Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 50 (2023) 50–56

Structural Integrity Procedia

www.elsevier.com/locate/procedia

16th International Conference on Mechanics, Resource and Diagnostics of Materials and Structures (MRDMS 2022)

Thin-walled shell service life under variable thermomechanical load

Emel'yanov I.G.[a], Hodak A.S.[b,*]

[a]*Institute of Engineering Science, Ural Branch of the Russian Academy of Sciences, 34 Komsomolskaya St, Ekaterinburg, 620046, Russian Federation*

[b]*Ural Federal University, 19 Mira St, Ekaterinburg,620002, Russian Federation*

Abstract

A method is proposed for determining the service life of a metal shell structure under variable thermomechanical loading. The operating stresses are determined by solving a nonlinear boundary value problem for a thin-walled shell of revolution. The service life of a metal structure under variable thermomechanical loads and taking into account contact with an aggressive environment is determined using the equations of low-cycle material fatigue. The method is demonstrated on the design of a muffle intended for high temperature annealing of electrolytic steel.

Peer-review under responsibility of the scientific committee of the MRDMS 2022 organizers

Keywords: shell; thermomechanical loading; stress state; low-cycle fatigue; service life.

1. Introduction

The need to solve problems of determining the strength and service life of metal structures under variable thermomechanical loads is quite common in engineering practice. The problem of determining the limit state of a structure under low-cycle and thermal fatigue conditions has its own specific features and is quite relevant.

The complexity of such problems lies in the simultaneous consideration of all factors affecting the material of the structure, namely mechanical forces, temperature, and exposure to an aggressive environment. There is no way to study experimentally the material for all the combinations of various physical loads that can act during the operation

* Corresponding author. . Tel.: +7-922-207-3447
E-mail address: emelyanov.ig.2016@mail.ru, ashodak@yandex.ru

2452-3216 © 2023 The Authors. Published by ELSEVIER B.V.

Peer-review under responsibility of the scientific committee of the MRDMS 2022 organizers
10.1016/j.prostr.2023.10.021

of structures. Therefore, to solve such problems, sometimes it is necessary to use model representations in the form of interpolation and extrapolation.

Cyclic elastoplastic deformation of a metal under actual operating conditions of structures can only be caused by a change in temperature. If the level of mechanical stresses in the structure does not depend on temperature cycles, it is considered that the material is subject to the phenomenon of non-isothermal low-cycle fatigue, in which the combination of force and temperature cycles are independent, Troshchenko (1994). Under thermal fatigue, the value of stresses and the nature of their changes over time are uniquely determined by the mode of temperature change, Troshchenko (1994), Gusenkov and Kotov (1988).

In this paper, a method for determining the service life of a shell metal structure, that is a muffle under variable thermomechanical loads is proposed. The muffle is intended for high-temperature annealing of electrolytic steel in bell-type furnaces. High-temperature annealing is carried out in order to form a coarse-grain oriented structure and to refine the metal. The investigated muffle is a thin-walled steel shell of revolution with a flat lid, loaded with an internal excess pressure of a hydrogen-containing gas and non-stationary thermal heating. Under the action of operational loads, noticeable residual deformations are formed in the muffle design. The interest of this problem lies in the fact that the proposed mathematical model for evaluating the resource of a thin-walled shell can be compared with a real physical experiment in the operation of the muffle structure.

2. Problem statement

The problem of determining the resource of a metal structure under non-isothermal loading processes can be represented as one consisting of several independent problems of mechanics, mathematical physics and materials science. The general task can be represented as:

1) development of a model of the structural element under study, which makes it possible to determine its stress state under thermomechanical loading;

2) development of a model that allows determining the distribution of temperature and hydrogen concentration in the structural element under study during operation;

3) determination of the mechanical parameters of the construction material under thermomechanical loading;

4) selection of a model for the degradation of material properties during operation and determination of the service life of the structure under various operating conditions.

The proposed method for determining the resource of metal structures will be demonstrated on a structural element, that is a muffle shell, is located vertically during operation. Inside the structure, there is nitrogen gas containing hydrogen with overpressure p. During operation, thermomechanical loads from its own weight, excess pressure, and thermal radiation influence on the shell. Thus, taking into account the vertical arrangement of the structure, its stress state will be axisymmetric.

This element of the muffle, for economic reasons, is made not of heat-resistant material, but of the St3 steel according to the Russian standard GOST 380-2005 (analogue St 37-3 DIN 17100, 1017 ASTM A568M). This steel is not designed for operation at temperatures above 500 ºC. However, the operating temperature of the muffle at some points in time can reach up to 1000 ºC and the muffle does not always lose its functional purpose. Therefore, it is of interest to evaluate the service life of this thin-walled structure under extreme operating conditions.

3. Assumptions and methods for solving the problem

3.1. Determination of the stress state of the muffle shell

Currently, there are a large number of computational programs to determine the stress state and thermal conductivity of various structural elements. Most often, when determining the charged state and temperature distribution, the finite element method is used as a numerical method, Gallager (1975), Zienkiewicz and Tailor (1989). Universal computing programs for solving problems of determining the service life do not yet exist due to the impossibility of formalizing various mechanisms for the degradation of structural materials during operation. Usually, when describing the geometry of thin-walled structures, finite elements based on various shell theories are used.

When determining the stress state of a thin-walled muffle structure, we will use the classical theory of shells based on the Kirchhoff – Love hypotheses, Donnell (1976), Grigorenko and Vasilenko (1981). We refer the shell under study to a continuous middle surface with curvilinear orthogonal coordinates s, θ, γ (where s is the meridional, θ - circumferential coordinates, and γ is the coordinate in the direction of the outer normal to the shell surface).

Given that the stress state of the shell under the acting thermomechanical load will be axisymmetric, the problem will be described by a system of six ordinary differential equations, Grigorenko and Vasilenko (1981), Shevchenko (1980), Emel'yanov (2009).

$$\frac{d\bar{Y}}{ds} = P_{ij}\bar{Y} + \bar{f}\,, \quad (i, j = 1,2,..6)\,, \; (s_0 \le s \le s_L) \tag{1}$$

with boundary conditions

$$B_1\bar{Y}(s_0) = \bar{b}_1\,, \; B_2\bar{Y}(s_L) = \bar{b}_2\,. \tag{2}$$

Here, $Y = \{N_r, N_Z, M_s, u_r, u_Z, \vartheta_s\}$ is the vector-function of the required solution; N_r and N_Z are radial and axial forces; u_r and u_Z are displacements; M_s is the meridional bending moment; ϑ_s is the angle of rotation of the normal to the shell surface. The elements of the matrix P_{ij} depend on the geometric and mechanical parameters of the shell, $\bar{f}$ is the vector whose components depend on the loads applied to the shell. B_1 and B_1 are given matrices; $\bar{b}_2$ and $\bar{b}_2$ are given vectors. The elements of a matrix P_{ij} and the column vector $\bar{f}$ are given in Grigorenko and Vasilenko monograph (1981).

When solving the linear boundary value problem (1), the Runge-Kutta method with discrete orthogonalization and normalization by S. K. Godunov is used, Grigorenko and Vasilenko (1981).

Since the shell of the muffle operates at elevated temperatures, the plastic deformations is possible. When the plastic deformation of the material is taken into account, the problem of determining the stress state becomes nonlinear. The problem will be described by the same system of equations (1), and the relationship between stress and strain will be linearized by the method of additional strains. This relationship is presented in the form of Hooke's law, but with additional terms that take into account the dependence of the mechanical properties of the material on deformation, Shevchenko and Babeshko (1980), Shevchenko and Prokhorenko (1981). In this case, the volumetric stress state of the shell will be compared with the uniaxial state in a simple tension of the sample

$$S = \frac{\sigma}{\sqrt{3}}\,, \; H = \frac{1+\mu^*}{\sqrt{3}}\varepsilon\,, \tag{3}$$

where σ and ε are stresses and strains during simple tension of the sample, and μ^* is the coefficient of transverse deformation, which is defined as

$$\mu^* = \frac{1}{2}\frac{1-2\mu}{2\mathrm{E}}\frac{\sigma}{\varepsilon}\,, \tag{4}$$

where E is the modulus of elasticity, μ is Poisson's ratio, and the intensities of shear stresses and shear strains S and H for the shell are defined as

$$S = \sqrt{(1/3)\cdot(\sigma_s^2 - \sigma_s\sigma_\theta + \sigma_\theta^2)}\,, \tag{5}$$

$$H = \sqrt{(1/6)\cdot[(\varepsilon_s - \varepsilon_\gamma)^2 + (\varepsilon_\gamma - \varepsilon_\theta)^2 + (\varepsilon_\theta - \varepsilon_s)^2]}\,, \tag{6}$$

where σ_s and σ_θ are the meridian and circumferential stresses, respectively, and ε_s, ε_θ and ε_γ are the components of deformations along the meridian, the circumference and the normal to the shell surface, respectively.

3.2. Muffle shell temperature during operation

High-temperature annealing of an anisotropic steel consists of stages namely: controlled heating, low-temperature and high-temperature holding and uncontrolled cooling under the muffles. During operation, the muffle is heated according to a rather complex law with a low heating rate and is automatically controlled by thermocouples. For the structure under study, we will assume that the temperature spreads uniformly over the body of the shell. Given the small thickness of the shell, the temperature across the thickness will be the same. Consequently, the mechanical properties of the material are assumed to be the same for all points of the muffle shell. As the material warms up, the properties of the material will change equally at all points of the muffle shell, in proportion to the time parameter t. Thus, for the shell structure under study, there is no need to solve the heat conduction problem. The change in the mechanical parameters of the shell material will depend only on the heating time t, i.e., on the operating time of the structure. Based on the technical conditions for high-temperature annealing, we assume that the temperature cycle of loading can be from T_{min} = 20°C to T_{max} = 1000°C and cooling can be from T_{max} = 1000°C to T_{min} = 20°C.

3.3. Mechanical parameters of the muffle material

As mentioned above, the cylindrical shell of the muffle is made of the St3 steel. It is known that the range of application of elements made of St3 steel is quite wide, but still has certain limitations, Zubchenko (2003). The effect of temperature on the mechanical properties of this steel has been well studied. The mechanical properties of steel when heated to a temperature of 200–250°C practically do not change. Heating above a temperature of 400°C leads to a drop in the yield strength and tensile strength, and at a temperature of 600–650°C, temperature plasticity sets in and the steel loses its load-bearing capacity. Therefore, the mechanical properties of steel at temperatures above 500°C have not been studied.

Table 1 shows the values of tensile strength σ_{ult}, yield strength σ_Y, and elastic modulus E for various temperatures for the St3 steel, Zubchenko (2003).

Table 1. The values of tensile strength σ_{ult} , yield strength σ_Y , and elastic modulus E for various temperatures for the St3 steel.

T, °C	20	200	300	400	500	600	800	900	1000
σ_{ult}, MPa	422	500	490	275	216	210	80	70	50
σ_Y, MPa	206	216	206	157	126				
E 10^{-5}, MPa	2	1.704	1.556	1.408	1.260	1.112	0.816	0.668	0.520

Taking into account the experimental data for stresses and at different temperatures, which are given by Zubchenko (2003), the stress-strain diagrams $\sigma = f(\varepsilon, T)$ for this steel can be approximated by bilinear broken lines with points of yield strength σ_Y, ε_Y and tensile strength σ_{ult}, ε_{ult} for different temperatures (Fig. 1).

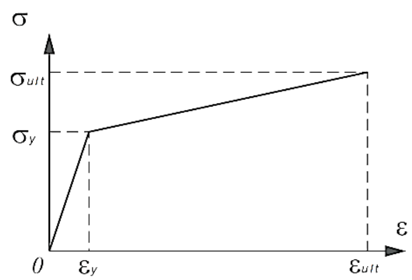

Fig.1. Tensile curve for theSt3 steel.

3.4. Influence of a hydrogen-containing medium on the mechanical parameters of the muffle

The inner surface of the muffle shell during operation is in contact with a protective gas containing hydrogen, and therefore the effect of penetrating hydrogen on the mechanical properties must be taken into account.

To assess the strength of the muffle shell, it is necessary to take into account the experimentally established fact of a change in the strength and plastic properties of the metal during hydrogenation. During the operation of structural elements, the relationship between stress σ, deformation ε, hydrogen concentration c, element temperature T, and operating time t can be represented as $\sigma = f(\varepsilon, T, c, t)$.

The problem of hydrogen diffusion and determination of the distribution of hydrogen concentration depending on time for a shell of revolution was considered in the literature, Emelyanov and Mironov (2019), Emel'yanov and Polyakov (2019). However, for the problem under consideration, since the shielding gas contains a small amount of 5.5% hydrogen, we will not take into account the change in mechanical properties due to its impact.

3.5. Model of low-cycle and thermal fatigue of the muffle material

The durability of the shell will be determined using the criterion of the limiting state of the material for a small number of loading cycles, taking into account heating. In the theory of low-cycle fatigue, three types of criteria are used, namely: deformation, energy, and criteria based on the allowance for material damage, Troshchenko (1994). We will use the deformation criterion, in which the quasi-static fracture is modeled as a result of the accumulation of plastic deformation up to the limit value, and the fatigue one as the nucleation of microcracks and the transformation of their macrocracks. The relationship between durability and plastic deformation per cycle in the region of low durability was first proposed in the form of a power law, Manson (1966). Subsequently, S. Manson transformed the power equations for various materials into a universal equation describing the relationship between the total deformation and the number of cycles to failure, taking into account the joint influence of the elastic and plastic components on durability. Experimentally verified on 29 metal alloys, this equation relates the range of total deformation $\Delta\varepsilon$, the coefficient of transverse narrowing ψ at rupture of the sample, the ultimate strength of the material σ_{ult}, the modulus of elasticity E and the number of cycles to failure N in the form, Troshchenko (1994), Manson (1966), Tretyachenko (1989),

$$\Delta\varepsilon = (\ln\frac{1}{1-\psi})^{0,6} \times N^{-0,6} + 3,5\frac{\sigma_{ult}}{E} \times N^{-0,1}\,. \tag{7}$$

In relation (7), the total deformation $\Delta\varepsilon$ can include the plastic and elastic parts of the cyclic deformation. Since the shell of the muffle under study is in a three-dimensional stress-strain state, the value of total deformation $\Delta\varepsilon$ we will compare with the equivalent deformation ε_i. The equivalent deformation ε_i is determined by the invariant value of the intensity of shear deformations H for the most loaded point of the shell

$$\Delta\varepsilon = \varepsilon_i\,,\ \varepsilon_i = \frac{\sqrt{3}}{1+\mu^*}H\,. \tag{8}$$

4. An example of determining the resource of a muffle structure under variable thermomechanical loading

The muffle design is loaded with an internal overpressure p = 0.037 MPa, muffle weight 1100 kg, and variable temperature T. The calculation scheme of the muffle design is shown in fig. 2.

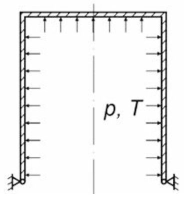

Fig.2. Calculation scheme of the muffle design.

The length of the cylindrical shell L = 3000 mm, with an outer diameter D = 1576 mm. Shell and cover thickness h = 8 mm.

When integrating the system of equations (1), the radius of the cover was divided into 40 steps of integration and orthogonalization, and the length of the cylindrical shell was divided into 120 steps of integration and orthogonalization.

To verify the solution, the obtained stresses of the muffle at the operating temperature T = 20°C were compared with the stress calculated for the shell loaded with internal pressure using the no moment theory, Pisarenko (1988). Far from the edges on the cylindrical part of the shell, the circumferential stresses practically coincide.

Since there is no information on the properties of the material above T = 500°C, the calculation of the stress state of the muffle shell was made only for the temperature regimes of operation of the muffle from T = 20°C to T = 500°C.

Table 2 shows the intensity of shear stresses S and shear strains H for the most loaded point of the muffle, namely the point on the inner surface of the cylindrical shell near the connection with the cover.

Table 2. The intensity of shear stresses S and shear strains H for the most loaded point of the muffle

°C	20	200	300	400	500
S, MPa	120.3	126.1	119.9	91.6	82.0
H	0.00105	0.00095	0.00105	0.00175	0.01353

It should be added that already at a temperature of T = 20°C, plastic deformation appears at the most loaded point of the muffle and 7 approximations are required to achieve accuracy $\chi = 0.01$ when solving a nonlinear problem Emel'yanov (2009). At T = 500°C, 34 approximations are required.

Using the equation for low-cycle fatigue (7), relations (8) and the found deformed state at the most loaded point of the shell (Table 2), the number of cycles before the destruction of the muffle was determined. At the same time, it was considered that the cycle is a loading with an internal overpressure of the gas and non-stationary thermal heating. Table 3 shows the number of cycles before failure N.

Table 3. The number of cycles before failure N

N, °C	20	400	500	600
$\varepsilon_i = \dfrac{\sqrt{3}}{1+\mu^*} H$	0.0014	0.00233	0.01803	0.0631
N	$2.25 \cdot 10^6$	$1.34 \cdot 10^6$	735	78

It follows from the calculations that up to the operating temperature of the muffle T = 400°C, the muffle shell is in the region of high-cycle fatigue, then at T = 500°C and above, in the region of low-cycle fatigue. For T = 600°C (Table 1) by extrapolation, the missing value of the yield strength was determined equal to σ_Y = 95 MPa. And then the number of cycles until the destruction of the shell of the muffle N = 78 is determined (Table 3). Due to computational difficulties (strong nonlinearity of the problem for the loss of the bearing capacity of the material), it is not possible to determine the stress state with a given accuracy and the number of cycles until the shell breaks at temperatures above T = 600 °C.

5. Conclusion

Thus, the paper proposes a method for determining the resource of a metal shell structure under variable thermomechanical loading. The method is based on solving a nonlinear boundary value problem for a thin-walled shell of revolution and equations for low-cycle material fatigue. The method is demonstrated for a muffle shell that is used for high temperature annealing of electrolytic steel. The service life of the metal shell of the muffle was determined under various thermal operating conditions.

References

Donnell L. H., 1976. Beams, Plates And Shells, McGraw-Hill, pp. 453.
Emel’yanov I.G., 2009. Contact problems of the theory of shells [in Russian], Ural Branch of the Russian Academy of Sciences, Yekaterinburg, pp. 185.
Emelyanov I. G., Mironov V.I., Hodak A.S., 2019. The boundary value problem of determining hydrogen concentration and the stress state in a titanium shell. AIP Conference Proceedings 2176, 030005, DOI: 10.1063/1.5135129.
Emel'yanov I.G., Polyakov A.A., Hodak A.S., 2019. Stressed state of a steel construction working in hydrogen containing environment. Journal of Physics: Conference Series, 1391, 012027, DOI: 10.1088/1742-6596/1391/1/012027.
Gallager R., 1975. Finite element analysis. Fundamentals, Prentice-Hall, Englewood Cliffs, New Jersey.
Grigorenko Ya. M., Vasilenko A. T., 1981. Theory of Shells of Varying Stiffness, Vol. 4. of the five-volume series Methods of Shell Design [in Russian], Naukova Dumka, Kiev, pp. 544.
Gusenkov A.P., Kotov P.I., 1988. Long-term and non-isothermal low-cycle strength of structural elements [in Russian], Mashinostroenie, Moscow, pp. 264.
Manson S.S., 1966. Thermal stress and low-cycle fatigue, McGraw-Hill Inc., US, pp. 404.
Pisarenko G. S, Yakovlev A. P., Matveev V. V., 1988. Strength of materials. Handbook [in Russian], Naukova Dumka, Kiev, pp. 725.
Shevchenko Yu. N., Babeshko M. E, Piskun V. V. et al., 1980. Solution of the axisymmetric thermoplastic problem for thin-walled and thick-walled bodies of revolution on a Unified Electronic Computer System [in Russian], Naukova Dumka, Kiev, pp. 196.
Shevchenko Yu. N, Prokhorenko I. V., 1981. Computational Methods for Shells, Vol. 3. Theory of Elastoplastic Shells with Noisothermal Loading Processes [in Russian], Naukova Dumka, Kiev, pp. 296.
Tretyachenko G.N., 1989. Mechanics of materials for power engineering [in Russian], Naukova Dumka, Kyiv, pp. 312.
Troshchenko V. T., Krasovsky A. Ya, Pokrovsky V. V., et al, 1994. Strength of materials to deformation and destruction. Reference manual. Part 2 [in Russian], Naukova Dumka, Kiev, pp. 703.
Zienkiewicz O.C., Tailor R.L., 1989. The Finite Element Method, McGraw-Hill, New York.
Zubchenko A.S., Koloskov M.M., Kashirsky Yu.V., et al., 2003. Reference book of steels and alloys [in Russian], Mashinostroenie, Moscow, pp. 784.