Ion-Plasma Treated Parts Quality Improvement Analysis Based on the Reliability Theory Criteria

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Abstract. The procedure of using reliability theory indices to evaluate parts vacuum ion-plasma treatment efficiency has been considered. Efficiency coefficient of technological procedures improving life and reliability of engineering parts taking into account alteration of average index value, its dispersion, and probability level of faultless operation has been suggested.

1. Introduction

Efficiency of procedures on reliability and quality improvement of parts by treatment is usually evaluated comparing average values of the given quality coefficient of a part with a coating and without it. However, this approach is not complete, as in some cases not only average index value, but the dispersion also changes. As a result, complete analysis based on criteria of reliability theory of part quality improvement with ion-plasma treatment is of interest. Moreover, methodology of reliability theory predicts significant impact of dispersion parameter on quality coefficients [1].

Actually, any coefficient of product quality formed when implementing a technological method is a random variable complying with the certain distribution law. This distribution is usually characterized by two numerical characteristics - mathematical expectation (average value) and dispersion (mean square deviation). Naturally, it is impossible to compare quantitatively two distributions of the quality coefficient values before and after treatment, but it is acceptable to be restricted by comparison of only average values at close values of their dispersions [1].

At the same time, in reliability theory, indices of ‘faultless probability’ and ‘g-percentile lifetime’ for objective evaluation are introduced. They compare indices with various dispersions, but they are not widely used in technical literature.

2. Formulation of the mathematical model for determination of performing the task probability

Let us consider methods of applying these indices of the reliability theory to evaluate efficiency procedures on vacuum ion-plasma treatment of parts. This method is connected with the task of determination of probability of the task performing [1] that can be formulated with the following way.

Let us assume a parameter of quality $Y$ is a random variable distributed according to the normal law with parameters $m_y$ (mathematical expectation) and $\sigma_y$ (dispersion). When using, parts are acted upon by external factors. Their evaluation gives limiting permissible value for the considered quality

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parameter. In general case, this limiting value $X$ is a random variable. This random variable due to the central limiting probability theorem would be distributed according to the normal law with parameters $m_x$ and $\sigma_x$. Then faultless operation on quality parameter $Y$ with probability $\gamma$ would be determined by the inequality:

$$P(Z = Y - X \geq 0) \geq \gamma.$$  \hfill (1)

In special cases, value $X$ can be a deterministic constant (limit value of an external stress, technological tolerance, permissible alteration of a parameter $y$, etc.); inequality signs can be inverse, values $Y$ and $X$ can be pre-failure lives or parameter values that vary with time, etc.

Since $Y$ and $X$ are subjected to Gauss distribution, their composition $Z = Y - X$ would be also subjected to Gauss distribution with parameters $m_z = m_y - m_x$ and $\sigma_z^2 = \sigma_y^2 + \sigma_x^2$, and probability of meeting condition (1) for the extreme case $P(z) = \gamma$ and $z = 0$ would be determined by the integral

$$\gamma = P(z = 0) = 0.5 - \Phi(U_\gamma(z = 0)).$$  \hfill (2)

where $\Phi(U_\gamma) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{U_\gamma} \exp\left(-\frac{\xi^2}{2}\right) d\xi$ – error integral, $U_\gamma(z) = -\frac{m_z}{\sigma_z}$ – quantile of Gauss distribution for some probability $\gamma$.

Let us transform the expression for the quantile $U_\gamma(z = 0)$ to the following

$$U_\gamma(z) = -\frac{n-1}{\sqrt{n^2 v_y^2 + v_x^2}},$$  \hfill (3)

where $n = m_y / m_x$ – safety factor (reliability margin); $v_x = \sigma_x / m_x$, $v_y = \sigma_y / m_y$ – coefficients of variations.

When value $X$ is a deterministic constant with the value $X = X_0$, expression for the quantile (3) is the following

$$U_\gamma = -\frac{n-1}{nv_y},$$  \hfill (4)

where $n = m_y / X_0$.

Before total analysis of equations (1-4), let us consider the example from practical experience of vacuum ion-plasma deposition [2-10].

3. Tests of samples with a coating and without it

Upon implementation of vacuum ion-plasma deposition technology of coatings based on titanium nitride to protect a part made of titanium alloy, the goal was set to discover influence of these coatings on endurance limit. In this connection, comparison tests of standard samples made of titanium alloy with coatings and without them were carried out. Next, a lot of compressor rotor blades were tested. Tests were carried out on smooth samples with round cross-section according to the scheme of pure bending under rotation up to complete destruction or $10^7$ cycles. The following results have been obtained: for the samples without a coating $\sigma_{\gamma_1} = m_y = 530$ MPa, $\sigma_y' = 58$ MPa; for the samples with a coating $\sigma_{\gamma_1} = m_y = 557$ MPa, $\sigma_y' = 45$ MPa.

Since the values $m_y'$ and $m_y$ differ insignificantly (5 %), the standard conclusion has stated that ion-plasma coatings obtained at the given mode do not decrease endurance limit. This fact has resulted in their further implementation (naturally, on substantial increase of wear resistance of the system). But
for the samples with a coating and without it, dispersion magnitudes of average values differ in 1.29 times. That is why let us calculate probabilities of faultless operation for two cases.

On the assumption that safety factor for the sample without a coating is chosen \( n' = 1.50 \), for the samples with a coating we get \( n = 1.58 \). Coefficients of variations are \( v_y' = 0.11 \) and \( v_y = 0.08 \), so quantiles (3) would be \( U'_y = -3.03 \) and \( U'_y = -4.59 \) for the samples without coatings and the samples with coatings respectively. Using the tables of error integral and according to (2) we would obtain the values of faultless operation for the sample without a coating \( \gamma' = 0.9987 \) and with a coating \( \gamma = 0.9999 \), so failure probability \( (1 - \gamma) \) has been decreased in \( (1 - \gamma)/(1 - \gamma') = 130 \) times.

Thus, efficiency of a vacuum ion-plasma coating can be evaluated as decrease of failure probability in 130 times because of fatigue, though average value of endurance limit has increased only by 5%. However, it is obvious that in most cases there is no need to provide computational probability of faultless operation at the level of ‘five nines’. That is why test results of the samples with and without coatings are to be reduced to the single reasonable value of faultless operation probability.

One possible variant of implementation of efficiency coefficient of conducted technological procedures is an approach similar to implementation and comparison of g-percentile lifetimes. Let us consider the leading example. When testing hard-alloy plates with a multilayer ion-plasma coating and without a coating in the delivery condition, the following results have been obtained for average pre-failure life and their dispersions \( m_y = 33.7 \text{ min}, m'_y = 22.5 \text{ min}, \sigma_y = 6.7 \text{ min}, \sigma'_y = 7.9 \text{ min.} \) Then, to complete the technological task with probability \( \gamma = 0.99 \) it is necessary to prescribe g-percentile lifetimes (efficient life) of instrument use according to (4):

\[
T_y = m_y \left(1 + U_y v_y \right); \quad T'_y = m'_y \left(1 + U_y v'_y \right),
\]

where in (4) it has been redesignated \( X_0 = T_y; X'_0 = T'_y; m_y = m; m'_y = m'; \sigma_y = \sigma; \sigma'_y = \sigma' \).

For the chosen probability of completing the technological task \( \gamma = 0.99 \) we get \( T_y = 18.0 \text{ min} \) and \( T'_y = 4.2 \text{ min} \). Thus, though increase of average pre-failure life of the instrument with the coating has increased in \( m_y / m'_y = 1.5 \) times, real increase of efficient instrument life has increased in \( T_y / T'_y = 4.3 \) times. Consequently, actual efficiency of the quality parameter (efficient life) is evaluated by the coefficient that is equal to:

\[
\alpha_{ef} = \frac{T_y}{T'_y} = \frac{m_y \left(1 + U_y v_y \right)}{m'_y \left(1 + U_y v'_y \right)}.
\]

### 4. Evaluation technique of a technological procedure on permissible g-percentile alteration of quality coefficient

Returning to the example with the endurance limit, we have suggested to evaluate a technological procedure on permissible g-percentile alteration of quality coefficient. In this case, similar to (5) and (6) efficiency coefficient of the technological procedure on the quality parameter \( Y \) is in the form of:

\[
\alpha_{ef} = \frac{m_y \left(1 + U_y v_y \right)}{m'_y \left(1 + U_y v'_y \right)}.
\]
of probability of faultless operation $\gamma$ on this parameter, we calculate according to equation (7) (value of a quantile $U_\gamma$ is determined using standard tables of error integral). For example, in the above considered example on endurance limit increasing $\alpha_{\sigma_\gamma} = 1.20$ at $\gamma = 0.9987$ and $\alpha_{\sigma_\gamma} = 1.37$ at $\gamma = 0.9999$, that is procedure efficiency gives index increase by 19% and 37% rather than 5%. In this case, it is clear that quality coefficient (7) also objectively signifies quality increase of a part on endurance due to deposition of vacuum ion-plasma coatings. Besides, in case of requirements raise to a part on the value of probability of faultless operation, efficiency of ion-plasma technology increases.

At the same time, particular interest is the strategy of increase of faultless operation probability on the given quality parameter. From (1) and (2) it is evident that increase of faultless operation probability $P \to 1$ is connected with necessity to provide rise of $|U_\gamma|$. Rise of $|U_\gamma|$ can be provided by the increase of $n$ and decrease of $v_y$ and $v_x$.

5. Results and discussion

Quantities $v_{x,y}$ are a variation coefficient of the admissible limit value for the considered quality coefficient, it depends on: stability of level and range of impacts on a part as a whole; transmitting these outer impacts on the part and the given quality parameter; operational stability of this part; assembly quality of the part, etc. That is within the framework of the procedure of ion-plasma treatment, quantities $v_x$ and $m_x$ are not to be altered.

In this connection, depending on relation between $v_x$ and $v_y$ ($\sigma_x$ and $\sigma_y$) it is possible to distinguish the following ranges. The first range is determined by the relation, the second range is determined by the relation $0.1\sigma_x \leq \sigma_y$, and the third one is determined by $\sigma_y \geq 10\sigma_x$.

It is seen from relation (3), that in the second and the third ranges, rate increase $|U_\gamma|$ is great (efficient regulation) while raising safety factor from $n = 1$ up to $n \equiv 1.5$. Then it substantially slows down. At the same time, influence of $v_y$ on $|U_\gamma|$ complies with hyperbolic law, and it substantially influences on the quantity $|U_\gamma|$, especially in the range $\alpha \approx 1$.

Thus, depending on correlation between $\sigma_y$ and $\sigma_x$, it is necessary to take different strategies on increase of faultless operation probability on the given quality parameter – to obtain increase of average value of the index, to obtain dispersion decrease of this index or to obtain both.

At the same time, it is necessary to keep in mind that increase of $n$ requires searching of new materials and creating new technology as far as technology concern. As far as design concern, increase of $N$ results in increase of structure mass, square of unsafe cross-sections, complexity of the structure itself, etc. Nevertheless, decrease of $v_y$ or $\sigma_y$ is connected with improvement of the technology process, decrease of coefficients of variations both properties of initial blanks and properties of the parameter at each production step including exclusion of manual labor and introducing automation. Moreover, to decrease dispersion, finishing technologies are especially important because they have positive technological heredity and low dispersion of output parameters, and vacuum ion-plasma technologies refer to them as shown in [2-4].

6. Evaluation technique of a technological procedure on permissible g-percentile alteration of quality coefficient

Thus, the use of suggested efficiency coefficient of technological procedures to increase working life and reliability of engineering parts objectively takes into account alteration of average value of the index, alteration of its dispersion. It also considers probability level of faultless operation at which this index is to be used; it reflects contemporary trends of reliability calculation of structures and parts, and shows
that possibility of dispersion reduction of quality coefficients is a substantial reserve of increase of engineering parts reliability.

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