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Decrease in mechanical properties, transient brittleness temperature, fatigue strength and corrosion resistance of Fe-C alloys

Boris Ermakov¹, Svetlana Vologzhanina², Sergej Bobrovskij³, Sergej Ermakov¹, Nikita Kanatnikov⁴, Alexander Khaimovich⁵ and Jurij Melnik⁶

¹ Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation

² Saint Petersburg National Research University of Information Technologies, Mechanics and Optics University ITMO, Saint Petersburg, Russian Federation

³ Togliatti State University, Togliatti, Russian Federation

⁴ Orel State University, Orel, Russian Federation

⁵ Samara National Research University, Samara, Russian Federation

⁶ Moscow State Technological University Stankin, Moscow, Russian Federation

E-mail: bobri@yandex.ru

Abstract. The paper presents the results of studies on the availability and resistance to brittle fracture of perspective austenitic chromium-nickel-manganese cryogenic steels, depending on the concentration and ratio of the nitrogen and vanadium content. The optimum content of these elements in deformed steels determined, the results of the studies and recommendations on the doping system are confirmed by the results of full-scale tests of low-temperature equipment under internal pressure in liquid nitrogen.

1. Introduction

Together with the International Academy of Cold, a set of works was carried out to clarify the performance of energy technology equipment made of carbon steel and operated in cold climates. The aim of the work was to create common principles for determining the life of equipment from these steels and to determine the factors that reduce the reliability and durability of equipment made from them [1, 2]. To this end, a model was developed for the development of grain-boundary segregations in low-carbon (0.05–0.20 % carbon mass) Fe – C alloys and an analysis of the effect of segregation processes on the mechanical properties, fatigue strength and corrosion resistance of these materials [3, 4].

The question of improving the mechanical properties of alloys is relevant from a technological point of view [5, 6]. Fatigue strength can be changed after processing technologies that are not related to chip removal, for example, by surface plastic deformation [7, 8]. This type of processing relates to finishing and hardening technologies [9, 10]. Processing of Fe – C alloys in the absence of lubricants can adversely affect the mechanical properties of the part [11, 12]. Tests show the need to pay attention to the durability of the tool for this type of treatment [13, 14]. The processing of the considered Fe – C alloys according to the above-mentioned technology will make it possible to improve the mechanical properties of finished products [15, 16, 17].



2. Materials and experimental technique

The tests were carried out on samples that were subjected to isothermal exposures in the temperature range of 200 - 900 °C. The exposure time varied from 0.01 to 10000 h and was selected taking into account the possible actual heating of the metal of the equipment of low-temperature equipment. The time required for the repair welding operation was taken as the minimum exposure time; the total term of high-temperature process heating for the service life of the equipment for gas cleaning and liquefaction systems was taken as the maximum. This made it possible to estimate the role of temperature and duration of heating in the redistribution of carbon and impurity elements in the boundaries of Fe – C grains of alloys, to trace the kinetics of the process of formation, development and resorption of grain boundary segregations of impurity atoms during long-term high-temperature processing of materials of low-temperature equipment. The distribution of impurity elements in the boundaries of hereditary (austenitic) and real (ferritic) grains has been studied.

3. Results

It has been shown that during high-temperature (above AC3) exposure, the boundaries of the Fe – C grains of the alloys are enriched with phosphorus and sulfur atoms, which form grain-boundary segregations, developing by a non-equilibrium mechanism.

Thus, in boiling Fe – C alloys, the grain-bound segregation of sulfur atoms can exceed its average content by about 1600 times (1273 K, 100 h), continuously increasing with increasing heating time and temperature. Introduction to Fe – C alloys of manganese, in the process of cast reducing, binds sulfur to a compound of the MnS type, and the concentration of sulfur atoms in the grain boundaries decreases sharply. The segregation of phosphorus atoms in the grain boundaries during heating above the AC3 point reaches a maximum concentration in the first 30 minutes of isothermal equalizing, and with a further increase in equalizing time slightly decreases. Maximum concentration levels of phosphorus atoms within austenite grains are achieved at isothermal equalizing at 600 °C, and the shape of grain-bound phosphorus segregation in this temperature zone is as close as possible to the equilibrium state - the most dangerous from the point of view of segregation on the properties of Fe-C alloys in general [18].

In the same temperature range, the maximum development of carbon segregation is noted within the boundaries of the Fe – C grains of the alloys. The maximum development of nitrogen atom segregations within the boundaries of Fe – C alloys falls within the temperature range of 400–450 °C. The saturation of the boundaries with nitrogen, basically, is completed in the first 30 - 60 minutes of isothermal exposures, and in the future, the process gradually fades out. Silicon atoms exhibit a maximum propensity for the formation of grain-boundary segregations in the temperature range of 600-700 °C.

Table 1. The effect of isothermal soaking temperature on the depth of the corrosion defect.

Element content in the alloy (mass %)		The penetration depth of the corrosion defect $\mu\text{m} / \text{h}$ after isothermal soaking, °C						
		200	300	400	500	600	700	800
C – 0.05	Depth	167.2	248.6	371.2	415.2	377.6	288.4	315.3
	Σ segr.*	7.26	8.02	18.28	22.96	51.96	16.31	26.09
C – 0.05; Mn – 0.23; Al – 0.05	Depth	131.2	151.2	150.8	162.8	297.3	186.5	180.1
	Σ segr.*	3.66	4.32	3.71	5.50	30.21	8.02	7.35
C – 0.20; Mn – 0.31; Al – 0.04	Depth	181.2	177.3	160.8	183.4	321.2	248.4	181.2
	Σ segr.*	4.45	4.38	2.70	4.42	34.33	7.28	3.98

* - Σ segr. – total content of impurity atoms in the boundaries of austenitic melting grains (% atoms)

4. Verification

The possibility of spreading the results of studies on the formation and development of grain-boundary segregations of impurity atoms in Fe – C alloys onto carbon steel of industrial production was studied

and proved. On the basis of a reasonable segregation model, an analysis was conducted of the reliability of the obtained prediction of changes in the complex of physical and mechanical properties of carbon steels after prolonged high-temperature heating.

For this purpose, metal cuts from auxiliary equipment for energy technology were analyzed. Cuttings of steels 10 and 20 of 4 steam pipelines, which worked for 130–249 thousand hours, were investigated. at temperatures of 200 - 450 °C and 4 vessels, working under pressure for 214 - 243 thousand hours at 270 - 475 °C. The equipment was installed in the open air, in the regions of Siberia and the Far North, where the average temperature of the coldest five-week days in the year is below –40 °C.

The analysis of metal cuts from equipment that had been operating for an estimated service life of more than 100 thousand hours confirmed the data obtained on the unity of segregation processes in experimental alloys and steel of industrial production. According to the results of studies of the cuttings, a number of practical conclusions were made, which significantly reduce the amount of monitoring of the actual state of the metal of equipment made from carbon steels, which is carried out during the work on extending its service life beyond the bounds.

It is shown that all equipment from carbon steels can be divided into two groups. The first is resource-dependent equipment with an operating temperature of more than 400 °C, the resource of which should be limited in accordance with the Rules for the Construction and Safe Operation of Rostekhnadzor Objects of the Russian Federation (usually 100 thousand hours). Extending the service life of such equipment is possible only when conducting direct tests of mechanical properties, since at given temperatures, segregation processes in steels lead to a redistribution of impurity elements in the grain boundaries, intensive development of grain-boundary segregations of phosphorus and other impurity elements viscosity, plasticity, fatigue strength and corrosion resistance.

The second is resource-independent with an operating temperature not exceeding 400 °C. At these temperatures, segregation processes in carbon steels are inhibited, changes in material properties during long-term (over 100 thousand hours) operation do not occur and reliable data on the mechanical properties of the metal can be obtained indirectly, for example, by recalculating its hardness measurements. Thus, the service life of such equipment can be extended on the basis of an analysis of its actual condition only by non-destructive methods, which greatly simplifies and cheapens the cost of work, reduces the time for their execution.

Based on the research, it was found that to increase the reliability and durability of materials made from carbon steels and operated in Siberia and the Far North, it can be recommended to implement processes that facilitate the grinding of austenitic grain - thermal cycling, micro-doping with strong carbide and nitride-forming elements in concentrations not exceeding their limiting solubility in solid solution, modifying with rare-earth elements and silicocalcium. At present, several new grades of carbon steels additionally microalloyed with vanadium and niobium, modified with calcium and other chemical elements, have been developed, the use of which has reduced the transition temperature of materials to temperatures below - 60 °C.

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Conclusions

It has been established that the decrease in mechanical properties, transitional brittleness temperature, fatigue strength and corrosion resistance of Fe – C alloys during isothermal exposures directly depends on the grain boundary distribution of impurity atoms.

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