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ANALYSIS OF CONSTRUCTIVE FACTORS AFFECTING THE FATIGUE STRENGTH OF METALLURGICAL EQUIPMENT PARTS

Annotation. The causes of fatigue failure of metallurgical equipment parts were analyzed. The correlation between the effect of the quality of surface treatment of the part on the fatigue strength has been established. The influence of local stress concentrators on fatigue strength has been determined. Recommendations for increasing the fatigue strength of the finished part were given.
Key words: fatigue failure, stress concentrators, endurance limit

Statement of the problem

The specific conditions of operation of metallurgical equipment, caused not only by dynamic loads, but also by the specialties of the course of the technological process, require attention when designing their units considering reliability and trouble-free operation [1].

In addition to ensuring reliability during operation, the components of the technological equipment must allow for easy adjustment, and in case of emergency breakdowns, allow for quick replacement or repair of individual components or parts, which in turn strengthens the already strict design restrictions in the development of components and aggregates of the metallurgical complex [2].

On the other hand, in the system for assessing the technical condition of mechanical systems according to individual risk indicators of their elements - risk analysis - failures of individual nodes or parts are "ranked" depending on the level of damage [3], i.e. the situation of advance planning of more extended service periods for the most responsible parts of nodes of metallurgical equipment is economically justified.

Thus, establishing the factors affecting the fatigue strength of parts at the stage of their design is an important task, the solution of which will allow not only to use materials more rationally, but also to extend the life cycle of the part as a whole.

Analysis of recent research and publications

As you know, fatigue is a rather complex process of accumulation of material damage under the influence of variable stresses. This process is gradual, extended over time and leads to a change in properties, the formation of cracks, their development and destruction. Its feature is that the accumulation of damage begins long before the final loss of performance of the part and proceeds imperceptibly. Statistical data show that the main reason for about 80% of equipment failures is fatigue failure [4]. Thus, in terms of reliability and durability of metallurgical equipment units, the problem of fatigue strength comes to the fore.

Cyclic loads are the main cause of fatigue failure. The parameters characterizing any cycle of alternating stresses are shown in Figure 1.

Cycle asymmetry coefficients – R_σ or R_τ – is equal to the ratio (taking into account the sign) of the minimum stress to the maximum [5]:

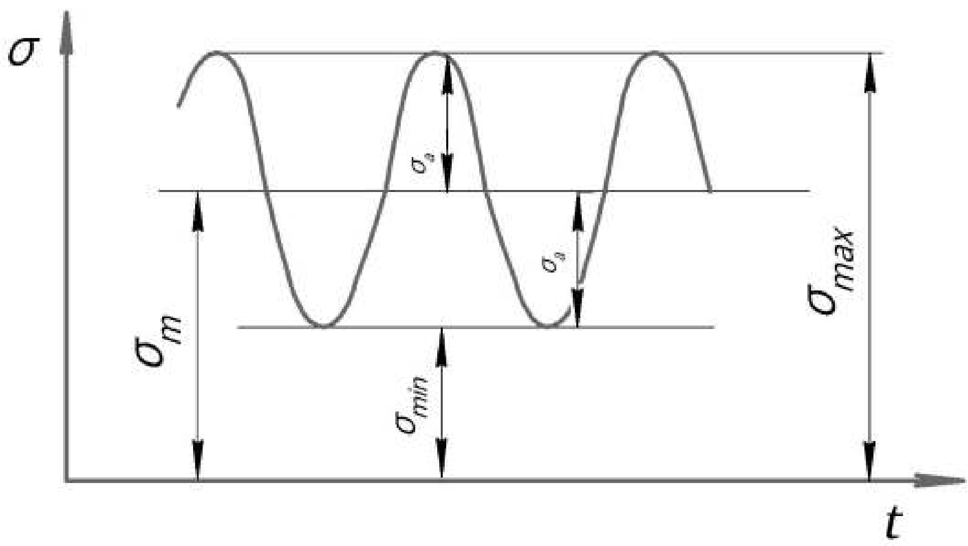
$$R_\sigma = \frac{\sigma_{min}}{\sigma_{max}} \text{ or } R_\tau = \frac{\tau_{min}}{\tau_{max}} \quad (1)$$

Depending on the value of the asymmetry coefficient, cycles are distinguished:

– symmetrical ($R = -1$, $\sigma_{max}=-\sigma_{min}$, $\sigma_m=0$);

– pulsating ($R = 0$, $\sigma_{min}=0$, $\sigma_m=0{,}5\sigma_{max}$);

– asymmetrical ($R = \sigma_{min}/\sigma_{max}$, $\sigma_{max}\neq\sigma_{min}$, $\sigma_m\neq 0$).



σ_{max} (τ_{max}), MPa – the greatest in terms of the algebraic value of cycle tension;

σ_{min} (τ_{min}), MPa – the smallest in terms of the algebraic value of the stress of the cycle;

σ_m (τ_m), MPa – average cycle stress

Figure 1 – Parameters characterizing the cycle of alternating stresses

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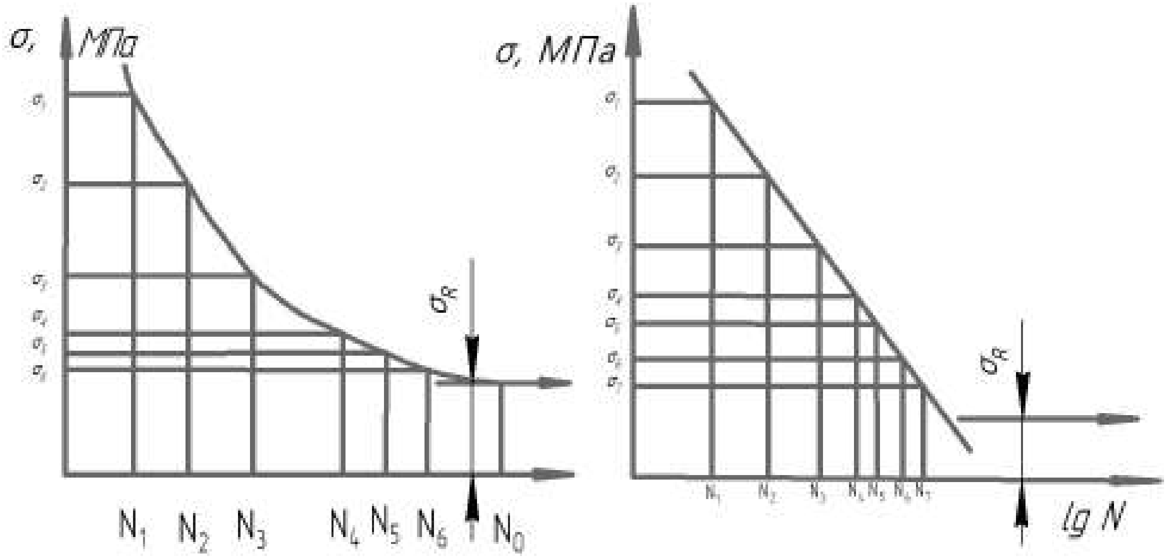
Endurance limit or fatigue limit is the maximum stress at which the material does not break under an almost unlimited number of stress changes [5].

Endurance limits are determined experimentally. The most common type of endurance tests under uniaxial stress is bending and strain tests.

The results of fatigue tests have a significant dispersion, so the construction of fatigue curves is preceded by statistical processing of experimental data. Fatigue curves (Fig. 2) are built in natural or semi-logarithmic coordinates based on the results of testing samples of 15–20 samples at each load level [6].

Endurance limit depends on values σ_m and σ_α. The graphic interpretation of this dependence is the diagram of the limit amplitudes (Fig. 3).

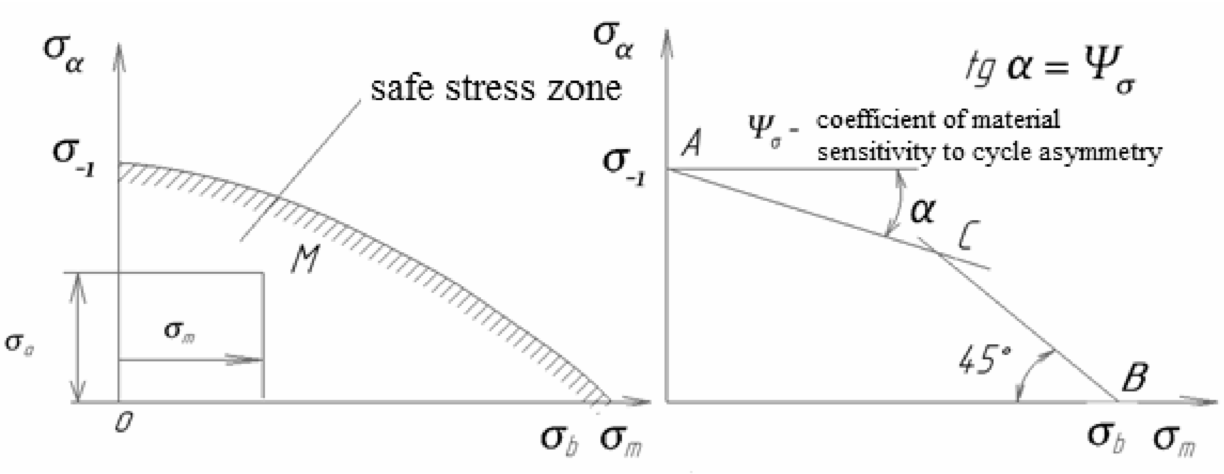
The meaning of the diagram of limit amplitudes is that if you set the point M with coordinates σ_m and σ_α that characterize the cycle (Fig. 3, a), then by location of the point M you can evaluate the strength of the sample. The area of the diagram below the curve is the safe stress area.



a b

Figure 2 – Fatigue curves in natural (a) and semi-logarithmic coordinates (b)

Schematic diagram is used for calculation purposes in practice since obtaining a diagram of the limit amplitudes requires considerable time spent on testing samples for various combinations of σ_m and σ_α, (Fig. 3, b).



a b

Figure 3 – Diagram of limit amplitudes in natural (a) and schematic (b) types

The performance of metallurgical equipment units is usually determined by the basic structures, such as various types of frames, casings [7], which consist to a greater extent of the same type of parts, the strength of which is a decisive factor for the life cycle of the entire unit.

It should be noted that the strength of parts under variable loads is always lower than the strength of smooth samples. Therefore, when calculating the durability of parts, it is necessary to take into account the influence of a number of factors on the reduction of strength characteristics.

Purpose of the study

The fatigue life of parts depends on many factors, the main of which are the size of the parts (scale factor), stress concentration, quality (roughness) of the surface of the part. Durability also depends on the chemical composition of the material, its structure, modes of thermal and mechanical processing, surface hardening, temperature, aggressiveness of the environment, etc. The purpose of the study was to establish the relationship between the influence of such factors as the quality of surface treatment of the finished part and stress concentrators.

Statement of the main research material

Given the fact that fatigue crack initiation occurs on the surface or near the surface layers [8], it can be concluded that the condition of the surface of the part has a significant effect on the resistance to fatigue failure, and is one of the main characteristics of the volumetric mechanical properties of the parts.

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Fatigue strength can be increased by improving the quality of the surface layer by its plastic deformation (rolling, shot blasting, etc.) [9] or by thermal and thermochemical treatment (surface hardening, nitriding, cyanidation, etc.) [10].

In the first case, the strengthening is created due to the compaction of the outer layers and the introduction of residual compressive stresses into them, which contributes to increased durability.

During thermal and thermochemical treatment, the structure, chemical composition, and physical and mechanical properties of the surface layer change, which also cause compression stresses [11].

Taking into account the effect of surface quality [12] on fatigue strength can be performed by entering into the calculation the surface quality coefficient, which is determined [5,13]:

$$\beta_\sigma = \frac{\sigma'_R}{\sigma_R}, \quad (2)$$

or

$$\beta_\tau = \frac{\tau'_R}{\tau_R} \quad (3)$$

where σ'_R τ'_R – endurance limit of samples with a given surface treatment;
σ_R, τ_R - endurance limit of carefully polished samples;

On the other hand, numerous experimental studies of parts show that in places of sharp changes in the shape of the cross-section, in the presence of slots, leaks, holes, grooves, etc., as well as in places of contact of parts, increased local stresses occur (Fig. 4). Therefore, stress concentration should be considered as a local or local increase in stress caused by a sharp change in the cross-section of the part and the presence of macrodefects in the structure [14].

The strength of parts with stress concentrators under the action of static loads practically depends on local stresses [15].

It is also worth considering that with cyclically changing stresses in the zone of the stress concentrator, a microcrack is creating, which gradually develops into macrocracks and weakens the cross-section of the part to such an extent that a sudden brittle fatigue failure occurs [8].

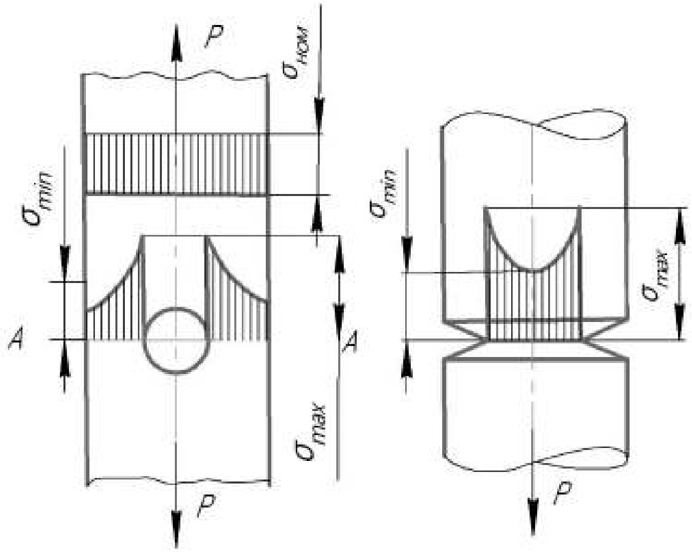

Figure 4 – To determine stress concentrators

Taking into account the influence of stress concentration on the reduction of endurance is carried out by entering into the calculation the effective concentration coefficient, which is determined [13]:

$$K_\sigma = \frac{\sigma_R}{\sigma_{RK}}, \tag{4}$$

where σ_R – endurance limit of smooth samples;

σ_{RK} – the endurance limit of samples with stress concentrators and cross-sectional dimensions are the same as those of smooth samples;

Numerical values of K_σ for the most typical stress concentrators are given in the reference literature. In the absence of reference data, K_σ can be determined approximately by the formula:

$$K_\sigma = 1 + q(\alpha_\sigma - 1) \tag{5}$$

where q – coefficient of sensitivity of the material to local stresses, for structural steels q=0,6-0,8;

α_σ – theoretical coefficient of stress concentration.

It is worth noting that when the size of the samples increases, the endurance limit decreases, especially in the presence of stress concentrators. This is due to the fact that the natural increase in the size of the part increases the number of material particles located near the surface and which are in the most stressed state. At the same time, the probability of the presence of various defects in the surface layer, which cause stress concentration, increases. With smaller parts, during mechanical

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processing, plastic deformation occurs to a relatively greater depth than with large parts, which also contributes to an increase in fatigue strength.

Conclusions Therefore, when designing parts of metallurgical equipment, taking into account the effect of stress concentration is possible by introducing the sensitivity coefficient of the material (4). When varying the coefficient of sensitivity of the material to local stresses in (4) in the numerical range from 0.6 to 0.8, it causes a decrease in the fatigue strength of the finished part by 20-40% in relation to smooth samples. Minimization of local stress concentrators such as holes, notches, cutouts, protrusions, as well as sharp changes in the cross-section of the part, will allow to increase the fatigue strength of the finished part in relation to the smooth sample by at least 20%.

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Аналіз конструктивних факторів, що впливають на втомну міцність деталей металургійного обладнання

Специфічні умови роботи металургійного обладнання, обумовлені не тільки динамічними навантаженнями, а й особливостями перебігу технологічного процесу, вимагають уваги при конструюванні їхніх вузлів з огляду на надійність та безвідмовну роботу. Завчасне планування більш подовжених строків служби найбільш відповідальних деталей вузлів металургійного обладнання є економічно обґрунтованим, тобто встановлення факторів, що впливають на втомну міцність деталей на етапі їхнього проєктування є важливим завданням, вирішення якого дозволить не тільки більш раціонально використовувати матеріали, а й подовжити життєвий цикл деталі в цілому.

Втома є доволі складним процесом накопичення пошкоджень матеріалу під впливом змінних напружень. Цей процес є поступовим, розтягнутим у часі та

призводить до зміни властивостей, утворенню тріщин, їхнього розвитку та руйнування. Його особливістю є те, що накопичення пошкоджень починається задовго до остаточної втрати роботоздатності деталі та протікає непомітно, отже в розрізі надійності та довговічності вузлів металургійного обладнання на перший план виходить саме проблема втомної міцності.

Встановлено, що на довговічність деталей металургійного обладнання значно впливають такі фактори як якість обробки поверхні готової деталі та концентратори напружень.

Визначено, що врахування впливу якості поверхні на втомну міцність можна виконати введенням у розрахунок коефіцієнта якості поверхні. Концентрацію напружень варто розглядати як місцеве або локальне підвищення напружень, викликане різкою зміною поперечного перерізу деталі та наявністю макродефектів структури.

При конструюванні деталей металургійного обладнання врахування впливу концентрації напружень можливе введенням коефіцієнта чутливості матеріалу. При варіюванні коефіцієнту чутливості матеріалу до місцевих напружень в числових межах від 0,6 до 0,8 викликає зниження втомної міцності готової деталі по відношенню до гладеньких зразків на 20-40 %. Мінімізація таких концентраторів місцевих напружень як отвори, виточки, вирізи, виступи, а також різкі зміни поперечного перерізу деталі, дозволить підвищити втомну міцність готової деталі по відношенню до гладенького зразка мінімум на 20 %.

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