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The durability of cryogenic structure materials

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According to world statistics, the main share of destruction in engineering practice occurs precisely because of fatigue, therefore, the fatigue problem is one of the most pressing scientific and technical problems of our time, which solution requires additional complex experimental and theoretical studies. The paper presents the experimental studies results of the effect of deep cooling on low-cycle fatigue and cyclic creep of stainless structural steel 03X20N16AG6 under conditions of a pulsating cycle of an external load change with a frequency of 0.033 s^{-1} (2 cycles/min) in air and environments of liquid refrigerants (nitrogen and helium) at temperatures of 293, 77 and 4.2 K, respectively

Keywords: structural alloys, deep cooling, low-cycle fatigue, cyclic creep

Довговічність матеріалів кріогенних конструкцій

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Світова статистика свідчить, що основна частка руйнувань в інженерній практиці відбувається через утому конструкцій і матеріалів. Тому проблема втоми є однією з найбільш актуальних науково-технічних завдань сучасності, вирішення якої потребує додаткових комплексних експериментальних і теоретичних досліджень. Серед відповідальних конструкцій і об'єктів низькотемпературного призначення широкого поширення набули зварні великогабаритні ємності і резервуари, що перебувають під тиском при температурах від 293 до 4,2 К. Такі будівельні конструкції, працюють в умовах циклічного від нульового розтягування, що повторюється з низькою частотою. Такі умови навантаження виникають при експлуатації посудин для транспортування і зберігання зріджених газів (кисню, азоту, водню, гелію), кріогенних трубопроводів, посудин високого тиску, кріогенераторов і т.п. Тому завдання оцінки несучої здатності і довговічності в умовах впливу циклічних навантажень в широкому діапазоні температур має надзвичайно важливе значення. У роботі наводяться результати експериментальних досліджень впливу глибокого охолодження на малоциклічна втому і циклічну повзучість нержавіючої конструкційної сталі 03Х20Н16АГ6 в умовах пульсуючого циклу зміни зовнішнього навантаження з частотою 0,033 $с^{-1}$ (2 цикл/хв) на повітрі і в середовищах рідких холодоагентів (азоту і гелію) при температурах 293, 77 і 4,2 К відповідно. Результати експериментальних досліджень підтвердили той факт, що в інтервалі температур 293 – 77 К на кривих циклічної повзучості стадія прискореної повзучості вельми обмежена по довговічності, або взагалі відсутня, тому можна з упевненістю сказати, що число циклів до руйнування стали 03Х20Н16АГ6 в малоциклової області буде визначатися її здатністю чинити опір деформації на сталій стадії

Ключові слова: конструкційні сплави, глибоке охолодження, малоциклічна втома, циклічна повзучість

Introduction

Metallurgy, mechanical engineering, energy, agriculture, food industry, energy, electronics, rocket and space technology - this is far from the complete list of national economy areas in which liquid cryogenic products (cryoproducts). The production volumes of such products and their use scale are constantly increasing. This is due to the fact that cryogenic temperatures (below 120 K) provide unique opportunities for the implementation of such physical phenomena and processes that do not manifest themselves under normal conditions, but are used very effectively in science and technology.

The solution of fundamental scientific problems and applied problems of both promising and current importance is determined by the level of cryogenic technology development and its practical application degree.

The continuous expansion of the liquid cryoproducts production scale has led in recent years to a significant increase in the volume of systems production for their storage and transportation. These systems, as a rule, are welded shell structures in execution, they are operated in difficult conditions of temperature and force effects. The specific weight of their products in the total output of cryogenic engineering products is very significant, and the operating conditions in comparison with other types of cryogenic structures are the most stressful.

For the manufacture of cryogenic shell structures, expensive non-ferrous alloys and special steels are used, the consumption degree that, taking into account the sufficient struction material consumption and the expanding production scale, is constantly increasing. Therefore, one of the most urgent for cryogenic engineering at present is the problem of reducing the material consumption of shell structures and increasing their reliability and durability. It is obvious that a solution to this problem for cryogenic engineering products can be achieved by improving the methods of their strength calculations based on taking into account the specific hardening effect of low temperature on structural alloys. Low-cycle fatigue is one of the main factors determining the durability (operating life) of the main structural parts. According to world statistics, a large part of failures in engineering occurs precisely because of fatigue. Therefore, the fatigue problem is currently one of the most relevant scientific and technical problems. Its solution requires additional complex experimental and theoretical studies [1].

Assessing the bearing capacity and durability under cyclic loading conditions is extremely important.

Welded large tanks and containers being under pressure at a temperature from 293 to 4.2 K are widespread among critical structures and units for low-temperature purposes. Such building structures operate under conditions of zero-to-tension stress cycle repeated at a low frequency. Such loading conditions take place during the use of containers for the transportation and storage of liquefied gases (oxygen, nitrogen, hydrogen, helium), cryogenic pipelines, high-pressure vessels, cryogenerators, etc. As a result of cyclic changes in loading (especially in concentrators zones), significant stresses can arise in the material of these structures. Therefore, stresses can reach and exceed creep strengths, which leads to their failure after a small number of loading cycles N_p [2].

Review of research sources and publications

In the total rolled production volume, structural steel makes the largest amount.

During their service, various facilities and structures made of these materials bear complex external loading (tensile, compressive, bending, shock, alternating signs or their combinations), experiencing fluctuations in ambient temperature in the summer and winter months. They are also exposed to the atmosphere and corrosive environment (sea and river water, aqueous solutions of salts, alkalis, acids, etc.).

Sharp drops in temperature under conditions of structurally constrained deformation lead to great residual stresses, which, combining with the stresses from external forces, complicate the operating conditions of the material and can lead to accidents if its quality is unsatisfactory [3, 4].

There are high demands on steel as a structural material. This is explained by difficult operating conditions of mechanisms and structures, especially in the northern regions, reduced design sections when creating modern structures, machine units, and mechanisms aimed to reduce their mass and metal consumption and the need to ensure reliability, durability, and safety of their operation. Depending on the conditions of use and operation, the requirements for structural steel may somewhat change, but the most important of them can be generally distinguished.

The structural steel of building structures must have a combination of high strength and plastic properties. Creep strength is the main structural characteristic among the strength properties. The choice of this characteristic as the basis for strength calculations is explained by the fact that at higher stresses, irreversible linear changes take place in the structure, which can lead to its failure. Increased creep strength allows reducing the design sections, and, consequently, the steel structure mass, or bearing higher operating stresses at the same mass.

As the structure operation experience shows, metal should have the property of local plastic deformation for relaxation of stress peaks in the zone of various concentrators (holes, grooves, undercuts, dents, lack of penetration, welding cracks, etc.) leading to the three-dimensional stress state. The better this property is, the more resistant the metal is to the occurrence and propagation of cracks at local overstresses, i.e., ultimately, the metal reliability in structures increases.

Along with the strength and plasticity properties, a very important role in ensuring reliability and structure performance is given to indicators that determine metal entering the brittle state. Firstly, this is the operating temperature of the constructed structure, the presence of a notch (concentrator), the load application rate, and the three-dimensional stress state degree.

Currently, the problem of increasing the metal resistance to brittle failure is becoming one of the most important. This is explained by the need to ensure the reliability of structures and machines under harsh climatic conditions. Besides, an increase in the scale of engineering structures, the use of large welded assemblies and structures with greater rigidity and lower flexibility than riveted structures, as well as the material behavior under conditions of a combination of high stresses and corrosive environments create conditions leading to brittle failure [5, 6].

To assess the tendency of steel to brittle failure, there is a widely used method of impact testing of standard samples with the determination of impact strength and temperature of entering the brittle state. The prevalence of this type of testing is explained not only by the simplicity of making samples and a simple method of the series test but also by the fact that statistically reliable relations are sometimes observed between the impact strength properties and the steel behavior during operation.

However, in most cases, impact strength testing of standard samples does not give a complete picture of the material behavior in a structure.

Therefore, they are trying to find better methods for determining the tendency of steel to enter the brittle state, which would more fully correspond to the real conditions of the metal behavior in structures.

While manufacturing metal structures and specific types of rolled products (for example, railroad rails), which bear alternating loads during operation, an important role is given to increasing the endurance limit as one of the factors determining their service life. The endurance limit increases with increasing strength, metal purity as for non-metallic inclusions, improving the quality of its surface. It is especially important to increase the endurance limit in the presence of stress concentrators.

A prerequisite for durability and reliability of structures and facilities is sufficiently high corrosion resistance. It is especially important to increase the corrosion resistance for high-strength steel due to decreased design sections of structural elements when using this steel. At smaller structural sections, corrosion damage is more dangerous than in thicker sections made of steel with reduced strength.

To prevent corrosion, steel is subjected to special alloying (chromium, nickel, copper, phosphorus), careful and timely painting, galvanizing, and phosphating. Recently, it has been proposed to apply a vinyl chloride covering on the metal surface.

Finally, structural steel must have satisfactory processing properties. First of all, it must meet the requirements of weld ability ensuring the same strength of the basic metal and the welded joint and has a minimal tendency to deformation aging. It must be processed without any special difficulties in the hot and cold states (rolling, forging, bending, processing on metal cutting machines), and be relatively inexpensive to manufacture.

Definition of unsolved aspects of the problem

It has been experimentally established that under low-cycle loading, directional plastic deformation of structural alloys takes place, which is most clearly manifested in the asymmetric loading cycle. The process of one-sided accumulation of plastic deformation ε_p occurring as a result of variable loads is called cyclic creep [1].

In some national works, as well as in the works of foreign authors, experimental data are given indicating that at high-stress levels and low loading frequencies, cyclic creep is a factor determining the material durability not only at the high-temperature but also for the temperature range of 293 and 77 K [1, 5].

Problem statement

Experimental study of the operating temperature effect on low-cycle fatigue, cyclic creep, and durability of materials of cryogenic structures based on the example of 03H20N16AG6 structural steel.

Basic material and results

In this work, experimental studies have been conducted to identify the effect of deep freezing on low-cycle fatigue and cyclic creep based on the example of 03H20N16AG6 stainless steel. Loading has been carried out in a pulsating cycle with a frequency of 0.033 s^{-1} (2 cycles/min) in air and liquid refrigerants (nitrogen and helium) at temperatures of 293, 77 and 4.2 K, respectively.

Analysis of the obtained experimental data has shown that directional plastic deformation takes place at the test temperature of 293 K in the range of fatigue life of $0.5\text{-}10^4$ cycles (Fig. 1). For comparison, the curves of cyclic creep for steel 03Kh13AG19 and PT3V titanium alloy are shown (Fig. 2, Fig. 3).

In 03H20N16AG6 steel, cyclic creep takes place most intensively in the zone of stresses corresponding to quasi-static failure (Fig. 1). The curves characterizing the kinetics of changes in plastic deformation depending on the number of loading cycles in this stress zone have three characteristic sections: unsteady decaying, steady, and unsteady accelerated creep. At the same time, plastic deformation mainly takes place during the last two stages.

A decrease in the test temperature to 77 K does not qualitatively change the nature of deformation and failure of the studied materials. However, there is a sharp deceleration of directional plastic deformation characterized by a change in the inclination angle of the steady creep sections on curves built for the same values of reduced stresses at test temperatures of 293 and 77 K respectively.

Thus, taking into account that in the temperature range of 293 and 77 K the stage of accelerated creep is very limited in terms of durability, or is absent at all on the cyclic creep curves, it can be said with confidence that the number of cycles before failure of these materials in the low-cycle zone will be determined by their ability to resist deformation at the steady-state.

At the same time, the kinetics of directional plastic deformation of 03H20N16AG6 steel at temperatures of 293 and 77 K can be described from the standpoint of the theory of hardening with a sufficient degree of accuracy. Significant changes in the behavior of structural materials occur when they are tested under deep freezing conditions (T = 4.2 K). The deformation mechanism changes, plasticity decreases sharply [7]. Deformation accumulated before failure takes place in the first loading half-cycle as a result of intermittent creep acts, the number of which is uniquely determined by the level of maximum cycle stresses [8 – 11].

With further cyclic loading, there is no plastic deformation of the material. This indicates that directional plastic deformation at T = 4.2 K is completely suppressed, and failure of the samples takes place as a result of the formation and development of a fatigue crack to the critical value.

At the same time, it should be noted that intermittent creep has been experimentally recorded for some structural materials at the initial stage of cyclic loading.

Consequently, the absence of cyclic creep in structural steel and alloys at T = 4.2 K cannot be considered as an established fact. Additional experimental studies are required for a deeper research of this phenomenon.

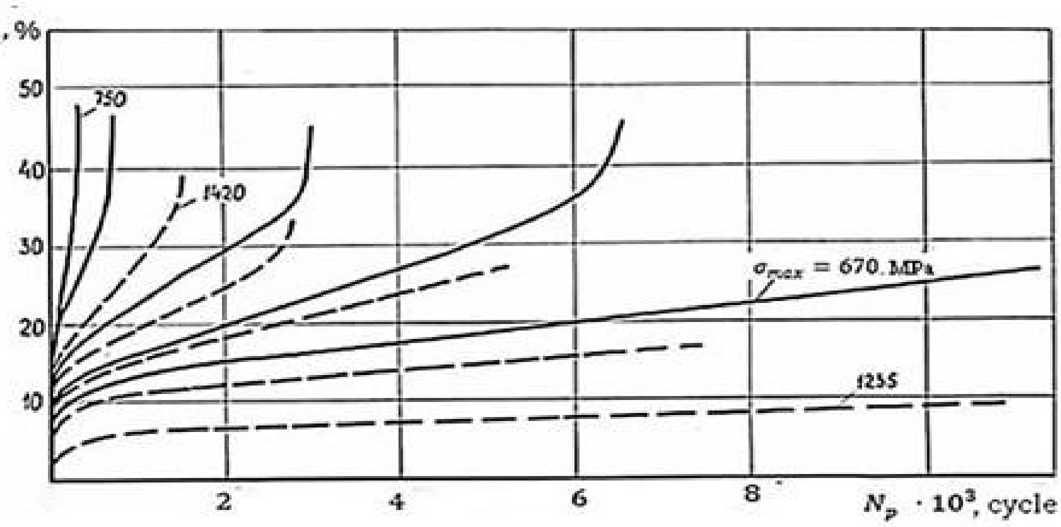

Figure 1 – Cyclic creep curves of 03H20N16AG6 steel
— - 293 K; ---- - 77 K

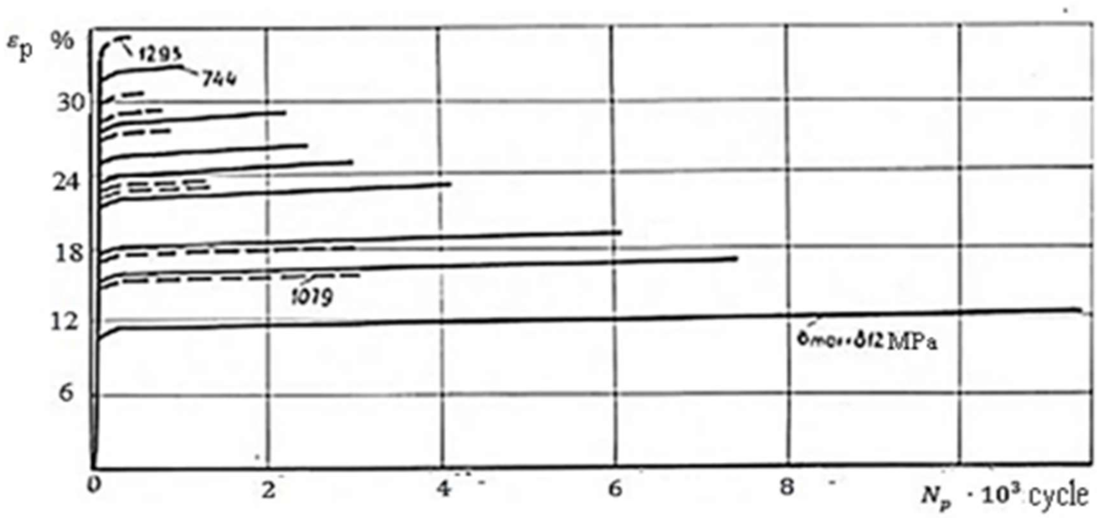

Figure 2 – Cyclic creep curves of 03Kh13AG19 steel
— - 293 K; ---- - 77 K

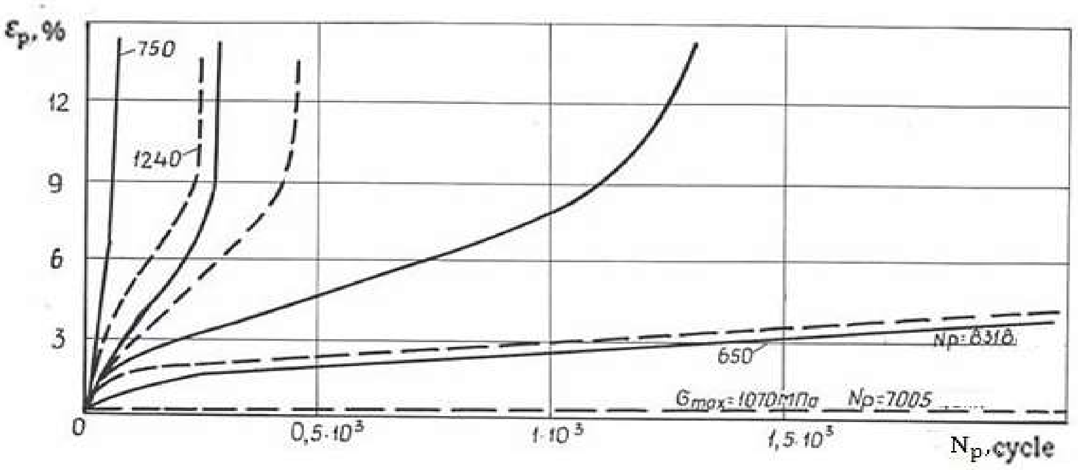

Figure 3 – Cyclic creep curves of PT3V titanium alloy
— - 293 К; ---- - 77 К

Conclusions

1. At the test temperature of 293 K in the range of durability of 0.5-10^4 cycles, 03H20N16AG6 steel has directional plastic deformation, which is a factor determining the durability of cryogenic structures.
2. For samples of 03H20N16AG6 steel, cyclic creep takes place most intensively in the stress range corresponding to quasi-static failure. They determine the service life of metal structures and specific types of rolled products.
3. Lowering the test temperature to 77 K does not make qualitative changes in the nature of the material deformation and failure. Therefore, the durability of cryogenic structures in this temperature range is completely controlled by the cyclic creep intensity.
4. At T = 4.2 K, directional plastic deformation of 03H20N16AG6 structural steel is completely suppressed, and failure takes place as a result of the formation and development of a fatigue crack to the critical value.

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