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Artificial neural networks for quality control by ultrasonic testing in resistance spot welding

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Abstract

An artificial neural network is proposed to solve problems in the interpretation of ultrasonic oscillograms obtained by the pulse echo method. The artificial neural network classifies resistance spot welds in several quality levels through their respective ultrasonic oscillograms. The inputs of the artificial neural network are vectors obtained from each ultrasonic oscillogram with the help of a MATLAB® program. The training of the artificial neural network uses supervised learning mechanism and therefore each input has the respective desired output (target). There are four targets, one for each considered quality level. The available data set is randomly split into a training subset (to update weight values) and a validation subset (to guard against overfitting by means of cross validation). The number of neurons in the hidden layers is selected considering the overfitting phenomenon. This research work has the aim of contributing to the automation of quality control processes in resistance spot welding.

Keywords: Resistance spot welding; Non-destructive testing; Ultrasonic oscillograms; Quality control; Artificial neural networks

1. Introduction

Resistance spot welding (RSW) is extensively used for joining sheet steel in the automotive industry [1,2]. The trend to reduce the high number of spot welds per vehicle (3000–4000 [3]) imposes the optimization and fine-tuning of reliable quality control systems [4].

The pulse echo method is an ultrasonic non-destructive testing technique suitable for the quality control in RSW [5,6]. This method obtains from each spot weld an ultrasonic oscillogram that allows estimating the quality level of the aforementioned spot weld. Sometimes the ultrasonic oscillogram is hard to interpret by a human expert or the task of interpreting repeatedly oscillograms for a long time gives rise to the drop of the human expert's efficiency [7]. Therefore, the automation of the interpretation of ultrasonic oscillograms would improve the quality control performance in RSW. Artificial neural networks (ANN) are mathematical models that imitate the behaviour of the human nervous system and hence have a parallel, distributed and adaptive processing capable of mapping non-linear and complex systems, in which the regression methods have their limitations [8–10]. For this reason, the ANN are extensively used in pattern recognition tasks [11–15]. The interpretation on each ultrasonic oscillogram, in order to classify the respective spot weld in a certain quality level, is a pattern recognition problem, so an ANN is proposed to carry out the automation of the interpretation of ultrasonic oscillograms.

An ANN, just like a human being, learns by means of training. A supervised learning mechanism is used in the training of the ANN in which a set of input/target pairs is utilized (a target is the desired output respective to a certain input). In the training, the synaptic weights (each link between neurons has a synaptic weight attached to it) are repeatedly adjusted to reduce the error between the experimental outputs and the respective targets until a certain value of error is achieved [16].

2. Experimental procedure

2.1. Materials and equipment

The chemical composition and the mechanical properties of the sheet steel are, respectively, shown in Tables 1 and 2. The sheet thickness is 1 mm.

The considered parameters in the RSW process (single-phase AC 50 Hz equipment) are:

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Table 1
Chemical composition of the sheet steel (wt.%)

C	0.05
Mn	0.26
Si	0.02
P	0.012
S	0.011
Al	0.033

Table 2
Mechanical properties of the sheet steel

Yield strength (MPa)	192
Tensile strength (MPa)	301
Total elongation (%)	40
Hardness (HV)	104

- Current intensity varies between 4 and 8 kA RMS [17,18]. The recorded values are gathered round five theoretical values (4, 5, 6, 7 and 8 kA RMS).
- Weld time varies between 4 and 20 cycles [17,18]. The recorded values are gathered round nine theoretical values (4, 6, 8, 10, 12, 14, 16, 18 and 20 cycles).
- Electrode sort depends on the copper alloy sort and on the thermal/mechanical treatment used for the alloy. Two copper alloy sorts (Cu–Cr and Cu–Be [18]) and three thermal/mechanical treatments [19,20] are selected, therefore there are six electrode sorts.
- Electrode force is fixed at 980.7 N.

The ultrasonic spot welding testing transducer uses a captive water column delay and a replaceable rubber membrane in order to provide good coupling to the weld surfaces. The transducer frequency is 20 MHz and the transducer diameter is 4.5 mm.

2.2. Inputs of the artificial neural network

The binary signal associated with each ultrasonic oscillogram is transformed into the input of the ANN by means of a MATLAB® program [4]. The input of the ANN must be representative of its respective ultrasonic oscillogram [15], therefore the transformation program must consider the main factors that characterize an ultrasonic oscillogram [5]: the attenuation of the ultrasonic wave and the one-layer echoes (caused by ultrasonic beam reflections that occur at the interface between the two sheets) between principal echoes. On the other hand, the input must not be too complex in order to avoid complicating the ANN and using redundant data. The decision that determines the input size is how many echoes in the ultrasonic oscillogram are considered. Fewer than six echoes are too few to be representative. More than six echoes are representative but they do not give significant information with regard to the information that is associated with six echoes. Therefore, the compromise solution considers the first six echoes in the ultrasonic oscillogram and the input of the ANN is a 10-component vector where (Fig. 1):

- The first five components are the relative heights of the echoes: the nth component ($n = 1, \ldots, 5$) is the height of the $(n + 1)$th echo (h_{n+1}) divided by the height of the 1st echo (h_1).
- The last five components are the distances between consecutive echoes: the nth component ($n = 6, \ldots, 10$) is the distance between the $(n - 4)$th echo and the $(n - 5)$th echo (d_{n-5}).

2.3. Classification of spot welds and characterization by ultrasonic testing

The quality level of a spot weld is estimated from its respective ultrasonic oscillogram. The estimation is based on the effect of the weld nugget of the spot weld on the ultrasonic wave. Two parameters of the weld nugget are considered [5]:

- *Weld nugget microstructure*. A weld nugget is a cast microstructure with coarser grains than the parent metal, therefore a weld nugget produces higher attenuation than the parent metal. The heat-affected zone (HAZ) is a small zone between the weld nugget and the parent metal. The HAZ is a recrystallized microstructure with fine and equiaxed grains that produce low attenuation. The influence of the HAZ on the respective ultrasonic oscillogram can be neglected.
- *Weld nugget size*. One-layer echoes appear between principal echoes if the weld nugget diameter is smaller than the width of the ultrasonic beam so that a part of reflections occurs at the interface between the two sheets. A thick weld nugget produces higher attenuation than a thin weld nugget.

The spot welds are classified into four possible quality levels [5,21] and a target (a two-component vector) is assigned to each one [22]:

- Good weld: (1 1).
- Undersize weld: (0 1).
- Stick weld: (1 0).
- No weld: (0 0).

2.3.1. Good weld

2.3.1.1. Weld nugget. The cast microstructure of the weld nugget has coarse grains. The weld nugget thickness is enough to produce high attenuation. The weld nugget diameter is larger than the width of the ultrasonic beam (Figs. 2 and 3).

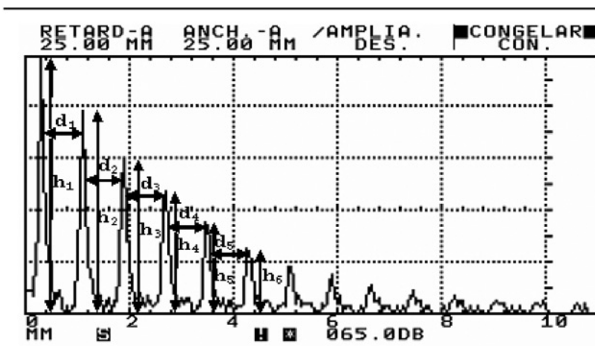
Ultrasonic oscillogram	Input of the ANN
	$\begin{pmatrix} h_2/h_1 \\ h_3/h_1 \\ h_4/h_1 \\ h_5/h_1 \\ h_6/h_1 \\ d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \end{pmatrix}$

Fig. 1. Input of the ANN (right) obtained from its respective ultrasonic oscillogram (left).