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Correlations between Process Variables and Weld Quality in Resistance Spot Welding Processes

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저항 점 용접법에서의 용접 변수와 용접품질과의 상관 관계에 대한 실험적 고찰

조 형 석 · 전 동 휘

초 록

저항 점 용접시 발생하는 어려운 문제점의 하나는 아무리 동일한 용접조건 하에서 용접을 한다 하더라도 균일한 용접품질을 얻을 수 없다는 점이다. 이는 주로 용접중의 전원에서의 변화로 인한 용접전류 및 전압변동, 용접모재의 표면상태 및 두께의 불균일, 두 전극의 마멸 및 맞춤상태 등의 인자 때문에 기인한다고 볼 수 있다. 이러한 문제점을 해결하기 위해서는 용접하는 도중에 수시로 용접 상태를 점검하여 용접조건을 그때 그때에 적합하게 변화시켜 주는 것이 바람직한데 우선 용접 상태를 판별하기 위해서는 용접품질(weld quality)을 잘 대변할 수 있는 용접법 변수를 찾아내는 것이 중요한 일이다. 따라서 본 논문에서는 용접품질에 관련되는 변수중, 전기동저항과 전극분리 현상을 측정해서 마이크로 컴퓨터를 사용하여 관련되는 특정값들을 구했고 이들과 인장실험에서 얻은 용접강도와의 상관관계를 얻음으로써 과연 어떠한 공정변수가 용접품질을 잘 대변해 줄 수 있는 가를 실험적으로 조사하였다.

1. Introduction

In resistance spot welding two pieces of sheet metals are brought together, and clamped by opposing copper alloy electrodes. The passage of a high current via the electrodes through the workpiece causes resistance heating at the interface. The welding current normally flows for a short time sufficiently to form a common weld nugget. In normal practice, the welding current, pressure applied to the workpiece and weld time are preset for a particular application, depending upon the material properties of the workpiece to be welded and upon the electrode tip geometry. Satisfactory machine settings will gurantee a good weld quality of the workpice.

However, even when the machine variables are held constant, there is considerable variation in the weld quality from part to part. This is due to variation in the welding current which is caused by changes in the surface condition of the workpiece, changes in the electrode tip diameter fit-up and changes in the impedance of the welding circuit. The shunting effect which may be a consequence of the presence of other spot welds is another source of quality variation. This necessitates the development of in-process monitoring techniques that can assess the quality of spot welds.

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Many variables associated with the welding process have been examined for the quality monitoring(1~13). The suggested process variables include: 1. welding current(1~4), 2. voltage drop across the two electrodes(1~3), 3. measurement of temperature of the weld nugget(4~7), 4. dynamic electrical resistance(2,5,8,13), 5. electrode head movement(1,6,9). Although various degrees of success have been claimed for the monitoring techniques cited above, some confusion still exists as to the selection of the most reliable technique for the practical applications. More frequently referred techniques seem to be monitoring of the dynamic resistance variation and measurement of the electrode movement during the weld formation. Several attemps(11,12) have been made to explain the relationship between the state of development of weld nugget and the pattern of the resistance variation and thus to relate the variation phenomena to the weld quality. Similar investigations(1,6,9) have also been carried out to explain the phenomena of thermal expansion of the weldment during the weld formation by measuring a relative movement of one electrode with respect to the other. This electrode movement has been suggested to be a good process variable for quality monitoring.

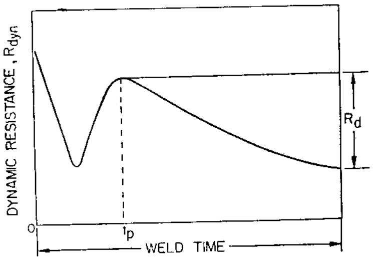
Since these investigations have been conducted under different experimental conditions, it is difficult to tell which technique is more preferable for the quality assessment. If the direct correlation data between the process varibles and the weld quality are available, we can easily recommend which technique is better for a particular application. This correlation information should be available in a quantitative form sufficiently to determine how much the relevant process variable is correlated to weld quality. The previous researchers, however, have not presented sufficient informations on the quantitative correlation value. Thus, the objective of this paper is to investigate quantitatively the direct correlation between the in-process variable and the weld quality, thus enabling one to use these data for satisfactory quality monitoring. The monitoring variables considered herein are the dynamic resistance and electrode movement. The dynamic resistance signal was measured by a weld checker, while the electrode movement trace was monitored by a displacement sensor. These two signals were sampled via A/D converter and stored in a microcomputer memory. These sampled data were then used to compute the characteristic values: The values associated with the dynamic resistance are the resistance drop occurred during the latter part of the welding period and the peak time at which a maximum value of the dynamic resistance occurs. The values associated with the electrode movement are the peak head movement and the rate of the displacement of the electrodes. Relative importance of such parameters is discussed in some detail by correlating these parameters with the weld strength.

2. Process Monitoring Variables

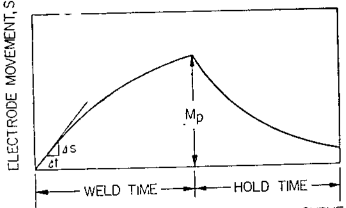
Fig. 1 shows typical traces of the monitoring variables, dynamic resistance and electrode movement. The term "dynamic resistance" refers to the quotient

$$R_{dyn}(t)=\frac{V_w(t)}{I_w(t)} \qquad (1)$$

where V_w and I_w are instantaneous values of weld voltage and weld current, respectively. As shown in Fig. 1(a) the resistance curve varies with time.



(a) TYPICAL DYNAMIC RESISTANCE CURVE



(b) TYPICAL ELECTRODE MOVEMENT CURVE

Fig. 1 Typical curves of the dynamic resistance and electrode movement

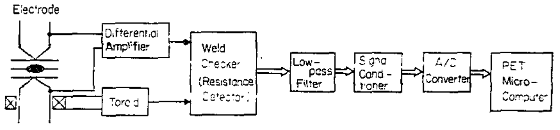
It has been shown that resistance-time curve is of two types. This figure shows one type of the curve in which the resistance initially rises but then falls, which is typical of mild steel workpieces. The other one has a tendency in that the resistance falls continuously throughout the weld time. This curve has been found to reflect the physical phenomenon occurring during the weld formation(1-5), and to vary considerably with current level, electrode force, material properties and surface conditions.

Typical electrode movement is shown in Fig. 1(b). The rise of the electrode displacement is due to thermal expansion caused by heat generated by the passage of electric current. Maximum expansion occurrs at termination of weld time. When current ceases, the electrode displacement starts to fall owing to cooling. Thus the electrodes move together again, and indentation occurs due to softening of the sheet. This phenomenon is well indicated in the latter part of the curve.

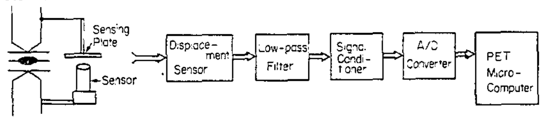
3. Instrumentation and Monitoring System

Fig. 2 shows a detailed block diagram of the measuring system to monitor the dynamic resistance and the electrode head movement. To obtain the instantaneous resistance value given in Eq. (1), the voltage difference across the electrode was obtained and amplified by a differential amplifier, and at the same time the weld current was measured by a toroid of ring shape installed around the bottom electrode. These two signals, are then used to obtain the $R_{dyn}(t)$ by aWeld Checker (MM502—A: Miyachi Electronic Co.). Since this produces a stairtype of the resistance signal due to averaging every half cycle, this was smoothed out by a low-pass filter of cut-off frequency 30Hz. This filtered signal was amplified and fed to A/D converter.

The electrode head movement was detected by a linear displacement transducer of non-contacting type (Ono Sokki VSO21). Since the electrode head movement which represents thermal expansion is the displacement of one electrode relative to the other, the noncontacting displacement sensor was fixed on a mounting frame which is mounted on the bottom electrode, while the detecting plate movable with the upper electrode was mounted on the head slide carring the upper electrode. The sensor was so mounted that the magnetic field generated by passage of the electric current should not influence the sensor output. To investigate any possible effect, calibrations of the output were conducted with and without the weld current flow, but noticiable variation was not observed from this sensor mounting position. The measured signal was fed to a lowpass filter for noise rejection, to the amplifier for adjusting the signal level and then to A/D converter for sampling, as shown in Fig. 2. In this way a good record of the relative movement between two electrodes was obtained. Detailed experimental arrangement can be seen in Fig. 3.

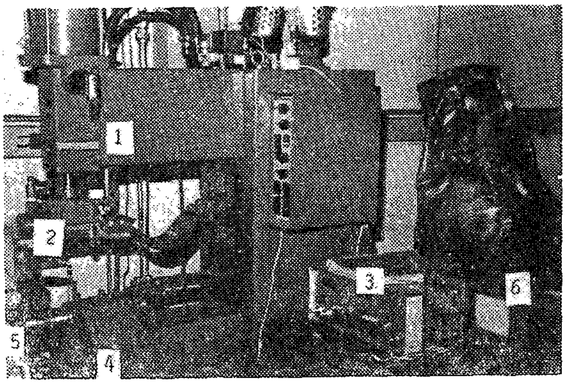


(a) Dynamic resistance sensing system



(b) Electrode movement sensing system

Fig. 2 Monitoring system



(1) Welder (4) Toroid
(2) Electrode (5) Non-contacting sensor
(3) Weld checker (6) Digital oscilloscope

Fig. 3 Overview of experimental equipments

The role of the microcomputer in this system is (1) to take in the monitoring data sampled by A/D converter and (2) to perform arithmatic computation of the characteristic values discusscd previously. Samping was done every 780 sec, which samples 20 data per ewery weld cycle time. This was considered to be enough data to represent the original analog signals. Using these data the microcomputer calculates the following characteristic values, as indicated in Fig. 1;

for the dynamic resistance

$$J_1=\Delta R=\bar{R}_d-R_d \qquad (2)$$

$$J_2=t_p=\bar{t}_p-t_p \qquad (3)$$

$$J_3=\sum_{k=1}^{N}R[_{\mathrm{dyn}}(k)-\bar{R}_{\mathrm{dyn}}(k)]^2 \qquad (4)$$

where R_d and t_p represent the resistance drop and peak time of a reference resistance curve, respectively N is the sampling number and R_{dyn} denotes a reference resistance variation curve obtained for a certain welding condition. The quadratic performance criterion J_3 is the integral of the square error occurred during the entire weld cycle.

for the electrode head movement

$$J_4=\frac{\Delta s}{\Delta t} \qquad (5)$$

$$J_5=M_p \qquad (6)$$

where Δs is the increament of the electrode movement (i.e., increament of thermal expansion), and M_p is the peak value of the movement. The J_4 value was easily obtained, since the electrode movement time curve keeps a good linearity up to some weld cycles for all test weldments. All the J values are to be correlated with the weld strength in the later section of this paper.

4. Experimental Procedures and Results

To obtain the correlation between the characteristic values given in Eqs. (2)~(6) and the corresponding weld strength a series of experiments was conducted. Fig. 3 shows a detailed instrumentation system for the experiments. The welding machine used was a single phase air spot welder (Cho Heung Electric Co.). As base material a cold rolled mild steel of thickness 1.6mm was used throughout the experiment, and all the test materials were degreased to keep a uniform surface condition. The experimental conditions were:

Welding cycle=16 cycle
Welding force=360 kgf
Workpiece thinkness=1.6 mm
Squeeze time=30 cycle
Bold time=30 cycle

These conditions were kept constant throughout the experiments, but the heat input i.e. welding current was randomly varied within some range to give an in-process disturbance. These variations were applied for 50 test workpieces. For each test weld all the J values were calculated via microcomputer and a maximum weld strength at which the fracture occurs was obtained via MTS(Model 810) using a tensile-shear test. All the J values and strength data thus obtained were used to determine the relationship of each J value and weld strength. The detailed jig configuration for the strength test is given in reference [14].

4.1. Resistance Drop v.s. Weld Strength

Fig. 4 shows the experimental relationship between the ΔR and weld strength. The difference of resistance drop is distributed in the range of -55 ~$10\mu\Omega$. Although the R varies very little, the corresponding strength variation is rather large, ranging from 500~1000kgf. For the smaller ΔR the data is more spread out from the correlation curve which is denoted by a solid line in the Figure. The correlation coefficient in this case is 0.9 and the

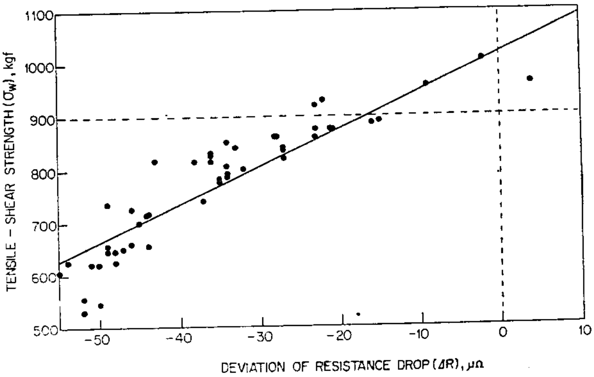


Fig. 4 Resistance drop v.s. weld strength

correlation curve is found to be

$$\sigma_w = 7.14 \Delta R + 1019.2 \qquad (7)$$

where σ_w is the weld strength.

From this result it can be asserted that for mild steel as the resistance drop increase, the weld strength approximately linearly increases. This supports the previous findings that increasing the weld current which results in larger nugget size reduces the final value of instantaneous resistance.

4.2. Peak Time v.s. Weld Strength

In Fig. 5 weld strength v.s. peak time is shown for the 50 weldments. As a result of the current variation the peak time varies rather widely within 100msec, whereas the corresponding strength variation covers 500 kgf. From this figure it can be seen that the relationship between weld strength and peak time shows a more pronounced linear correlation than that of the resistance drop. As the peak time gets longer, the weld strength is almost linearly decreased. The correlation coefficient is found to be 0.97, which also indicates strong correlation. The experimental formula relating the weld strength and peak time is obtained to be

$$\sigma_w = -3.85 \Delta t_p + 956.3 \qquad (8)$$

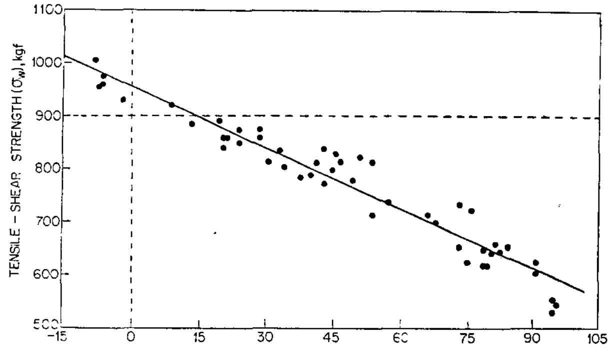


Fig. 5 Peak time v.s. weld strength

This quantitative relationship given in Eq. (8) well explains the previous observation that for mild steel, progressively increasing the weld current moves the maximum of the resistance curve to shorter weld times; increasing the weld current normaly yields high weld strength, unless expulsion does not occur.

4.3. Resistance Error v.s. Weld Strength

Fig. 6 shows how summation of the square error occurred throughout the weld time varies with the weld strength. As indicated in Eq. (4), the error indicates here the instantaneous differential value between a reference resistance curve and actual resistance curve obtained from each weldment. The reference resistance curve was arbitrary chosen and obtained with a fixed weld current level, $i = 8250A$ but with other conditions unchanged. Strength error in this case denotes absolute value of deviation of the weld strength from the one obtained for the reference resistance curve. In contrast to the cases of peak time and resistance drop, the data are more scattered from the fitted line, indicating less correlation between two variables. Although the correlation is not high, this result has some indication in that as the resistance error increases, the strength deviation roughly increases. The correlation coefficient is 0.86 and the correlation curve fitted to a straight line is found to be

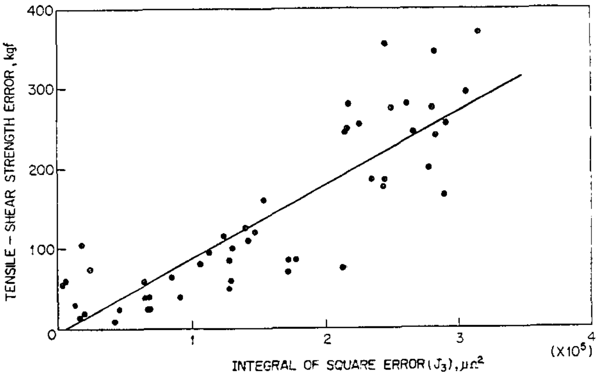


Fig. 6 Integral of square error v.s. weld strength

$$\sigma_w = 9.2 \times 10^{-4} \{ \sum_{k=1}^{N} [R_{dyn}(k) - \bar{R}_{dyn}(k)]^2 \} - 4.94 \qquad (9)$$

These results indicate that the entire resistance curve gives less indication of the weld quality than those variables such as the peak time and the resistance drop. Physically, the peak time corresponds to the initiation of fusion, and nugget development is described by slope of curve after the peak time which determines the resistance drop. It is, therefore, expected that these two characteristic values are more correlated with the weld strength.

4.4. Rate of the Electrode Movement v.s. Weld Strength

Fig. 7 shows the relationship between rate of the electrode movement and weld strength. These data show a nonlinear correlation between two variables. The weld strength increases with the rate of the electrode movement at a nonlinear rate. For lower values of the rate of the electrode movement the strength quite rapidly increases but for higer values the rate of the strength increase is reduced. Although the data has not been obtained in case of splashing, there is a value of the rate of the electrode movement above which splashing occurs. In this case the strength will no longer increase with the rate of the electrode movement. From the figure it can be seen that the correlation is quite strong, the coefficient being 0.956. The fitted curve is obtained to be

$$\sigma_w=-1455\left(\frac{\Delta s}{\Delta t}\right)^2+3821\frac{\Delta s}{\Delta t}-1487 \qquad (10)$$

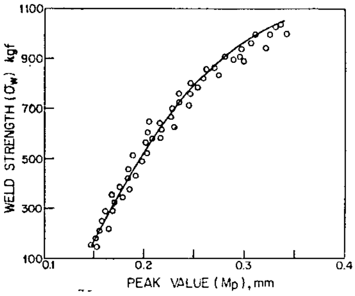


Fig. 7 Peak value v.s. weld strength

4.5. Peak Movement v.s. Weld Strength

In Fig. 8 variation of the weld strength with the peak movement is plotted. The peak movement due to thermal expansion ranges from 0.15-0.35mm, but even for this small variation, the corresponding strength is considerably varied. The strength increases with the peak movement in an approximately linear way, although the exact correlation curve is not linear as indicated in the figure. This is due to the fact that, although amount of the thermal expansion is not directly proportional to weld current input some other factors such as electrode embedding and thermal contraction also affect the total head movement. These combined processes give an approximately linear relationship. The correlation is also quite strong and the coefficient is obtained to be 0.968. The curve fitting of these data yields.

$$\sigma_w=-16899M_p^2+1279M_p-1367 \qquad (11)$$

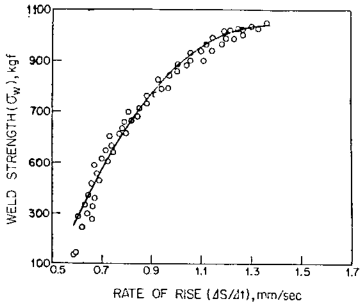


Fig. 8 Rate of rise v.s. weld strength

Observations from Figs. 7 and 8 show that the electrode movement curve has a strong correlation with weld strength. The coefficient in this case approaches to unity, which is much higher than those of the resistance variable. This implies that changes in the shape of the electrode movement curve strongly reflects changes in physical properties and indicates the phenomenon of nugget development.

5. Conclusions

System variables associated with the nugget formation during spot welding processes are directly correlated with the weld quality in order to provide an efficient basis for process controller designs. The process variables used herein was the dynamic resistance and the electrode head movement. These variables were monitored and sampled via a microcomputer to obtain the characteristic values such as (1) peak time, (2) resistance drop, (3) integral of the square error associated with the dynamic resistance, (4) peak head movement and (5) rate of the displacement of the electrode movement. For each test weldment all the values were computed immediately after sampling and maximnm weld strength was experimentally obtained, using a tensile-shear test.

The results obtained from the experiments show the following major findings:

(1) The whole resistance curve itself does not

represent a good quality indicaltion, rather the peak time and resistance drop of the curve are good indicative of weld strength.

(2) Weld strength linearly increases with the resistance drop but is inversely proportional to the peak time.

(3) Peak value and rate of the electrode head movement curve yield better correlation with weld strength than the characteristic values of the resistance curve. These values have a nonlinear relationship with weld strength.

From these results it can be concluded that both the resistance variation and electrode movement may be used as effective means of indicating weld strength. In view of quality indication the electrode movement trace appears to be superior to the dynamic resistance value.

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