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ORIGINAL ARTICLE

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Quantity analysis for welding performance in manufacturing processes

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Abstract Welded bond quality is a very important working aspect for the manufacturing and construction industries. A product is affected by quality of welding. A set of evaluation methods for welding operators is proposed in this paper, based on a theoretical analysis, to assure the quality of product. A new index using a categorical quantity expression to evaluate the welding performance is proposed. The mathematical relationship of welding performance, number of bad welds and the maximum tolerable number of bad welds are derived. Then, the best estimators and the deviations of this index are statistically inferred. Finally, a procedure and criteria are proposed to evaluate the performance of a welding operator. This evaluation method can be used in decision-making for the selection of a welding operator. Besides, it can also be used as an analytical tool to evaluate and improve the welding ability of a welding technician and the welding performance of a welding operator.

Keywords Index of welding performance · Evaluation procedure · Best estimator

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1 Introduction

Welded bonding is connected to the boundary of the material in order to economize the use of material, keep the rigidity of the steel and maintain a good appearance of the material in the process of manufacturing of boats, cars, motorcycles, machinery equipment and steel structures etc. Presently, automatic welding machines are generally used for welding in manufacturing industry. Nevertheless, working conditions preclude their use in some parts of manufacturing and construction engineering, and so man-made welding must be used to make the welds. A good welding skill is required to reach the required standard. Otherwise, welding defects are induced by improper operations, bad maintenance and lack of skill of welding operators. Electric fusion welding is a widely used welding method that uses welding a rod as an electrode flux to from a 1,500°C electric arc flux from the tip of the welding rod and solder. This high temperature causes the welding rod and solder to be melted together at the weld point. Because of bad welding techniques, and inappropriate welding procedures and sequences, flaws occur in the welds, such as: at welding seams, edges of welds under cut, insufficient fusion, inadequate depth of welding, welds containing impurities and air bubbles, insufficient cross-section, unsatisfactory welding shape, welding overlap and distortion. These defects bring stress concentration, lack of strength and residual stress that affect the quality of the product tremendously. Therefore, the welding procedure should be checked particularly carefully to achieve a high quality and safe product.

Control charts of P and Pn [1, 2] are drawn based on a batch or daily check, to check whether the welding performance meets the requirement or not. These control charts use the principle of statistics to put these inspected values in an exact order to find the reasons for extraordinary unsatisfactory welds. According to the variations of the processes of manufacturing and construction and the sampling error, the weld defects can be detected and handled based on the principle of statistics to maintain the specified quality of the product. The quality requirement closely links to the welding performance of the welding operator and welding techniques of welding technician. Consequently, the purpose of this research is to develop a set of evaluation methods for assessing the theoretical welding performance. This systematic procedure assists the manufacturer to judge the performance of an automatic welding operator and select a superior welding technician.

The proposed evaluation method of performance is based on Marr [3] who has described a method evaluation performance to analyse the efficiency and effectiveness of welding assignments. Chow et al [4] proposed that the important service items must be established to evaluate the service performance. Tucker [5] discussed the innate character and defects of each index of the major research methods and their achievements. The other related researches refer to references [3, 6, 7, 8, 9, 10]. Charnes et al [11] showed that a representative of important evaluation items could be used to choose a suitable analysis method. A systematic and practical evaluation method for welding performance contributes to the control and management of the quality and performance of a weld. Therefore, a set of evaluation methods is proposed in this paper to judge the performance of a welding operator and a welding technician. There are two parts in this method: (1) the definition of an index of welding performance and (2) an evaluation procedure and criteria. This research proposes a new framework of indices of welding performance with explicit quantity expressions to calculate this index. It represents the relationship of welding performance, to the number of unqualified points of a weld and the maximum tolerable number of unqualified points of a weld. Then a set of inspection procedures is proposed to examine the welding performance of a welding operator and a welding technician, which is the basis of a procedure substantial theory.

2 Index of welding performance and measurement

Currently, welding bond is the most effective method and satisfactory method to connect material, but the quality of welding is affected by the welding operator and welding technician, which influences the quality of the product. An explicit quantitative expression to evaluate the performance of a welding operator and a technician based on an unsatisfactory welding ratio is described in this paper. The merit of this ratio is that it expresses a relative relationship that avoids the deviations induced by various numbers of inspections. In accordance with the definition of the unsatisfactory welding ratio, a lower unsatisfactory welding ratio indicates a better welding performance and vice versa.

The unsatisfactory welding ratio (p) is the ratio of the number of unqualified welds and number inspections. The definition of this ratio shows as follows:

$$p = \frac{NU}{NI} \tag{1}$$

Where:
NU number of unqualified welding;
NI number of inspections.

Generally, the unsatisfactory welding ratio belongs to a quality property of an attribute. Therefore, a Bernoulli distribution is applied to describe the welding performance of a welding operator and welding techniques. For example, let $X=1$ represents a poor performance of a welding operator and techniques. And when, $X=0$ the performance of a welding operator and welding techniques approaches perfect. Therefore, the random variable obeys the Bernoulli distribution of parameter of p. That is $Pr(X=1)=p$ and $Pr(X=0)=1-p$.

As a result, the lower the unsatisfactory welding ratio the better is the welding performance and the reliability of the welding operator and technicians. To reduce the unsatisfactory welding ratio, the upper limit of the unsatisfactory welding ratio, which is the minimum requirement of manufacturing, is required of the welding operators and welding technicians.

The upper limit of the unsatisfactory welding ratio should be established to evaluate the welding performance of the welding operator and welding technicians. According to the lower limit of welding performance, required by manufacturing, the index of welding performance can be defined for convenient usage, as follows:

$$S_{pi} = \frac{P_{0i} - P_i}{P_{0i}}, i = 1, 2, \cdots, k \tag{2}$$

Where:
P_{0i} the upper limit of the unsatisfactory welding ratio, for the i production line by manufacturing;
P_i is the required unsatisfactory welding ratio for welding operator on the i production line.

From Eq. 2, when the unsatisfactory welding ratio is less than the lower limit of welding performance ($P_i < P_{0i}$), then $S_{pi} > 0$ and the smaller is the unsatisfactory welding ratio the larger is the index of welding performance. When the unsatisfactory welding ratio is larger than the upper limit of welding performance ($P_i > P_{0i}$), then, $S_{pi} < 0$. Therefore, when the index of welding performance is larger than 0, it shows that the welding performance meets the requirement. Contrarily, when the index of welding performance is less than 0, it indicates that the welding performance does not reach the specific requirement. The maximum value of welding performance is 1 and the associated unsatisfactory welding ratio is 0. The welding performance is perfect in this circumstance.

3 Estimator for index of welding performance

According to various numbers of inspections for different production lines, the population of unsatisfactory welding ratio is an unknown parameter and it can be estimated from sampling. The unsatisfactory welding ratio P_i of a welding operator i for each production line should be obtained to evaluate the index of welding performance. In accordance with various numbers of inspections for each batch from the different production lines, the random variable X_{ijh} represents hth inspection of the jth batch of ith welding operator. Where $i = 1, 2,..., k$, that is, there are k production lines; $j = 1, 2,..., m$, that is, there are m suites for each inspection; $h = 1, 2..., n_{ij}$, that is, the number of inspections n_{ij} of jth batch of ith welding operator. Let $X_{ijh} = 1$, represent that hth inspection of jth batch of the ith welding operator fails. When, $X_{ijh} = 0$, it means that the quality of the hth inspection of the jth batch of the ith welding operator is superior. The random variable X_{ijh} obeys the Bernoulli distribution with the parameter P_i. Consequently, the mean value $\bar{p}_i = \frac{D_i}{n_i}$, evaluated from the sampling of the unsatisfactory welding ratio is used to estimate P_i. Where $n_i = \sum_{j=1}^{m} n_{ij}$ indicates the total number of inspections of m batches of samples for the ith welding operator. $D_i = \sum_{j=1}^{m} D_{ij}$ expresses the total number of unqualified inspections of m batches of samples for the ith welding operator. $\hat{p}_{ij} = \frac{D_{ij}}{n_{ij}}$ represents the total unsatisfactory welding ratio of the jth batches of samples for the ith welding operator. According to the above-mentioned method, the inspected samples for the mth batches of samples for the ith welding operator are put in order, as listed in Table 1.

Thus, the natural estimator of S_{pi}, which is shown as follows, can be derived based on Table 1.

$$\hat{S}_{pi} = \frac{p_{0i} - \bar{p}_i}{p_{0i}}, i = 1, 2, \cdots, k \tag{3}$$

The average unsatisfactory welding ratio $\bar{p}_i$ is the uniformly minimum variance of the unbiased estimator ($UMVUE$) for p_i under the assumption of Bernoulli distribution. $UMVUE$, is the minimum variation of all the unbiased estimators.

$\hat{S}_{pi}$ is the unbiased estimator of S_{pi} (that is $E[\hat{S}_{pi}] = S_{pi}$. Actually, $\hat{S}_{pi}$ is a function of the adequate complete statistic $\bar{p}_i$. Therefore, $\hat{S}_{pi}$ is the best estimator of S_{pi}. Thus, the variation of the best estimator $\hat{S}_{pi}$ can be derived as follows:

$$Var(\hat{S}_{pi}) = \frac{(1 - S_{pi})[1 - p_{0i}(1 - S_{pi})]}{n_i p_{0i}} \tag{4}$$

4 Test of the index of welding performance

When the index of welding performance $\hat{S}_{pi}$ is larger, then the value of P_i is smaller. That is, a lower unsatisfactory welding ratio shows a better performance of the welding operator. Assuming the required performance for ith welding operator, it must be greater than C_i $(0 < C_i < 1)$. The hypothesis testing from reference [12], is shown as follows:

H_0: $S_{pi} \le C_i$; (welding performance is poor)
H_a: $S_{pi} > C_i$; (welding performance is fine)

Assuming the significance level is α, then the testing rule (rejecting region) is $\{\hat{S}_{pi} | \hat{S}_{pi} \geqslant C_{0i}\}$. Where C_{0i} is the critical value, which can be determined by the following equation.

$$P(\hat{S}_{pi} \geqslant C_{0i} | S_{pi} = C_i) = \alpha \tag{5}$$

According to $E[\hat{S}_{pi}] = S_{pi}$ and $Var(\hat{S}_{pi}) = \frac{(1-S_{pi})[1-p_{0i}(1-S_{pi})]}{n_i p_{0i}}$, thus let

$$Z = \frac{\sqrt{n_i p_{0i}}(\hat{S}_{pi} - C_i)}{\sqrt{(1 - C_i)[1 - p_{0i}(1 - C_i)]}} \tag{6}$$

In accordance with the central limit theorem, the random variable Z approaches a standard normal distribution when the sample size is large enough. Equation 4 can then be expressed as follows:

$$P\left(Z \geqslant \frac{\sqrt{n_i p_{0i}}(C_{0i} - C_i)}{\sqrt{(1 - C_i)[1 - p_{0i}(1 - C_i)]}}\right) = \alpha \tag{7}$$

Table 1 The inspected samples for mth batches of samples for the ith welding operator

Inspected samples (j)	Number of Sample (n_{ij})	Total unqualified welded bond $D_{ij} = \sum_{h=1}^{n_{ij}} X_{ijh}$	The total unsatisfactory welding ratio $\hat{p}_{ij} = \frac{D_{ij}}{n_{ij}}$
1	n_{i1}	D_{i1}	$\hat{p}_{i1} = \frac{D_{i1}}{n_{i1}}$
2	n_{i2}	D_{i2}	$\hat{p}_{i2} = \frac{D_{i2}}{n_{i2}}$
⋮	⋮	⋮	⋮
j	n_{ij}	D_{ij}	$\hat{p}_{ij} = \frac{D_{ij}}{n_{ij}}$
⋮	⋮	⋮	⋮
m	n_{im}	D_{im}	$\hat{p}_{im} = \frac{D_{im}}{n_{im}}$
Σ	$n_i = \sum_{j=1}^{m} n_{ij}$	$D_i = \sum_{j=1}^{m} D_{ij}$	$\bar{p}_i = \frac{D_i}{n_i}$

According to Eq. 6, the value of C_{0i} can be expressed as follows:

$$C_{0i} = C_i + Z_\alpha \sqrt{\frac{(1-C_i)[1-p_{0i}(1-C_i)]}{n_i p_{0i}}}. \quad (8)$$

Where: Z_α is upper αth quantile of a standard normal distribution, that is $P(Z > Z_\alpha) = \alpha$.

In order to conveniently apply this in practice, a set of test of procedures is developed as follows:

1. Determine the value of C_i, that is, the basic required performance of the welding operator and welding technicians. Determine the significance level α, generally α is equal to 0.05 or 0.01.
2. Determine m suites of sample size and calculate the total number of sample sizes $n_i = \sum_{j=1}^{m} n_{ij}$.
3. Calculate the estimation of the index in accordance with number of sample size n_i and assuming $\hat{S}_{pi} = V_i$.
4. According to Eq. 7, the critical values are calculated based on $\alpha = 0.05$ and $\alpha = 0.01$ assuming $\alpha = 0.05$ the $C_{0i} = C_{Si}$ or $\alpha = 0.01$ the $C_{0i} = C_{Li}$.
5. Judge whether the welding performance meet the requirement or not. Methods of judgment are indicated as follows:
   a) If $C_{Si} \le V_i < C_{Li}$, the welding performance attains the requirement of significance level; if $C_{Li} < V_i$, the welding performance reaches the strictest requirement of significance level.
   b) If $V_i < C_{Si}$, the welding performance does not achieve the required welding performance.

5 Case study

The index of welding performance provides a number to test whether the welding performance of welding operators and welding technicians reach the required technical standard. To illustrate the above-mentioned evaluation method for welding operators and welding technicians, a realistic case study is used to make description of this evaluation procedure. There are three different production lines in an automobile-manufacturing factory. The welding operators of each production line are operated and maintained by various units of technicians. In order to establish the maintenance and quality control capability of these three units, the quality of welds is sampling by selective examinations by the production management unit. Table 2 is the welding inspection record for the three different production lines.

Step 1: The basic requirement of welding performance for the production management unit of the automobile manufacturing factory is $C_i = 0.40$. Then, the significance level of α for $\alpha = 0.05$ and $\alpha = 0.01$, respectively.

Step 2: The sample size of welding bond inspections for various items of spot tests is between 100 and 250. The total numbers of tests are shown in the following table:

	A unit	B unit	C unit
total numbers of welding test	1540	1565	1565

Step 3: Calculate the estimated value of $\hat{S}_{pi}$, shown in the following table:

	The welding inspection record of A unit	The welding inspection record of B unit	The welding inspection record of C unit
$\hat{S}_{pi} = V_i$	0.6753	0.0405	0.0032

Step 4: Calculate the critical value based on $\alpha = 0.05$ and $\alpha = 0.01$.

	The welding inspection record of A unit	The welding inspection record of B unit	The welding inspection record of C unit
C_{Si}	0.486884	0.451443	0.400017
C_{Li}	0.486873	0.450068	0.400017

Table 2 The welding inspection record of A,B,C units of production lines of automobile manufacturing factory

The welding inspection record of A unit		The welding inspection record of B unit		The welding inspection record of C unit	
Number of inspection	Number of unqualified	Number of inspection	Number of unqualified	Number of inspection	Number of unqualified
100	2	150	2	200	9
150	4	100	3	120	8
200	2	150	5	150	5
150	1	200	6	250	10
120	3	120	4	100	5
100	3	120	3	130	7
250	4	115	2	100	6
200	3	250	8	150	9
150	1	210	7	200	11
120	2	150	3	155	8

Step 5: According to the computation data, the welding performance for the A unit is $C_{Li} < V_i$, thus the welding performance reaches the strictest requirement; the welding performance for B unit is $C_{Si} \leq V_i < C_{Li}$, thus, so welding performance attains requirement; the welding performance for C unit is $V_i < C_{Si}$, so, the welding performance does not achieve the requirement. The maintenance and quality control capability for the welding operators of the C unit is insufficient; the technological process should be reviewed or technological re-education to improve the work performance should be undertaken.

6 Conclusion

An outline of this proposed evaluation method uses statistical inference to develop a test procedure and provide an index of welding performance. The advantages of this index are that it can directly calculate and be easily applied to real work. This evaluation method combines theoretical analysis with reality. A suite of a five-step evaluation procedure is proposed to deal with these test problems in accordance with calculation of the proposed evaluation index. This quantification method explicitly appraises the welding performance and judges whether the welding performance meets the production and engineering quality requirement or not.

Statistical inference derives the best estimator. The benefit of this method is that it provides a convenient evaluation procedure for a manufacturing and construction engineering unit to evaluate the welding technology and maintenance capability of welding technicians and operators. In addition, this evaluation procedure helps manufacturing industry to examine the performance of welding operators as well as offering welding technicians an analytical approach to improve welding procedures and quality control capability.

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