A SEQUENTIAL PROBABILITY RATIO TEST METHOD FOR QUALITY MONITORING IN ROBOTISED GMA WELDING

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ABSTRACT

This paper deals with the problem of automatic monitoring the weld quality when welding with Gas Metal Arc (GMA) in short circuiting mode. Experiments with two different types of T-joints are performed in order to provoke optimal and non-optimal welding conditions. During the experiments, voltage and current are measured from the welding process. A simple statistical change detection algorithm for the weld quality, the repeated Sequential Probability Ratio Test (SPRT), is used. The algorithm can equivalently be viewed as a cumulative sum (CUSUM)-type test. The test statistics is based upon the fluctuations of amplitude in the weld voltage. It is shown that the fluctuations of the weld voltage amplitude decreases when the welding process is not operating under optimal condition. The results obtained from the experiments indicate that it is possible to detect changes in the weld quality automatically and on-line.

NOMENCLATURE

\textbf{CUSUM} : Cumulative sum  
\( g_k \) : Decision function  
\textbf{GMA} : Gas metal arc  
\( h \) : Threshold for alarm  
\( i, j, k, l \) : Integers  
\( K(\mu_1, \mu_0) \) : Kullback information  
\( N(0, 1) \) : Normal distribution function  
\( N \) : Number of samples in each section  
\( p_0(y_i) \) : Probability density function  
\( s_i \) : Increment of \( S_j \)  
\( S_j \) : Log-likelihood ratio for observation from \( y_i \) until \( y_j \)  
\textbf{SPRT} : Sequential probability ratio test  
\( t_a \) : Alarm instant  
\( Y_i \) : AC power of the weld voltage

\( Y \) : Vector of AC powers  
\( v_i \) : Weld voltage at the sampling instant  
\( \bar{v} \) : The mean of the weld voltage  
\( \alpha \) : False alarm probability  
\( \theta_0 \) : Parameter before change  
\( \theta_1 \) : Parameter after change  
\( \mu_0 \) : Mean value of the AC power of the weld voltage during optimal condition  
\( \mu_1 \) : Mean value of the AC power of the weld voltage during non optimal condition  
\( \nu \) : Change magnitude  
\( \sigma^2 \) : Variance of the AC power \( y_i \)  
\( \tau \) : Mean delay for detection

1 INTRODUCTION

The Gas Metal Arc (GMA) welding is widely used for automatic or robotic welding applications due to specific advantages such as reduced spatter and smooth bead appearance. There are two stable metal transfer modes in GMA welding; short circuiting metal transfer at low arc voltage and spray metal transfer at high voltage. One cycle of welding voltage waveform corresponds to transferring a molten droplet in short circuiting transfer mode. Hence it is possible to evaluate the stability or regularity of metal transfer from welding voltage measured during the welding process.

In order to assess process stability, calculation of standard deviation and different ratios or indices of suitable weld parameters such as, arc and short circuiting time, short circuit current, mean weld voltage and current etc. are common suggested methods in published works in this field \cite{1, 2, 3, 4, 5, 6}.

Monitoring systems of weld parameters, such as ADM III, Arc guard, and Weldcheck are commercially available \cite{7, 8}. They all work in a similar way; voltage, current and other process signals are measured, presented and compared with preset nominal values. An alarm is triggered when a difference from preset values

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exceeds a given threshold. The performance of ADM III, Arc guard, and Weldcheck has not, however, been well documented to the authors’ knowledge.

Experiments have shown that optimal stability occurs when the number of short circuits per seconds are at their maximum [9, 10]. Deviation from the optimal condition leads to a larger probability of spatter, uneven weld bed and other fusion defects. In this case the welding process is said to operate under non-optimal condition.

Thus, a suitable parameter for detection of changes in the weld quality, is the variance of the amplitude of the weld voltage. This parameter is used to form a test statistics which is fed into a repeated Sequential Probability Ratio Test (SPRT) algorithm [11]. The algorithm may equivalently be viewed as a cumulative sum (CUSUM) type test. The SPRT is optimal in the sense that it minimizes the worst mean delay for detection given a specified probability of false alarm [12]. In addition, storage and computational requirements for the repeated SPRT are less as compared to fixed sample-size tests.

2 EXPERIMENTS

2.1 Instrumentation

The experimental setup is made up of a welding power source, a Motoman robot carrying a welding torch, a positioner, a welding table and instrumentation for recording weld voltage and current, see figure 2. The welding torch is fixed in at angle of 45 degrees to the welding table and the lead angle is 0 degrees. The distance between the contact tube tip and the plate is 11 mm.

The weld voltage is measured between an electrode applied to the contact tube and a reference electrode screwed into an aluminum plate which serves as an insulated welding table [13]. The current is measured with a current sensor, LEM Module LT 500-S, equipped with a transformer. The sensor is mounted around the return conductor. The sampling frequency is 8.192 kHz, and the resulting lowpass filter has a cut frequency of 1.0 kHz. The data are transferred for permanent storage on a personal computer.

Two different commercial welding equipments, Migatronic BDH S50 and Kemppi P500, were used for the experiments. The wire feed rate was measured to be approximately 113 - 120 mm/s and the nominal welding speed was set at 10 mm/s. The filler wire material used in the experiment was ESAB OK 12.51 with a diameter of 1.0 mm. The shielding gas used was Atal: 80%Ar/20%CO₂. The flow rate of shielding gas was set at 15 l/min.

![Figure 1: A schematic illustration of the weld voltage and current in short-circuiting welding.](image1.png)

The metal transfers are reflected in the weld voltage as almost zero voltage events, denoted short-circuit time. The time between the short-circuit instants is denoted short arc time.

The paper is organized as follows. Section 2 describes some experiments. Changes in the weld quality is provoked in weldings in a controlled manner while the weld voltage and current from this process are monitored. Some changes of the the variance of the amplitude of the weld voltage during a welding pass are observed. Section 3 deals with the design of the repeated SPRT algorithm. The section concludes by showing how the algorithms are used to detect defects in the weld joint. Section 4 deals with tuning and estimation of parameters used in the algorithm. Robustness of the proposed algorithm is also considered. The repeated SPRT is then evaluated using experimental data. The paper concludes with a discussion of the performance of the method in section 5.

![Figure 3: Steel T-joints provoking defects in weld joints. a) Reference T-joint, front view b) Reference T-joint, side view c) T-joint with step disturbance, front view](image3.png)
2.2 Test Specimens

The aim of the experiments is to provoke non-optimal welding conditions in a controlled manner while monitoring the weld voltage and current from the process. Non-optimal welding conditions were provoked using a T-joint where gaps have been cut out in the standing plate, see figure 3 part c. This specimen is denoted a 'T-joint with step disturbance.' During the step disturbance, the welding process is assumed to operate under non-optimal conditions. A second specimen shown in parts a and b is a T-joint with the standing plate in perfect contact with the laying plate. This specimen was used to produce normal or reference weldings and is thus denoted a 'reference T-joint.' During normal welding, the welding process is assumed to operate under optimal welding conditions. The specimens comprised of two rectangular 200 x 10 x 3 mm plates of mild steel SS 1312. For the T-joint with step disturbance, the dimension of the gap was 2 x 50 mm. See figure 3 part c.

2.3 Observations

Typical recordings of the weld voltage and current are shown in figure 4. Parts a and b show the results of a normal weld; and parts c and d show the result of a welding during step disturbance.

In order to obtain an uniform weld quality the welding process must be stable. To achieve a stable welding process, it is necessary to balance the melting rate of the wire with the wire feed speed. When the melting rate of the electrode and the metal transfer from the electrode wire to the work piece occur at regular intervals, the probability of stable weld process is increased. The metal transfers are reflected in the weld voltage as almost zero voltage events of 2 ms in figure 4 part a and part c. The almost zero voltage event is denoted short-circuit time. The time between the short-circuit instants is denoted short arc time.

Experiments have shown that optimum stability occurs when the number of short circuits per second are at their maximum given that the short circuit time exceeds 1 ms. This fact is often used by human welders to identify the behavior of the arc by listening to the frequency of the sound emitted by the arc. When the short circuit time is less than 1 ms, the amount of spatter will increase.

2.4 Test Parameter

The variance of the amplitude of the weld voltage might be a suitable parameter for detection of changes in the weld quality. When the variance of the weld voltage is larger than the variance during normal conditions spatter has occurred. When the variance of the weld voltage is less than the variance during normal conditions the number of short circuits per second are not at their maximum, indicating that the welding process is disturbed. To avoid confusion of ideas the variance of the amplitude of the weld voltage is in the sequel denoted AC power.

The weld voltage is divided into k sections, with N = 1024 samples in each section. The AC power is calculated for each section and is given an index, i, defined by the position in the sequence. The AC power is estimated as follows:

\[ y_i = \frac{1}{N-1} \sum_{t=1}^{N} (v_t - \bar{v})^2 \]  

where \( v_t \) is the weld voltage, \( N \) is the number of data points and \( \bar{v} \) is the mean of weld voltage calculated as

\[ \bar{v} = \frac{1}{N} \sum_{t=1}^{N} v_t \]  

The estimated AC power is shown in figure 6 part b. Note the decrease in mean of the AC power estimate \( y_i \) during step disturbance, indicating non-optimal stability. The sequence \( y = (y_0, y_1, \ldots, y_k) \) is assumed to be
Figure 4: Weld voltage and current. Normal weld: a) Measured voltage and b) measured current. During step disturbance: c) Measured voltage and d) measured current.

independent and Gaussian distributed with mean value \( \mu \) and constant variance \( \sigma^2 \).

3 FAULT DETECTION ALGORITHM

Let \( y = (y_0, y_1, \ldots, y_k) \) denote a random sample of scalar random variables of AC power, each of which is Gaussian distributed:

\[
p_g(y_i) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(y_i - \mu)^2}{2\sigma^2}} \quad (3)
\]

The welding process is known to operate under either optimal \( (\theta = \mu_0) \) or non-optimal \( (\theta = \mu_1) \) conditions where \( \mu_0 > \mu_1 \). Furthermore, we assume that prior to \( t = 0 \), \( \theta = \mu_0 \) and it may only change to \( \theta = \mu_1 \) at one of the \( n \) sampling instants. Consider the problem of testing \( k + 1 \) hypotheses \( H_0, H_1, \ldots, H_k \):

\[
H_0: \theta = \mu_0 \quad \text{for} \quad 1 \leq i \leq k
\]

\[
H_j: \theta = \mu_0 \quad \text{for} \quad 1 \leq i \leq j - 1 \quad \text{and} \quad \theta = \mu_1 \quad \text{for} \quad j \leq i \leq k \quad (4)
\]

If the instant of change \( j \) is fixed, then the Sequential Probability Ratio Test (SPRT) between \( H_0 \) and \( H_j \) is based on a comparison of the likelihood ratio [11]:

\[
S_j^k = \sum_{i=j}^k s_i \quad (5)
\]

where

\[
s_i = \ln \frac{p_{\mu_1}(y_i)}{p_{\mu_0}(y_i)} \quad (6)
\]

to a threshold \( h \). At the sampling instant \( k \), \( S_j^k \) is computed. If \( S_j^k \geq h \), a defect in the weld joint is detected. In the scalar independent case \( S_j^k \) is repeatedly updated as:

\[
S_{j+1}^k = S_j^k + s_i \quad (7)
\]

In the case of a change in the mean value \( \mu \) of an independent Gaussian random sequence \( y_k \) with known variance \( \sigma^2 \), the sufficient statistics \( s_i \) is calculated as

\[
s_i = \frac{\mu_0 - \mu_1}{\sigma^2} (\mu_0 + \mu_1 - 2y_i) \quad (8)
\]

which we write as

\[
s_i = \frac{\nu}{\sigma^2} (\mu_0 - y_i - \frac{\nu}{2}) \quad (9)
\]

where

\[
\nu = |\mu_0 - \mu_1| \quad (10)
\]

is the change in magnitude. The SPRT is optimal with respect to the worst mean delay, when the error probability for false alarms goes to zero. The instant of change \( j \) is in fact unknown, but may be estimated using the maximum likelihood principle [14], leading to the decision function and alarm instant:

\[
g_k = \max_{0 \leq j \leq k} S_j^k \quad (11)
\]

\[
t_a = \min \{k : g_k \geq h\} \quad (12)
\]

The algorithm has been formulated as a set of parallel SPRT’s, but may equivalently be viewed as repeated SPRT or a CUSUM - type test. The connection between these alternative points of view has been investigated by [11]. The decision function \( g_k \) introduced in 11 becomes in repeated SPRT formulation

\[
S_k = [g_{k-1} + s_i]^+ \quad (13)
\]

and in the Gaussian case

\[
S_k = [S_k+ \frac{\nu}{\sigma^2} (\mu_0 - y_i - \frac{\nu}{2})]^+ \quad (14)
\]
where \((x)^+ = \sup(0,x)\). The alarm threshold \(h\) is chosen by a tradeoff between worst mean delay for detection, \(\tau\) and false alarm probability \(\alpha\). The CUSUM algorithm is optimal when \(\alpha\) goes to zero [12]:

\[
\tau \sim \frac{\ln \alpha^{-1}}{K(\mu_1, \mu_0)} \text{ when } \alpha \to 0
\]

(15)

where

\[
K(\mu_1, \mu_0) = E_{\mu_1} \ln \frac{p_{\mu_1}(y_i)}{p_{\mu_0}(y_i)}
\]

(16)

is the Kullback information. In Gaussian case the Kullback information is

\[
K(\mu_1, \mu_0) = \frac{(\mu_1 - \mu_0)^2}{\sigma^2}
\]

(17)

Due to Wald’s inequality the alarm threshold satisfies

\[
\alpha = e^{-h}
\]

(18)

and thus the alarm threshold is easy to obtain [15]. The complete fault detection algorithm may be summarized as follows:

**Algorithm:** For each section \(k\) of 1024 data samples:

1. calculate AC power \(y_i\)
2. calculate \(g_k = [g_{k-1} + s_i]\)
3. if \(g_k \leq 0\) then \(g_k = 0\)
4. if \(g_k \geq h\) then set Alarm

### 4 EVALUATION AND TUNING

#### 4.1 Evaluation

In order to evaluate the proposed detector, two batches, each of 180 samples of the parameter \(y_i\), originating from weld voltages from normal welds and welds during step disturbance respectively, were used, see figure 5. A sample length of 184 and welding speed at 10 mm/s corresponds approximately to a 20 cm weld joint.

The estimated AC power of the weld voltage \(y_i\) is assumed to be independent, Gaussian distributed with mean value \(\mu_0\) and \(\mu_1\) under normal and fault condition respectively. The variance \(\sigma\) is assumed to be constant under all conditions. For each batch of data, mean and variance are estimated, see table 4.1.

<table>
<thead>
<tr>
<th>Index (i)</th>
<th>(y_i)</th>
<th>(\bar{y}_i)</th>
<th>(s_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1, 10, 20)</td>
<td>(y_i)</td>
<td>(\bar{y}_i)</td>
<td>(s_i)</td>
</tr>
</tbody>
</table>

![Graph](image)

Figure 5: The AC power \(y_i\) during normal weld. The AC power \(y_i\) during step disturbance. The AC power \(y_i\) is based on 1024 samples of the weld voltage.

\(\chi^2\) tests shows that the AC power \(y_i\) under fault condition, in contrast to normal conditions, is neither independent nor Gaussian. Furthermore, the variance is not equal under both conditions, see table 1. The algorithm is still chosen, because the algorithm is robust with respect to independent as well as demand for equal variance [16, 17]. In addition, storage and computational requirements for the repeated SPRT are moderate.

#### 4.2 Tuning

In the proposed algorithm the only tuning parameter is the threshold \(h\). Using formula 15 we can compute worst mean delay for detection, \(\tau\) and false alarm probability \(\alpha\) and use these for choosing a relevant alarm threshold, \(h\). When the false alarm probability \(\alpha\) is chosen to \(10^{-9}\), the alarm threshold \(h\) is calculated to be \(h = 21\). However, since \(y_i\) under fault conditions is correlated and can not be assumed Gaussian and since we assume \(\sigma^2 = 6.76\), the alarm threshold \(h\) is set conservatively. Thus, in order to maintain the false alarm probability, \(\alpha > 10^{-9}\) the alarm threshold, \(h\) is set at 25.

<table>
<thead>
<tr>
<th>Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>(h) alarm threshold</td>
</tr>
<tr>
<td>(\alpha) false alarm probability</td>
</tr>
<tr>
<td>(\sigma^2) variance</td>
</tr>
<tr>
<td>(\mu_0) mean during normal condition</td>
</tr>
<tr>
<td>(\mu_1) mean during non optimal condition</td>
</tr>
<tr>
<td>(\nu) magnitude of change</td>
</tr>
</tbody>
</table>

Table 2: Design parameters selected for the fault detection algorithm. The welding speed is set at 10 m/s.

![Table](image)
5 RESULTS AND CONCLUDING REMARKS

5.1 Test of the SPRT algorithm

The repeated SPRT algorithm was tested on 31 specimens. A total of 15 experiments were conducted for reference T-joint and sixteen experiments were conducted for the T-joint with step disturbance. The recording time of the measured signals was 15 s.

The test was designed as follows: When the alarm turns on and there is a step disturbance, the test results in a detection; and when the alarm does not turn on, there is a nondetection. If the alarm turns on and there is no step disturbance, the result is a false alarm.

5.2 Results

The results of the test are shown in table 2. Typical behavior for a T-joint with a step disturbance, is shown in figure 6. The top diagram of the figure, part a, shows the weld voltage, and part b shows the weld current. Part c shows the corresponding AC power $y_i$ and the actual position of the step disturbance along the weld joint. Part d of the figure shows the decision function $g_i$ and the Alarm.

<table>
<thead>
<tr>
<th>Type of T-joint</th>
<th>Reference Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of specimens</td>
<td>15</td>
</tr>
<tr>
<td>Detection</td>
<td>15</td>
</tr>
<tr>
<td>Nondetection</td>
<td>0</td>
</tr>
<tr>
<td>False Alarm</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3: The experimental results of the test of the SPRT algorithm. The magnitude of change, $\nu$, is set at 9.2 and the welding speed is set at $= 10$ m/s.

<table>
<thead>
<tr>
<th>Type of T-joint</th>
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<tr>
<td>Nondetection</td>
<td>0</td>
</tr>
<tr>
<td>False Alarm</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4: The experimental results of the test of the SPRT algorithm. The magnitude of change, $\nu$, is set at 2.63 and the welding speed is set at $= 10$ m/s.

Figure 6: Illustration of the detection of step disturbance: Measured weld voltage and current are shown in part a and b respectively. The corresponding AC power $y_i$ and the actual position of the step disturbance are shown in part c. The behavior of the decision function $g_i$ and Alarm time is shown in part d. The Alarm time is indicated by a vertical line in the figure. The magnitude of change is set at 9.2 and the welding speed is set at $= 10$ m/s.

5.3 Concluding Remarks

All the experiments have shown consistent results: During the step disturbance the AC power of the weld voltage decreases. The proposed SPRT algorithm is designed to detect these sudden jumps in the average level of the AC power. Four of the step disturbances, however, were not detected when the change magnitude, $\nu$, was set at 9.2. As the minimum value for which the SPRT algorithm can detect is $\mu_0 - \nu/2$ and as the AC power value also during step disturbance are above this critical value the Alarm is not triggered. Therefore, in order to enhance the performance of the algorithm the change magnitude $\nu$ should be set to a lower magnitude of change than 9.2. The limit case is $\nu = 0$, but it is known that SPRT algorithm detects a magnitude change between $1/2 \sigma$ and $1 \frac{1}{2} \sigma$ from the target value, $\mu_0$, much more quickly than for example a Shewhart chart. Only one of the step disturbances was not detected when $\nu$ was set at 2.63, see Table 4.

References


