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ORIGINAL ARTICLE

Resistance spot welding control based on fuzzy logic

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Abstract Resistance spot welding is one of the most important welding procedures. Therefore, a lot of research is done in order to increase its cost effectiveness. One of the problems is short electrode life, especially when coated materials are welded. This paper presents a fuzzy logic-based controller which is capable of detecting expulsion and stopping the welding process when it occurs. Consequently, electrodes are spared of unnecessary high stresses which occur when the energy is being poured into the weld region after expulsion. Their life is therefore substantially increased.

Keywords Resistance spot welding · Fuzzy logic · Process control

1 Introduction

Resistance welding (RW) can be defined as a group of welding processes that produce coalescence of the faying surfaces using the heat obtained from the resistance of the workpieces to the flow of electrical current in the circuit which the workpieces are a part of and by the application of pressure [1]. There are several different versions of RW. The most widely used is resistance spot welding (RSW). RSW is one of the major welding technologies used in the appliance, electric, and aviation industries. The automotive industry, however, is the major user. RSW is widely used in an automotive body assembly. There are thousands of spot welds on an automobile body [2, 3]. As their properties significantly affect the durability and crashworthiness of the vehicle [4], improving their quality is an ongoing process in RSW research [5–9].

The most common type of power source used in RSW utilizes two silicon-controlled rectifiers (SCRs) that are connected in parallel: one to pass the current during the positive half cycle and the other during the negative half cycle as shown in Fig. 1. The primary current i_P conduction is started with a pulse on one of the gate electrodes (G1 or G2 in Fig. 1) of each of the SCRs, as shown in Fig. 1. The primary current is started with pulses on the gates and continues until the end of each half cycle. The firing angle determines the effective value of the primary current and can, therefore, together with the transformer setting, be used to control the effective welding current i_W. The main drawback of SCR power source from the control theory point of view is the fact that its output can only be changed twice during each period of the net frequency. Advanced middle frequency DC sources use higher frequencies (up to 20 kHz) and are, therefore, along with other advantages, more applicable for advanced control algorithms. As a consequence of the changing primary current, there is a certain amount of welding voltage U_W on the secondary part of the welding transformer that causes the electrical current to flow in the secondary circuit. The current flow through the workpieces generates heating. The intensity of the heat generation depends on the resistance distribution in the secondary circuit. By far the greatest part of the total resistance (electrode resistance, contact resistance at the eletrode/workpiece interface, workpiece resistance,

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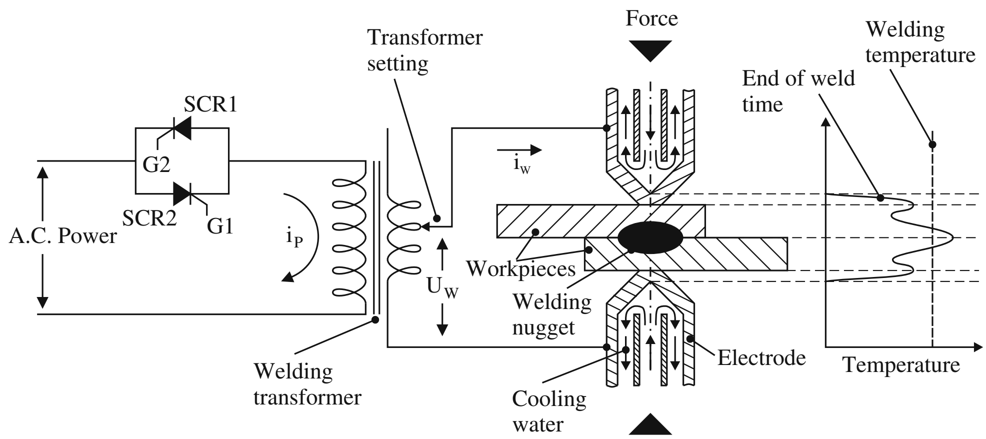


Fig. 1 Schematic representation of resistance spot welding [1]

and workpiece/workpiece interface contact resistance) is the contact resistance at the workpiece/workpiece interface [10]. Therefore, the most intense heating occurs at this interface. Consequently, the temperature increases beyond the welding temperature, as shown in the temperature profile in Fig. 1. As a result, a volume of material (the so-called welding nugget) is formed between the workpieces. The size (diameter) of the welding nugget is important because after cooling down, it defines the strength of the weld. If other parameters remain constant, the size of the welding nugget increases with the welding time. The size of the nugget, however, cannot be increased indefinitely. It is, of course, limited by the thickness of the workpieces. In fact, even before the welding nugget expands to the outer surfaces of the workpieces, the weld would collapse because of the decreasing amount of solid material around the welding nugget, which is no longer able to withstand the pressure of the electrodes. The result is an expulsion of the molten material at the faying surface or the electrode workpiece interface. The latter may severely affect surface quality and electrode life, but not the strength of the weld if it is limited to the surface [11]. On the other hand, expulsion at the faying surface is highly undesirable in terms of the weld strength because it involves loss of liquid metal from the nugget during welding. So although the expulsion does not necessarily imply a decreased weld strength [12] and might in some circumstances even be used as visual indicator of a "correct" welding process [13], it is generally considered undesirable due to a higher electrode wear, a higher energy consumption, an unsatisfactory visual appearance of the weld, and a reduced corrosion resistance of coated materials. Beside that, even if the expulsion does not decrease the weld strength, it might decrease the energy absorption capability of the weld [14]. In high strength steels, it might also cause voids and porosity [13].

The use of zinc-coated steels has attracted much attention over the past decade due to their good corrosion resistance and relatively low cost [15]. However, electrode wear of Zn-coated steels continues to be a significant issue, due to its lower electrical resistance, lower melting temperature, and accelerated degradation of resistance welding electrode tips. Electrode wear adversely affects the cost and productivity of automotive assembly welding due to reduced weld quality, reliability, and robustness. This mandates increased inspection rates and greater control of welding parameters. Consequently, large potential cost savings and quality improvements are expected from substantial improvements in electrode life, and a lot of research has been done in this area [15–21]. An efficient transfer of heat from the electrode to the cooling water can reduce the electrode temperature and limit thermal degradation of the electrode material. A proper electrode temperature results in longer electrode life [21]. The electrode life can also be extended if energy input into the weld region is limited. When expulsion occurs, there is no reason to add any more energy, so the welding process should be stopped at that point because further temperature increase can substantially increase the electrode temperature and therefore decrease the electrode life. In this paper, an algorithm for expulsion detection based on fuzzy logic is presented. The control system using this algorithm is of the on–off type measurement-based feedback control system [1]. It stops the welding when expulsion occurs. Similar approach based on neural networks was already used [22]. The problem is, however, that neural networks might have problems of convergence during learning process. Beside that, they tend to be computationally demanding and are therefore not very suitable for real-time applications. Another approach can be used if modeling of expulsion is considered [11]. The main advantage of this approach is the possibility of expulsion prediction. The problem is, however, that there are so many disturbances in RSW that it is almost impossible to get an accurate model of the process.

2 Measurement

The following materials were used in the experiment:

– Mild steel RSt 13
– Mild steel RSt 42-1
– Zinc-coated steel USt 10 (zinc coating 275 g m^{-2})
– Zinc-coated steel FePO4 (zinc coating 140 g m^{-2})

All the samples were 2 mm thick, 10 cm long, and 5 cm wide.

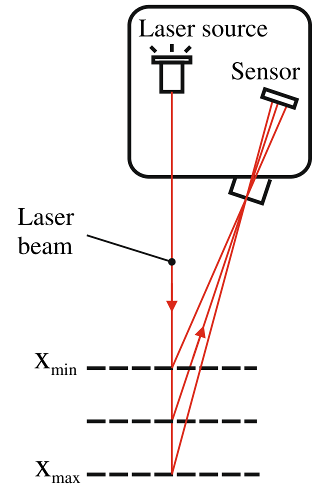
The measurement setup is shown in Fig. 2. The following variables were measured for all the samples at the sampling rate of 10 kHz:

– The welding voltage U_w
– The induced voltage U_i (used to obtain the welding current I_w)
– The electrode displacement x
– The welding force F_w

The welding voltage U_w can be measured directly on the electrodes. The induced voltage was measured using the Rogovsky coil (TECNA 1430). The signal is proportional to the derivative of the welding current I_w, so it must be integrated in order to get the welding current [23]. The electrode displacement was detected as the movement of the upper electrode. A laser triangulation sensor (MEL Mikroelektronik M5L/10-10B24NK) was used for that purpose. The principle of measurement is shown in Fig. 3. As the sensor uses the optics for the measurement, it is insensitive for the electromagnetic interference due to large welding currents. The welding force was measured using the piezoel. sensor (KIAG SWISS Type 903A) and the charge amplifier (Kistler Type 5006). The results of the measurements (the welding voltage U_w and the induced voltage U_i) were then used to obtain the dynamic resistance R_d. It can be obtained in different ways [24]. In this paper, the welding voltage U_w and the welding current I_w at the moment of zero-induced voltage U_i ($\frac{di_w}{dt} = 0$) were used (time t_k in Fig. 4). The reactance equals zero at this moment and the dynamic resistance can therefore be easily obtained. It can, however, only be obtained once in each half-cycle.

The typical signals for a weld with expulsion are shown in Fig. 5. The moment of expulsion is marked with a dashed line. When the expulsion occurs, the

Fig. 3 Laser triangulation sensor



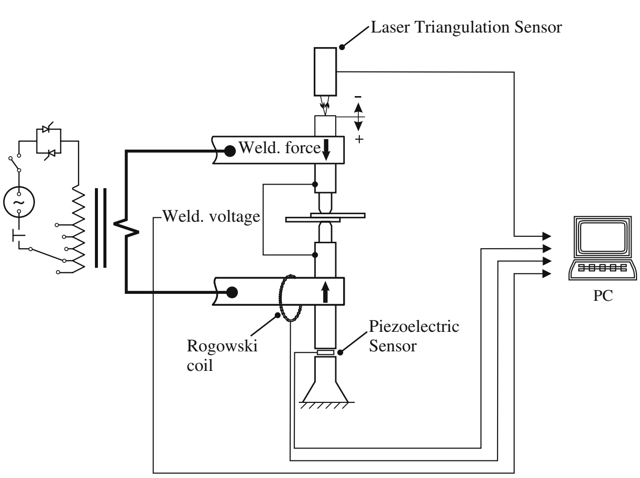


Fig. 2 Measurement setup

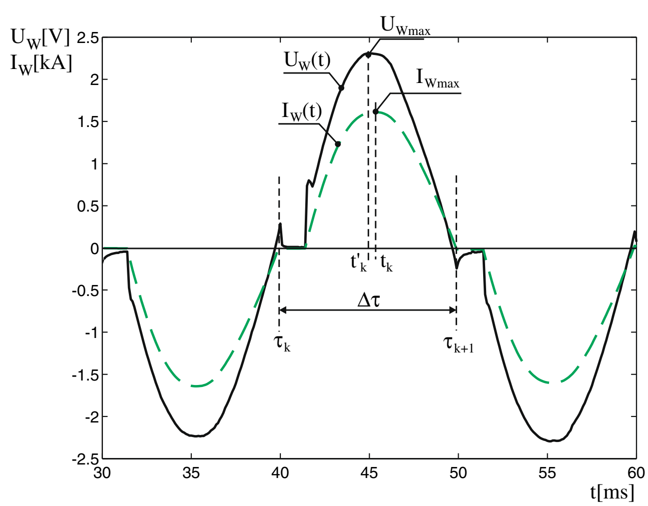


Fig. 4 Welding voltage and welding current waveform

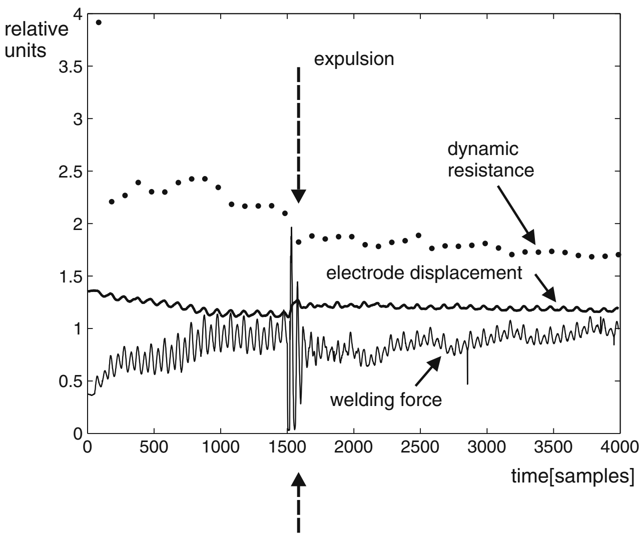


Fig. 5 Typical signals for a weld with expulsion

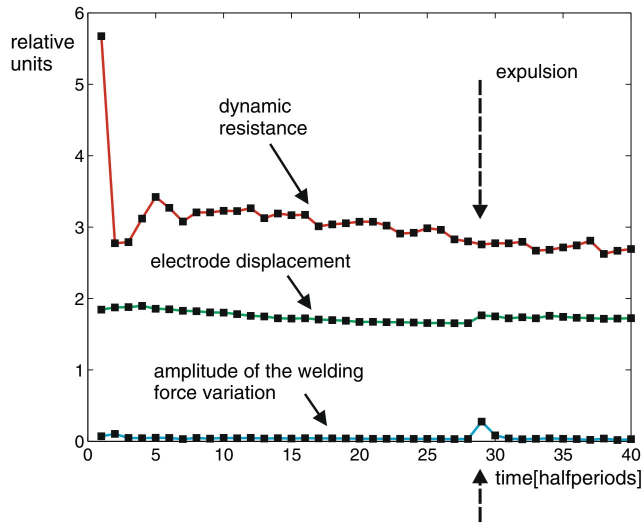


Fig. 7 Typical signals for zinc-coated steel

following phenomena, which vary in their intensity, can be observed in any of the four materials:

– A decrease in the dynamic resistance R_d
– An increase in the electrode displacement x_d
– An increase in the variation of the welding force F_w

Due to the fact that SCR-based welding sources can be controlled only twice in each period, all the signals were modified to resemble the dynamic resistance signal. The electrode displacement signal was filtered using a moving average filter of 20 points and determined at the same moments as dynamic resistance (Figs. 6, 7, and 8). In order to get the welding force variation, the filtered welding force (the moving average of 100 samples) was obtained first. Then, it is subtracted from the welding force. The absolute value of the resulting signal is filtered again with the moving average filter of 100 samples. The resulting signal (the amplitude of welding force variation) is shown in Figs. 6, 7, and 8.

Figures 6, 7, and 8 show signals in three cases. The first one (Fig. 6) is representative for mild steels. A distinct change in all three signals can be seen, when expulsion occurs. So it is very easy to determine the moment of expulsion in this case. The changes in zinc-coated steel are much less obvious. Figure 7 shows one example, where it would still be possible to determine the moment of the expulsion based on the amplitude of the welding force signal variation alone. The last

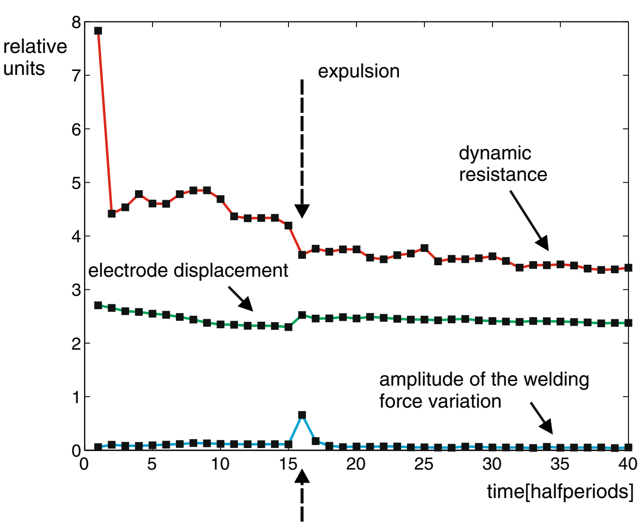


Fig. 6 Typical signals for mild steel

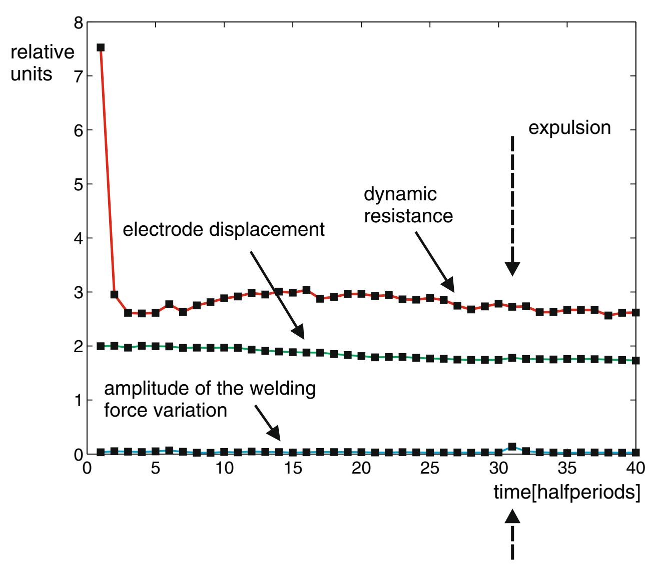


Fig. 8 Zinc-coated sample with complicated signals

case (shown in Fig. 8) is the case, where it is difficult to detect the moment of expulsion. If the amplitude of the welding force variation signal alone is used, it is impossible to make a clear distinction for all the samples because there is also random variation in this signal as well. In this case, it is beneficial to use other signals as well. We namely know that, beside increase in welding force variation, there must also be a decrease in the dynamic resistance and an increase in the electrode displacement signal. One solution to this situation is the application of neural networks [22]. The more elegant one is the application of fuzzy logic.

3 Fuzzy logic

Fuzzy logic is one of the artificial intelligence techniques. It is applicable in different areas of science and engineering [25–27], so a basic understanding of its capabilities is essential for every scientist or engineer.

3.1 The basics of fuzzy logic

3.1.1 The definition of fuzzy sets

The concept of fuzzy sets as a generalization of crisp sets was first introduced by L. A. Zadeh [28]. Crisp as well as fuzzy sets can be defined by a characteristic function μ. The domain of μ is the universal set X. The range depends on the type of the set. Crisp set can be defined by a characteristic function μ_S:

$$\mu_S : X \to \{0, 1\} \tag{1}$$

the range of which is a two element set {0, 1}. The value of μ_S at x equals 1 if $x \in S$ and equals 0 if $x \notin S$. So each element either is in the set S, or is not. Fuzzy set on the other side is defined by a characteristic function μ_A:

$$\mu_A : X \to [0, 1] \tag{2}$$

In this case, the range is an interval [0, 1]. If the value of a characteristic function μ_A for a certain $x \in X$ equals $y \in [0, 1]$, we say that x is a member of A with a membership value of y.

3.1.2 Operations on fuzzy sets and fuzzy relations

Operations on fuzzy sets are just an extension of operations on crisp sets. As crisp sets are just a special case of fuzzy sets, operations on fuzzy sets should imply known relations on crisp sets if they are applied only on them.

A fuzzy set C is a union of fuzzy sets A and B ($C = A \cup B$) if the following equality holds for every $x \in X$:

$$\mu_C(x) = \max[\mu_A(x), \mu_B(x)] \tag{3}$$

A fuzzy set C is an intersection of fuzzy sets A and B ($C = A \cap B$) if the following equality holds for every $x \in X$:

$$\mu_C(x) = \min[\mu_A(x), \mu_B(x)] \tag{4}$$

Fuzzy union and intersection can be defined in other ways as well, but the ones presented in Eqs. 3 and 4 are most common.

Fuzzy relations are extension of relations known from classical set theory. Crisp relation R is defined as a subset of a direct (Cartesian) product of universal sets X and Y.

$$R \subset X \times Y = \{(x, y) \mid x \in X, y \in Y\} \tag{5}$$

Crisp relation can therefore be defined with the following characteristic function:

$$\mu_R : X \times Y \to \{0, 1\} \tag{6}$$

Fuzzy relation R differs from a crisp one only in its codomain. In this case, it is an interval [0, 1] instead of a two-element set {0, 1}.

$$\mu_R : X \times Y \to [0, 1] \tag{7}$$

At this point, the problem of the definition of a direct product of fuzzy sets arises. Let a fuzzy set A be a subset of an universal set X and fuzzy set B a subset of an universal set Y. A fuzzy set C is a fuzzy Cartesian product of sets A and B if it is a subset of the set $X \times Y$ with the following characteristic function:

$$\mu_C(x, y) = \min(\mu_A(x), \mu_B(y)) \tag{8}$$

For the purpose of fuzzy logic, it is important to define the composition of fuzzy relations. Let C and D be fuzzy relations and subsets of $X \times Y$ and $Y \times Z$, respectively. Fuzzy set E is a composition of fuzzy relations C and D ($C \circ D$) if it is a subset of $X \times Z$ with the characteristic equation [29]

$$\mu_E(x, z) = \max_{y=Y} (\min(\mu_C(x, y), \mu_D(y, z)) \tag{9}$$

A special case of this definition is the case when one fuzzy relation is replaced with a fuzzy set. Let fuzzy set A be a subset of X and fuzzy relation C a subset of $X \times Y$. Their composition B is a subset of the universal set Y with the characteristic function

$$\mu_B(y) = \max_{x=X} (\min(\mu_A(x), \mu_C(x, y)) \tag{10}$$

The above equation is used extensively in fuzzy logic.

3.1.3 Fuzzy inference

Logic operates with statements and predicates. Let $p(x)$ be an open statement or predicate defined on a set X. Let set P consist of all elements $x \in X$ which make the statement $p(x)$ true. If the statement $p(x)$ is defined as: "*x is less than 3*", the set P consists of all real numbers in the interval $(-\infty, 3)$. Predicate (in crisp set case) can therefore be defined as:

$$\mu_P : X \rightarrow \{0, 1\} \tag{11}$$

Fuzzy predicate is an extension of crisp one.

$$\mu_P : X \rightarrow [0, 1] \tag{12}$$

Fuzzy predicate enables us to use mathematical logic in a sense closer to human reasoning. The statement "*An x-year old person is young*" is, for example, very difficult to characterize with a crisp set. If we set the boundary between young and old at 30 years, it would mean that a person at the age of 29 is young and a person 1 year older is old. Such a sharp difference does not make sense. We would also get different statements from different people. A 10-year-old child would probably consider a 30-year-old person old. The same person would be considered young for a 70-year-old man. Fuzzy sets can be applied to "soften" the transition between young and old. An example of such a softening is shown in Fig. 9. Until a person is 20 years old, he belongs to a group of young people with a membership value of 1. Between the ages 20 and 50, the membership gradually decreases from 1 to 0 and remains 0 after the age of 50. It is obvious that fuzzy logic resembles human reasoning.

Fuzzy predicates can be used to form compound statements (logical and, logical or, etc.). Let p and q be predicates characterized with sets P and Q. The following (compound) statements can be defined:

- Conjunction (logical and): $p \wedge q \;\Rightarrow\; P \cap Q$
- Disjunction (logical or): $p \vee q \;\Rightarrow\; P \cup Q$
- Negation: $\neg p \;\Rightarrow\; \overline{P}$
- Equivalence: $p \Leftrightarrow q \;\Rightarrow\; P = Q$
- Implication: $p \Rightarrow q \;\Rightarrow\; \overline{P} \cup Q$

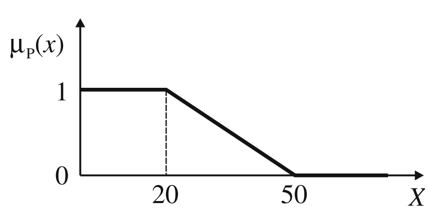


Fig. 9 Characteristic function of the soft predicate "*An x-year old person is young*"

Table 1 The truth table for implication

p	q	$p \Rightarrow q$
t	t	t
t	f	f
f	t	t
f	f	t

The last one is especially important for fuzzy logic-based control applications. The truth table for implication is shown in Table 1. Implication is false (f) only when the statement p is true (t) and the statement q false (f). If the sets P and Q are subsets of the same universal set, implication can be characterized by a Venn diagram as shown in Fig. 10. A compound statement called modus ponens is defined as

$$p \wedge (p \Rightarrow q) \Rightarrow q \tag{13}$$

As the statement is true for any combination of statements p and q, it is a tautology. It is often applied for control related purposes (Table 2).

3.2 The application of fuzzy logic

In control applications, a modified modus ponens rule is usually used.

$$p' \wedge (p \Rightarrow q) \Rightarrow q' \tag{14}$$

It is used when input p' is not exactly the same as the premise p. Using fuzzy sets, this rule corresponds to

$$Q' = P' \cap (\overline{P} \cup Q) \tag{15}$$

The implication $P \cap Q$ is usually used instead of $\overline{P} \cup Q$. The main reason for this modification is the fact that we want to exclude the implication of the type "If water level is not too high, close the valve". In mathematical sense, this implication is correct, but it does not make sense in control-related applications. The characteristic function of a fuzzy set Q' can therefore be defined in the following way

$$\mu_{Q'}(y) = \max_{x \in X}\left(\min(\mu_{P'}(x), \mu_{P \cap Q}(x, y))\right)$$
$$= \max_{x \in X}\left(\min(\mu_{P'}(x), \mu_P(x), \mu_Q(y))\right)$$

Fig. 10 Implication in Venn diagram

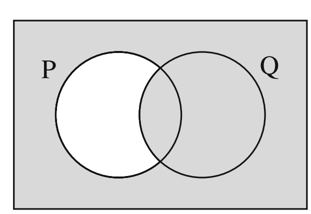


Table 2 Modus ponens

p	q	$p \Rightarrow q$	$p \wedge (p \Rightarrow q)$	$p \wedge (p \Rightarrow q) \Rightarrow q$
t	t	t	t	t
t	f	f	f	t
f	t	t	f	t
f	f	t	f	t

If the equality

$$\min(\mu_{P'}(x), \mu_P(x), \mu_Q(y))$$
$$= \min\left(\min_{x \in X}(\mu_{P'}(x), \mu_P(x)), \mu_Q(y)\right)$$

is taken into account, we get the following result

$$\mu_{Q'}(y) = \max_{x \in X}\left(\min(\mu_{P' \cap P}(x), \mu_Q(y))\right) \tag{16}$$

If the input is crisp value a, which is usually the case, we define the input P' as

$$\mu_{P'}(y) = \begin{cases} 1; & y = a \\ 0; & y \neq a \end{cases} \tag{17}$$

After the characteristic function of the set Q' is calculated, we must determine the output of the controller. Fuzzy set is namely inappropriate for that purpose. This process is called defuzzification. For that purpose, we usually calculate the center of gravity according to the following equation [30]:

$$T = \frac{\int_Y \mu_{Q'}(y) \cdot y \, dy}{\int_Y \mu_{Q'}(y) \, dy} \tag{18}$$

4 Results

In our case, the following rules were applied:

- If resistance increases and displacement decreases and force increases than expulsion yes
- If resistance decreases or displacement increases or force decreases than expulsion no

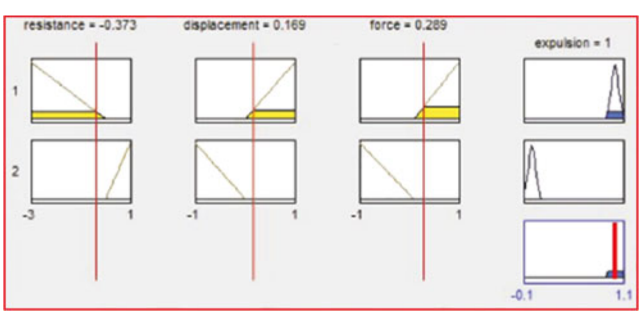


Fig. 11 An expulsion sample

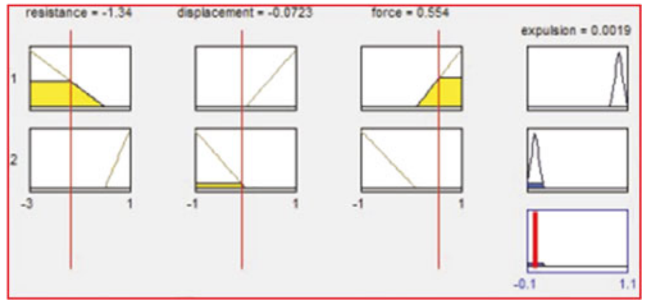


Fig. 12 A nonexpulsion sample

The characteristic functions for increase or decrease were selected so that the border between them is a small positive value (around 10% of a typical expulsion values). This must be done in order to reject samples where resistance increases, displacement decreases, and force increases but expulsion nevertheless does not occur. Such samples, however, do randomly occur. The characteristic functions for expulsion variable were named yes and no and are shown in Figs. 11 and 12.

The shape of the characteristic functions are such that if expulsion occurs, an output close to 1 is expected, and if there is no expulsion, an output close to 0 is expected. Figure 11 is a case where expulsion occurs because resistance increases, displacement decreases, and force increases sufficiently enough. Figure 12 is a case where all three signals decrease. In that case, the second rule is applied and the result is no expulsion.

This type of fuzzy-logic based algorithm can be applied in an on–off type measurement-based feedback control system [1]. The welding process goes on while

Fig. 13 A specimen welded without the application of the fuzzy controller (*left*) and a specimen welded with application of the fuzzy controller (*right*)

the fuzzy controller output is equal to 0. As soon as the output is changed to 1, the welding is stopped. There is no additional input of energy into the weld region, and the temperature does not increase anymore. The electrodes are spared and their life is extended accordingly. The comparison between a weld without this type of control and a weld with it is shown in Figs. 12 and 13.

If the specimens are compared, it can be seen that the indentation of the specimen on the left (the one welded without the application of the fuzzy controller) is much larger because the welding did not stop, when the expulsion occurred. Specimen on the right was welded with the same parameters, but when the expulsion occurred, the welding process was stopped. Therefore, the indentation is smaller. Beside that, the temperature of the electrodes does not increase further, and consequently, the electrode life is increased. This algorithm was successfully tested on all the samples of four materials mentioned earlier (52 samples in total).

5 Conclusion

A fuzzy logic-based expulsion detection system is less cumbersome to program than neural network based one. Beside that, no training is needed. Fuzzy logic-based system can also be extremely fast because a lookup table can be formed based on the fuzzy inference and a correct output is obtained immediately. Consequently, it can easily be applied in real-time environment. If other materials are used (aluminum for example) and the welding process cannot be successfully controlled using only the signals presented in this paper, other signals can be added and their behavior during expulsion should be observed. The rules can than be easily modified to incorporate this signal as well. In this way, the set of materials, where expulsion can be detected, is enlarged.

The proposed algorithm is capable of significantly reducing the thermal stress on the electrodes because the welding process is stopped if/when expulsion occurs. Due to this fact, the electrode life is prolonged. The applicability of the proposed algorithm depends on the number of signals needed in order to detect expulsion. In mild steel case where only dynamic resistance is needed, there are almost no additional costs because it is easy to measure welding voltage and welding current. If the welding force and the electrode displacement signal are needed as well, there is additional cost due to sensory equipment needed to measure these two signals.

In our research, we were limited with the capabilities of the AC welding source. The energy was delivered in packages (half-periods of net voltage) so there was no continuous measurement of dynamic resistance. This is possible if a more modern DC welding source is used. Such a source also makes it possible to control the welding process with much higher frequency. In future, it would therefore be interesting to research the applicability of the proposed algorithm for expulsion prediction, when DC welding sources are used.

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