Submerged Arc Welding Online Quality Evaluation Using Infrared Thermography Based Fuzzy Reasoning

Yazid LAIB DIT LEKSIR 1,2, Salah BOUHOUCHE 1, Mohamed Seghir BOUCHERIT 2, Jurgen BAST 3

1 Iron and Steel Applied Research Unit – CSC, BP 196 Annaba, 23000, Algeria
2 Algerian Institute of Technology - ENP, 10 Avenue Hacene Badi El Harrach, Algiers, 16100, Algeria
3 HGUM, Institut für Maschinenbau, TU Bergakademie Freiberg, Cotta Strasse 4, D-9596, Germany
E-mail: yaziddl@yahoo.fr

Abstract
A method for welding quality evaluation, which combines model identification and fuzzy sets methods, is proposed. To account for welding quality variations, the proposed approach is based on an optimal reference Gauss distribution temperature along of the welding line in order to take into account the eventual process changes. Fuzzy analysis is then applied to the generated residual data to give an evaluation of the welding condition. This approach is applied to welding process for constructing a complementary condition monitoring system which permits an online quality evaluation. The temperature measurement is carried out using an infrared camera. Simulation results based on the measured surface temperature and generated residual data, show that the new approach is easily implementable and gives good evaluation online.

Keywords: Heat Affected zone of Welding Process, Infrared temperature measurement, Gauss distribution model, Residual generation, intelligent modeling, Fuzzy reasoning, Quality evaluation

1. Introduction

Welding metallurgy is concerned with the application of well-known metallurgical principles for assessment of chemical and physical reactions occurring during welding. On purely practical grounds it is nevertheless convenient to consider welding metallurgy as a profession of its own because of the characteristic non-isothermal nature of the process. In welding the reactions are forced to take place within seconds in a small volume of metal where the thermal conditions are highly different from those prevailing in production, refining and fabrication of metals and alloys.

- High peak temperatures, up to several thousand C°.
- High temperature gradients, locally of the order of $10^3$ C°/ mm.
- Rapid temperature fluctuations, locally of the order of $10^3$ C°/s.

It follows that a quantitative analysis of metallurgical reactions in welding requires detailed information about the weld thermal history. From a practical point of view the analytical approach to the solution of heat flow problems in welding is preferable, since this makes it possible to derive relatively simple equations which provide the required background for an understanding of the temperature-time pattern. However, because of the complexity of the heat flow phenomena, it is always necessary to check the validity of such predictions against more reliable data obtained from numerical calculations and temperature measurements. Although the analytical models suffer from a number of simplifying assumptions, it is obvious that these
solutions in solutions, in many cases, are sufficiently accurate to provide at least a qualitative description of the weld thermal programme.

An important aspect of the present treatment is the use of different dimensionless groups for a general outline of the temperature distribution in welding. Although this practice involves several problems, it is a convenient way to reduce the total number of variables to an acceptable level and hence, condense general information about the weld thermal distribution. There are many developed works in the field of quality control of welding, the most commonly used are:

- The evaluation - based on computer vision and signal processing methods, which allow non destructive on-line real-time processing [1, 2, 3, 4, 5, 6, 7]. The input of the system in this case is an information of one or two dimensions signal (image). The used algorithms are based on simple or complex analysis such as the comparative thresholds or other complex techniques.
- Intelligent methods, including fuzzy methods and expert systems, have also been considered in several works [8, 9, 10]. The system uses fuzzy rules and membership functions of linguistic variables, conducts inference and defuzzification, and gives a global quality evaluation of welding.

Fault detection and isolation (FDI) methods based on Multivariate statistical process control (MSPC) techniques, including the residual generation, have been widely considered as a promising approach for mining monitoring and control - relevant information from process history data, its successful applications have been reported in numerous process industries [11, 12, 13]. Traditionally, the FDI method, as a part of the MSPC technique takes an important place in monitoring methods, some works are extended to process and quality evaluation [14]. Quality evaluation of welding, using FDI based residual analysis, remains relatively new and it will be developed in this paper.

In this work, an extension of FDI methods, using the combined approach based on the fuzzy reasoning of generated residual, is considered. This approach combines the following two steps:

- The first step is a modeling and residual generation part: residual is generated by the difference between the real thermal distribution \( \sigma_r(x) \) measured by an infrared camera and the optimal thermal distribution \( \sigma_o(x) \) obtained from optimal welding conditions.
- The second step is a fuzzy evaluation of the generated residual for condition monitoring and quality evaluation of welding.

This hybrid form gives a global evaluation of the weld quality according to the residual evolutions, the main motivations to use such approach based on residual generation and fuzzy reasoning are:

- The nature of the process application, characterized by a contactless temperature measurement using infrared camera;
- The evaluation of the quality indexes requires a soft sensing approach;
Usually, a combined approach between residual generation and evaluation is strongly recommended for an automatic evaluation of the quality product. Generally, the residual is used in fault detection and diagnosis without an analysis of its impacts on the product quality [15, 16, 17].

The quality evaluation of a batch process is naturally a fuzzy form: it uses a comparison of the quality level between different repeated steps.

This paper is organized as follows: In section 2, a brief description of welding process dynamics, characterized by the interaction between the input power and the temperature distribution at welded point, is given. Heat conduction models are also briefly introduced. In Section 3, the thermographic temperature measurement of HAZ is proposed and the measurement system characteristic is also given. Section 4 considers results analysis and quality evaluation of welding on the basis of the residual importance. In the end, the fuzzy system is tested; a good agreement between the welding quality evaluation by expert and the process parameters variations are obtained.

2. Welding System Identification and Modeling

Submerged Arc Welding (SAW) is a high quality welding process with a very high deposition rate. It is commonly used to join thick sections in the flat position. SAW is usually operated either as fully mechanized or automatically processed. However, it can be used semi-automatically as well. During SAW process, operator cannot observe the weld pool and not directly interfere with the welding process. As the automation in the SAW process increases, direct effect of the operator decreases and the precise setting of parameters become much more important than manual welding processes. In order to obtain high quality welds in automated welding processes, selection of optimum parameters should be performed according to engineering facts. Usually in such automated processes elements to be joined move and a welding device passing the filled wire is motionless. We consider in this part the dynamic behaviour of the welding temperature as a system activated by its input parameters. On the welding point, we suppose that the heat losses from free surfaces by radiation and convection are usually negligible. We note that the temperature distribution can generally be obtained from the fundamental differential equations for heat conduction in solids. For uniaxial heat conduction, the governing equation can be written as:

\[
\frac{\partial T(x,t)}{\partial t} = a \frac{\partial^2 T(x,t)}{\partial x^2}
\]  

(1)

Where \( T \) is the temperature, \( t \) is the time, \( x \) is the heat flow direction, and \( a \) is the thermal diffusivity. The thermal diffusivity is related to the thermal conductivity \( \lambda \) and the volume heat capacity \( \rho C \) through the following equation:

\[ a = \frac{\lambda}{\rho C} \]  

(2)

For biaxial and triaxial heat conduction we may write by analogy to equation (1):

\[
\frac{\partial T(x,y,t)}{\partial t} = a \left[ \frac{\partial^2 T(x,y,t)}{\partial x^2} + \frac{\partial^2 T(x,y,t)}{\partial y^2} \right]
\]  

(3)
\[
\frac{\partial T(x, y, z, t)}{\partial t} = a \left[ \frac{\partial^2 T(x, y, z, t)}{\partial x^2} + \frac{\partial^2 T(x, y, z, t)}{\partial y^2} + \frac{\partial^2 T(x, y, z, t)}{\partial z^2} \right]
\]

The above equations must clearly be satisfied by all solutions of heat conduction problems, but for a given set of initial and boundary conditions there will be one and only one solution. The welding system dynamic can be identified by the impulse response of the temperature given by Fig.1. Equations (1), (3) and (4) are controlled by their boundary and initial conditions [18].

![Input Welding Heat impulse](image1)

![Output welding Temperature distribution](image2)

Figure 1. Dynamic response of the welding temperature

Welding source is characterised by its power Q, after metal fusion and heat transfer, the temperature dynamic \( T'(y) \) in each point is defined by the impulse response as a Gauss curve. The tempo-spatial temperature distribution is presented in Fig.2; where \( T_0 \) is the initial temperature of the welded point, and \( t_1 \) and \( t_2 \) are two different times.

![Dynamic response of the welding temperature](image3)

Figure 2. Dynamic response of the welding temperature
3. Thermographic measurements

The vision system elaborated within the framework of the research described in the paper has been assigned to SAW welding process (Fig. 3). The system has included hardware and software parts. The hardware part has consisted of a camera and a portable PC to make recordings in real time. The main task of this part was to observe the process by means of IR camera. The device used was a FLIR ThermaCAM A40 imaging system. It has a 240×320 pixels focal-plane-array uncooled microbolometer detector, with a sensitive range of 7.5-13 mm. Imaging and storage was made at a frequency rate of 50Hz. The PC is equipped by powerful software that is Thermacam researcher 2.9, this software is used to analyse dynamic IR radiation records including the emissivity calculations.

Figure 3. Industrial SAW welding stand

Figure 4. Thermal image acquired during welding process

Table 1 Specification of thermo-cam

| Thermo-cam (FLIR-A 40 series) | - Solide state, uncooled micro bolometer detector, 7.5 to 13 µm  
| - -40°C to +2000°C storage temperature range  
| - Solide object materials and emissivity: 0.1 to 0.95  
| - For short distance, humidity is default value of 50%  
| - 0.08°C at 30°C thermal sensitivity |
3.1 Heat affected zone monitoring and welding quality evaluation

In the last decade, quality control methods have proved to be a powerful tool in the area of product and process engineering for solving low cost quality control and inspection using classification and evaluation methods. However, their online application needs data acquisition, training, validation and testing using new algorithms, which are time-consuming in the case of large data sets. In a welding process, generally, an optimal thermal profile of the Heat Affected Zone (HAZ) guaranteed an optimal quality of the welding process, and the temperature distribution of the HAZ is generally Gaussian. Any deviation between the optimal thermal distribution ($\sigma'_o(x)$) and the real thermal distribution ($\sigma'_r(x)$) is considered as a source of a possible defect. In recent years, many works based on conventional and advanced methods have been considered; however, FDI theory and methods are not yet fully tested and applied.

The quality evaluation and monitoring scheme proposed in this paper uses the FDI principle which is divided into two parts: the first part is a residual generator and the second is a fuzzy reasoning approach. Evaluation is naturally a fuzzy expert-system because it generally uses rules and word evaluation such as “good”, “poor”, “medium” etc.

4. Residual generation

The proposed scheme for welding quality evaluation is based on the residual fuzzy sets analysis, this is illustrated in Fig.5. It first considers a residual $e'(x)$ obtained as the difference between the optimal and real thermal distributions ($\sigma'_o(x)$) and ($\sigma'_r(x)$) respectively, then fuzzy rules is operated on the integrated form of residual defined by $\phi'$ and its changes $\Delta\phi'$.

![Figure 5. Principle of welding quality evaluation by residual fuzzy reasoning](image)

We can now describe the scheme in details:

Let the optimal thermal distribution ($\sigma'_o(x)$) of the HAZ and the real measured thermal distribution ($\sigma'_r(x)$), the residual is defined as:

$$e'(x) = \sigma'_o(x) - \sigma'_r(x)$$

(5)
The global residual characterizing a welding sequence is given by the following formula:

\[ Q' = \sum_{t=t_1}^{N} \sum_{x=x_1}^{x_F} e'(x)^2 \]  

(6)

N is the final sampling number, \( x_1 \) and \( x_F \) are the initial and final coordinates of the HAZ. \( t \) is the time of the HAZ temperature measurement. This global residual gives an evaluation of the quality of welding sequence given by the sum of the dissipated superheat at different times \( t_1 \) and \( t_F \). \( t_1 \) and \( t_F \) are the initial and final time of the welding sequence.

Fig. 6 shows a typical optimal HAZ thermal distribution (\( \sigma'_1(x) \)), using such reference profile, residuals have been generated and plotted in different graphs (Figs. 7).

![Figure 6. Typical HAZ temperature distribution (\( \sigma'_1(x) \))](image)

![Figure 7a. Residuals of welding line 1](image)

![Figure 7b. Residuals of welding line 2](image)
Fuzzy rule-based systems have been successfully applied to various applications in different areas such as control and classification [19, 20]. While the main objective in the design of fuzzy rule-based systems has been to maximize performance, their comprehensibility has also been taken into account in some recent studies. The comprehensibility of fuzzy rule-based systems is related to various factors:

- Comprehensibility of fuzzy partitions (e.g., linguistic interpretability of each fuzzy set, separation of neighbouring fuzzy sets, the number of fuzzy sets for each variable).
- Simplicity of fuzzy rule-based systems (e.g., the number of input variables, the number of fuzzy if-then rules).
- Simplicity of fuzzy if-then rules (e.g., type of fuzzy if-then rules, the number of antecedent conditions in each fuzzy if-then rule).
- Simplicity of fuzzy reasoning (e.g., selection of a single winner rule, voting by multiple rules).

Figure 8. Evolution of the input residuals

4.1 Evaluation using fuzzy sets
This paper shows how a small number of simple fuzzy if-then rules based on the residual and its variations can be selected for designing a comprehensible fuzzy rule-based system for condition monitoring and evaluation. As shown in Fig. 5, fuzzy reasoning operates on the residual. To evaluate the welding quality, we use in this scheme the residual value $Q^t$ and its variation $\Delta Q^t$. Theoretically, it is possible to extend the residual variations to a higher derivative form such as $\Delta^2 Q^t, \Delta^3 Q^t, \ldots, \Delta^n Q^t$. This extension is useful for systems that have high dynamic variations, but generally a Jacobean or/and Hessian is sufficient.

Using if-then rules of the following form of n-dimensional pattern classification problem is defined as:

**Rule** $R_q$: If $x_1$ is $A_{q_1}$ and $\ldots$ and $x_n$ is $A_{q_n}$ then Class $c_q$ with $CF_q$

where $R_q$ is the label of the $q^{th}$ fuzzy if-then rule, $x = (x_1, \ldots, x_n)$ is an n-dimensional pattern vector, $A_{q_p}$ is a fuzzy set, $c_q$ is a consequent class, and $CF_q$ is a weight rule or membership value in the unit interval $[0, 1]$.

The precision of correlated relation between the different HAZ distributions is given by the residual. The quality of welding from a pass to another is evaluated according to the importance of the residual $Q^t$ and its change $\Delta Q^t$, its fuzzy reasoning based rules are used as a tool for qualifying the quality of welding on the basis of the quality evaluation connected to the residual importance. It uses linear memberships functions as shown in Fig. 6.

The following fuzzy rules associated to the linear membership functions are applied:

- **If** $\Delta Q^t$ is Minimum AND $Q^t$ is Minimum **THEN** the quality is Very Good (VG)
- **If** $\Delta Q^t$ is Minimum AND $Q^t$ is Medium **THEN** the quality is Good (G)
- **If** $\Delta Q^t$ is Minimum AND $Q^t$ is Maximum **THEN** the quality is Medium (M)
- **If** $\Delta Q^t$ is Medium AND $Q^t$ is Minimum **THEN** the quality is Good (G)
- **If** $\Delta Q^t$ is Medium AND $Q^t$ is Medium **THEN** the quality is Medium (M)
- **If** $\Delta Q^t$ is Medium AND $Q^t$ is Maximum **THEN** the quality is Poor (P)
- **If** $\Delta Q^t$ is Maximum AND $Q^t$ is Minimum **THEN** the quality is Poor (P)
- **If** $\Delta Q^t$ is Maximum AND $Q^t$ is Medium **THEN** the quality is Poor (P)
- **If** $\Delta Q^t$ is Maximum AND $Q^t$ is Maximum **THEN** the quality is Very Poor (VP)

According to the above rules, the quality index can be written as:

$$\text{quality} = \text{fuzzy}[Q^t, \Delta Q^t]$$  \hspace{1cm} (7)

Where “fuzzy” is the fuzzy model given by the above fuzzy rules.

Fig.7a, Fig.7b and Fig.7c showed the residual distribution of the HAZ at different time. Residual is obtained by the difference between the HAZ distribution reference given in (Fig 6) and the actual HAZ distribution measured by the IR camera at different time. It is considered three (03) welding sequences given by Fig. 7 with five (05) time profile ($t_1 > t_2 > t_3 > t_4 > t_5$).

Evaluation system is given by a fuzzy system defined by its membership functions of inputs (Fig.9a and Fig.9b), the membership function of output is given by Fig.9c. Final quality evaluation illustrated by Fig.10 is obtained using the above Gaussian membership function and fuzzy rules. It is considered a fuzzification and rules based on the $Q^t$ and its changes $\Delta Q^t$, this
process enables to take account of the dynamic behavior of the residual. Output of the fuzzy system is an evaluation of the welding quality using an index in the range of [0-1] (Fig.10).

**Figure 9a. Membership function of $Q'$**

**Figure 9b. Membership function of $\Delta Q'$**

**Figure 9c. Membership function of output Q (quality index)**
5. Conclusion

Online quality evaluation is carried out by residual processing, fuzzy system based membership functions and fuzzy rules is applied and a global quality evaluation is done according to the deviations of HAZ temperature from their habitual values, this temperature is measured using IR camera. The application of such method is made using typical and real HAZ distribution in welding process. The proposed approach improves the welding process monitoring and gives a global quality evaluation and reduces the quality control cost.

References


