연 구 논 문

가속도계를 이용한 마이크로스폿용접의 인프로세스 모니터링

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In-Process Monitoring of Micro Resistance Spot Weld Quality using Accelerometer

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Abstract

This study is to propose an in-process monitoring system for micro resistance spot welding processes using minute accelerometer. A minute accelerometer is mounted on the upper moving electrode tip holder. With its high sensitivity and frequency response characteristics, accelerometer output signal has been successfully recorded and integrated twice to reflect electrode expansion during micro spot welding processes. The analysis of electrode expansion pattern was attempted to find its correlation with spot weld quality. Major previous findings[1-6] regarding spot weld quality assessment with the electrode expansion signal in large scale resistance spot welding processes were proved to be true in this in-process monitoring system.

Key Words : Micro spot welding, Accelerometer, Dynamic electrode movement, Nugget size

1. Introduction

Conventional, large scale resistance spot welding (RSW) is one of the most effective assembly methods because it is simple in operation and low in cost. Due to its high productivity, RSW is widely used in many automated and robotized production lines, e.g. automobile, electronic parts and industrial/ home appliances. The process has minor drawbacks, as it is influenced by various factors which results in quality deviations from weld to weld. In order to increase the reliability of each spot and to reduce the risk of part failure, a reliable quality monitoring system is crucial. For mass production line, it is necessary to develop in-process inspection method.

In order to find reliable monitoring variables indicative of weld quality, electrical and mechanical process variables have been studied[1]. The electrical variables are welding current, welding voltage, input power and dynamic resistance, while the mechanical variables are temperature, workpiece deformations and electrode displacement (expansion). Among them, the dynamic electrical resistance and the dynamic displacement curves proved to provide the most significant information concerning the nugget formation[1-2]. While the dynamic resistance is an indirect measure of nugget formation, the dynamic electrode displacement is a direct measure and response of nugget formation and growth. Hence, the electrode displacement is one of the important process variables that can provide real-time information useful for monitoring and controlling RSW quality[1-5].

Micro resistance spot welding (MRSW) is a group of micro-joining processes, in which a micro-joint is formed between two thin sheet metals by Joule heating. When the welding current is passed through the faying interface, the material around the contact point will be molten and gradually forms a nugget. The nugget then solidifies on cooling and forms a joint spot. With the advent of IT (information technology) era, numerous electronic parts and micro miniature mechanical parts have been joined by MRSW methodology. In this mass production processes, few attempts have been made to assure good micro spot weld quality in view of in-process monitoring. This is due to difficulty in determining process variables to assess weld quality in MRSW processes. Moreover, the ongoing trend of microminiaturization in electronic and mechanical parts of IT devices makes it more and more difficult to control micro spot weld quality.

Since metals expand remarkably upon melting, electrode displacement reflects nugget formation and growth. Previous researches[1-6] have shown that electrode displacement (expansion) patterns are well correlated with the size and shape of the weld nugget in conventional, large scale RSW processes. Gap sensor, LVDT and optical linear encoder have been used to pick up the electrode movement. However, in MRSW processes the amplitude of the displacement is very small, typically of the order of micro meters for the case of sheet metal thickness being 0.1 mm.

Recently, Chen and Farson[7] proposed two methods for measurement of electrode displacement. One was a high-speed video system with a long-range microscope. The other was fiber optic sensor system. The two methods worked complementary to each other. Tseng et al[8] used a laser displacement sensor to develop an on-line monitoring system for MRSW.

In this work, new method for electrode displacement monitoring in MRSW is proposed. A minute accelerometer was mounted on upper moving electrode tip holder. The analog accelerometer output was double integrated using hardware integrator. The recorded output was analyzed and validated by a series of experiments.

2. Dynamic Electrode Displacement (Expansion) and its Monitoring

The process of RSW occurs through the localized melting of the faying surface due to the heating caused by the electric current. During the formation of a weld nugget, heat generation is the main factor for weld nugget formation which is interrelated to other factors, such as electrode force, welding current, welding time and material characteristics. Relevant parameters which can be monitored from the welding process are instantaneous change of the resistance and the displacement of electrode due to thermal expansion and contraction. The mechanism of nugget formation, such as surface breakdown, asperity collapse, heating of the work pieces, molten nugget formation, nugget growth and mechanical collapse, can be understood through the analysis of dynamic expansion curve. Fig. 1 shows a schematic diagram of the typical pattern of the dynamic electrode movement curves and its interpretation. The curve shows time record of electrode movement signal during weld and hold cycle.

At the very short period of stage I, electrode force is being applied, the upper and lower electrodes move towards each other by very small

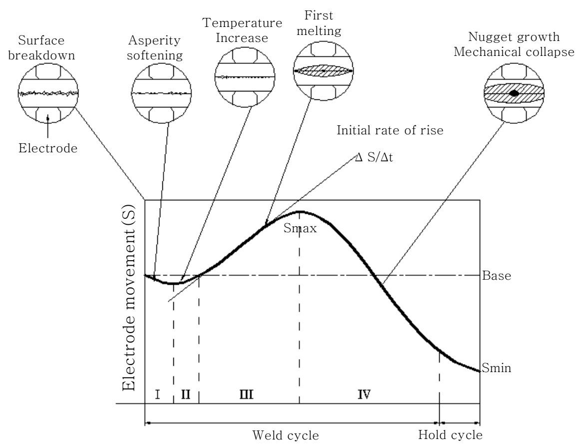


Fig. 1 Typical electrode movement curve

amount. For harder specimen, like stainless steel, this movement of electrode is considerably smaller. In stage II and stage III, surface breakdown and asperity collapse are followed by the initiation of weld current flow. Remarkable amount of thermal expansion due to continuous Joule heating causes continuous increase in the electrode separation. As the size of the molten nugget and the cross-sectional area available for current flow increases in stage IV, material around molten nugget becomes soft and plastic deformation occurs. With the occurrence of mechanical collapse, both electrodes move closer to each other. This phenomenon is called electrode embedding[4].

Since the electrode displacement is the global vector sum of all the local deformation around nugget volume, the electrode movement manifests itself during welding by two dominant mechanisms.

$$\text{Electrode movement} = \text{thermal expansion} - \text{electrode embedding} \qquad (1)$$

Hence, peak value is observed at get even point between expansion and embedding in the early stage IV. After peak, electrode moves closer to each other since embedding is dominant over expansion. The electrode movement pattern shows gradual decrease. In case of excessive heat input, sudden drop can be observed due to expulsion.

Due to sophisticated mechanism of heat generation and heat loss, net heat input for each stage of welding is difficult to be calculated nor measured by any electrical parameters such as weld current, voltage and dynamic resistance. The heat generation depends on weld current distribution and the global bulk resistance across the two electrode tips. The global dynamic resistance is sum of many components of contact resistance and material bulk resistance which also vary with local temperature. The heat loss also depends on temperature gradients and tem perature-dependent thermal conductivities of workpiece materials and electrodes.

While the dynamic resistance is an electrical measure of RSW processes, the electrode movement signal is a typical mechanical measure. That is the reason why the electrode displacement monitoring is more important than dynamic resistance monitoring. The electrode movement signal has many advantages over the dynamic resistance considering the fact that RSW is a thermo-electro-mechanical process. The net heat input effective for heating, melting and plastic deformation can be indirectly measured by electrode movement. Since the electrode movement involves many complicated and coupled phenomena such as plastic deformation, heating, thermal expansion and melting, it is a characteristic feature of RSW process. Therefore, characterization of the process is possible by monitoring the electrode movement.

Since all the process information regarding temperature variation around nugget forming zone are directly related with mechanical process variables such as expansion, melting, contraction and deformation due to plastic metal flow, the net heat input can be inferred by analysis of electrode movement. Therefore, characterization of RSW processes is possible by monitoring the electrode movement signal. The amount of thermal expansion, melting and expulsion can be correlated to the initial slope and magnitude of electrode movement curve[4-5].

3. Experimental Setup

All experiments were performed with a micro spot welding machine (MSSPOT-2000). The welder was operated with a servo-actuated electrode force and direct current controlled by FET. Compared to the traditional air-actuated system, the servo-actuated welding system has many advantages such as precise electrode force control, soft touch feature and multiple stage application of electrode force. The electrodes used were Copper-Chrome (Cu-Cr, 99.2-0.8%): the upper electrode (diameter=3 mm) was machined to have a shape of dome with tip diameter less than 1mm, while the lower electrode was polished to have a flat tip. The specimens were two Nickel 200 alloy sheet metal (thickness=1.6 mm, width=5 mm, see Table 1). A small Bakelite fixture was attached to the upper electrode holder and a minute accelerometer (PCB Piezotronics Model 352C65) was mounted on it. Accelerometer is a low cost, light weight sensitive sensor which can precisely measure all the acceleration experienced by an object or component to which it is attached. It has sensitivity of 100 mV/g [10.2 mV/(m/s^2)], 0.3 Hz to 12 kHz frequency range. Other equipments were set and configured as shown in Fig. 2. During welding, the electrode moves upwards and downwards directions due to thermo-physical processes occurring during welding. The accelerometer successfully detected and measured instantaneous acceleration of upper electrode tip during its movement. The accelerometer analog output was scaled and fed into the hardware integrator designed for double integration as shown in Fig. 3. This hardware integrated the accelerometer data twice. The double integrated signal, which is considered as dynamic electrode movement signal, was sampled with digital storage oscilloscope and analyzed.

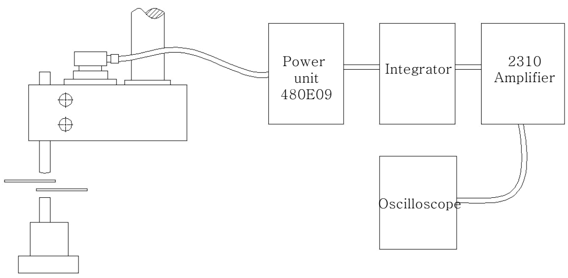


Fig. 2 Accelerometer mounting and system configuration

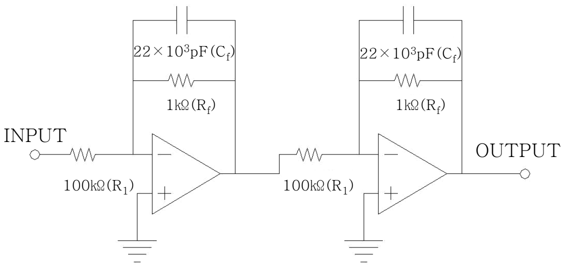


Fig. 3 Hardware circuit diagram for double integration

Table 1 Components of Nickel 200 alloy

Element	Carbon	Manganese	Silicon	Sulfur	Iron	Copper	Nickel+Cobalt
%	0.07	0.35	0.25	0.01	0.25	0.15	base

4. Results and Discussion

The electrode displacement is a dynamic system response caused by thermal expansion and embedding, which are characteristic features of MRSW as well as RSW. In large scale RSW processes, the peak magnitude of electrode displacement is around multiples of 100 micro meters. Hence, it can be easily measured using LVDT, gap sensors and optical encoders. On the other hand, in MRSW processes, the peak value of displacement is usually less than 10 micro meters, which is too small to be measured by conventional displacement sensors. In view of this characteristic of minute displacement and apparent time rate change of the electrode movement, use of accelerometer can be an appropriate alternative.

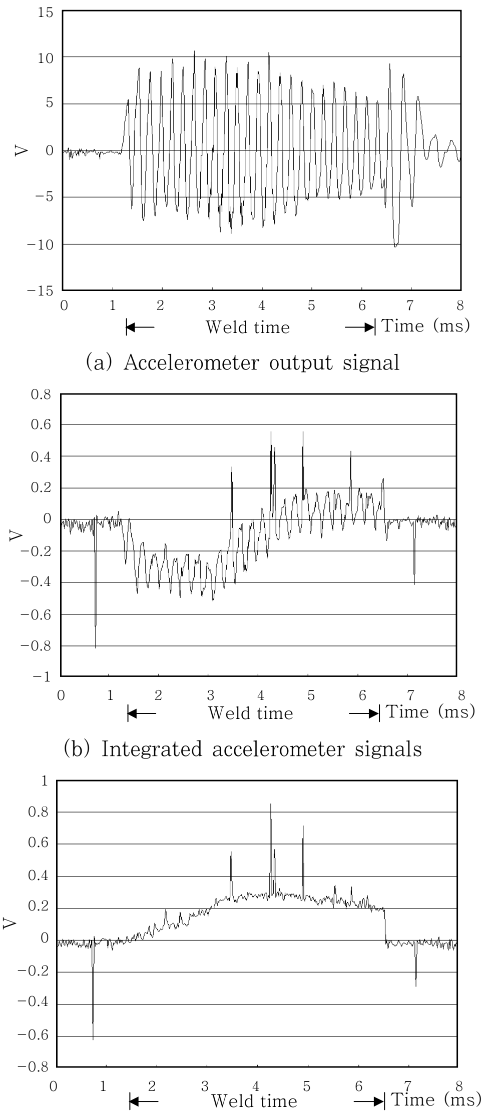
An accelerometer can easily pick up the instantaneous acceleration experienced by electrode head as shown in Fig. 4(a). Integrated and double integrated signal of accelerometer output are shown in Fig. 4(b) and Fig. 4(c), respectively. The physical meaning of the integrated output in Fig. 4(b) is 'electrode head velocity'. The reason for negative part of the velocity waveform is inverting input of the integrator as show in the Fig. 3.

The double integrated signal can be converted into actual electrode (head) displacement signal through the following calibration procedure. The signal was low-pass filtered with cut off frequency of 30 Hz. The electrode displacement signal can be denoted by:

$$E_0 = \frac{1}{(RC)^2} \int_0^t \int_0^t E_{IN} d^2 t \qquad (2)$$

where E_{IN} *denotes accelerometer analog output (conversion factor: 23.725㎛/V)*

Verification of this proposed measuring system was done through actual welding experiment at various current levels and electrode force. The dynamic electrode displacement curves, as shown in Fig. 5, were obtained for the following condition: weld time = 5 ms, sheet metal thickness = 0.16



(a) Accelerometer output signal

(b) Integrated accelerometer signals

(c) Double Integrated accelerometer signal

Fig. 4 Original, integrated and double integrated signals(Weld current=1.5 kA, electrode force=4 kgf, weld time=5 ms)

mm, electrode force = 4 kgf.

As shown in Fig. 5 for various current levels, the dynamic displacement curves show increasing trend at the beginning of weld stage, which reflects varying degree of thermal expansion of the weldment. As the nugget size gets bigger and bigger, material around nugget volume becomes soft and mechanical collapse begins, followed by electrode embedding. Thus, as explained by the Equation (1) in the Section 2, peak point in each curve can be observed. Gradual increase in the initial slope and peak value was observed with gradual increase of weld current. The weld current

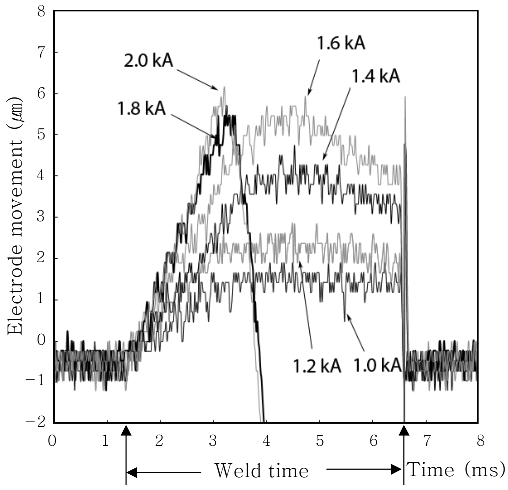
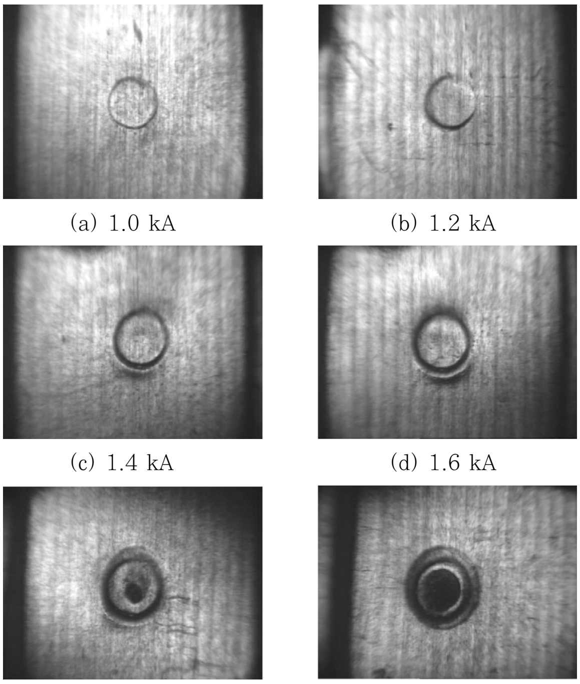


Fig. 5 Dynamic electrode displacement curves for various weld current

of 1.6 kA was found proper for this specimen, in which case the electrode movement curve is almost identical to typical curve in Fig. 1. Further increase of current beyond this value caused excessive heating, thus expulsion occurred with weld current level higher than 1.8 kA. Sharp increase in the slope and sudden drop of electrode displacement were observed.

By examining indentation and burn mark left on the surface of weldment, the above reasoning can be also confirmed. Varying degree of indentation (embedding) depth and burn mark is shown in Fig.6. The increase of indentation depth indicates gradual nugget growth with increased current level. Empirical criterion for good spot weld joint is that the indentation depth should range from 10% to 15% of the weldment thickness. Appropriate indentation depth satisfying this criterion was obtained at weld currents ranging from 1.4 kA to 1.6 kA as shown in Fig. 6. The general trend is that thermal expansion is dominant, i.e., indentation cannot occur due to small nugget with insufficient heat input. Further increase of weld current results in larger nugget and indentation is prevailing due to enlarged plastic region around the nugget at the near end of cycle.

In Figs. 7 (a), (b), (c) and (d), variation of electrode movement pattern in accordance with changes in welding conditions is examined together with corresponding weld nugget size. In each figure,

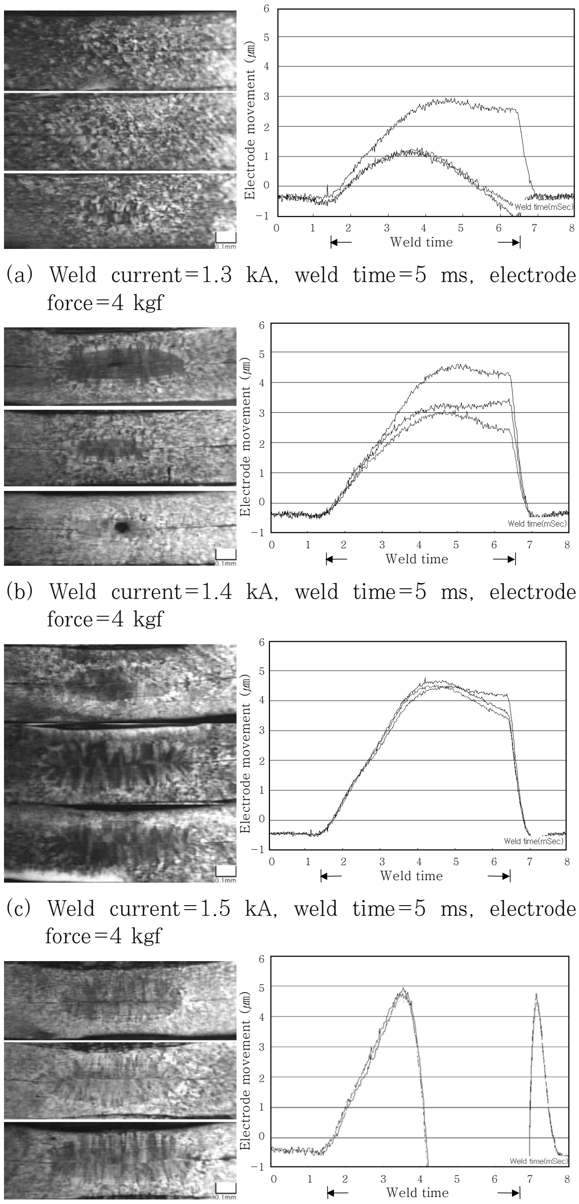


(a) 1.0 kA (b) 1.2 kA

(c) 1.4 kA (d) 1.6 kA

(e) 1.8 kA (f) 2.0 kA 1mm

Fig. 6 Photographs of indentation for various weld current(Electrode force=4 kgf, weld time=5 ms)



(a) Weld current=1.3 kA, weld time=5 ms, electrode force=4 kgf

(b) Weld current=1.4 kA, weld time=5 ms, electrode force=4 kgf

(c) Weld current=1.5 kA, weld time=5 ms, electrode force=4 kgf

(d) Weld current=1.7 kA, weld time=5 ms, electrode force=4 kgf (expulsion occurred)

Fig. 7 Photographs of cross-sectioned weldment and corresponding electrode movement

three photographs of the cross-section indicate nugget size for identical welding condition. The cross-section of weld nugget, shown in Fig. 7(a), reveals only interfacial coalescence of two sheet metals occurred with insufficient heat. The corresponding movement signal shows electrode head displacement for the case of an undersized nugget which is frequently referred as "stuck weld". The electrode movement curve for this welding condition is similar to the typical electrode displacement but its peak value is as small as 1~3 micro meters. Fig. 7(b) shows that as the current level is increased, an increase in initial slope and peak value was observed. In comparison to Fig. 7(a), comparatively better nugget shape is observed in Fig. 7(b). Further increase of current level up to 1.5 kA, a typical ellipsis-shaped nugget with reasonable size is obtained as shown in Fig. 7(c). It is notable that the electrode displacement curve shows typical pattern as explained in Fig.1. And more consistency in the curve pattern for three repeated trials indicates this welding condition is appropriate and guarantees stable welding.

As the weld current level is further increased to 2.0 kA, expulsion of the weld metal (splashing) occurred and thus irregular nugget shape was obtained due to loss of material splashed into the adjacent area in the interface. In the Fig. 7(d), the electrode movement curve shows sudden drop due to expulsion from 5 micrometer to minus value (usually amplifier saturation limit). At the end of weld time, the upper electrode moves upwards, then accelerometer picks up the acceleration again. Hence double integrated signal shows sudden rise.

It has been shown that initial rate of rise (see Fig. 1) at the beginning of electrode movement has good correlation to the nugget size and similar but less consistent relation between peak values of the electrode movement and the nugget size. In addition, end slope of electrode movement at the near end of weld cycle has been introduced as important parameter that plays an important role in spot welding. Thus, overall pattern of the electrode movement curve provides significant information concerning the formation of weld nugget[5].

As have been already verified by previous researches[1-5], notable implicit correlation between electrode rate of rise and nugget diameter was proposed for the case of large scale RSW processes. By examining Fig. 8, similar reasoning can be applied for the case of MRSW processes. The increase in nugget diameter causes increase in the rate of rise of electrode movement as shown in Fig. 8. Also, we can find a good correlation between nugget penetration and rate of rise of electrode movement in Fig. 9. The correlation between rate of rise and nugget diameter/penetration reveals that we can apply this proposed method for in-process monitoring of weld quality in MRSW processes.

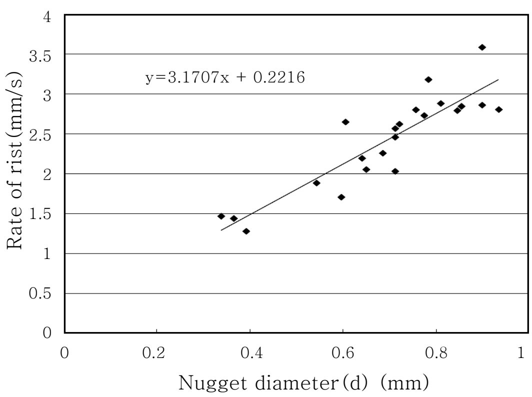


Fig. 8 Rate of rise vs. nugget diameter(Weld current=1~2 kA, weld time=5 ms, electrode force=4 kgf)

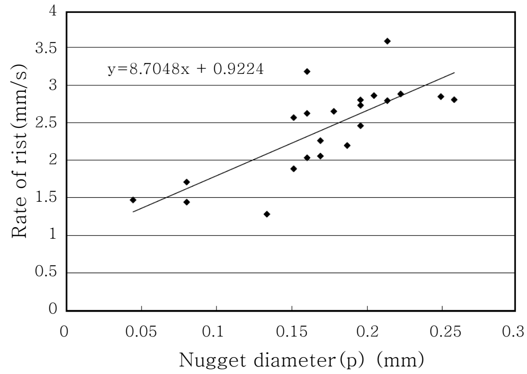


Fig. 9 Rate of rise vs. nugget penetration(Weld current=1~2 kA, weld time=5 ms, electrode force=4 kgf)

5. Conclusion

New in-process monitoring system for micro resistance spot welding was proposed. A minute accelerometer sensor was mounted on upper electrode of a micro spot welding machine. During weld time, electrode head acceleration due to thermal expansion and embedding was picked up by accelerometer. The accelerometer analog output signal was integrated twice and plotted. The plots were proved as dynamic electrode movement curves through a series of experiments.

A good correlation between the rate of rise in the electrode movement curve and nugget size (diameter and penetration) was found. This implicit correlation between electrode expansion curve patterns and weld quality was found to be in a good agreement with many previous researches on electrode head movement monitoring system for large scale resistance spot welding processes.

Accelerometer is simple, light weight and very sensitive sensor. It can be easily installed on the electrode holder and it has no or very little effect on the electrode head dynamic behavior. Even a small amount of electrode head movement can be precisely measured since minute accelerometer detects all accelerations experienced by electrode. This technique is quite promising in the sense that it is readily applicable for in-process monitoring system for micro resistance spot welding processes to assure quality welds in mass production.

6. References

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Appendix Rate of rise and corresponding nugget size

Electrode force(kgf)	Weld current(kA)	Nugget diameter(mm)	Nugget penetration(mm)	Rate of rise (mm/s)
4	1.3	N/A	N/A	
		N/A	N/A	
		0.33	0.04	1.4678
	1.4	0.59	0.08	1.7068
		0.36	0.08	1.4392
		0.39	0.13	1.2788
	1.5	0.54	0.15	1.8844
		0.71	0.16	2.0306
		0.64	0.16	2.0533
	1.6	0.64	0.18	2.1937
		0.68	0.16	2.2583
		0.71	0.19	2.4582
	1.7	0.60	0.17	2.6502
		0.72	0.16	2.6231
		0.71	0.15	2.5668
	1.8	0.78	0.16	3.1812
		0.77	0.19	2.7306
		0.75	0.19	2.8021
	1.9	0.80	0.22	2.8823
		0.89	0.21	3.586
		0.84	0.21	2.7926
	2.0	0.89	0.20	2.8608
		0.93	0.25	2.8056
		0.85	0.24	2.8471