ТЕХНОЛОГІЇ ОТРИМАННЯ ТА ОБРОБКИ КОНСТРУКЦІЙНИХ МАТЕРІАЛІВ

TECHNOLOGIES OF OBTAINING AND PROCESSING OF CONSTRUCTION MATERIALS

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STRENGTH CALCULATION METHODOLOGY FOR THE TECHNOLOGICAL CONTAINERS FOR CHEMICAL HEAT TREATMENT OF WORKPIECES

Purpose. *Development of a strength calculation methodology for the special technological containers for chemical heat treatment of workpieces, which considers the consequences of complex influence of the load and the main technological factors. Creation of possibility of full-value mathematical modelling of the special technological containers with complex three-dimensional geometric shape for chemical heat treatment of workpieces using the finite element method.*

Research methods. *Mathematical modeling taking into account the hypothesis of linear failure accumulation from low-cycle fatigue and creep of material.*

Results. *A strength calculation methodology for the special technological containers for chemical heat treatment of workpieces has been developed, which considers the consequences of complex influence of the load and the main technological factors: high-temperature corrosion, interaction with the chemical environment, creep, low-cycle fatigue. This methodology makes it possible to determine safe operation life of the containers. Load combinations have been considered. The main features of the design of the technological containers for chemical heat treatment of workpieces have been considered.*

Scientific novelty. *It has been considered at calculations of the special technological containers the consequences just of the complex influence of the load and the main technological factors which occur during the chemical heat treatment of workpieces: high-temperature corrosion, interaction with the chemical environment, creep, low-cycle fatigue.*

Practical value. *The developed methodology provides the possibility of full-value mathematical modelling of the special technological containers for chemical heat treatment of workpieces using the finite element method. It opens a way for multi-criteria optimization of the design of the containers with complex three-dimensional geometric shape with prospect of reduction of their weight with a certain resource of safe operation. This is one of the main factors of the practical value of this work because the containers for chemical heat treatment of workpieces are made of expensive heat-resistant steels. One factor more is the possibility to determine safe operation life and thus satisfy the requirements of safety engineering.*

Key words: *container, chemical heat treatment, model, stress, high-temperature corrosion, low-cycle fatigue, creep, operation, operation life, safety.*

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Introduction

Improvement of calculation models of technological devices is one of the important conditions for ensuring of their safety. Development of a strength calculation methodology for the special technological containers for chemical heat treatment of workpieces is associated with the important scientific and practical task to ensure the fulfillment of safety requirements at the heat treatment bays of the corresponding departments of enterprises.

Review

The Rules for the Design and Safe Operation of Lifting Cranes [1], in accordance with paragraph 1.2k of these Rules, are not applicable to special containers, which includes the containers for chemical heat treatment.

Other regulatory documents related to the ordinary containers, in particular – [2, 3], also do not contain rules for design of the containers for chemical heat treatment.

Many literature sources are devoted to consideration of the separate factors influencing the containers for chemical heat treatment. In particular, the book [4] discusses the problems of thermal fatigue for various parts. The book [5] deals with the strength calculation methodology under low-cycle mechanical loading. The book [6] highlights low-cycle fatigue and creep under high temperature testing. The handbook [7] provides rich data on fatigue strength calculations, including influence of high temperatures on metal fatigue. The book [8] describes influence of cyclically varying temperatures on steel products. Fatigue of elements under thermomechanical loading, mainly under thermocycling, is also investigated in the books [9, 10]. However, anyone of the listed sources don't consider simultaneously all the factors influencing the containers for chemical heat treatment.

Thus, the authors were unable to find in the literature sources a calculation methodology that allows to consider simultaneously all the factors influencing the containers for chemical heat treatment.

Purpose

The purpose of this article is to develop a strength calculation methodology for the technological containers for chemical heat treatment of workpieces, which allows to consider in a complex way the main influencing factors.

Research and its methods

Main influencing factors

The technological containers for chemical heat treatment of workpieces are subjected to long-term exposure under high temperature and chemical action, as well as cyclic loading. Thus, main factors influencing them are the following:

- high-temperature creep;
- low-cycle fatigue from cyclic action of mechanical and thermal loads;
- aggressive chemical actions.

Features of container design

The technological containers for chemical heat treatment as a rule are made of heat-resistant chromium-nickel austenitic steel, the normative operating temperature of which exceeds the maximum working temperature of heat treatment process, at which this container has to be used, by at least 50 °C (if the container is intended for quenching or chemical heat treatment – by at least 100 °C).

The selected steel has to be cyclically stabilizing or cyclically hardening, taking into account the cyclic character of container loading. Steels that are cyclically stabilizing at normal temperatures as a rule are becoming cyclically hardening at high temperatures, according to [5]. Steels are becoming cyclically soften when the following condition is satisfied [5]:

$$\frac{\sigma_{0.2}}{\sigma_b} \geq 0.6, \qquad (1)$$

where $\sigma_{0.2}$ – conventional yield strength, MPa;

σ_b – ultimate strength, MPa.

Shape and size of the containers are determined by the characteristics of the technological process, in particular, by the type of furnace and workpiece characteristics. It is preferably to make the container symmetrical with a removable bottom, and to make all its elements of the same material. The container must not have open local cavities or gaps between its elements. An example of the container design is shown in Fig. 1.

The container design must not have stress concentrators with a theoretical stress concentration factor of more than 1.5 (excluding welds). All sharp edges must be replaced with fillets with radius of at least 5 mm, if the containers are intended for quenching or chemical heat treatment.

The most rational is making of the cast containers because of characteristic features of welding of heat-resistant austenitic steels and the difficulty of performing of many fillets using machining. Usage of welding can be considered reasonable only if usage of casting is technologically impossible.

Figure 1. Container for chemical heat treatment

It may be provided in the design a possibility of installation of the bottom on the body through a ring of soft heat-resistant material, for example – asbestos, to reduce impact loads.

Grip units for slinging as a rule are made in the form of trunnions or lugs. Their thickness must be comparable to the thickness of the base metal of the container body to reduce thermal stresses.

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Consideration of aggressive chemical effects

Chemical effects on the containers can be divided into surface (corrosive) and penetrating (associated with changes in chemical composition and mechanical properties) [10, 13].

The penetrating effect most of all influences the plastic properties of the material. It must be considered when determining the admissible plastic strain.

The corrosive effect can lead to significant thinning of the metal at the maximum working temperature of heat treatment process. It is appropriate to consider the corrosive effect together with the thickness tolerances of the container elements. These factors can be considered in the form of an arithmetic sum of quantitative characteristics [11].

The total tolerance on the thickness δ_S is determined by the dependence:

$$\delta_S = \delta_1 + n_2 \cdot \delta_2 + \delta_3, \qquad (2)$$

where δ_1 – negative tolerance on the thickness in accordance with the design documentation and regulatory documents for purchased products, mm;

n_2 – number of surfaces exposed to corrosion (two or one);

δ_2 – the corrosion value of one surface during the design period, mm;

δ_3 – the mechanical wear value of the surface, mm.

$$\delta_2 = v_c \cdot t_e, \qquad (3)$$

where v_c – metal corrosion rate in the working environment at the maximum working temperature of heat treatment process, mm/year;

t_e – design operation life, years.

The mechanical wear value δ_3 can be considered primarily for a grip units for slinging.

In addition the values of δ_2 and δ_3 can be limited by the maximum values, which are established for diagnosing an operation life of the container.

The total tolerance on the thickness δ_S is subtracted from the nominal metal thicknesses before the strength calculation (without violating the symmetry of the elements).

Consideration of high-temperature creep and low-cycle fatigue

The phenomena of fatigue and of creep have to be considered at calculation of the containers of heat-resistant austenitic chromium-nickel steel. The main characteristics of the creep are the creep strength and the long-term strength [14]. The process of metal failure is mainly caused by fatigue phenomenon at low temperatures; the process of metal failure is mainly determined by creep at high temperatures [15]. That's why the character of the fatigue curve changes at the high temperatures: the fatigue limit decreases significantly, and the horizontal part of the plot becomes increasingly inclined to the abscissa axis, forming a reverse change of the gradient. The fatigue limits are conditional values equal to the stresses corresponding to a certain number of cycles before failure at high temperatures [7]. That's why it is necessary to consider low-cycle fatigue [8].

Long-term static load has a great influence on the number of cycles to failure at high temperatures [9]. The fatigue resistance must be considered as the sum of failures from fatigue and long-term static load in this case [16]. The linear failure accumulation hypothesis is the most acceptable at high temperatures [6]. This hypothesis can be expressed in relative times as follows [16]:

$$\frac{1}{t_m} = \frac{1}{t_s} + \frac{1}{t_c}, \qquad (4)$$

where t_m – time to failure under combined load;

t_s – time to failure under long-term static load;

t_c – time to fatigue failure under cyclic load.

Obviously, it can be considered for the containers that the period of loading cycle t_p coincides with the duration of holding under static load. If all components of the equation (4) will be multiplied by the value t_p, it can be rewritten:

$$\frac{1}{n_m} = \frac{1}{n_s} + \frac{1}{n_c}, \qquad (5)$$

where n_m – number of cycles before failure under combined load (cyclic with holding);

n_s – number of cycles before failure under long-term static load;

n_c – number of cycles before fatigue failure.

The initial and final sections of the creep curve are nonlinear under static load. However, the dependence can be considered linear under long-term load [16]:

$$t_s = \frac{[\varepsilon_a]}{v_c}, \qquad (6)$$

where $[\varepsilon_a]$ – admissible plastic strain;

v_c – creep rate at a given temperature and stress.

For practical use, equation (6) must be improved:

$$n_s = \frac{[\varepsilon_a]}{s_{nc} \cdot s^{н}_{nc} \cdot t_p \cdot v_c}, \qquad (7)$$

where $s^{н}_{nc}$ – safety factor for consideration of the nonlinear sections of the creep curve;

s_{nc} – safety factor for consideration of v_c and $[\varepsilon_a]$ value deviations.

The maximum stresses σ_{max} and the operating temperature of the cycle can be considered as the same for the loading and holding stages at operation. These values have to be used at determination of the creep rate.

The value v_c is determined from reference literature. Its dimensions must be correlated with the dimensions of other parameters in equation (6). The values of safety factors may be taken $s^{н}_{nc}$=2, s_{nc}=2.5, according to the data of [16] and [6].

The obtained n_s value must be compared with the number of cycles before failure n_f according to the base

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time t_l for long-term strength determination, which is used in admissible stress determination:

$$n_f = \frac{t_l}{t_p}. \tag{8}$$

The following condition must be satisfied in this case:

$$n_s \leq n_f. \tag{9}$$

If condition (9) is not satisfied, then $n_s = n_f$ must be accepted.

Model of plastic strain accumulation at low-cycle fatigue is based on the Manson-Coffin equation [5]:

$$\varepsilon_p \cdot n_c^m = [\varepsilon_a], \tag{10}$$

where ε_p – plastic strain;

m – power factor (empirical).

The equation (10) is transformed into the following dependence [5] after transfer to conditional stresses and consideration of the elastic component of strain and cycle asymmetry:

$$s_\sigma \cdot \sigma_a = \frac{E \cdot [\varepsilon_a]}{2 \cdot n_c^m + 0.5 \cdot k_r} + \frac{k_{-1} \cdot \sigma_b}{1 + k_{-1} \cdot k_r}, \tag{11}$$

where σ_a – cyclic stress amplitude, MPa;

E – Young's modulus, MPa;

σ_b – ultimate strength, MPa;

s_σ – safety factor by stress;

k_r – factor considering cycle asymmetry;

k_{-1} – material constant.

The second component in the equation (11) corresponds to elastic strain.

The constant k_{-1} is determined by the dependence [5]:

$$k_{-1} = \frac{\sigma_{-1}}{\sigma_b}, \tag{12}$$

where σ_{-1} – conditional fatigue limit, MPa.

The factor considering cycle asymmetry is determined by the formula [5]:

$$k_r = \frac{1+r}{1-r}, \tag{13}$$

where r – cycle ratio.

Dependence (11) considering (12), (13) is taken as the basis for further calculations.

The loading cycle can be considered pulsating ($\sigma_{min}=0$) if the container weight is relatively small. The pulsating cycle is characterized by values $\sigma_a = \sigma_{max}/2$, r=0. In this case factor considering cycle asymmetry $k_r=1$.

In this case, equation (11) can be converted to the following form:

$$s_\sigma \cdot \sigma_{max} = \frac{E \cdot [\varepsilon_a]}{n_c^m} + \frac{2 \cdot k_{-1} \cdot \sigma_b}{1 + k_{-1}} \tag{14}$$

It is more convenient to rewrite equation (14) in the following form to determine the number of cycles before fatigue failure n_c:

$$n_c^m = \frac{E \cdot [\varepsilon_a]}{s_\sigma \cdot \sigma_{max} - \frac{2 \cdot k_{-1} \cdot \sigma_b}{1 + k_{-1}}}. \tag{15}$$

The safety factor is taken $s_\sigma=2$ according to [5], [6]. The values of E, σ_b, k_{-1} are determined at operating temperature of the cycle [5]. It must be used the value $k_{-1}=0.4$ according to [5]; this value can be decreased if reliable data are available. It can be used the value m=0.5 according to [5].

The number of cycles before fatigue failure n_c must be not more than the base number of cycles $\mathbf{n_b}$=10000. It must be used the value $n_c=n_b$ if n_c is more than n_b, or if the right part of equation (15) is negative or equal to infinity.

Consideration of load combinations

It is reasonable to consider two load combinations in the calculations as a rule: holding of the container with the nominal load in a furnace at the maximum operating temperature of heat treatment, and removing the container with the nominal load from a furnace. The finite element method can be used to determine the design stresses.

The admissible stresses are determined for each of the materials from which the container elements are made. The basic mechanical properties of the materials are determined for the temperature of correspondent load combination.

The basic mechanical properties are the ultimate strength σ_b and the long-term strength $\sigma_l(t_l)$ at the base time t_l. The Young's modulus E and the percentage reduction of area ψ are determined at the same time at the given temperature for further usage in calculations. Material characteristics for welds can be determined using correction factors.

The admissible stress [σ] for each material is determined as the minimum of the following values [11]:

$$[\sigma] = \min\left\{\frac{\sigma_b}{s_b}; \frac{\sigma_l(t_l)}{s_l}\right\}, \tag{16}$$

where s_b = 2.6 – safety factor for ultimate strength;

s_l = 1.5 – safety factor for long-term strength [11].

Zones of maximal stress have to be determined at each calculation performed for loading variants during stress analysis. The maximal stresses have not exceed the correspondent allowable stresses (considering used materials). The stress in the container and its components in the calculation is taken as σ_{max}, if the ratio $\sigma_{max}/[\sigma]$ will be the greatest considering materials.

The determination of the admissible plastic strain $[\varepsilon_\mathbf{a}]$, which is used in prediction of the operation life of the container, is carried out using the percentage reduction of area ψ for the temperature of the loading variant under calculation.

The value $[\varepsilon_a]$ is calculated according to the dependence [5]:

$$[\varepsilon_a] = \frac{1}{2} \cdot \ln \frac{1}{1-\psi_p}, \tag{17}$$

where ψ_p – design percentage reduction of area.

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The value of ψ_p is determined by the dependence:

$$\psi_p = \frac{\psi}{s_{\psi 1} \cdot s_{\psi 2}}, \qquad (18)$$

where $s_{\psi 1}$, $s_{\psi 2}$ –correction factors.

The plastic properties of steels deteriorate during prolonged operation at high temperatures [11], [17]. $s_{\psi 1}=1$ is accepted if the percentage reduction of area ψ is determined taking into account long-term (at least t_l) thermal exposure (at the temperature of the loading variant under calculation); $s_{\psi 1}=3$ is accepted in the absence of such data.

Long-term usage of the containers during chemical heat treatment leads to change in the chemical composition of their surface layers and, first of all, to change in their plastic properties (penetrating effect) [17], [18]. $s_{\psi 2}=1$ is accepted if the container is not intended to operate under the influence of penetrating chemical medium. $s_{\psi 2}=2.5$ is accepted if the container can be used for carburizing or nitrocarburizing, because it can cause carburization of the container surface. $s_{\psi 2}=1.2$ is accepted if the container is intended for nitriding.

Results

Calculation of the number of cycles to failure n_m is performed separately for each loading variant using correspondent values of t_p, σ_b, E, t_f, σ_{max} and $[\varepsilon_a]$. Calculations are carried out using dependencies: (5), (7), (8), (9), (15).

Complex physical and chemical processes occur in the metal, in particular, large and rapidly changing thermal stresses, which at the first stage are partially compensated by the stresses of phase transformations, if the container is used for quenching [18]. Value n_c in equation (5) should be substituted by the value $n_c^{'}$ for containers intended for quenching, because cyclic quenching does not have a significant effect on creep processes under long-term static loading. It has to be determined by the relation [18]:

$$n_c^{'} = \frac{n_c}{s_c^{'}}, \qquad (19)$$

where $s_c^{'}=12$ – correction factor.

Discussion

If σ_{max} action areas for two loading variants are the same, then the numbers of cycles to failure n_{m1} and n_{m2} obtained for them are combined using the formula:

$$\frac{1}{n_m} = \frac{1}{n_{m1}} + \frac{1}{n_{m2}}. \qquad (20)$$

The smallest value n_m^{min} has to be selected among the obtained numbers of cycles to failure n_m, which corresponds to the estimated operation life of the container.

Conclusions

Thus, the above-described strength calculation methodology for the technological containers for chemical heat treatment of workpieces allows to consider complex of the main factors influencing it. The authors plan to improve the consideration of quenching in calculations, as well as to develop an operation life diagnostic methodology for the technological containers for chemical heat treatment of workpieces in the future.

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МЕТОДИКА РОЗРАХУНКУ МІЦНОСТІ ТЕХНОЛОГІЧНОЇ ТАРИ ДЛЯ ХІМІКО-ТЕРМІЧНОЇ ОБРОБКИ ДЕТАЛЕЙ

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Мета. *Розробка методики розрахунку міцності спеціальної технологічної тари для хіміко-термічної обробки деталей, яка враховує наслідки комплексного впливу навантаження та головних технологічних факторів. Створення можливості повноцінного математичного моделювання спеціальної технологічної тари для хіміко-термічної обробки деталей, яка має складну просторову геометричну форму, із застосуванням методу скінчених елементів.*

Методи дослідження. *Математичне моделювання з урахуванням гіпотези лінійного підсумовування ушкоджень матеріалу від малоциклової втоми та повзучості.*

Отримані результати. *Розроблена методика розрахунку міцності спеціальної технологічної тари для хіміко-термічної обробки деталей, яка враховує наслідки комплексного впливу навантаження та головних технологічних факторів: високотемпературної корозії, взаємодії з хімічним середовищем, повзучості, малоциклової втоми. Ця методика дає можливість визначення ресурсу безпечної експлуатації тари. Враховано комбінації навантажень. Розглянуто основні особливості конструкції технологічної тари для хіміко-термічної обробки деталей.*

Наукова новизна. *Врахування при розрахунку спеціальної технологічної тари наслідків саме комплексного впливу навантаження та головних технологічних факторів, що виникають при хіміко-термічній обробці деталей: високотемпературної корозії, взаємодії з хімічним середовищем, повзучості, малоциклової втоми.*

Практична цінність. *Розроблена методика надає можливість повноцінного математичного моделювання спеціальної технологічної тари для хіміко-термічної обробки деталей із застосуванням методу скінчених елементів. Це відчиняє шлях до багатокритеріальної оптимізації конструкції тари, яка має складну просторову геометричну форму, з перспективою зменшення її маси при певному ресурсі безпечної експлуатації. Оскільки тару для хіміко-термічної обробки деталей виготовляють з коштовних жаростійких сталей, це є одним з головних факторів практичної цінності розробки. Іншим фактором є можливість визначити ресурс безпечної експлуатації та таким чином задовільнити вимоги техніки безпеки.*

Ключові слова: *тара, хіміко-термічна обробка, модель, напруження, високотемпературна корозія, малоциклова втома, повзучість, експлуатація, ресурс, безпека.*

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