Justification of rejection values of defect characteristics in ultrasonic testing of welded joints

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Abstract. Probabilistic models of substantiation of rejection values of the measured characteristics of defects during ultrasonic testing of welded joints using phased antenna arrays that reduce possible test errors are considered. It is shown that the most important for usage are the reliability indicators of non-destructive testing, taking into account the sub-rejection. The recommended application areas for evaluating the reliability D* criteria of ultrasonic testing using alternative and quantitative indicators for selecting rejection values of measured defect characteristics have been determined.

1. Introduction

Most often, non-destructive testing of welded joints is subject to hazardous production facilities [1]. To carry out their control, methodological documentation is needed, including, in particular, rejection indicators that meet certain standards for the admissibility of welding defects. Moreover, the choice of rejection indicators has a significant impact on the reliability of non-destructive testing.

In accordance with GOST (Russian National Standard) 20911-89 “Technical Diagnostics. Terms and definitions” “reliability of technical diagnostics (control of the technical condition) is the degree of objective correspondence of the results of diagnosis (control) to the actual technical condition of the object. With regard to non-destructive testing quantitatively the reliability of the control is calculated as the probability of making error-free decisions when assessing the quality (condition) of controlled object [2–4].

2. Analysis of reliability indicators of non-destructive testing

To determine the reliability indicators of non-destructive testing, the values of possible control errors are estimated: errors of the 1st kind (supplier risk – α, over rejection) and errors of the 2nd type (consumer risk – β, under-rejection). The reliability of the control can be calculated by the formulas [4, 5]:

\[ D_\alpha = 1 - \alpha, \]
\[ D_\beta = 1 - \beta, \]
\[ D_\Sigma = 1 - (\alpha + \beta). \]
Federal rules and regulations “Basic requirements for non-destructive testing of technical devices, buildings and structures at hazardous production facilities”, approved by order of the Federal Service for Environmental, Technological and Nuclear Supervision No. 490 of 21.11.2016, have established that the choice of non-destructive testing technologies and means should be carried out on the basis of the condition for ensuring the detection of unacceptable defects. Thus, the applied indicators of the reliability of control should, first of all, be focused on reducing the values of possible control errors of the 2nd kind. Taking this into account, the indicator \( D_\Sigma \) is of particular interest, which, since under-rejection is more dangerous than over-rejection, protects the interests of the supplier well and not fully the consumer, and \( D_\beta \), which protects only the interests of the consumer [4, 5]. Two types of determination of indicators of reliability are possible: by alternative and quantitative characteristics.

2.1. The choice of rejection values of the characteristics of defects in assessing the reliability of control indicators for an alternative criterion

In assessing the reliability of an alternative criterion, a matrix is used (table 1), comparing the test method with the reference one, which is recommended to open the controlled welds.

**Table 1.** Matrix for assessing the reliability of control by the number of checked items (on an alternative criterion).

| The number of controlled items \( n_\Sigma = n_g + n_n + n_\alpha + n_\beta \) | Reference method (opening) |
|---|---|
| | Fit | Unfit |
| Trial method | Fit | Twice fit \( n_g \) | Under rejection \( n_\beta \) |
| | Unfit | Over rejection \( n_\alpha \) | Twice unfit \( n_n \) |

Reliability can be calculated by the formulas:

\[
D_\alpha = \frac{(n_\Sigma - n_\alpha)}{n_\Sigma} = 1 - \frac{n_\alpha}{n_\Sigma} \\
D_\beta = \frac{(n_\Sigma - n_\beta)}{n_\Sigma} = 1 - \frac{n_\beta}{n_\Sigma} \\
D_\Sigma = \frac{(n_\Sigma - n_g - n_n - n_\alpha - n_\beta)}{n_\Sigma} = 1 - \frac{(n_\alpha + n_\beta)}{n_\Sigma} \tag{2}
\]

With the most common of the physical types of non-destructive testing, ultrasonic testing of the boundary corresponding to the standard-acceptable defect size \( h_n \) and the adopted rejection level of the ultrasonic signal amplitude \( A_{br} \), divide the correlation field “defect size – ultrasonic signal amplitude” into four areas corresponding implicitly to four cells of the validity matrix: \( n_g, n_n, n_\alpha, n_\beta \) (figure 1).

![Figure 1](image-url)  
*Figure 1.* Graphic model of point estimate of the reliability of ultrasonic testing on an alternative basis (distribution of experimental points), \( n_g, n_n \) are twice fit and twice unfit elements of welded joints, respectively; \( n_\alpha, n_\beta \) are over rejection and under rejection respectively.

The most significant internal defects in butt welded joints are lack of penetration. They are often found, have a significant impact on the carrying capacity of welded joints and their occurring is rather difficult to prevent [4].
With traditional ultrasound testing, basic information about the detected defect is usually obtained on the basis of an analysis of the corresponding amplitude of the echo signal. At the same time, there is a good correlation between the amplitude of the echo signal and the penetration depth located in the lower part of the butt joints [4]. Considering that the use of phased array antenna technology also makes it possible to estimate the real sizes of defects [6], it is advisable to investigate not only the correlation fields “the amplitude of the echo signal \( A \) is the penetration depth \( h \)”, but also the correlation fields “measured penetration depth \( h_i \)” and “real non penetration depth \( h_r \)”.

Schemes for determining the rejection values of the amplitude of the echo signal and the size of the defect (depth of non penetration) based on the assessment of the reliability of control on an alternative criterion are proposed. The rejection values determine how the ordinates of the points of intersection of the values of the normative – acceptable size of the defect with the lower limit of the scatter of the correlation dependence “the measured characteristic of the defect – size of the defect”.

Thus obtained rejection values of the amplitude of the echo signal \( A_{br} \) (figure 2a) and the measured depth of non penetration \( h_{br} \) (figure 2b) practically ensure the absence of under rejection. Analysis showed that to determine the rejection values of the measured characteristics of defects, it is advisable to use the ranges of variation \( \pm 2\sigma \). The use of ranges of \( \pm 3\sigma \) realizes the rejection values of the measured characteristics of defects, which without thoroughly increase the errors of the 1st kind (over rejection).

**Figure 2.** Schemes for determining the rejection value of the amplitude of the echo signal \( A_{br} \) (a) and
the rejection value of the depth of non penetration $h_{ne}$ (b) based on the use of the assessment of the reliability of control on an alternative criterion.

As an example, an assessment of the reliability of ultrasonic testing on an alternative criterion of a one-sided butt-welded joint made of low-carbon steel with a thickness of 10 mm was made (rejection sensitivity $S_{eqv} = 2 \text{ mm}^2$, the allowable depth of penetration $h_a = 2 \text{ mm}$) (figure 3). The control was performed by Harfang flaw detector with a phased antenna array of the PE-5.0M3208P type with a frequency of 5 MHz, consisting of 32 elements with a pitch of 0.8 mm. The antenna array was located on a standard prism of rexolite T1-WOD with a width of 28 mm and a tilt angle of 35°.

The rejection value of the amplitude of the echo signal by the correlation dependence “the amplitude of the echo signal $A$ – the depth of the non penetration $h$” must be reduced by 11 dB, which practically ensures that there is no under rejection on signal amplitude (figure 3a). Similarly, on the correlation dependence “measured depth of non penetration $h_i$ – real depth of non penetration $h_p$”, with a rejection value of 1.4 mm depth, there will be practically no non penetration on depth of non penetration (figure 3b).

![Figure 3](image_url)

**Figure 3.** Determination of the rejection value of the amplitude of the echo signal by the correlation dependence “the amplitude of the echo signal $A$ – depth of non penetration $h$” (a) and the rejection value of the depth of the non penetration according to the correlation dependence of “measured depth of non penetration $h_i$ and is the real depth of the penetration $h_p$” (b).

### 2.2 The choice of rejection values of the characteristics of defects in assessing the reliability of control indicators on a quantitative criterion

A scheme for determining the rejection value of the size of the defect based on the assessment of the reliability of control on quantitative basis (figure 4) is proposed. The assessment of the reliability of quantitative basis is associated with the modeling of the conditional boundary of the division of production into fit and unfit and finding errors of the 1st and 2nd kinds. To obtain graphic image of the complete model for assessing the reliability indicators based on quantitative basis, it is necessary to build three functions: the operational characteristic of the control $G(h) = 1 - W_\Sigma(h)$ or the total detection function of defects $W_\Sigma(x) = 1 - G(x)$, the distribution defects function on depth $f_n(h)$, accuracy function of the evaluation of depth of defects $f_b(h)$. The usage of these functions makes it possible to determine the errors of rejecting: the probability of not detecting unacceptable $\Delta \chi$ defects, the probability of under rejecting $\chi$ defects, the probability of over rejecting $\chi$ defects [7, 8].

The composition of functions $f_n(h)$ $W_\Sigma(h) = f_{on}(h)$ is the probability distribution of defects that are detected during ultrasound testing. The steeper the function $W_\Sigma(h)$ is and located to the left, the more the functions $f_{on}(h)$ and $f_{b}(h)$ will coincide. During development of technology and the choice of means of ultrasonic testing, they try to ensure maximum detection of defects, and the function $f_{on}(h)$...
shows the possibilities of control. The composition of the functions $f_p(h)$ ($1-W(h) = f_{ob}(h)$) allows you to determine the errors in estimating the size of defects.

**Figure 4.** The scheme for determining the rejection value of the size of the defect based on the use of a graphic image of the complete model for assessing the reliability of a quantitative criterion.
The rejection value of the size of the defect is determined by the location of the accuracy function of estimating the size of defects \( f_v(h) \). The function \( f_v(h) \) should be located in such a way as to minimize the value of \( \chi_{\beta} \).

Graphic image of the complete reliability assessment model for example for which the reliability of ultrasonic testing on alternative criterion was estimated above in this article (see figure 3) is shown in figure 5. The numerical values of screening errors, that is, the corresponding areas on the graphic image of the full assessment model reliability, calculated by calculating the areas on the graphic image using scale paper.

![Graphic image of the complete model of ultrasonic testing reliability assessment for a regulatory-admissible defect \( h_n = 2 \) mm.](image)

**Figure 5.** Graphic images of the complete model of ultrasonic testing reliability assessment for a regulatory-admissible defect \( h_n = 2 \) mm.

**2.3. Analysis of rejection values of characteristics of defects obtained during assessing the reliability of control indicators for the alternative and quantitative criteria**

Reliability indicators obtained during evaluating by alternative criterion and during evaluating by quantitative criterion have sufficiently close numerical values (table 2).

| Table 2. Comparison of indicators of reliability at assessment on alternative criterion and quantitative criterion. |
| --- | --- |
| Criterion of evaluation | Confidence factor |
| | \( D_{\Sigma} \) | \( D_{\beta} \) |
| Ultrasonic test using phased antenna array | Alternative | 0.863 | 0.91 |
| | Quantitative | 0.82 | 0.952 |

With a standard-permissible defect depth \( h_n = 2 \) mm to ensure under rejection \( \chi_{\beta} \approx 0 \), the rejection value of depth of defect, determined from graphic image of complete model of assessment of reliability, is \( h_{br} = 1.8 \) mm. The rejection value of the depth of the defect, obtained with an alternative approach, is numerically smaller and amounts to \( h_{br} = 1.4 \) mm. Due to the scatter of the obtained rejection values of the depth of the defect with different approaches in its determination, it is advisable
when assigning the rejection value to be guided not only by increasing the requirements for the quality of the welded joint, but also take into account the material costs of the defect correction.

Bear in mind that the use of different methods for assessing the reliability of control requires the use of different sets of necessary data and has differences in what rejectionable measured characteristics of defects can be obtained (figure 6).

![Figure 6](image)

**Figure 6.** Comparison of methods for assessing the reliability of control for determining the rejection values of the measured characteristics of defects according to the necessary data and obtained rejection measured characteristics of defects.

Evaluation of reliability of ultrasonic testing on alternative criterion allows selection of the rejection values of the amplitude of echo signal and size of defect, ensuring reduction of under rejection. This requires only knowledge of correlation dependencies “amplitude of echo signal – size of defect” and “measured size of defect – real size of defect.” Assessment reliability on the basis of quantitative criterion allows to select only rejection value for the size of defect, which ensures reduction of under rejection. This requires knowledge of distribution of defects sizes, their detectability and accuracy of estimating sizes of defects.

3. **Conclusion**
Advantage of evaluating reliability of ultrasonic testing on alternative criterion to determine the rejection values of measured characteristics of defects is the ability to assess the rejection values of
amplitude of echo signal and size of defect, which provide reduction of under rejection. Usage of assessment of indicators of reliability of control on alternative criterion is advisable for operational control of product, for example, during operation. Assessment of reliability by quantitative criterion makes it possible to select only rejection value of the size of defect, which ensures the reduction of under rejection. Assessment of reliability of control on quantitative criterion provides additional important information on the distribution of defects in size, the detectability of defects and accuracy of estimation of the size of defects, which is appropriate for regulating the technology of manufacturing (repairing) products and the technology of their ultrasonic testing.

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