Primary Circuit Dynamic Resistance Monitoring and its Application to Quality Estimation during Resistance Spot Welding

Weld strength and nugget diameter were estimated by using primary circuit process parameter as a real-time in-process monitoring system

BY Y. CHO and S. RHEE

ABSTRACT. Resistance spot welding is one of the most widely used processes in sheet metal fabrication. Improvements in quality assurance are important to increase welding productivity. Until now, quality estimation was performed using dynamic resistance at the secondary circuit, which is easily measured. However, this method has many problems when applied to in-process real-time systems. In this study, weld quality was ensured through the use of a new dynamic resistance monitoring method. This method used instantaneous current and voltage values measured at the primary circuit. A weld quality estimation system is suggested using these variables. For quality estimation, ten factors relating to quality were extracted from the primary circuit dynamic resistance, measured in the timer. The relationship between these factors and weld quality was determined through a regression analysis. Four regression models were developed using the results of the analysis in order to estimate weld strength and nugget diameter. Neural network models were also suggested using these factors. The results of the neural network were compared with those of the regression models. This was designed so weld quality estimation could be obtained upon completion of welding. Moreover, the proposed method using the primary circuit dynamic resistance has an advantage over the conventional one, such as obtaining information on quality without the use of extra devices.

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This paper was presented at the AWS 81st Annual Convention, April 25–27, 2000, Chicago, Ill.

Introduction

For several decades, resistance spot welding has been an important process in sheet metal fabrication. The automotive industry, for example, prefers spot welding for its simple and cheap operation. Recently, however, attempts are being made to reduce the number of spot welds to increase productivity. In order to minimize the number of spot welds and satisfy essential factors such as strength, weld quality must be obtained. Traditionally, to check weld quality, destructive and nondestructive tests were used on randomly sampled workpieces at the production site. These processes, however, can only be examined off-line, making it impossible to receive pertinent information regarding the weld quality during the process. Weld quality estimation must be done in real time to monitor and repair weld defects as they occur.

As resistance spot welding has electromechanical elements, various weld quality control techniques have been proposed based upon the following process parameters: dynamic resistance, welding current, voltage, and electrode displacement (Refs. 1, 2). In general, electricity-based systems, which maintain the voltage or the current at a constant preset level (Refs. 3, 4), have been used to control those parameters automatically. Although the general voltage supply is reliable, severe voltage fluctuations may occur in some areas and, in such situations, automatic voltage regulators have been employed. The idea to maintain constant power or current for a set period of time has also been employed in cases where the impedance changes during welding. In addition, a combined current and voltage regulator, which adjusts the phase-shift control automatically, was introduced. Investigations based upon the thermal expansion have been undertaken in attempts to control the quality as well.

KEY WORDS

Resistance Spot Welding
Inductive Noise
Primary Circuit
Dynamic Resistance
Regression Analysis
Correlation
Neural Network
Quality Estimation

A resistance spot welding machine has moving parts such as electrodes or arms. Moreover, a direct relationship between the rate of electrode separation and the properties of the weld exists. Johnson, *et al.* (Ref. 2), developed a spot-weld correction system based on sensing the weld thermal expansion in which correction was achieved by automatic adjustment of weld load. A real-time adaptive spot welding control system based upon a measurement of electrode displacement was also operational on the factory floor throughout the recent study (Ref. 5). Resistance correction technique forms another basis for an automatic quality control system in spot welding (Ref. 6). In the early 1970s, commercial units of these quality control systems were developed and attached to welding machines in the auto body industry (Ref. 4).

Measurement of dynamic resistance has been one of the most effective techniques of quality monitoring and estimation during the past several decades. Some of the earliest and simplest techniques were to monitor the voltage and current at the secondary circuit. The electric parameters, however, vary frequently during welding cycles due to resistance change.

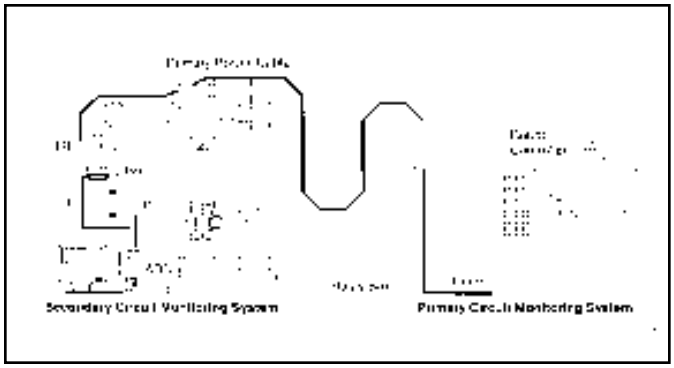

Fig. 1 — Schematic diagram of resistance spot welding monitoring system.

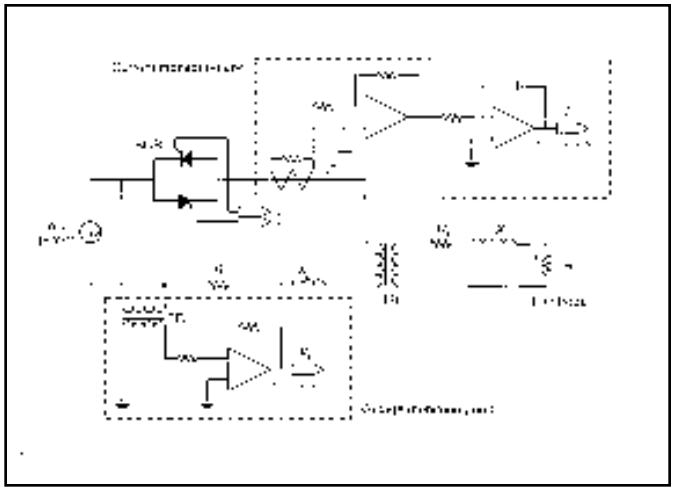

Fig. 2 — Simplified welding machine circuitry including primary circuit monitoring units.

Therefore, the monitored power input may not be appropriate, and the true energy state of welding is not represented. Dynamic resistance, on the other hand, has relatively accurate information on energy generation during nugget formation (Ref. 7). In earlier studies (Ref. 8), the potential of dynamic resistance as a parameter indicative of weld quality was explored. The values of dynamic resistance as a nominal condition of test welding were sampled and stored in an electronic memory. These values were compared with values sampled at the production welds. The values in agreement with those for the test weld, within an acceptance band, might then be considered as good as the initial test weld. Another quality evaluation technique was proposed with microprocessor-based resistance monitoring system as an in-process scheme (Ref. 9). The dynamic resistance characteristic of an accepted weld was computed as a reference in the monitoring system. The next procedure was very similar in comparison to the first example except not only the absolute values were compared to the reference but also the slopes of the dynamic resistance characteristics.

In order to acquire the resistance signal, the dynamic resistance was calculated from the welding current, and the voltage was measured at the secondary circuit using an oscilloscope in the early stages (Refs. 10–12). The physical meaning of resistance variation, however, could not be clearly explained in these studies. Dynamic resistance was calculated more efficiently by applying the root mean square (rms) value of the measured signal to the analog circuit using the Hall-effect sensor and voltage-measuring devices (Ref. 13). In this study, the effect of the dynamic resistance on the nugget formation and ensuing dynamic resistance pattern were considered. The study was useful in explaining the variations of the dynamic resistance according to the nugget formation, such as the collapse of the contact resistance, the increasing temperature of the faying surface, and the melting and plastic deformation of the nugget. Kaiser, *et al.* (Ref. 14), and Thornton, *et al.* (Ref. 15), attempted to examine the nugget formation according to changes in contact resistance. Kaiser, *et al.*, explained the effect of the dynamic resistance and initial contact resistance on the lobe curve, while Thornton, *et al.*, looked into the contact resistance of the aluminum alloy and the ensuing dynamic resistance variance.

Research based on dynamic factors continues to be carried out regarding weld quality estimation (Refs. 16–20). In a weld quality estimation system using multiple linear regression analysis (Ref. 16), weld quality was examined by defining the relationship between factors, such as electrode displacement, dynamic resistance, and weld quality. Livshits (Ref. 18) suggested a system that could more commonly be used. In his research, the dynamic resistance based on the current density of the faying surface was used to assure weld quality. Research was also performed on weld quality estimation using an intelligent algorithm such as the neural network on resistance spot welding. Brown, *et al.* (Ref. 19), used the normalized dynamic resistance, welding current, and electrode diameter to predict the nugget diameter, which was closely related to weld strength. Dilthey, *et al.* (Ref. 20), however, examined the shear strength using welding current and voltage through a similar method.

Although such studies based on results obtained from the secondary circuit can be applied to real-time weld quality estimation, in-process usage has several limitations. These limitations include the installation location of the voltage measuring device and increased costs due to additional measuring devices. Therefore, in this study, the primary circuit dynamic resistance was used, which proved efficient for in-process application. By comparing the rms dynamic resistance acquired from the traditional method of the secondary circuit monitoring system with the proposed dynamic resistance based on the primary circuit monitoring system, it became evident there was a direct relationship between the primary and secondary circuit dynamic resistance. Furthermore, the primary circuit dynamic resistance was used to estimate the weld quality. Tensile shear strength and nugget diameter were estimated through the regression analysis and neural network. Throughout the research, a system was proposed in which the weld quality could be estimated in real-time upon completion of the weld.

Process Parameter Monitoring

Inductive Noise and Dynamic Resistance Monitoring

As the resistance spot welding is processed, the electrical resistance variation of the welds, due to the Joule heat generated by the weld current, becomes one of the most important factors in nugget formation. Unlike the initial contact resistance of the faying surface, the dynamic resistance includes information on nugget formation as welding occurs (Refs. 13, 15, 21, 22). Generally, the resistance can be obtained by the voltage divided by the current. In resistance spot welding circuitry, however, many problems occur in the measurement of resistance due to the inductive reactance elements of the electrical circuit. A simple means to acquire dynamic resistance, uninfluenced by inductive noise, is to use the rms value. When the rms voltage detected across the electrode, which does

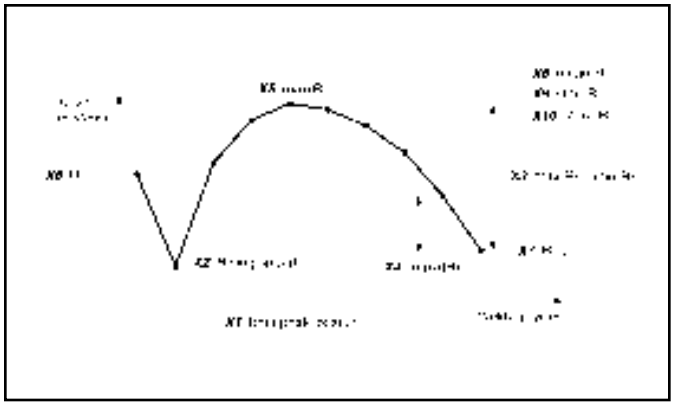

Fig. 3 — Primary circuit dynamic resistance pattern and quality estimation factors.

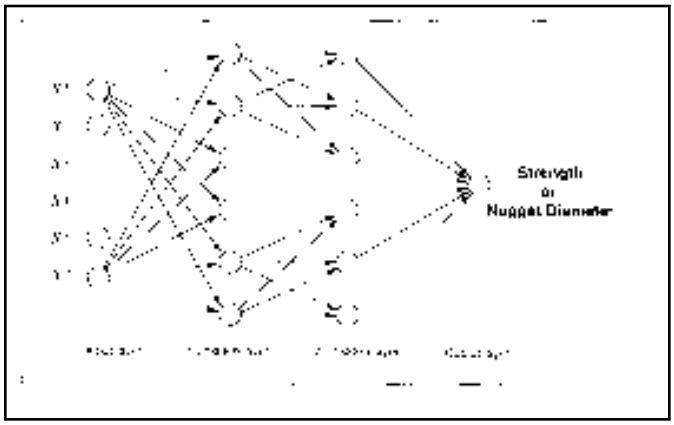

Fig. 5 — The neural network architecture.

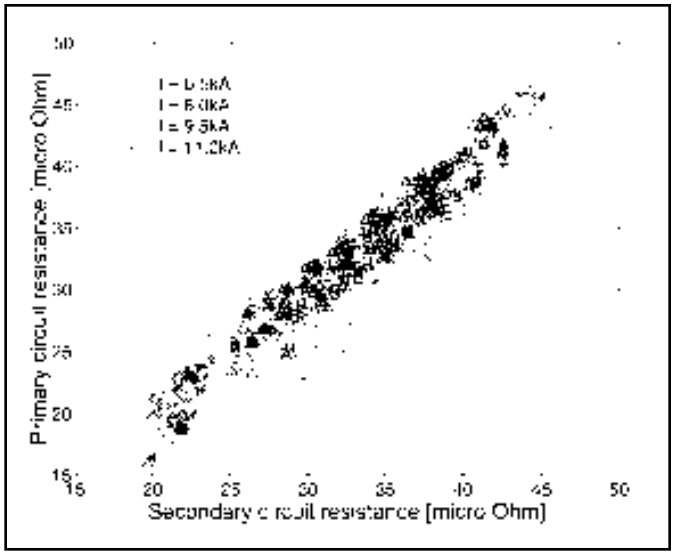

Fig. 4 — Linear relationship plot between primary and secondary dynamic resistance.

not include much inductance (Ref. 12), is divided by the rms current of the secondary circuit, resistance can be obtained with no consideration to the phase shift due to the inductive noise. Another way of effectively eliminating the inductive noise from the dynamic resistance is to use the voltage and current when the welding current is at the peak value of each cycle. This method is based on the principle that only the pure resistance element, not the inductive reactance element, influences the impedance of the alternating current circuit when the rate of change of current equals zero (Refs. 1, 9, 15, 23). The greatest advantage of this method is that the pure resistance variation at the secondary circuit can be monitored at the primary circuit.

Figure 1 is a schematic diagram of the resistance spot welding system generally used in auto body manufacturing. The welding current that is controlled in the timer of the welding machine is passed through the transformer TR to the welding gun by the primary power cable. As the secondary circuit dynamic resistance monitoring system of this study, welding voltage and current are measured in terms of rms values. By attaching the clips to each electrode tip, the instantaneous welding voltage drop was measured. The Hall-effect sensor located on the lower arm of the welding machine monitored the current flowing in the secondary circuit. By using an analog-to-digital converter (ADC), the analog voltage and the current were monitored simultaneously. In the earlier study (Ref. 1), when a 60-Hz alternating current was used, a sampling rate of more than 1 kHz should be used. However, in order to effectively reflect the sharp voltage waveform produced by the electrical triggering of the silicon controlled rectifier (SCR) to the resistance value, a sampling rate of 6 kHz was used in this study. This allowed the calculation of the dynamic resistance with the 50 numbers of data per half cycle. By using the digitized voltage and current, each rms value of a half cycle was calculated. As another approach, this research introduced a process to detect the dynamic resistance from the timer as a primary circuit monitoring system, using a microprocessor. In the primary circuit, the welding voltage and current could be detected without extra measuring devices; thus, this method could be used effectively as an in-process system. This method will be addressed in the following sections.

Analysis of Welding Machine Circuit

The resistance spot welding machine consists of a relatively simple electric circuit that includes a transformer. The simplified equivalent circuit is shown in Fig. 2. In the figure, the primary circuit elements are shown as subscript p and the secondary circuit elements as s. In the primary circuit, R_p stands for the total resistance value of the primary circuit. X_p stands for the primary leakage reactance. In the secondary circuit, R_s stands for the total resistance value of the secondary circuit, which includes the welding gun and the electrode. X_s stands for the secondary leakage reactance. R_L stands for the resistance change across the electrodes. When the secondary circuit elements are shifted to the primary circuit, the resistance of the circuit, including shifted secondary circuit elements, which are shown as the reflected impedance described with the transformer ratio a, can be written as an equivalent resistance R and an equivalent inductive reactance X in Equations 1 and 2, which corresponds with the primary circuit current.

$$R = R_p + a^2\left(R_s + R_L\right) \tag{1}$$

$$X = X_p + a^2 X_s \tag{2}$$

By using the inductive elimination method, as stated in the preceding section, the inductive reactance X can be removed to calculate the dynamic resistance from the measured current and voltage of the primary circuit. Also, if assumed the transformer will operate ide-

ally and the resistance change due to the temperature change of the entire welding machine circuit can be ignored, the relationship between the resistance across the electrodes R_L and the measured dynamic resistance R_{meas} from the voltage V_p and the current I_p in the primary circuit can be shown in Equation 3 below.

$$R_{meas} = \frac{V_p}{I_p} = R_p + a^2\left(R_s + R_L\right) \quad (3)$$

Where I_p is the peak current value of the instantaneous current from the primary circuit and V_p is the voltage at that moment.

Primary Circuit Dynamic Resistance Monitoring and Quality Estimation Factors

The primary current made by the phase control was measured using the current transformer (CT) from the inside of the timer. This primary current waveform was appropriately amplified using the gain selector. The signal at this stage includes high-frequency noise from the SCR current control unit and amplifier. By using the integrator, which has a suitably selected condenser, the high-frequency noise signal can be converted into a noise-free welding current waveform. The welding voltage was detected at the primary circuit and was attenuated using the measuring transformer. The monitoring trigger pulse was created when the rate of change of current reached zero, triggering the sample and holding circuit, which were connected by the detected welding current and the attenuated primary voltage. The instantaneous welding current and voltage were converted into digital values by the analog-to-digital converter. These values were used to calculate the dynamic resistance by dividing the current from the voltage of half cycle. The measured dynamic resistance R_{meas} includes the resistance of the primary circuit resistance R_p and secondary circuit resistance R_s and R_L. Therefore, to measure the resistance of the weld, the R_p and R_s must be removed effectively from the calculated resistance value. Fortunately, in the general resistance spot welding machine, the square of the transformation ratio a^2, shown in Equation 3, has an order of hundreds or thousands, so the R_p included in the calculated dynamic resistance R_{meas} is a relatively small value. In other words, the R_p can be ignored. With the proper measurement, the resistance of the secondary circuit R_s also can be obtained. This method converts the primary circuit dynamic resistance into the dynamic resistance change across the electrodes.

Table 1 — Correlation Coefficients, Root Mean Square Errors, and Maximum Errors between Primary and Secondary Dynamic Resistance

6.5 kA			8 kA			9.5 kA			11 kA		
R	E_{rms}	E_{max}	R	E_{rms}	E_{max}	R	E_{rms}	E_{max}	R	E_{rms}	E_{max}
0.9207	2.0223	7.6392	0.9519	1.5340	4.1564	0.9625	1.5967	4.4573	0.9682	2.1217	6.0091

Table 2 — Correlation Coefficients between Independent Variables Extracted from the Primary Circuit Dynamic Resistance and Dependent Variables of Weld Strength *YS* and Nugget Diameter *YD*

	YS	YD	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
X1	–0.957	–0.978	1.000									
X2	0.864	0.895	–0.892	1.000								
X3	0.894	0.910	–0.891	0.972	1.000							
X4	0.589	0.626	–0.636	0.884	0.817	1.000						
X5	0.524	0.488	–0.458	0.639	0.689	0.535	1.000					
X6	0.374	0.347	–0.326	0.359	0.401	0.229	0.363	1.000				
X7	–0.906	–0.937	0.924	–0.950	–0.947	–0.799	–0.509	–0.357	1.000			
X8	–0.551	–0.592	0.609	–0.816	–0.740	–0.942	–0.353	–0.152	0.771	1.000		
X9	0.255	0.274	–0.219	0.526	0.536	0.636	0.624	0.114	–0.428	–0.577	1.000	
X10	0.576	0.616	–0.616	0.850	0.790	0.961	0.534	0.211	–0.780	–0.898	0.654	1.000

The primary circuit dynamic resistance is generally in a formation, as shown in Fig. 3. After monitoring, ten factors were extracted and used in the weld quality estimation based on the dynamic resistance pattern. First, the location of the beta peak X1, which is related to the initial nugget formation, and the rising speed of the dynamic resistance after the alpha peak X2, which is related to the heating rate of the faying surface, were selected as the geometric extraction factors. Based upon similar dynamic resistance analysis (Refs. 13, 14), beta peak is a balance point between a resistance increase, resulting from increasing temperature, and a resistance drop due to molten nugget growth and mechanical collapse. Therefore, the beta peak tends to be reached earlier in high heating rate (*i.e.*, current level) and later in low heating rate. To make the estimation factor reflect the variations in resistance value, the difference between the maximum and minimum values of the dynamic resistance X3 and the maximum value of the dynamic resistance variation in each cycle X4 were selected. At low currents, the heating rate is relatively slow, resulting in small changes in resistance. At expulsion level currents, however, large variations of resistance can be observed, such as from a sharp drop due to the reduction in material thickness and an increase in effective contact area. Also, the absolute values of the monitored dynamic resistance, such as the maximum value of the dynamic resistance X5, the initial resistance X6, the final dynamic resistance X7, and the average value of the total dynamic resistance X8 were selected as estimation factors. The standard deviation of the dynamic resistance X9 and the standard deviation of the dynamic resistance variation per cycle X10 were used to comprehend the effect of the trends in resistance variation.

Experiment

Welding was performed on a 0.7-mm-thick sheet of uncoated low-carbon steel. A resistance spot welding machine using single-phase, 60-Hz alternating current with an attached pneumatic cylinder was used. A 16-mm-diameter, dome-type electrode with a 6-mm-diameter, flat tip end made with copper alloy of RWMA class II was used. Welding was performed on a specimen prepared according to an AWS standard (Ref. 24) while varying the current under ten cycles of welding time and 2.45kN of electrode force. The welding current was increased at 1.5-kA intervals starting from 6.5 kA up to 11 kA. Welds were tested in tensile-shear to determine the ultimate strength and measured nugget diameter. These readings were used as the criterion for weld quality.

Results and Discussion

Relationship between Primary and Secondary Circuit Dynamic Resistance

In order to investigate the relationship between the dynamic resistance of the primary and secondary circuits, the experimental results were analyzed statistically. First, the welding was carried out by selecting four levels of current. The experiment used the one-way factorial design with nine replicates under each condition. The selection order of the

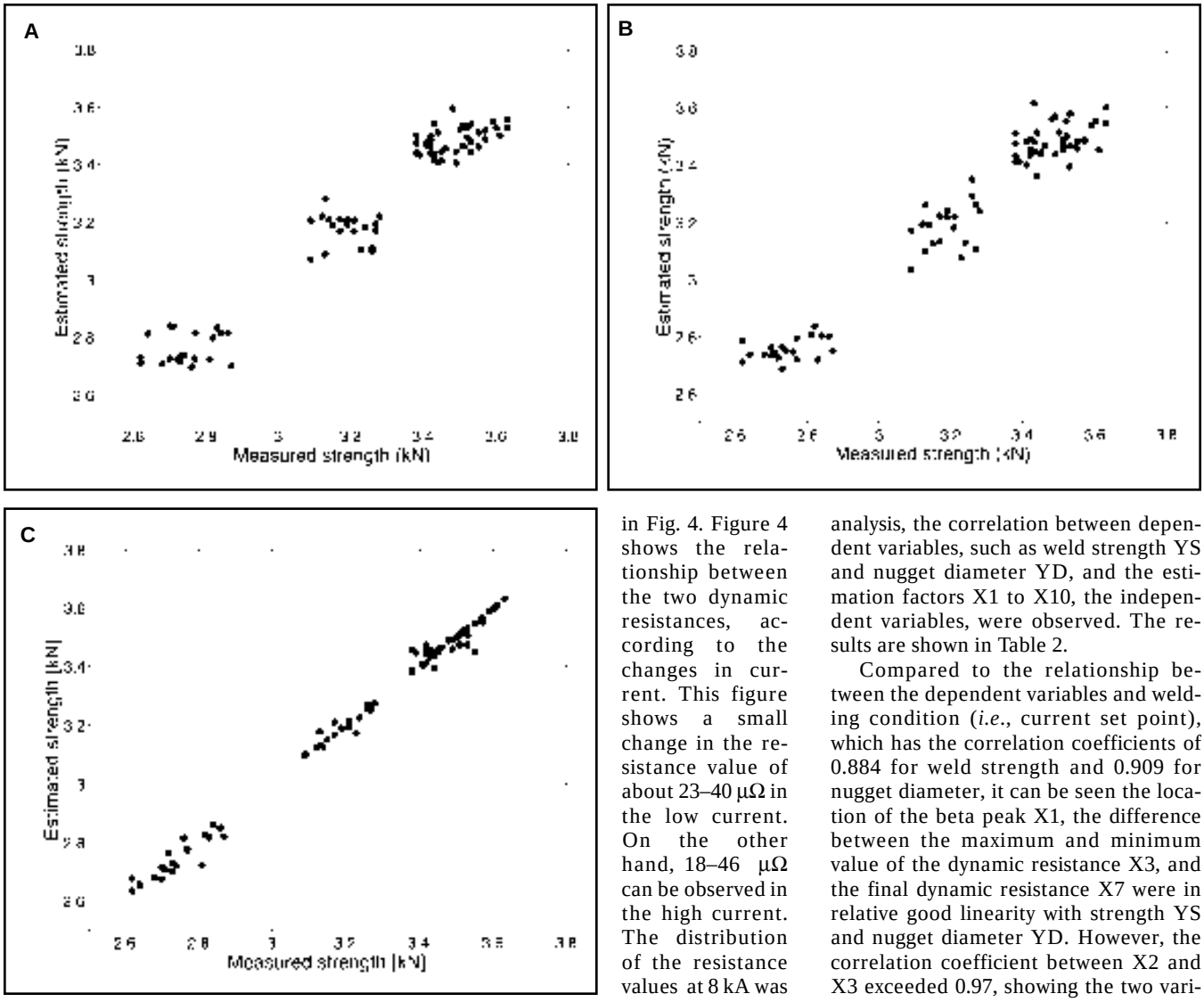

Fig. 6 — Strength estimation results of the models. A — Linear model; B — nonlinear model; C — neural network model.

experimental schedule was done randomly to reduce, as much as possible, the error generated by noise such as electrode wear or measurement settings. To quantitatively check the relationship between the secondary and primary circuit dynamic resistance, a correlation analysis was carried out. The results, shown in Table 1, are the correlation coefficient of the two dynamic resistance values and the corresponding rms error E_{rms} and maximum error E_{max}. Although the correlation coefficient somewhat increased as the current increased, the rms error showed a minimum value at the current set point of 8 kA. This is not because the two data coincide better as the current increased but because the sudden decrease in resistance in the expulsion of the high current caused a gap in the resistance value, which is relatively larger than that of the other conditions. This can be seen in Fig. 4. Figure 4 shows the relationship between the two dynamic resistances, according to the changes in current. This figure shows a small change in the resistance value of about 23–40 μΩ in the low current. On the other hand, 18–46 μΩ can be observed in the high current. The distribution of the resistance values at 8 kA was gathered around the central line without any abnormal protrusions, showing the lowest rms error. The distribution also coincided relatively well with the central line under most conditions, excluding a few anomalies. Through the result described herein, it can be seen the suggested primary circuit dynamic resistance can be used in the same way as the secondary circuit dynamic resistance.

Quality Estimation by Regression Analysis

To estimate weld quality for resistance spot welding, regression models were formulated through multiple linear and nonlinear regression analyses. The tensile shear strength and the nugget diameter were selected as dependent variables, and ten estimation factors were used to determine the regression equation. Before performing the linear regression analysis, the correlation between dependent variables, such as weld strength YS and nugget diameter YD, and the estimation factors X1 to X10, the independent variables, were observed. The results are shown in Table 2.

Compared to the relationship between the dependent variables and welding condition (*i.e.*, current set point), which has the correlation coefficients of 0.884 for weld strength and 0.909 for nugget diameter, it can be seen the location of the beta peak X1, the difference between the maximum and minimum value of the dynamic resistance X3, and the final dynamic resistance X7 were in relative good linearity with strength YS and nugget diameter YD. However, the correlation coefficient between X2 and X3 exceeded 0.97, showing the two variables were very closely related in terms of linearity. Therefore, when these variables are used simultaneously in the regression model, a multicolinearity effect can be observed. Thus, there was a possibility the error rate of the regression models, which included all these variables, would increase. In order to overcome such problems, the independent variables were inputted in order from those having the highest explainability regarding weld quality, and a regression analysis using the stepwise method to determine the regression model was performed. The variables were applied to the regression model in stages, based on the partial correlation and significance probability values of the regression coefficient, until the significance level exceeds 0.10, at which point they were eliminated. Tables 3 and 4 show the variables entered at each stage, the significance probability values of the coefficients, and the coefficients of determination R^2 according to the model in each stage.

An observation of Model I, which is a

linear regression model for strength estimation, shows X1, X5, X4, and X3 are entered into the regression equation in that order. In the case of X5 in Model I-4, the variable is excluded in Model I-5 as it is not statistically significant. Though X5 has been eliminated, the determination coefficient maintains a value of 0.941. In Model II, which is a linear model for nugget diameter estimation, X1, X7, X3, X4, and X2 are selected into the estimation model at each stage, and then X3 is excluded as stated above. The final linear regression equations of Model I and Model II, based on the above results, are shown in Equations 4 and 5.

$$YS = 3.453 - 0.0973 \cdot X1 - 0.0108 \cdot X4 + 0.0218 \cdot X3 \quad (4)$$

$$YD = 7.596 - 0.277 \cdot X1 - 0.0802 \cdot X7 + 0.0641 \cdot X4 + 0.0901 \cdot X2 \quad (5)$$

The regression coefficients, which have been standardized to observe the effect of each factor on the strength and diameter, are shown in Table 5. According to this table, the location of beta peak X1 has the greatest effect on both strength and diameter estimation, followed by the difference between the maximum and minimum value of the dynamic resistance X3 in strength estimation and the rising speed of the dynamic resistance X2 in diameter estimation.

Nonlinear regression models using the above variables are shown in Equations 6 and 7. The nonlinear regression models are formulated by analyzing the factors used in the linear model, with logarithm, and then inverse-transformed. The factors, which determine the regression model, are selected with the same method used in the linear regression analysis. The results are shown in Tables 6 and 7. In Model III, which is a model for the estimation of strength, X2, X4, X7, and X5, are entered into the nonlinear regression model in that order. X2, X4, X3, and X5 are used in Model IV, which estimates nugget diameter. As in the linear regression model, the determination coefficient increases as the factors are entered. The effects of each factor on the nonlinear model are shown in Table 8.

$$YS = 2.6143 \cdot X2^{0.119} \cdot X4^{-0.0461} \cdot X7^{-0.166} \cdot X5^{0.160} \quad (6)$$

$$YD = 30.9384 \cdot X2^{0.347} \cdot X4^{-0.0888} \cdot X3^{0.161} \cdot X5^{-0.778} \quad (7)$$

Table 3 — Significance Probability Values of Regression Coefficients for the Stepwise Regression Analysis and Its Results for *Model I*

	Significance probability values of entered variables					
	Constant	X1	X5	X4	X3	R^2
Model I-1	4.9E-102	9.79E-44	—	—	—	0.916
Model I-2	2.5E-20	8.48E-40	2.52E-03	—	—	0.926
Model I-3	5.02E-19	7.83E-37	3.83E-04	4.18E-02	—	0.930
Model I-4	1.63E-21	3.15E-13	7.25E-01	4.26E-05	1.95E-04	0.941
Model I-5	9E-58	5.65E-16	—	1.32E-05	2.55E-07	0.941

Table 4 — Significance Probability Values of Regression Coefficients for the Stepwise Regression Analysis and Its Results for *Model II*

	Significance probability values of entered variables						
	Constant	X1	X7	X3	X4	X2	R^2
Model II-1	2.79E-86	5.96E-55	—	—			0.957
Model II-2	2.94E-45	3.63E-22	1.42E-04	—			0.964
Model II-3	3.00E-19	9.96E-22	8.60E-02	9.70E-02			0.964
Model II-4	6.04E-25	8.28E-17	3.92E-05	9.61E-05	1.21E-07		0.976
Model II-5	1.96E-23	1.12E-10	1.44E-05	2.11E-01	4.44E-07	1.92E-02	0.978
Model II-6	6.92E-25	1.7E-10	9.62E-07	—	6.48E-09	1.19E-05	0.977

Table 5 — Standardized Regression Coefficients of the Final Linear Models

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Model I-5	–0.672	—	0.491	–0.239	—	—	—	—	—	—
Model II-6	–0.478	0.439	—	–0.354	—	—	–0.361	—	—	—

Table 6 — Significance Probability Values of Regression Coefficients for the Stepwise Regression Analysis and Its Results for *Model III*

	Significance probability values of entered variables					
	Constant	In X2	In X4	In X7	In X5	R^2
Model III-1	5.54E-86	1.33E-42	—	—	—	0.910
Model III-2	1.02E-89	3.55E-40	1.22E-08	—	—	0.941
Model III-3	2.51E-10	4.38E-21	3.10E-09	1.19E-02	—	0.946
Model III-4	1.18E-03	2.62E-19	5.57E-10	2.31E-03	3.17E-02	0.949

Quality Estimation by Neural Network

Following the regression analysis, the multilayer artificial neural network, which was learned through the error back-propagation method, was used to estimate weld quality. The formation of the neural network was determined through the previously mentioned regression analysis results. The X1, X2, X3, X4, X5, and X7 factors applied to linear and nonlinear models were selected as input variables for the neural network quality estimation models such as Model V for strength estimation and Model VI for nugget diameter estimation. Two hidden layers with six nodes were used to determine the output values of weld strength and nugget diameter, respectively. This neural network architecture is shown in Fig. 5.

Performances and Evaluation of the Models

Two methods were used to evaluate the performance of each model, and each estimation result was represented using the coefficient of correlation R and root mean square error. In the first method, the original data used in formulating each regression model and neural network were used in a model to estimate the performance of the suggested model. In the second method, multiple regression with a validation test (Ref. 16) was introduced. First, a single data point was removed from the data set of N data points, and the remaining set of N-1 data points was used to make an estimation model. The removed single data point was then applied to this model to obtain a validation result. This procedure was repeated N-times for each piece of N data in the data set, obtaining N validation results. Tables 9 and 10 show the results of strength and diameter estimation through such methods. As expected, the results from the data used in formulating the model provided more accurate results, but the results of the validation test also showed good estimation performance with only a small dif-

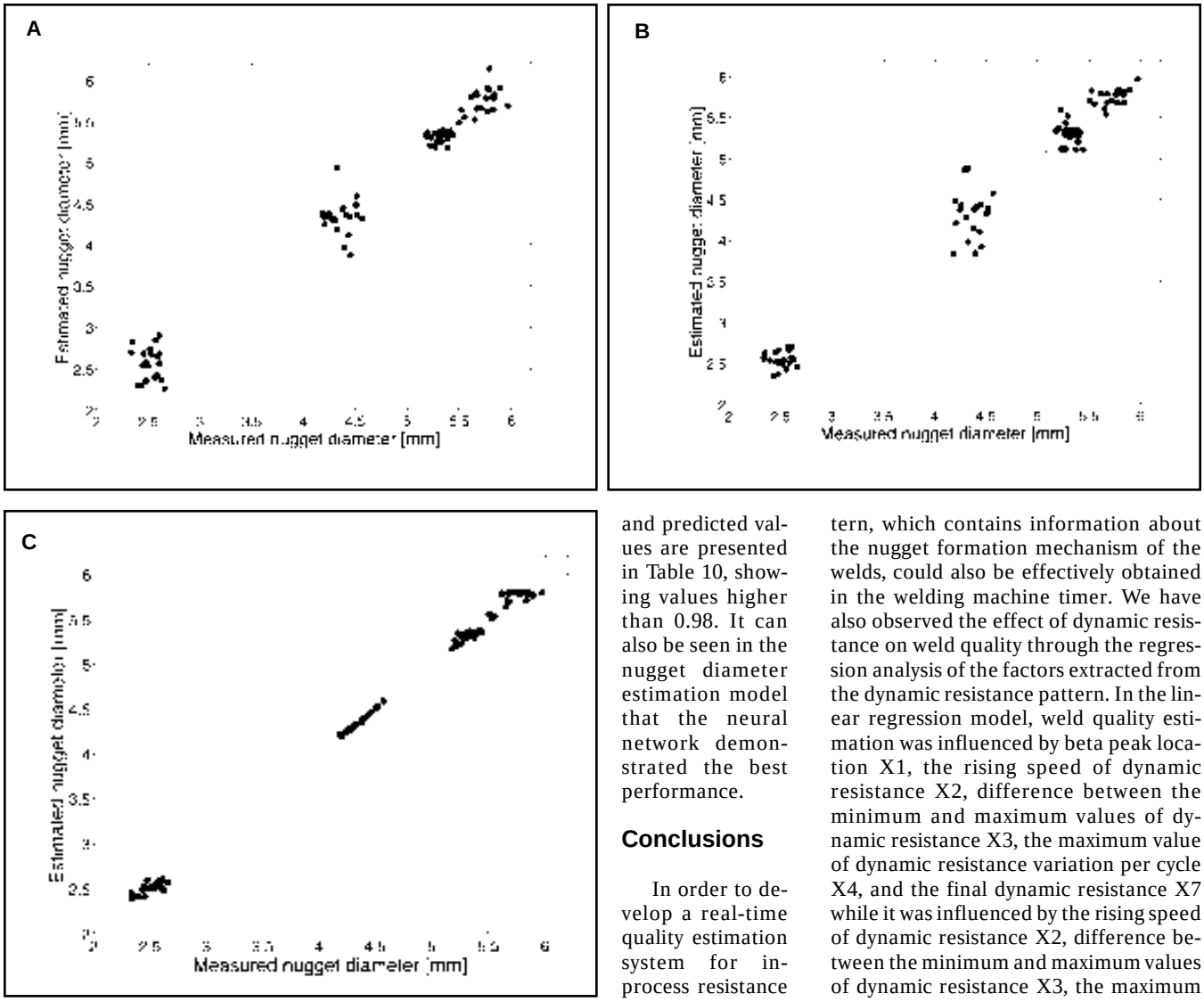

Fig. 7 — Nugget diameter estimation results of the models. A — Linear model; B — nonlinear model; C — neural network model.

ference from the previous results.

In strength estimation, the neural network model showed the best performance followed by the nonlinear regression model and the linear regression model. These results can be seen in Fig. 6. The estimation performance was especially good in the neural network model. Evaluating the nugget diameter estimation, the linear model showed similar, but slightly better, results than the nonlinear model. Figures 7A and B shows the results for nugget diameter estimation for linear and nonlinear regression models. Although the distribution range of the estimated result near a nugget diameter of 4–5 mm is up to 1.3 mm, overall estimation results show good correspondence with measured nugget diameter. The correlation coefficients between measured and predicted values are presented in Table 10, showing values higher than 0.98. It can also be seen in the nugget diameter estimation model that the neural network demonstrated the best performance.

Conclusions

In order to develop a real-time quality estimation system for in-process resistance spot welding, the welding variables were monitored at the primary circuit of the welding machine and the dynamic resistance obtained was used to estimate weld strength. In order to effectively eliminate the unwanted inductive noise, the primary current and voltage were measured when the rate of change of current was zero. These were used to calculate the primary circuit dynamic resistance using the microprocessor of the welding machine timer. The welding machine circuit with a transformer was also analyzed, and the primary circuit dynamic resistance was converted into a dynamic resistance of the welds. To consider the relationship between dynamic resistance and secondary circuit dynamic resistance, a correlation analysis was carried out. It was shown the correlation coefficient was more than 0.92 and maximum error was only 7.6392 μΩ. Therefore, the dynamic resistance pattern, which contains information about the nugget formation mechanism of the welds, could also be effectively obtained in the welding machine timer. We have also observed the effect of dynamic resistance on weld quality through the regression analysis of the factors extracted from the dynamic resistance pattern. In the linear regression model, weld quality estimation was influenced by beta peak location X1, the rising speed of dynamic resistance X2, difference between the minimum and maximum values of dynamic resistance X3, the maximum value of dynamic resistance variation per cycle X4, and the final dynamic resistance X7 while it was influenced by the rising speed of dynamic resistance X2, difference between the minimum and maximum values of dynamic resistance X3, the maximum value of dynamic resistance variation per cycle X4, the maximum value of dynamic resistance X5, and the final dynamic resistance X7 in the nonlinear model.

As another method of evaluating weld quality, a neural network with two hidden layers was used. The factors determined in the regression analysis were used as the input while the strength and nugget diameters were selected as the output. According to the performance results of quality estimation through such models, the weld strength estimation showed a maximum error of 0.2061 kN, a correlation coefficient exceeding 0.96, and an rms error under 0.0836 kN. The neural network showed the most accurate results in nugget diameter estimation as well as in the strength estimation. The performance of the nugget diameter estimation showed a maximum error of 0.66093 mm, correlation coefficient over 0.98, and an rms error under 0.2317 mm. According to the results described in this paper, not only can weld quality estimation be performed without the attach-

ment of additional monitoring devices in the secondary circuit of the welding machine but also real-time quality estimation is made possible.

Acknowledgment

This work was supported by a grant from the Brain Korea 21 Project and Critical Technology 21 Project of the Ministry of Science and Technology, Korea.

Table 7 — Significance Probability Values of Regression Coefficients for the Stepwise Regression Analysis and Its Results for *Model IV*

	Significance probability values of entered variables					
	Constant	In X2	In X4	In X3	In X5	R^2
Model IV-1	3.98E-42	6.92E-47	—	—	—	0.930
Model IV-2	1.71E-48	5.44E-49	2.41E-13	—	—	0.965
Model IV-3	8.36E-40	1.41E-17	2.77E-15	4.52E-04	—	0.971
Model IV-4	3.08E-08	6.49E-19	3.15E-13	1.57E-06	2.37E-06	0.978

Table 8 — Standardized Regression Coefficients of the Final Nonlinear Models

	In X1	In X2	In X3	In X4	In X5	In X6	In X7	In X8	In X9	In X10
Model III-4	—	0.962	—	–0.443	0.076	—	–0.320	—	—	—
Model IV-4	—	0.867	0.380	–0.264	–0.115	—	—	—	—	—

Table 9 — Strength Estimation Results as Correlation Coefficients, Root Mean Square Errors, and Maximum Errors for the Original and Validation Data Set

	Linear			Nonlinear			Neural		
	R	E_{rms}	E_{max}	R	E_{rms}	E_{max}	R	E_{rms}	E_{max}
Original data set	0.9702	0.0751	0.1719	0.9726	0.0721	0.1838	0.9959	0.0284	0.1002
Validation data set	0.9652	0.0836	0.1967	0.9684	0.0774	0.2061	0.9943	0.0290	0.1053

Table 10 — Nugget Diameter Estimation Results as Correlation Coefficients, Root Mean Square Errors, and Maximum Errors for the Original and Validation Data Set

	Linear			Nonlinear			Neural		
	R	E_{rms}	E_{max}	R	E_{rms}	E_{max}	R	E_{rms}	E_{max}
Original data set	0.9889	0.1871	0.6013	0.9877	0.1949	0.5790	0.9989	0.0571	0.1767
Validation data set	0.9853	0.2040	0.6609	0.9816	0.2317	0.6378	0.9975	0.0583	0.1790

Reference

1. Gedeon, S. A., Sorensen, C. D., Ulrich, K. T., and Eagar, T. W. 1987. Measurement of dynamic electrical and mechanical properties of resistance spot welds. *Welding Journal* 66(12): 378-s to 385-s.

2. Johnson, K. I., and Needham, J. C. 1972. New design of resistance spot welding machine for quality control. *Welding Journal* 51(3): 122-s to 131-s.

3. Wood, R. T., Bauer, L. W., Bedard, J. F., Bernstein, B. M., Czechowski, J., D'andrea, M. M., and Hogle, R. A. 1985. A closed-loop control systems for three-phase resistance spot welding. *Welding Journal* 64(12): 26 to 30.

4. Johnson, K. I. 1973. Quality control resistance welding quality-control techiniques. *Metal Construction* and *British Welding Journal* 5(5): 176–181.

5. Haefner, K., Carey, B., Bernstein, B., Overton, K., and D'andrea, M. 1991. Real-time adaptive spot welding control. *Transactions of the ASME, Journal of Dynamic Systems, Measurement, and Control* 113(3): 104–112.

6. Towey, M., and Andrews, S. R. 1968. Instantaneous resistance during spot weld formation as a parameter for an automatic control system. *Welding and Metal Fabrication* 36(10): 383–392.

7. Tsai, C. L., Dai, W. L., Dickinson, D. W., and Papritan, J. C. 1991. Analysis and development of a real-time control methodology in resistance spot welding. *Welding Journal* 70(12): 339-s to 351-s.

8. Andrews, D. R., and Bhattacharya, S. 1973. Quality control resistance-weld monitoring for production. *Metal Construction* and *British Welding Journal* 5(5): 172–175.

9. Patange, S. R., Anjaneyulu, T., and Reddy, G. P. 1985. Microprocessor-based resistance welding monitor. *Welding Journal* 64(12): 33–38.

10. Studer, F. J. 1939. Contact resistance in spot welding. *Welding Journal* 18(10): 374-s to 380-s.

11. Tylecote, R. F. 1941. Spot welding part II: contact resistance. *Welding Journal* 20(12): 591-s to 602-s.

12. Roberts, W. L. 1951. Resistance variations during spot welding. *Welding Journal* 30(11): 1004-s to 1019-s.

13. Dickinson, D. W., Franklin, J. E., and Stanya, A. 1980. Characterization of spot welding behavior by dynamic electrical parameter monitoring. *Welding Journal* 59(6): 170-s to 176-s.

14. Kaiser, J. G., Dunn, G. J., and Eager, T. W. 1982. The effect of electrical resistance on nugget formation during spot welding. *Welding Journal* 61(6): 167-s to 174-s.

15. Thornton, P. H., Krause, A. R., and Davies, R. G. 1996. Contact resistances in spot welding. *Welding Journal* 75(12): 402-s to 412-s.

16. Hao, M., Osman, K. A., Boomer, D. R., and Newton, C. J. 1996. Developments in characterization of resistance spot welding of aluminum. *Welding Journal* 75(1): 1s-s to 8-s.

17. Chakalev, A. A., and Vishnyakov, I. V. 1994. Controlling the properties of welds in resistance spot welding. *Welding International* 8(10): 810–813.

18. Livshits, A. G. 1997. Universal quality assurance method for resistance spot welding based on dynamic resistance. *Welding Journal* 76(9): 383s-s to 390-s.

19. Brown, J. D., Rodd, M. G., and Williams, N. T. 1998. Application of artificial intelligence techniques to resistance spot welding. *Ironmaking and Steelmaking* 25(3): 199–204.

20. Dilthey, U., and Dickersbach, J. 1999. Application of neural networks for quality evaluation for resistance spot welds. *ISIJ International* 39(10): 1061–1066.

21. Cho, Y., Rhee, S., Shin, H. I., and Bae, K. M. 1999. Characterization of primary dynamic resistance in resistance spot welding. *Journal of the Korean Welding Society* 17(2): 159–165.

22. Cho, Y. 2000. A study of dynamic resistance monitoring and intelligent quality estimation for the manufacturing process automation during resistance spot welding, Ph. D. dissertation. Seoul, Korea, Hanyang University.

23. Savage, W. F., Nippes, E. F., and Wassell, F. A. 1978. Dynamic contact resistance of series spot welds. *Welding Journal* 57(2): 43-s to 50-s.

24. American Welding Society. 2000. *Recommended Practice for Resistance Welding.* C1.1M/C1.1.

25. Kimchi, M. 1984. Spot weld properties when welding with expulsion — comparative study. *Welding Journal* 63(2): 58-s to 63-s.