Materials and Design 30 (2009) 2547–2555

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Regression modeling and process analysis of resistance spot welding on galvanized steel sheet

Luo Yi [a,b,*], Liu Jinhe [a], Xu Huibin [b], Xiong Chengzhi [b], Liu Lin [b]

[a] School of Material Science and Engineering, Northwestern Polytechnical University, Xi'an, 710072 Shanxi, People's Republic of China
[b] School of Material Science and Engineering, Chongqing Institute of Technology, Chongqing 400050, People's Republic of China

ARTICLE INFO

Article history:
Received 16 June 2008
Accepted 23 September 2008
Available online 30 September 2008

Keywords:
Galvanized steel sheet
Spot welding
Process parameters
Regression model
Nugget diameter
Tensile–shear strength

ABSTRACT

The resistance spot welding process of galvanized steel sheet used in the body manufacturing of family car was investigated on the basis of mathematical models. Method of non-linear multiple orthogonal regression assembling design was applied in experiment. The indexes studied in experiment were nugget geometry and tensile–shear strength of spot welds. Furthermore, four process parameters, namely welding current, electrode force, welding current duration and preheat current, and interactions among them were considered as the factors impacting indexes. The mathematical models developed were optimized by means of variance analysis. The experimental results showed that there was a more accurate prediction on nugget size and mechanical properties of spot welds by the models optimized. With these prediction results, the optimization of welding process also was realized by the analysis to the effect of parameters and interactions on the welding quality.

1. Introduction

Resistance spot welding (RSW) is one of the major welding technologies used in the industry of conveyance manufacturing, especially in automobile manufacturing. For example, there are 3000–6000 spot welds in a car. As existence of spatter generating and electrode contamination during the spot welding of galvanized steel sheet, the weldability of galvanized steel sheet is poorer than that of ordinary steel sheet, which is a limitation to the appliance of galvanized steel sheet and the large-scale automatic fabrication of automotive products.

The tensile–shear strength of spot weld, which is often associated with the effective area of nugget to load, is an important index to welding quality [1]. So, investigation on the relations between the strength of spot weld or nugget geometry and process parameters is the key to solve the RSW problem of galvanized steel sheet.

To achieve this, an experimental program devised by the method of non-linear multiple orthogonal regression assembling design was performed to reduce the cost and time, as well as to obtain the required information about the effects and interactions of process parameters on the nugget geometry and mechanical properties of spot welds. And, the mathematical models were developed to predict spot weld quality for the given process parameters. These models will also help to evaluate the interaction effects of parameters and optimize the welding process design to obtain high-quality spot welds at a relatively low cost.

2. Welding process

2.1. RSW thermal effects

During the RSW, metal sheets are compressed together tightly under the action of electrode force at the welding location. Nugget is forming on the contact interface between specimens as a result of the heat created by electrical resistance while the welding current passing from the electrodes through the work [2,3]. And then the effect of welding is realized. So the welding thermal effect mainly relies on the three factors, namely welding current, current duration and contact resistance. During welding, the welding thermal effect Q is

$$Q = \eta \cdot \int i^2(t) \cdot r(t) \cdot \mathrm{d}t \tag{1}$$

where η is welding thermal efficiency, i is welding current and r is material resistance. So the Q is the cumulative effect of i and r to duration of current (t).

A series of resistances constituted by the secondary circuit of resistance welding machine and workpieces are shown in Fig. 1, and the total resistance is

$$R = R_c + 2R_w + 2R_{ew} + 2R_e \tag{2}$$

* Corresponding author. Address: School of Material Science and Engineering, Chongqing Institute of Technology, Chongqing 400050, People's Republic of China.
E-mail address: luoyi@cqit.edu.cn (Y. Luo).

0261-3069/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.matdes.2008.09.031

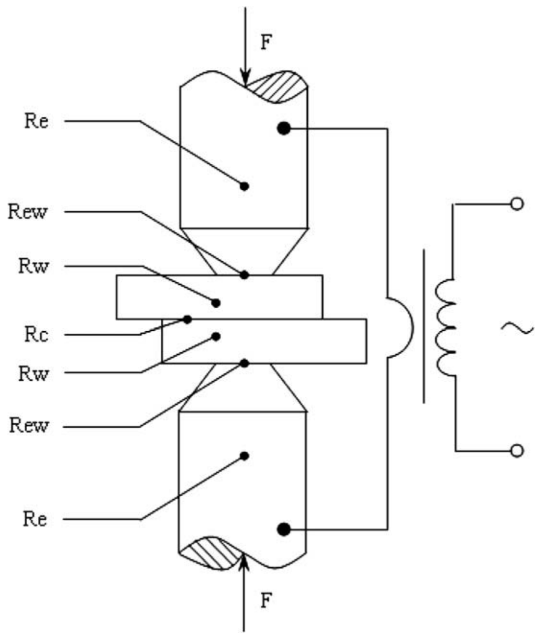

Fig. 1. The resistances in RSW, where F is electrode force, R_e is electrode resistance, R_{ew} is specimen-electrode contact resistance, R_w is specimen resistance and R_c is specimen contact resistance.

where the value of R_e could be ignored because of the electrodes made of copper alloy with low resistance. So, the resistance in welding circuit shown as Eq. (2) could be simplified as

$$R = R_c + 2R_w + 2R_{ew} \tag{3}$$

where R_{ew}, R_w and R_c are the resistance variation with the material of specimens, which determines the temperature distribution and the effect of metal melting in a spot weld during welding, as well as the weldability [4,5]. Based on this fact, the galvanized steel sheet has a poorer weldability against to ordinary steel sheet due to the zinc coat with smaller contact resistance and higher conductive properties. In fact, the resistance heat generated on the interface between workpieces has an intimate relationship with the contact resistance R_c. More heat generation and better weldability are produced with larger value of R_c. The R_c is not a static resistance but a time-varying parameter under the actions of welding current and electrode force during welding. So the variations of quality information are recorded in R_c varying, which is influenced by the contact status variation with welding current and electrode force, as well as the material property and the surface status of workpieces. In view of all these mentioned above, the actions of interactions among welding current, electrode force and duration of them on quality of spot weld could not be ignored during the welding. So, the nugget geometry relying on the resistance heat and mechanical properties would depend on a certain marching between these three factors.

2.2. Nugget geometry and mechanical property of spot weld

The same to metallurgical structure, the nugget geometry, which relates to the effective area to load, has an intimate relationship with mechanical properties of spot weld. Here, the parameters of nugget diameter (d) and penetration ratio (A) were introduced to describe the nugget geometry (Fig. 2).

Obviously, the resistance heat generated on the interface between workspieces is influenced by the variation of welding current, electrode force and current duration [6–8]. The values of d and A would depend on the resistance heat during welding.

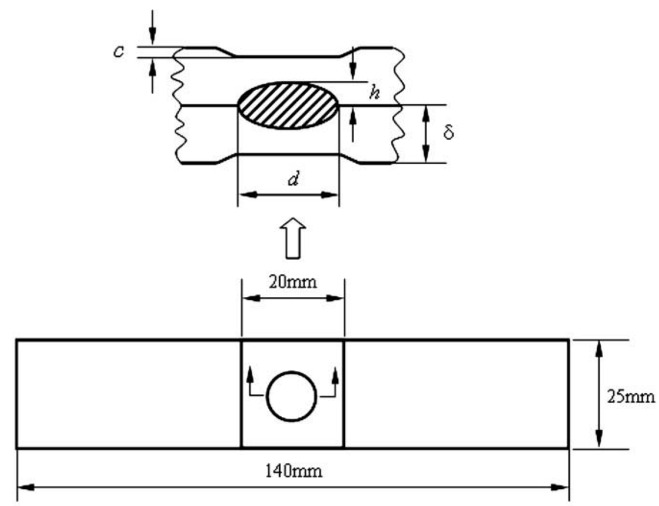

Fig. 2. Specimen specification and nugget geometry, where c is indentation depth, h is 1/2 nugget height, δ is slab thickness, d is nugget diameter and $A = \frac{h}{\delta - c} \times 100\%$.

And the mechanical properties would be varying with the actions. Here, the tensile–shear strength (F_t) was introduced to describe the mechanical properties of spot weld. Referring to Fig. 3, there is an eccentricity Δ between tensile axes of overlap joints. The tensile stress and shear stress are all playing a role during tension test to spot weld because of the eccentricity. So, the mechanical properties of spot welds are described by the tensile–shear strength.

The effects of welding process parameters on the values of d, A and F_t of spot welds have a changing characterized by linearity without regarding to the spatter and phase transition during the welding. Otherwise, it will reflect non-linear changing.

3. Experimental work

3.1. Test specimens

The materials used in experiment were commercially available galvanized steel sheet widely used in car fabrication. The specimen was made as the specification of 80 mm × 25 mm × 1 mm refer-

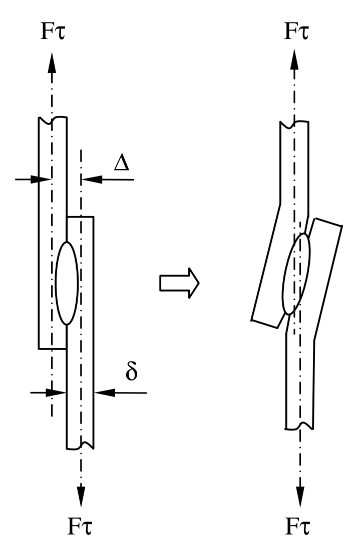

Fig. 3. The tensile–shear strength definition and calculation from laboratory test. Δ is eccentricity and δ is thickness.