. (1) presents the objective function:

$$Z(i)=\sum_{j=1}^{Q} w_j \left[(Y_j^{\mathrm{m}} - T_j)^2 + (\sigma_{Y_j}^{\mathrm{m}})^2 + \sum_{k=1}^{P} (\sigma_{X_k}^{\mathrm{m}})^2 \left(\frac{\partial Y_j^{\mathrm{m}}}{\partial X_k} \right)^2 \right] \tag{1}$$

where $Z(i)$ is the objective function to be minimized, i.e., the lower function values, the higher the process quality. For each variable adjust (treatment "i"), a Z value can be obtained; w_j are weights to take into account units and the relative importance of each quality characteristic. Q is the total number of responses, T_j the target, or the ideal value to, to the response j, Y_j^{m} the predicted mean for each quality response j, $\sigma_{Y_j}^{\mathrm{m}}$ the predicted variance for each quality response j, and $\sigma_{X_k}^{\mathrm{m}}$ is the standard deviation estimate for each controllable factor k.

The objective function $Z(i)$ associates a numerical value with the level of quality of a product or process. It is composed of three terms. The first one accounts for deviations from target values. The last two terms account for two sources of variability: (1) variability due to non-controllable factors (noise factors) and (2) variability due to fluctuations on "controllable" factors (process variables).

However, Eq. (1) presents its results in dimensionless values, which have only comparative use. Caten [1], in an optimization study for a chemical industry, suggests a procedure to find a constant that changes these dimensionless values into monetary ones. The cited industry has a production line set to fabricate a specific chemical. Depending on the final quality, the product may be classified into two categories (high or low quality), and it is sold with different prices. The non-quality cost for a class A product (high quality) is 64 units of Eq. (1) and its retail price is 1.42 US$/kg. The low quality product (B class) has a 179 units cost and a 1.07 US$/kg price. The constant was defined as the reason between the price and the quality differences. Once calculated this constant, the non-quality monetary costs were found by multiplying the Z function by the constant.

Besides the advantage of putting the non-quality costs into a more understandable base, the described procedure permits that the researcher adds an operational costs function to the Z function and performs an optimization to find the best compromise between quality and fabrication costs.
(5) Optimization: this step refers to numerical optimization of the objective function and it may be accomplished by a number of methods (simulated annealing, genetic algorithm, augmented Lagrange multiplier method, etc.). The lowest value of the Z function presents the variables adjusts that deliver the highest quality, i.e., the adjusts that lead the responses to the fulfillment of the three objectives previously cited.

After the optimization step, the value of objective function obtained for a process can be compared to the correspondent value of any other process, in order to verify which one of then is the most suitable for a given application. But this comparison is only possible if the Z function for both processes had been built with the same responses.

The origin of the present study was the interest of a mechanical industry in replacing the SMAW (shielded metal arc welding) process in its fabrication line of pressure vessels. The vessels are made with mild steel, 9.52 mm (3/8 in.) thick and the plates are welded with four passes, in a butt joint configuration (two passes with cellulosic electrodes and two with rutilic). Two alternative welding processes were pre-selected with the aid of literature: SAW (submerged arc welding) and GMAW (gas metal arc welding). Both have substantially higher deposition rates than the SMAW and offer good bead quality. The SAW and the GMAW processes are easily found in any industry whose products require metal joining in a large scale.

The goal of this article is to present a new way of deciding which one of the alternative processes is the best for the given application. The selection was carried using the traditional criteria of operational costs, as well as the non-quality costs. The search for the optimum (and the final comparison) was based on the minimization of an objective function Z, which takes into account the economic characteristics of the process (deposition efficiency and fabrication costs) and the geometric characteristics of the bead (penetration, width, and reinforcement).