Physico-mathematical model for bellows expansion joint efficiency by different manufacturing technologies

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Abstract. Increasing the reliability and improving of the technical characteristics of bellows and bellows expansion joints widely used in various fields of technology is a recent issue today. To solve this issue, a physico-mathematical model of functioning and measuring the reliability performance of bellows expansion joints is developed. The model includes two mechanisms of fatigue breakdown and wear: the Rehbinder effect and fretting. The developed model allows for calculating cyclic operation life for different bellows expansion joints. The model describes bellows expansion joints by three parameters: growth rate of a microcrack due to the Rehbinder effect, speed of fretting wear, and value of reversible period of microcracks formation. One can experimentally measure these parameters for different constructions and technologies of manufacturing of bellows expansion joints. Today, there are various technologies of bellows expansion joints manufacturing, including promising technologies of modification using fluoro-organic surfactants. The developed model is applied for assessment of different manufacturing technologies. Based on the analysis of the physico-mathematical model, the requirements for technologies are defined that lead to increasing of reliability performance of bellows expansion joints.

1. Introduction
Currently bellows expansion joints (BEJ) are widely used in various fields of technology, such as nuclear engineering, oil and gas industries, shipbuilding, electrical engineering, mining engineering, etc. [1-5]. Events that took place in recent years, such as the Fukuyama nuclear power plant disaster, have demonstrated that improvement of BEJ reliability and technical characteristics is a pressing issue. To solve it, it is necessary to analyze physical mechanisms of BEJ functioning, and provide its mathematical description based on reliability indicators, such as cyclic technological lifespan (TL). For multilayer BEJs, the value of the cyclic TL is determined by the operating time until the failure. Failure is considered to be the moment of loss of a hermetic seal of a multilayer BEJ. In this research, such description of functioning and BEJ reliability indicators is further elaborated. It can be used to
assess different BEJ manufacturing technologies, as well as possible design and technological improvements of BEJs.

A promising area for improving parameters of multilayer BEJs is the use of SAA nanocoatings based on organofluorine compositions (OFC) that are applied to the BEJ layer surfaces [6,7]. The practical application of one of these OFCs (named "MOKOM") [7,8] confirmed that they improve reliability of cutting tools and die blocks, as well as extend cyclic technological lifespan (TL) of the BEJs. For both surfaces of each BEJ layer organofluorine SAA nanocoating was applied during upgraded BEJ manufacturing process [8]. Usually, mechanical or hydraulic technologies are used for manufacturing multilayer BEJs, when its layers of metal have no surface coating [3,8]. In comparison with generic manufacturing technology, a modified method of manufacturing BEJs introduces additional technological operations: the process of applying SAA nanocoating to the layers of BEJs. This research provides mathematical connections of BEJ TL and different manufacturing technologies. This allows for assessing effectiveness of technologies used.

2. Physical mechanisms of formation and growth of cracks in a multilayer BEJs

Fatigue failure of the material surface layer under multiple load actions leads to formation and growth of microcracks inside highly deformed layers of a BEJ. Microcracks advance as a BEJ functions, and, combined with fatigue wear of the metal, lead to loss of a BEJ hermetic seal, i.e. to its failure. In case of multilayer BEJs, two types of fatigue wear occur:
- Microcracks are developed on the BEJ surface, mainly due to the Rehbinder effect.
- Fretting wear is developed between BEJ layers due to fretting friction between them.

When liquid leaks inside a BEJ (which is usually seen in real life), the inner surface of the BEJ develops microcracks due to a Rehbinder effect. They grow into bigger cracks and eventually cause BEJ failure. Microcracks are formed in places where the crystal structure is defects, or at the grain boundaries. The process of fatigue breakdown (FB) of the metal in a BEJ begins on the side that separates a BEJ and liquid. Most often, the liquid is water, with a molecule size about three angstrom. During cyclic testing, as well as operation, in the BEJ, its surface layers of metal, plastic deformations and microcracks emerge. At first, they are reversible, however, they grow over time [3,9,10]. Microcracks grow since water molecules act as a wedge due to Rehbinder effect, in addition to the wedging action of liquid that leaked into a crack [3]. The total wedging force depends on the size of liquid molecules and their properties. These two effects cause development of fatigue microcracks that gradually grow deeper into the material and turn into macrocracks.

To sum it up, development of cracks for the metal BEJ has three stages.
- First stage. Microcracks appear and disappear. They are reversible and do not advance.
- Second stage. Irreversible microcracks appear and growth in places with microdefects.
- Third stage. Microcracks are transformed into cracks, with the growth speed increasing. The third stage of crack development quickly leads to a complete mechanical destruction of a BEJ layer.

At the first stage, the cracks have not yet appeared. This stage of FB is characterized by a number of operating cycles \( N_{00} \) that correspond to the duration of the reversible stage of FB. For generic BEJ manufacturing technology, the first stage takes a small amount of time in a technological lifespan. Therefore, we can assume \( N_{00} = 0 \). For a modified BEJ manufacturing process, a protective layer is added, therefore, \( N_{00} \) is a positive value.

At the second stage, a microcrack appears and grows. It is assumed that the depth of a microcrack at which the second stage ends and the third stage starts is over a millimeter [3,11]. Usually, the thickness of one BEJ layer does not exceed 0.3-0.8 mm, so the loss of a hermetic seal of one BEJ layer occurs at the second stage of microcrack development.

Here, we will introduce the average cyclic growth rate of the microcrack: \( V_R \) (mm/cycle). It is determined mainly by the Rehbinder effect. We believe that the growth rate of the \( V_R \) microcrack remains the same for all BEJ layers.

Simultaneously with the FB process, in multi-layer BEJs fretting friction occurs at the boundaries of two adjacent layers of BEJ's shell [3,9]. It is a complex process that includes: fretting friction,
fatigue and other processes. As a practical result of this process, a layer of fretting wear appears and grows. For it, we will use a cyclic fretting wear rate \( V_F \) (mm/cycle): it will reflect the increase of fretting wear in a BEJ for one load cycle.

Because of the above mentioned effects, in the first layer of the BEJ a fatigue microcrack appears and grows at a cyclic rate of \( V_R \). A sublayer of fretting wear also grows. When a fatigue crack meets a fretting wear sublayer, a BEJ layer loses its tightness and liquid quickly leaks into the interlayer space. After that, in the next layer, a new microcrack begins to develop due to the Rehbinder effect. Locations of microcracks in the first and second layers of a BEJ may differ from each other. A microcrack grows on the second layer of the BEJ until it meets a fretting wear sublayer. After that, the second BEJ also loses its hermetic seal. According to the same scenario, the FB process and loss of a hermetic seal develops on all other layers of a multilayer BEJ. The moment of failure for a BEJ corresponds to the loss of a hermetic seal in the last layer of the BEJ shell.

The fretting phenomenon can significantly reduce the benefits from using multilayer BEJ, while efficiency of a BEJ is largely determined by a parameter \( \gamma = \frac{V_F}{V_R} \), which characterizes a ratio of the fretting wear cyclic rate to the microcrack growth cyclic rate. In addition to a parameter \( \gamma \), it is convenient to use a coefficient \( \beta = \frac{\gamma}{1 + \gamma} \). Applying this logic of FB development in a BEJ, it is possible to build a mathematical model that describes functioning of the BEJ until its failure; i.e. for a cyclic TL of the BEJ.

3. Physico-mathematical model of multilayer BEJ functioning and failure

Figure 1 shows a diagram of an M-layered BEJ. For this model parameters of the BEJ layers themselves are used, as well as parameters of physical sublayers formed by fretting friction at BEJ layer edges.

![Figure 1. Geometrical and physical parameters of a multilayer bellows expansion joint.](image)

For M-layered BEJ, with \( D \) (mm) thickness of each layer, the following values are used to describe the process of BEJ functioning. \( l_k \) is depth a microcrack grew into a layer \( k \) up to the whole layer thickness. \( \delta_k \) is a value by which a fretting wear sublayer increased as a microcrack grows inside the \( k \)-th layer of a BEJ. \( d_k \) is a full fretting wear sublayer thickness at the \( k \)-th BEJ edge at the time layer \( k \) loses its hermetic seal. In addition, it is necessary to introduce the total value \( L_K \) of a microcrack and fretting wear formed inside layer \( k \) after a previous BEJ layer of lost its tightness. It is calculated by the formula:

\[
L_K = l_k + \delta_K .
\]

This scenario of FB development in a BEJ requires a set of recurrent formulas, for all layers of the BEJ, which determine BEJ functioning until failure:

\[
L_N = L_{N-1} + \delta_N.
\]
Layer (1): 
\[ \delta_1 = D \beta; \quad l_1 = D/(1+\gamma); \quad L_1 = D; \quad d_1 = \delta_1. \] (2)

Inner layer (k), \( k = 2, \ldots, M-1): 
\[ L_K = D - 2\cdot d_{K-1}; \quad \delta_K = \beta \cdot L_K; \quad l_K = L_K/(1+\gamma); \quad d_K = d_{K-1} + \delta_K. \] (3)

Layer (M): 
\[ L_M = l_M = D - d_M. \] (4)

This set of formulas (2)-(4) allows for establishing dependences between BEJ functioning and its technological and structural parameters.

Practically, to characterize BEJ functioning, \( N \) (cycle) of cyclic BEJ's TL is used, which is the sum of \( N_{00} \) and the total (for all layers) fatigue crack value \( L_R \): 
\[ N = N_{00} + L_R / V_R; \quad L_R = \sum_{K=1}^{M} l_K. \] (6)

It is convenient to use a coefficient \( K \) to assess the functioning efficiency of a BEJ: it shows what part of the BEJ total thickness is occupied by growing microcracks. Given these considerations, the formulas for TL of a BEJ are as follows:
\[ N = N_{00} + M D K(\gamma, M) / V_R; \quad K(\gamma, M) = L_R / (M D); \] (7)

Values of \( V_R \) rate and \( \gamma \) parameter can be determined experimentally (via relevant tests) for different BEJ structures, as well as for different operating conditions.

Figure 2 demonstrates dependency between the effectiveness coefficient \( K \) and parameter \( \gamma = (V_F / V_R) \), as well as \( M \) number of BEJ layers.

Figure 2. Dependency between efficiency coefficient \( K \) and \( \gamma \) parameter for BEJs with different number of layers (M).

The analysis of these dependences shows that to improve the reliability of a BEJ (its cyclic TL), it is desirable to use BEJ manufacturing technologies that provide \( \gamma \) parameter values in the range \( 0 < \gamma < 0.1 \). In this case, the main process of BEJ fatigue wear will be a microcrack growth process, and fretting wear between BEJ layers will have little effect on BEJ's TL.

4. Comparison of functioning reliability by different BEJ manufacturing technologies

The general physico-mathematical model (6), (7) is applicable to all existing BEJ manufacturing technologies. Thus, for a conventional BEJ manufacturing process, a cyclic TL that is denoted here by \( N_1 \), is described by the following formula:
\[ N_1 = M D K(\gamma_1, M) / V_R. \] (8)

Here, the parameter \( \gamma_1 \) corresponds to the rate of fretting wear that occurs when conventional manufacturing technologies and standard materials are used for BEJ. According to test results for BEJs [8], it is possible to estimate that \( \gamma_1 \) parameter's range is \( 0.35 \leq \gamma_1 \leq 0.45 \). This means such technology is not very efficient when it comes to BEJ TL.
Organofluorine SAA nanocoating of all BEJ layers does not change its strength characteristics, but it can increase TL and durability of a BEJ up to several times [8]. To describe functioning of such BEJs, a previously used scenario of FB and fretting wear development should be supplemented with the following two factors. Due to their properties [6,7], OFA nanocoating can result in reduced fretting friction (wear fretting rate $- V_{2F}$) between the inner layers of the BEJ shell. It can be taken into account by replacing $\gamma$ parameter with $\gamma_2 = V_{2F} / V_R$ in the mathematical model. It is obvious that $0 \leq \gamma_2 \leq \gamma$. Conducted experiments and tests confirm that the rate of fretting wear can decrease by several times when MOKOM OFC is applied (the exact number depends on the BEJ structure and the load parameters) [8].

In addition, at the boundary between a BEJ and liquid, the applied SAA layer is a multilayer structure (with a number of layers ranging from 5 to 20-30 layers) [3,6]. As a result, a BEJ has a protective SAA layer that prevents the Rehbinder effect for two reasons. Multilayer SAA coating protects BEJ surface from the Rehbinder effect up until it loses its uniformity. In addition, SAA molecules are much bigger in size if compared to water molecules (ten or more times), which also prevents the Rehbinder effect. These factors lead to an additional cyclic operating time of $N_{00}$, which corresponds to the first stage of microcrack development at the BEJ – liquid boundary.

During the first stage, the fretting wear process between BEJ shell layers exists. It causes thickness reduction for each inner BEJ layer by a value $(2 \delta_{00})$; and the thickness of the first and the last layers of BEJ is reduced by the value $\delta_{00}$. Therefore, the equation for $L_R$ is as follows:

$$ L_R = M (D - 2 \delta_{00}) K (\gamma_2, M) + 2 \delta_{00}; \quad \delta_{00} = N_{00} V_{2F} = \gamma_2 N_{00} V_R; \quad (9) $$

Taking into account the formula (6), the BEJ’s cyclic TL, which is denoted by $N_2$, can be determined as:

$$ N_2 = N_{00} + \left[ M (D - 2 \delta_{00}) K (\gamma_2, M) + 2 \delta_{00} \right] / V_R; \quad (10) $$

Formula (10) can be converted to a form that will make modified technology advantage over a conventional method apparent:

$$ N_2 = N_{00} + \left[ M (D - 2 \delta_{00}) K (\gamma_2, M) + 2 \delta_{00} \right] / V_R; \quad (11) $$

Since the available SAA nanolayer can reduce the fretting friction between BEJ layers, the ratio is $K (\gamma_2, M) / K (\gamma_1, M) \geq 1$. For example, according to test results [5], $\gamma_2$ parameter can be estimated in range $0.035 \leq \gamma_2 \leq 0.05$. Thus, when modified BEJ production technology is used, cyclic TL can be increased several-fold due to reduced fretting friction.

The second factor of TL increase is creation of a protective layer on the boundary between a BEJ and liquid, which can lead to higher values of $N_{00}$. Tests result show that this value is comparable to TL of a BEJ manufactured using conventional technology.

Sometimes a simplified modification technology for BEJs is used. In this case, only one BEJ surface is coated with SAA, the one that borders with liquid. The cyclic TL for this technology designated as $N_3$ is described by formulas similar to (10)-(11):

$$ N_3 = N_{00} + \left[ M (D - 2 \delta_{00}) K (\gamma_1, M) + 2 \delta_{00} \right] / V_R; \quad \delta_{00} = N_{00} V_{2F} = \gamma_1 N_{00} V_R; \quad (12) $$

$$ N_3 = N_1 + N_{00} \left[ 1 + 2 \gamma_1 (1 - M K (\gamma_1, M)) \right]; \quad (13) $$

The difference between this method and conventional technology is that one protective layer is added at the boundary with liquid, which leads to an additional cyclic operating time of $N_{00}$, which is the same as in case of fully modified technology. It cheapness and simplifies manufacturing and can result in TL increase comparable to $N_1$.

Here, we can estimate the contribution a protective layer (additional operating time $N_{00}$) makes into the overall balance of TL. From (11), (13) it is clear that $N_{00}$ contributes to the TL balance via an influence coefficient $F(\gamma, M)$:

$$ F(\gamma, M) = 1 + 2 \gamma_1 (1 - M K (\gamma_1, M)) \quad (14) $$

Figure 3 demonstrates dependency between this coefficient $F(\gamma, M)$ and $\gamma$ parameter for BEJs with different number of layers (M).
Figure 3. Dependency between function $F (\gamma, M)$ and $\gamma$ parameter. Graphs correspond to BEJs with different number of layers: $M = 2, 4, 6$.

If behavior of the influence coefficient is analyzed, it is clear that protective layer contribution is highest by low values of $\gamma$ parameter. By very high $\gamma$ values, the contribution of $N_{00}$ also increases, but contribution of FB to TL greatly decreases. It means one and the same protective layer is more efficient for modified BEJ technology than for a conventional BEJ manufacturing method.

5. Conclusion

Based on the proposed physico-mathematical model and its application to existing BEJ manufacturing technologies, it is possible to draw the following conclusions.

It is preferable to use BEJ manufacturing methods that provide small values of $\gamma$ parameter in the range $0 < \gamma < 0.1$. Thus, it is necessary to develop BEJ manufacturing technologies with fretting wear reduced by several times. One of such technologies is modification of BEJ layer surfaces via nanocoating using organofluorine compositions, for example, “MOKOM”.

The growth rate of microcracks in BEJs is mainly conditioned by the Rehbinder effect, which depends on the type of liquid and BEJ material. Therefore, one of the ways to increase the TL is to create an efficient protective layer between liquid and a BEJ surface material that contacts it. This effect is implemented both in a simplified and full modification technologies of BEJ manufacturing.

To maximize TL, by designing and selection of multilayer BEJ, material thickness and number of BEJ layers should be optimized.

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