Special Issue

ISSN 1225-6153
Online ISSN 2287-8955

Effect of Initial (Reference) Welding Current for Adaptive Control and It's Optimization to Secure Proper Weld Properties in Resistance Spot Welding

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(Received August 16, 2015 ; Revised August 25, 2015 ; Accepted August 27, 2015)

Abstract

Many automotive companies are endeavoring to improve the quality of resistance spot welding by updating body-in-white (BIW) production line with adaptive control spot welding system to compensate the process disturbances such as gap, electrode wear, oxidized surfaces, poor fit up and adhesive etc. Most of the commercial adaptive weld controllers require proper “Initial Welding Schedule” or “Reference weld” to achieve compensation in welding parameters during real time welding. In this study, the compensation of a commercial adaptive weld controller had been observed and analyzed thoroughly for various process disturbances to find optimal initial welding schedule. It was observed that 90 percent of the expulsion current in constant current control as reference welding schedule conferred the maximum button diameter in adaptive control welding. Finally, effects of each disturbance in combined field disturbances system with adaptive control had also been confirmed with the design of experiment (DOE) by minitab®16 for combined disturbances situation and suitability of optimum initial weld current had also established with real body part validation test.

Key Words : Resistance spot welding, Adaptive control, Optimal welding current, Process disturbances.

1. Introduction

Resistance spot welding is one of the main manufacturing techniques for sheet metal structures. Automobile industry, for instance, uses thousands of resistance spot welds (abbreviated as RSW or spot weld) to assemble the body-in-white (BIW) for vehicles. The quality of the RSW welds determines the durability and integrity of the auto body. Therefore, the quality of the welds is very important to the strength and quality of BIW. However, there is no effective nondestructive real time quality evaluation method till now[1] and RSW suffers from a major persistent problem i.e. inconsistent quality from weld to weld[2] because of the complexity of the process as well as for numerous source of variation, noise, and errors including: workpiece thickness and/or stack up variations; assembly fit-up variations; electrode deformation, contamination, or wear; cooling or force variations or variations in mechanical compliance; and electrical fluctuations in the form of dips or surges. Therefore, automobile industries are using process control or Adaptive technology to ensure weld quality in the production process[2]. Moreover, Feng et al[3] suggested that to consistently achieve good resistance spot welds, two conditions must be met. First, an optimum set of welding parameters must be defined to produce the properties desired of the weld. Secondly, control must be implemented to maintain the process variables within necessary ranges within very short time so that

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Journal of Welding and Joining, Vol.33 No.6(2015) pp13-20
http://dx.doi.org/10.5781/JWJ.2015.33.6.13

Table 1 Sheet combination and welding parameter used for this study

Steel sheet combination			Welding parameters		
Type	Thickness (mm)	Tensile strength (MPa)	Force (KgF)	Time (cycle)	Current (kA)
SGACUD	0.7	270	250	14	4.9 ~ Expulsion
SGAFC 1180	1.2	1180			

optimized welds can be made with good reproducibility. Although it has been recognized that by adaptive control of spot welding machines, significant improvement has been made in part productivity and in the weld quality, but limited research has been conducted to evaluate the effect of reference weld schedule since one of the most important keys to adaptive control is a responsive system for adjusting input parameters i.e. effective heat input in a timely way[2].

However, welding schedule with too high heat input (or expulsion condition) produces poor quality welds and not able to use the adaptive control in proper way in the manufacturing line. Therefore, the successful performance of adaptive controller is a key factor in the weld quality. Therefore, this paper describes the setting of initial welding schedules (or *Reference Weld*) in terms of welding current. More specifically, implementation of *Reference Weld* that culminated in the successful completion and operation of adaptive control in a real spot welding in the factory floor.

2. Materials and Methods

The experiments were performed using customized spot welding system with robot operated servo controlled C-type weld Gun integrated with commercial MFDC adaptive weld controllers, namely A, B and C etc. Fig. 1 shows the details of the welding system used. In this study, a dissimilar combination of two steel sheets of total thickness of 1.9mm was used. The top sheet is SGACUD (thickness = 0.7mm) having ultimate tensile strength of 270MPa and the bottom sheet is SGAFC1180 (thickness = 1.2mm) having ultimate tensile strength of 1180MPa. Both steel sheets are galvannealed with a coating thickness about 11μm in the both

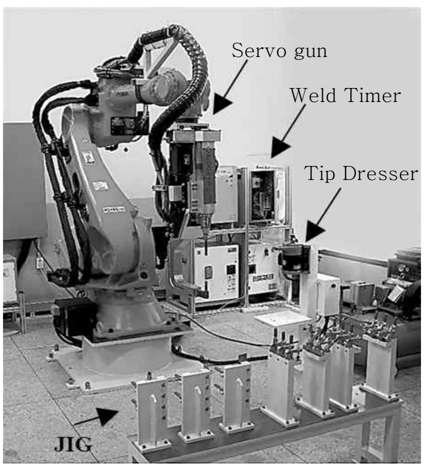

Fig. 1 Schematic of experimental setup used in this study; Robot with servo controller, electrode tip dresser, weld timer with adaptive control function, and sample jig

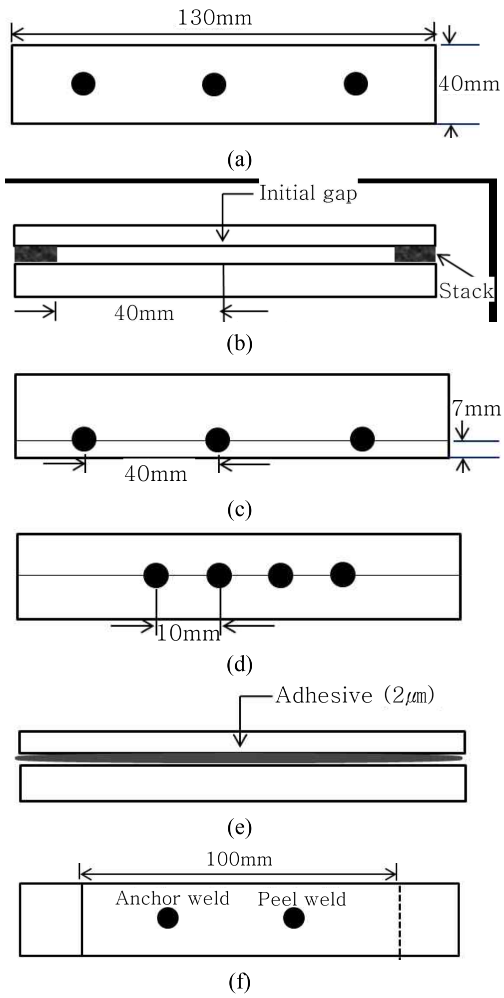

Fig. 2 Test coupons configuration and dimensions for (a) Reference weld, (b) Initial gap, (c) Flange weld, (d) Shunt weld, (e) With adhesive and (f) Peel test

sides of the sheet. The sheet combination used for describing this study is listed in the Table 1 along with welding parameters. The electrodes were Cu-Cr dome-type with electrode face diameter 6mm. The water cooling rate was 6 liter/min. During experiment, the squeeze and hold time were set as 5 cycles and 10 cycles respectively. Fig. 2 illustrates the test coupons configuration and dimension used for this study. For weldability evaluation, coach peel test was performed and button diameter was measured according to AWS D 8.9. Nugget macrostructures were evaluated by optical microscope Olympus BX51M after mounting and polishing in accordance with standard metallurgical procedures. For etching, a mixture of 1%HCl, 3% Picric acid and 96% ethanol was used.

3. Results and Discussion

3.1 Weldability Evaluation in constant current

The weldability of a specific material or sheet combination is defined as the capacity for being welded under a particular welding schedule. The suitable current range was considered to be the interval between the point at which the minimum button or nugget diameter equaled to **4√t** (t, is the thickness of thin sheet in case of dissimilar stack) depending on base metal strength, and also to the point of expulsion[4]. To determine weldable current range in constant current control, several currents at the step of 0.5kA were selected at 250kgF electrode force and 14cy weld time for the perfect fit up (*Referred as no disturbance in the later*) stack of SGACUD (0.7mm) and SGAFC1180 (1.2mm). Fig. 3 shows the obvious effect of the welding current on the weld growth for the stated sheet combination in constant current control. It can be seen that nugget diameter almost linearly increases with welding current except at expulsion current [Star marks (★) in the Fig. 3] since expulsion involves loss of liquid metal from the nugget during welding[5]. Fig. 4 illustrates the nugget micrographs for different current at 250kgF electrode force and 14cy weld time. This experiment yields that minimum current (*when nugget/button diameter equaled to* ***4√t***) is 5.9kA and maximum current (*current without expulsion or Expulsion - 0.4kA*) is 8.8kA.

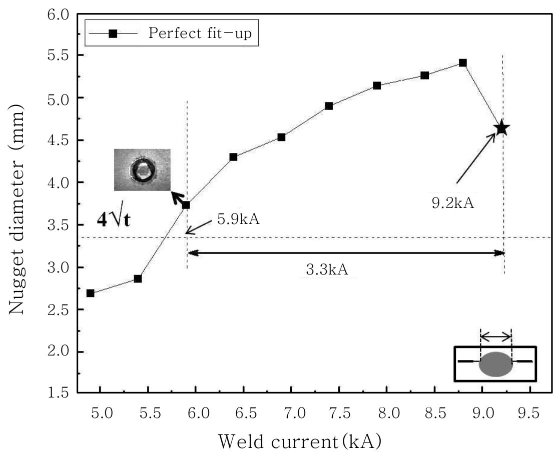

Fig. 3 Weld growth curve for perfect fit up sheet combination in constant current mode (Weld force: 250kgF, Weld time:14cy)

3.2 Effect of Initial Current on Weldability in Adaptive Control

The volume of material melted depends on the amount of heat generated and directly affects weld strength. The theoretical Joule heat developed in abutting workpiece can be computed from the formula,

$$H = I^2 R t. \tag{1}$$

where H = heat (in Joules), I = current passing through the workpiece (in amperes), R = electrical resistance to current in the pieces being welded (in ohms), and t = time of welding current passage (in seconds). As can be seen in equation (1), welding current is the major pa-

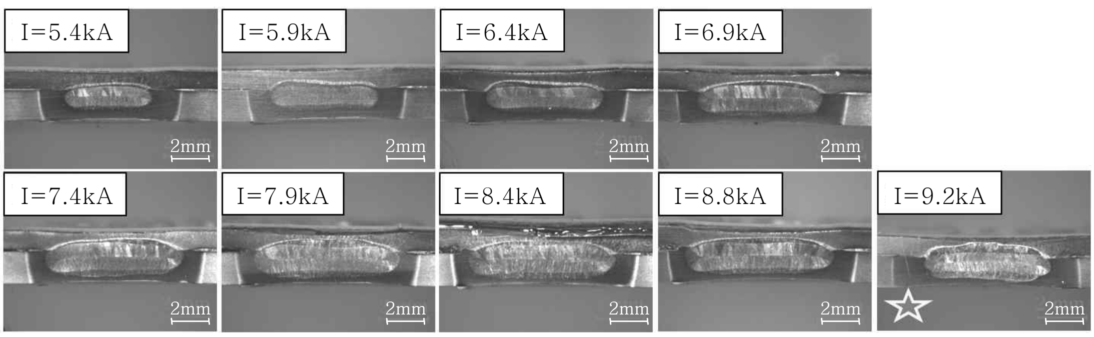

Fig. 4 Nugget macrographs with weld current for perfect fit up sheet combination (Weld Force: 250kgF, Weld time: 14cy)

rameter which is squared to contribute to heat generation. In other ways, H.S.Cho and Y.J.Cho explained that nugget volume at the end of welding increases proportional to the rate of overall heat generation[6]. Therefore, firstly, to find out the effect of initial welding schedule for adaptive control, various levels of weld current such as 5.3kA (60% of 8.8kA), 7.0kA (80% of 8.8kA), 8.0kA (90% of 8.8kA) and 8.8kA (100% of 8.8kA in constant current) had been applied for same sheet combination as initial or reference current for no disturbance (perfect fit up) and with 2mm initial gap condition. Fig. 5(a) confirms that with increasing current, button diameter increases because of higher welding current due to compensation algorithm than the reference welding current which has been illustrated in details in the section 3.3 and 3.4; current 7.0 kA (80% of 8.8kA) or above results button diameter well above 5√t (*Button diameter,* ***d = 5√t*** *conventionally considered as a critical button diameter to ensure plug failure even for similar ultra high strength steel combination*) in constant current control mode. Similarly, 7.0kA (80% of 8.8kA) and 8.0kA (90% of 8.8kA) current confer button diameter well above 5√t in adaptive control mode even with field disturbance of 2mm Gap. However, 8.8kA (100%, maximum current without expulsion in constant current control) produces expulsion even if there is no process disturbance as shown in Fig. 5(b). It is worth to note that adaptive control parameters setting kept quite wide to be compensated by both weld current and weld time.

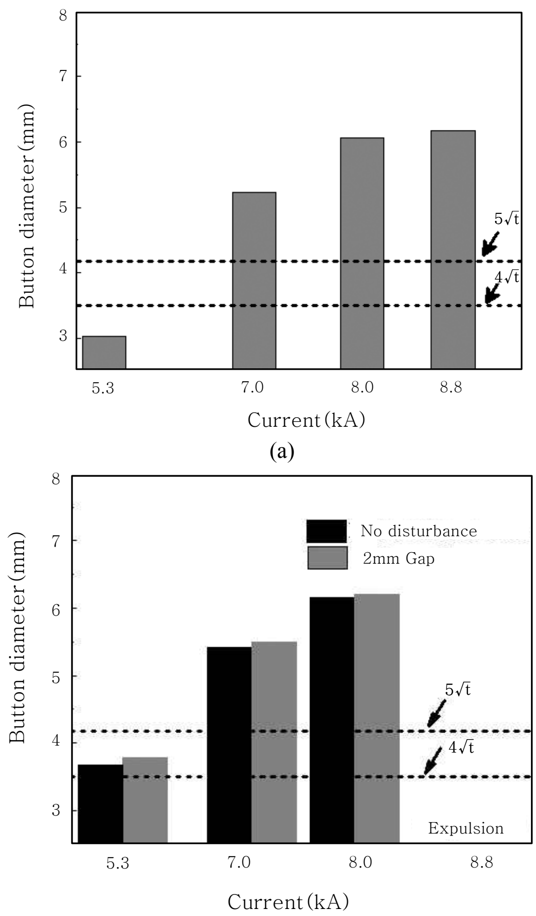

Fig. 5 Effect of initial current on button diameter and expulsion (a) Constant current control, (b) Adaptive control (weld time: 14cy, electrode force: 250kgF)

3.3 *Analysis of the compensation algorithm of Adaptive timer/controller*

Commercial welding controllers are different in terms of algorithm to yield better weld quality after performing compensation depending on various process disturbances. Therefore, it is first and the most important steps to study the control algorithm before explain the adaptive weld quality. The compensation function of the said weld timer is described in the Fig. 6 for no dis-

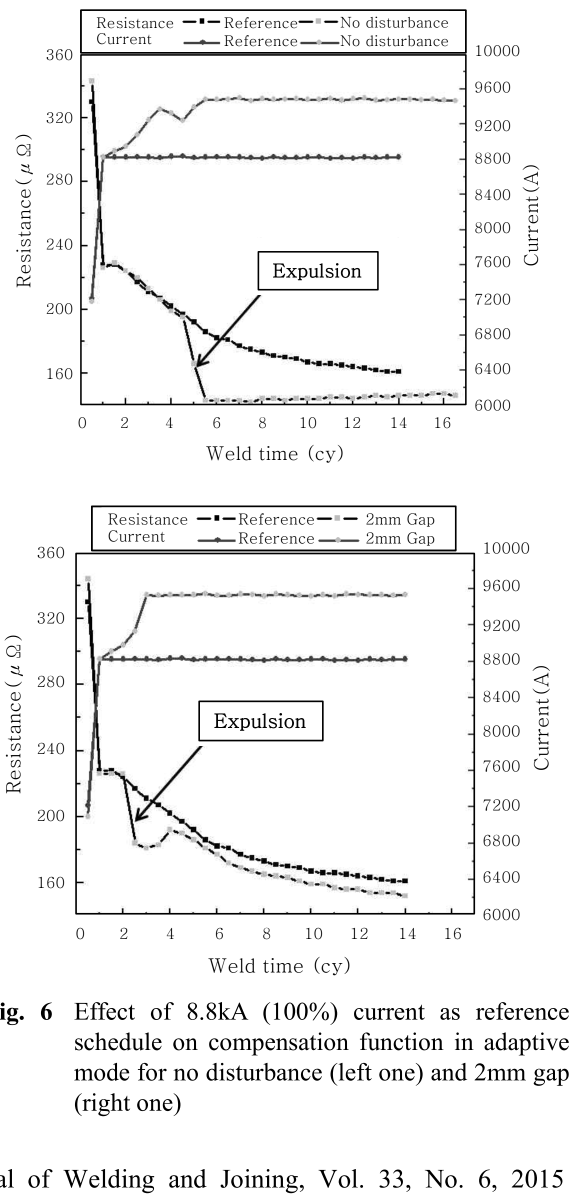

Fig. 6 Effect of 8.8kA (100%) current as reference schedule on compensation function in adaptive mode for no disturbance (left one) and 2mm gap (right one)

turbance and for 2mm Gap when the initial current was set at 8.8kA (100%, maximum current without expulsion in constant current control). The compensation behavior is shown side by side for no disturbance and 2 mm gap respectively at 8.8kA current as initial current. It can be clearly seen that current increased in both cases, mostly after 2 weld cycle to compensate any deviation in dynamic resistance from reference weld (see Fig. 6). Moreover, the resultant peak current reaches to about 9.4kA after 2cy weld time which is much higher than the maximum weld current (before expulsion) in constant current mode and produces expulsion[7]. This is the reason why 8.8kA current as reference weld schedule finally gives expulsion which is not desirable in the production process.

In contrast, From Fig. 7 (left one), it can be seen that due to small deviation in dynamic resistance with reference weld in case of no disturbance, current value almost remains constant with reference current until 4 weld cycle, then it starts to increases since controller encounters little lower resistance than reference weld and reaches to about 8.6kA. Likewise, with 2 mm Gap, during initial weld time (up to 4~5cy) cycle, resistance is higher than reference weld so current remains at a level with reference weld (Fig. 7 right one). Then resistance starts to drop and therefore current increases and reaches to almost 8.6kA which is still below 8.8kA (maximum current in constant current). That's why 8.0kA current is suitable to produce expulsion free weld in adaptive control mode even with the presence of gap in the weld. In addition, Fig. 8 illustrates compensation behavior in a weld timer used in the study at weld current 8.0kA (90% of 8.8kA) for others 10 types of process disturbances. Form Fig. 8(b), it can be clearly seen that current increased with each disturbances, mostly after 2 weld cycle to compensate with any deviation in

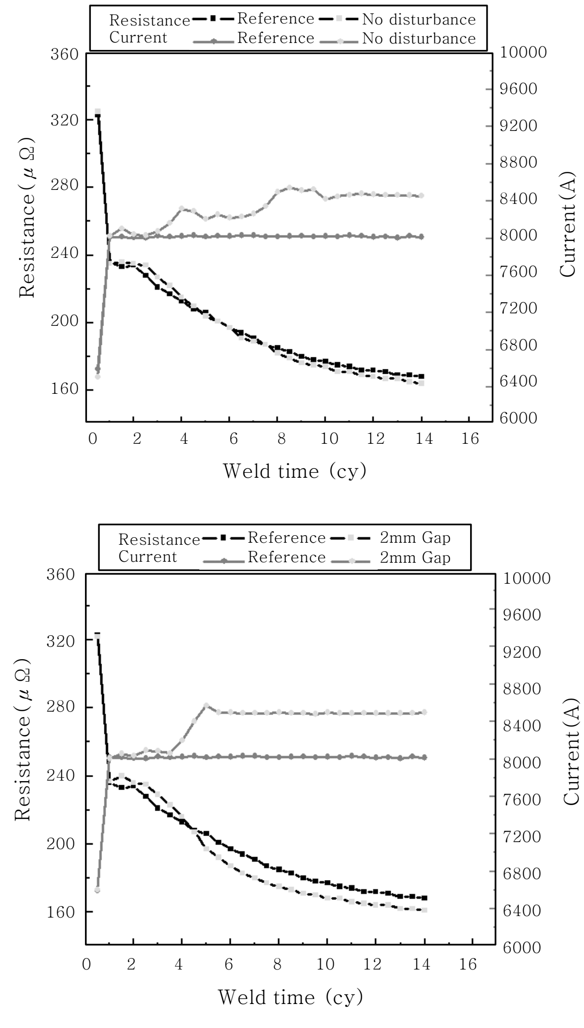

Fig. 7 Effect of 8.0kA (90% of 8.8kA) current as reference schedule on compensation function in adaptive mode for no disturbance (left one) and 2mm gap (right one)

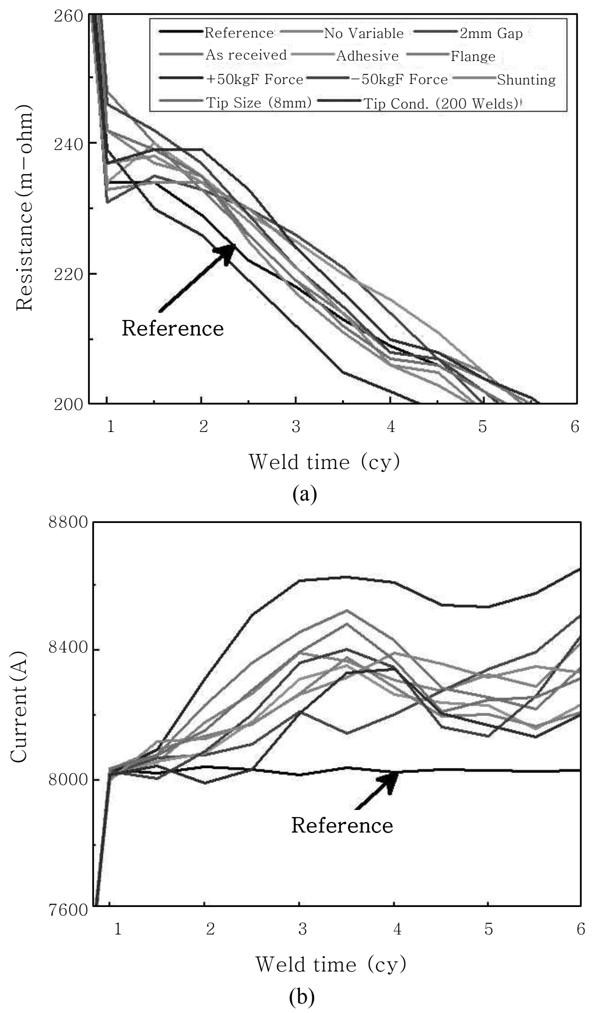

Fig. 8 Compensation of the weld timer for various process disturbances in adaptive mode with weld time (a) change in dynamic resistance, and (b) change in current with respect to reference weld

dynamic resistance from reference weld as shown in the Fig. 8(a). Moreover, the resultant peak current reaches to about 8.8kA which is the optimum weld current in constant current mode. This is attributed to the fact that 8.0kA current as reference weld schedule finally gives expulsion free weld which is most desirable in the production process.

3.4 Analysis of the compensation on button diameter and in combined disturbance systems

In addition, the effect of compensation function on button diameter has been depicted in the Fig. 9 for various field disturbances such as gap, adhesive, shunt, tip condition etc. The experimental results suggest that button diameter after peel test is well above 5√t and almost close to maximum button diameter (~6.2mm) possible with 8.8kA at constant current control mode.

Since manufacturing line often encounters more than one field disturbances at a time, so the effects of each disturbance in combined field disturbances system with adaptive control has also been confirmed with the design of experiment (DOE) by minitab®16. The details boundary conditions of DOE are given in the Table 2(a) and outcome of expulsion obtained experimentally is outlined in the Table 2(b). Fig. 10 illustrates that lower electrode force (50kgF lower than optimum) has the highest influence on Expulsion[8]. However, this disturbance effect can easily be eliminated in the production line. Hence 90% of maximum current (without expulsion) in constant current control is suitable as Initial welding schedule for adaptive weld controller with appropriate electrode force.

To find the suitability of initial weld schedule (optimum current level); a validation test is further performed with actual B-pillar part of the side structure. The sheet com-

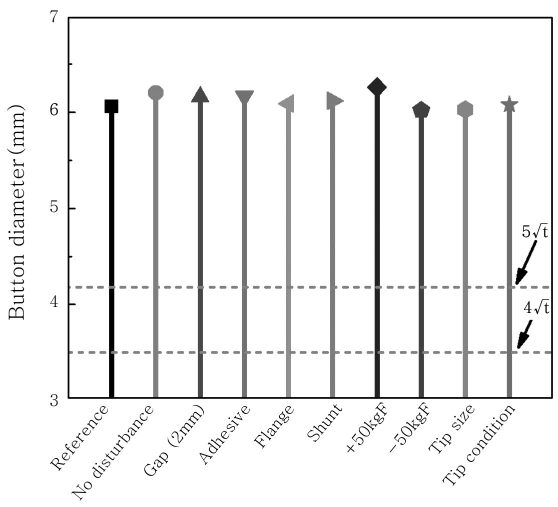

Fig. 9 Effect of initial condition on button diameter with 10 field disturbances in adaptive control

Table 2 (a) Boundary condition for DOE, and (b) Results of experiment designed by DOE

Factors	Variable	Level	
		Low(-1)	High(1)
A(Gap)	D1	0	3
B(Adhesive)	T	0	2
C(Force)	kgf	200	300
D(Tip condition)	Spot	0	200
E(Flange)	D_2	7	20
F(Shunt)	D_3	10	30

(a)

Std. Order	Gap	Adhesive	Flange	Shunt	Force	Tip condition	Expulsion
1	0	0	7	10	200	0	2
17	0	0	7	10	300	200	1
9	0	0	7	30	200	200	1
25	0	0	7	30	300	0	1
5	0	0	20	10	200	200	1
21	0	0	20	10	300	0	1
13	0	0	20	30	200	0	1
29	0	0	20	30	300	200	1
3	0	2	7	10	200	200	1
19	0	2	7	10	300	0	1
11	0	2	7	30	200	0	2
27	0	2	7	30	300	200	2
7	0	2	20	10	200	0	1
23	0	2	20	10	300	200	1
15	0	2	20	30	200	200	2
31	0	2	20	30	300	0	2
2	3	0	7	10	200	200	2
18	3	0	7	10	30	0	1
10	3	0	7	30	200	0	2
26	3	0	7	30	300	200	1
6	3	0	20	10	200	0	2
22	3	0	20	10	300	200	1
14	3	0	20	30	200	200	2
30	3	0	20	30	300	0	1
4	3	2	7	10	200	0	2
20	3	2	7	10	300	200	1
12	3	2	7	30	200	200	2
28	3	2	7	30	300	0	1
8	3	2	20	10	200	200	1
24	3	2	20	10	300	0	1
16	3	2	20	30	200	0	2
32	3	2	20	30	300	200	2
*1 Indicates no expulsion and 2 indicates expulsion							

(b)

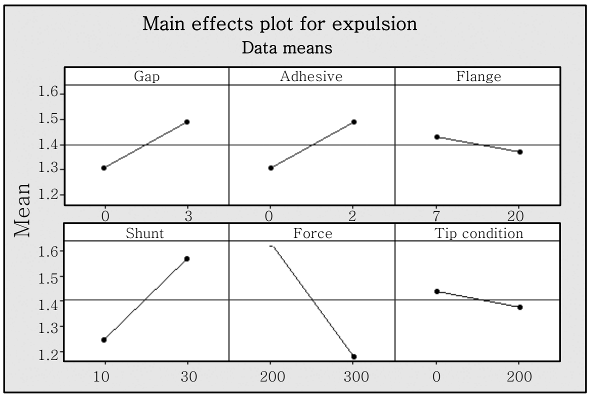

Fig. 10 Effect of each disturbance on expulsion with DOE analysis

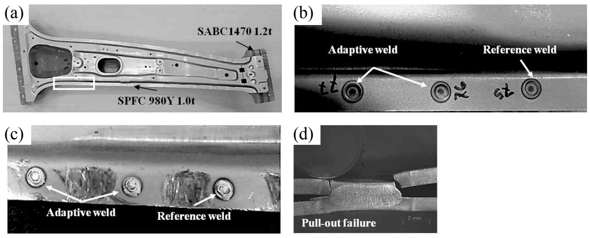

Fig. 11 Details of validation test (a) Sheet combination, (b) Weld spot, (c) Plug failure (d) Nugget image of adaptive weld

bination was Al-HPF 1470 (1.2mm) and SPFC980Y (1.0mm). The maximum current (expulsion- 0.2kA) without expulsion was 7.2kA at 350kgF and 15cy weld time in constant current control. The detailed findings are shown in the Fig. 11. As mentioned, the initial weld schedule is applied at the optimum level of current i.e. 90% of 7.2kA current in *adaptive control* (Weld Force: 350kgF; Weld time: 15cy; Current: 6.5kA) and resultant weld gives plug failure as shown in the Fig. 14(c) and resultant nugget diameter is almost 5.49mm which is also above 5√t, see Fig. 14(d). The results of validation test with implementation of optimum current for adaptive control at B-pillar part directly shows the good quality of spot welds.

4. Conclusions

According to this investigation, it has been seen that optimum level of initial current is important to reduce expulsion and to ensure maximum button diameter i.e. weld strength even in adaptive control mode. Adaptive control is not the sole solution to compensate disturbances effect during production as thought of; however, optimum initial current or initial schedule has to be assigned for its successful completion of operation. The following conclusions can be drawn from this study:

1) Maximum current without expulsion in constant current control is not suitable for compensation in adaptive mode; 90% of maximum current (without expulsion in constant current) is found optimum for proper compensation in adaptive mode for various disturbances to ensure maximum nugget/button diameter since adaptive mode increase the heat input (current) than reference heat input (current).

2) Lower force than optimum force as weld parameter is prone to expulsion occurrence even at optimum initial current; fixed electrode force can easily be maintained in the production process.

3) Since, real production line is integrated with various process disturbances, optimum initial current for adaptive control ensure the maximum performance of adaptive control (or compensation) with harsh field disturbances.

4) The validation procedure with high strength steels (higher than 980 MPa, including hot stamping steels) combination with B-pillar part guarantee the button diameter higher than 5√t in spot welds without expulsion at the optimum current level and ensure the clean body with reliable B-I-W, which possess the high energy absorption during the car crash.

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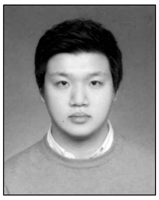

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