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Adaptive resistance spot welding method that reduces the shunting effect

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ABSTRACT

A reference-based adaptive resistance spot welding (RSW) method intended to reduce the shunting effect in short-pitch ($\leq$ 40 mm) RSW is proposed in this study. As the weld pitch decreases, the nugget diameter and dynamic resistance level concurrently decrease by an amount equivalent to the increased shunting effect. Based on this fundamental relationship, an exponential model capable of predicting weld pitch as a function of dynamic resistance was estimated. Next, the relationship between the nugget diameter and the heat input as a function of weld pitch was investigated, and a logistic growth model capable of predicting heat input compensation was established. These exponential and logistic growth models form the basis of the proposed RSW method's control algorithm. The proposed RSW method compensates for the heat input loss caused by the shunting effect by adjusting welding time in real time under a constant current control until the predicted heat input compensation is obtained. Experimental results indicated that the RSW method proposed in this study concurrently increased the nugget diameter and decreased the shunting effect in short-pitch RSW compared with conventional welding method results. This finding suggests that the proposed reference-based adaptive RSW method is effective in reducing the shunting effect in short-pitch RSW.

1. Introduction

A desire to increase vehicle fuel efficiency and decrease carbon dioxide (CO_2) emissions has led to the development of enforceable regulations such as the Corporate Average Fuel Efficiency (CAFE) Standards, which are designed to improve the fuel economy of light trucks and cars [1]. To meet these standards, the automotive industry's original equipment manufacturers (OEMs) have developed and applied distinctive lightweight technologies. These lightweight technologies must also meet various vehicle crashworthiness standards. For example, Sherwood et al. [2] investigated various vehicle designs using full-scale tests in response to the Small Overlap Frontal Crashworthiness Evaluation introduced by the Insurance Institute for Highway Safety (IIHS) in 2012. More recently, Nguyen et al. [3] investigated various vehicle designs using computer-based crash simulation models in response to this same IIHS standard. To satisfy both weight reduction and improved vehicle crashworthiness, various types of high-strength steel (HSS) sheets have been applied to vehicle bodies.

Resistance spot welding (RSW) is the main joining technology for automotive steel sheets. Oikawa et al. [4] reported that lower quality RSW occurred when joining HSS sheets than conventional steel sheets because of high alloying element content that decreases weld toughness. Yu et al. [5] investigated the contributing factors for narrow suitable welding ranges (weld lobes) of HSS sheet based on the tensile shear strength (TSS) of the spot welds and welding signals, including dynamic resistance and welding power. Furthermore, Natale et al. [6] reported that the cross tension strength (CTS), absorbed energy, and fatigue strength in the welds decreased as the strength of HSS increased. These findings suggest that inadequate design of welded joints in HSS can degrade the strength of a vehicle body. Therefore, it is necessary to develop welding methods that enhance the mechanical performance of vehicle body parts consisting of HSS and joined by RSW.

To date, welding methods have focused on either improving the (1) weld's material and mechanical properties or (2) the welded joint design. Considering the weld's material and mechanical properties, Duan et al. [7] proposed a novel postweld heat treatment method that applied a cross-directional current to the resistance spot welds and investigated its effect on the nugget shape, microstructure, and mechanical properties. The results showed that the crosscurrent postweld heat treatment enhanced the efficiency of postweld heat treatment and improved the mechanical performance of the nugget. Similarly, Taniguchi et al. [8] applied a pulsed current pattern comprising a combination of short cool

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time and short-time, high-current postheating to welds and investigated the effects on joint strength in ultrahigh-strength steel. Most recently, Sajjadi-Nikoo et al. [9] investigated three types of in situ postweld heat treatments on the mechanical properties of transformation-induced plasticity steel resistance spot welds. Alternatively, Yu et al. [10] used constant power control welding to increase nugget size and improve the weldability of a 1-GPa grade twin-induced plasticity steel.

Considering the welded joint design, Shibuya [11] found that short-pitch RSW, with a pitch of ≤ 40 mm, was significantly effective in increasing vehicle body strength. Similarly, Kuhn and Mallick [12] found that short-pitch RSW proportionally increased the strength of a welded structure by increasing the number of weld spots. Chang and Cho [13] found, however, that when the pitch between welds was reduced, the quality of the subsequent weld was adversely affected due to the shunting effect. Therefore, to realize the benefits of short-pitch RSW, a method for reducing the shunt effect is required.

Wang et al. [14] considered the effect of material, surface conditions, welding sequence, and other parameters on shunting. Experimental results showed that weld pitch and surface condition had dominant effects on shunting. Alternatively, Li et al. [15] developed an analytical model to investigate the effects of various process parameters on minimum weld pitch for certain sizes of shunted welds. Ooka et al. [16] used a three-dimensional RSW simulation to investigate the shunting effect phenomenon and proposed a welding method that compensated for heat loss due to the shunting effect in short-pitch RSW. More recently, Shibuya [11] proposed an adaptive short-pitch RSW method that stabilized weld quality in a production line. Recently, some *smart welding systems* have been developed and applied in production lines to address abnormal conditions, including short weld pitch, poor fit-up, and electrode tip wear. Although several previous studies have investigated the shunting effect phenomenon in RSW, fewer studies have considered the development of adaptive RSW methods that directly reduce the shunting effect.

In this study, a reference-based adaptive RSW method that reduces the shunting effect is proposed. In particular, an exponential model capable of predicting weld pitch as a function of dynamic resistance was established. Next, the relationship between the nugget diameter and the heat input as a function of weld pitch was investigated, and a logistic growth model capable of predicting heat input compensation was established. The proposed adaptive RSW method, which can more fully realize short-pitch RSW benefits by reducing the shunting effect, was developed using these two regression models. The proposed RSW method compensates for the heat input loss caused by the shunting effect by adjusting welding time under a constant current control (CCC) until the heat input compensation is achieved. Finally, the proposed RSW method was experimentally verified.

2. Experimental methods and materials

2.1. Experimental apparatus

A medium-frequency, direct-current (MFDC) RSW apparatus was developed to support initial investigation of the shunting effect and subsequent application of the proposed RSW method's control algorithm intended to reduce the shunting effect. Fig. 1 shows the configuration of the MFDC RSW apparatus, including the function of and signal flow for each component.

A 32-bit digital signal processor (TMS320F2812) was used to control the apparatus. This processor generated a 1-kHz pulse width modulation (PWM) signal to control the welding current and received the welding voltage and current signals at its secondary circuit. The processor also generated an analog signal using a digital-to-analog circuit to control an electropneumatic regulator (ITV3050-31-4S), which set the electrode force. A gate driver was used to amplify the PWM signal's voltage from 3.3 to 15.0 V and switch the insulated gate bipolar transistor (IGBT) modules (CM300DY-28 H). Using the PWM signal's 1-kHz frequency, an inverter changed the power from direct current (DC) to alternating current (AC). A transformer (PSG6130) changed the high-voltage, low-current AC with a 1-kHz frequency to a low-voltage, high-current AC with a 1-kHz frequency then subsequently generated DC power using diodes in the transformer. The current from the transformer was smoothed by the impedance of the weld gun. Finally, a pneumatic pedestal welding machine, capable of applying an electrode force of 2.0–12.0 kN, was used.

Fig. 2 shows the block diagrams for the overall proposed RSW method (Fig. 2(a)) and for the welding current control (Fig. 2(b)). To reduce the shunting effect in short-pitch RSW, an adaptation scheme module was added to the MFDC RSW system. The function of this module includes the processing of welding signals, estimation of weld pitch, prediction of heat input compensation amounts, and control of the welding process. Further details are described in Section 2.4.

2.2. Experimental materials

Short-pitch RSW is generally adopted in vehicle body reinforcement members to improve vehicle crashworthiness. To effectively apply the short-pitch RSW to automotive parts, the shunting effect caused by short weld pitch should be overcome. To this end, three types of steel sheets were used in this study to mimic the three-sheet lap welding combination used in crash members (comprising a low-carbon outer panel, HSS reinforcement member, and HSS inner structure): low-carbon steel (SGACEN), dual-phase steel (DP980), and complex-phase steel (CP1180). Table 1 lists the chemical compositions, coatings, tensile strengths, and thicknesses for each material considered. The stacking order is as follows: the positive electrode side sheet is SGACEN, the middle sheet is CP1180, and the negative electrode side sheet is DP980. Cu-Cr dome-type cap tips having a tip radius of 40 mm and a tip diameter of 6 mm were used, and the tips were stabilized by making 50 welds prior to experiment.

2.3. Experimental design

To support the initial investigation of the shunting effect in RSW, various weld pitches and currents were considered under constant welding time, electrode force, hold time, and cooling water condition. Table 2 lists the welding conditions used. To support this investigation, the steel sheets were cut into test specimens measuring 30 × 100 mm.

To determine the minimum welding current value, a series of single spot welding tests was conducted at 0.5-kA intervals. The current immediately before expulsion was considered the minimum welding current. During experimentation, the welding current and voltage were measured using the sensors in the MFDC RSW apparatus and used to calculate the dynamic resistance and heat input. The welding current was indirectly measured using the toroidal coil in the transformer and integrator circuit; the voltage was directly measured using clips attached at both ends of the electrode tips. The 25 data of the current and voltage were sampled every 0.5 ms, and these measurements were averaged to calculate the dynamic resistance and heat input as follows:

$$r(t) = v(t)/i(t) \tag{1}$$

$$Q = \int i(t)\cdot v(t)\cdot dt = \int p(t)\cdot dt \tag{2}$$

where $r(t)$ is the dynamic resistance, $v(t)$ is the voltage, $i(t)$ is the welding current, and $p(t)$ is the power measured every 0.5 ms, and Q is the total heat input during the entire welding time.

Fig. 3 depicts the welding sequence applied to the test specimens using various weld pitches and currents under constant welding time, electrode force, hold time, and cooling water condition. Weld pitch is defined as the center-to-center distance of each of the weld segments in this study. The first test weld—the *shunt weld*—receives all of the applied welding current and is therefore unaffected by shunting. The second test weld—the *shunted weld*—shares the applied welding current