

# Hot-salt corrosion PT-7M, 42XHM, Inconel 690 and Incoloy 800 Alloys

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## 1. Introduction

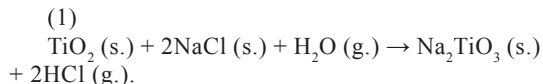
This work was carried out with the aim of studying the resistance of pipe samples from PT-7M, 42XHM, Inconel 690, Incoloy 800 alloys to hot-salt corrosion upon contact with crystalline chlorides, alkali metal bromides at temperatures typical for the operation of heat exchange equipment from 150° C to 300 ° C . Titanium alloys used in heat exchange equipment are subject to hot-salt corrosion [1].

From the operational experience of naval aviation, it is known that hot-salt corrosion is a serious danger for equipment made of titanium alloys, but the working temperatures in these cases are much higher than the temperatures characteristic of heat exchange equipment. Studies of the causes of destruction were carried out at temperatures of 400°C and above [2]. The use of the results obtained in them does not provide sufficient information and representativeness in the temperature range of 150 - 300°C. Special tests were carried out to determine the resistance to hot-salt corrosion of the PT-7M, 42XHM, Inconel 690, Incoloy 800 alloys.

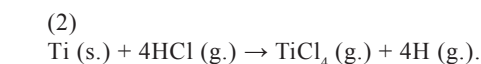
## 2. Mechanism of hot-salt corrosion of titanium alloys

As noted in [3-5], hot-salt corrosion occurs when contacting titanium and titanium alloys with crystalline halide salts (chlorides, bromides, iodides) and the presence of water (bound in crystal hydrates of salts, occluded in salt crystals, from an air atmosphere) at temperatures above 250°C. Crystal salt of alkali and alkaline-earth metals causes hot-salt corrosion most effectively. Titanium alloys, containing, as well as alloy PT-7M, aluminum, are the most susceptible to this type of corrosion. It can be assumed that hot-salt corrosion is a type of chemical corrosion, not electrochemical,

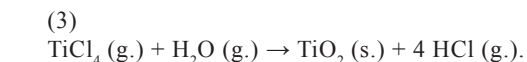
it is associated not with dissolution, but with the appearance of new chemical compounds during the interaction of crystalline salts and metal. These substances are formed mainly at the grain boundaries, where the concentration of impurities is increased. They have physicochemical properties different from corrosive metal and, therefore, foreign inclusions appear at the base of the metal and, accordingly, the continuity is broken. Researchers [3-5] associate hot-salt corrosion with the successive course of the following reactions:



The oxide film on titanium and titanium alloys reacts with crystalline salts and water to form sodium titanate ( $\text{Na}_2\text{TiO}_3$ ) and hydrogen chloride (HCl), which then reacts with titanium to release atomic hydrogen and gaseous titanium chloride IV ( $\text{TiCl}_4$ ):



Hydrogen at the time of release is absorbed by the metal, which leads to hydrogenation in the area of corrosion processes, and titanium chloride IV is subject to hydrolysis under the action of water vapor to form hydrogen chloride and, eventually, through a series of intermediate products of hydrolysis, titanium oxide ( $\text{TiO}_2$ ):



Hydrogen chloride can further react with titanium by reaction (2) to form titanium chloride IV ( $\text{TiCl}_4$ ), and so on. The proposed mechanism explains the high rate of occurrence of hot-salt corrosion.

**Table 1.** Chemical composition of samples from PT-7M and 42XHM (% mass).

Material	Ni	Cr	Fe	Ti	Al	Zr	Si	O	H	N	Mn	Σimp
IIT-7M	-	-	0.25	0.04	1.9	2.3	0.12	0.07	0.006	0.03	-	0.30
42XHM	base	42.1	0.6	0.25	0.4	-	0.25	-	-	-	0.2	-

**Table 2.** Chemical composition of samples Inconel 690 and Incoloy 800 (% mass).

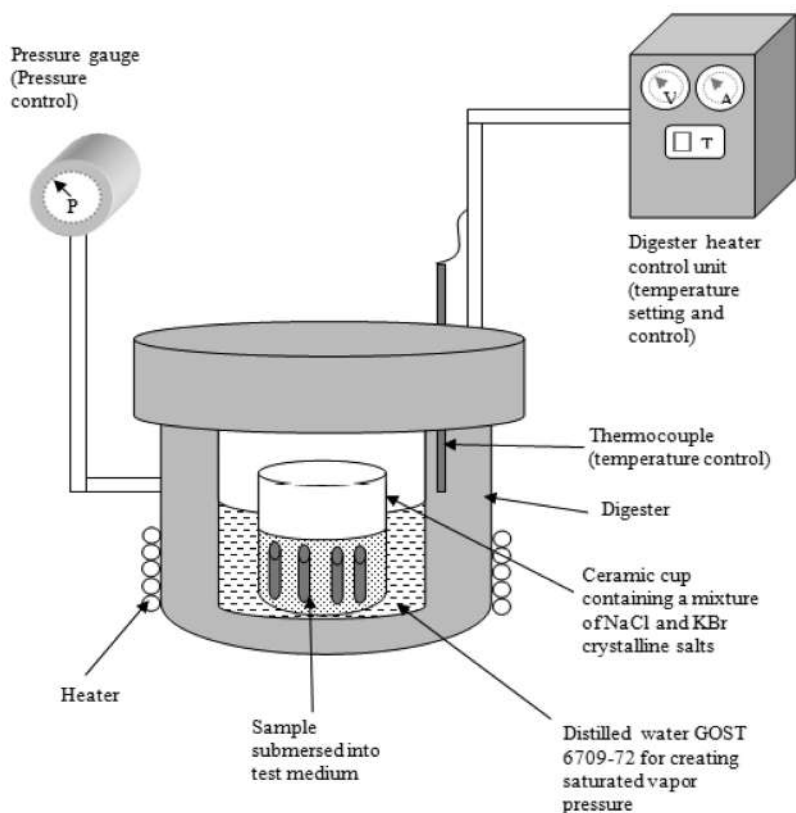
Material	C	Ni	Cr	Fe	Mn	Cu	Al	Ti	Si, no more	S, no more	P, no more
Inconel 690	0.019	base	30,1	9,2	0,35	0,2	-	0,5	0,35	0,003	0,0012
Incoloy 800	0.09	32	21,3	rest	1,45	0,73	0.47	0.24	0,81	0,007	-

**3. Materials and research methods**

The objects of study are samples - fragments of pipes made PT-7M, 42XHM, Inconel 690 and Incoloy 800 alloys. The following were tested: PT-7M alloy – is a pipe fragment 13x1.5 mm and length 40 mm; 42XHM alloy – is a pipe fragment

13x1.5 mm, length 20 mm; Inconel 690 alloy – is a pipe fragment 25.5x3.5 mm, length 20 mm; Incoloy 800 alloy – is a pipe fragment of 12.5 x1.5 mm and a length of 20 mm. The chemical composition of the samples is presented in table. 1 and 2.

Comparative corrosion tests of samples were carried out on the stand for corrosion tests [7],



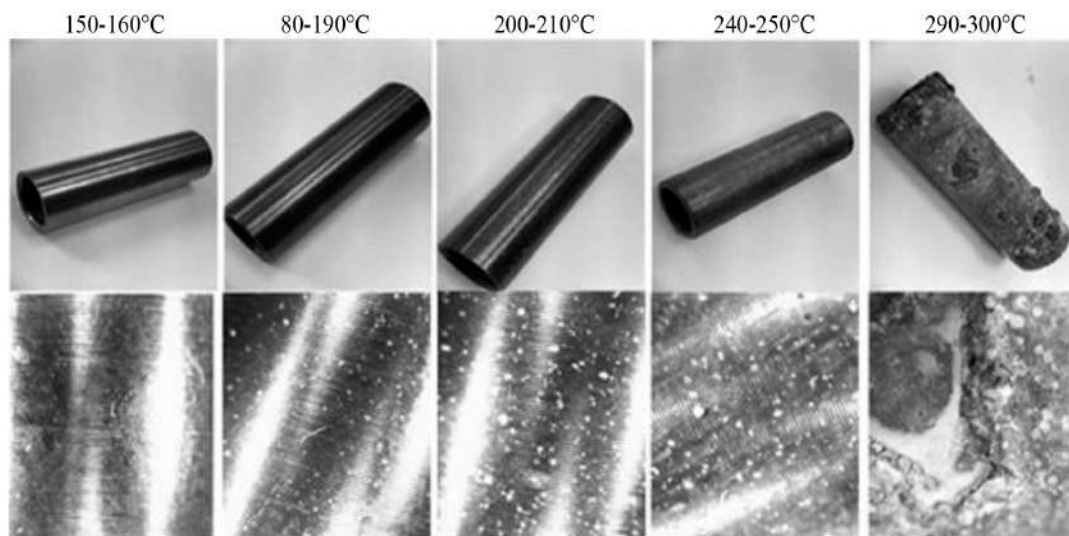
**Figure 1.** Corrosion Test Stand Autoclave

shown in Fig. 1, in a mixture of crystalline salts of NaCl and KBr, taken in a ratio of 300:1 by mass, corresponding to the ratio in sea water, the size of salt crystals did not exceed 0.3 mm. The test duration is 500 hours. The temperatures at which the tests were carried out (150, 180, 200, 240, 290°C) completely cover the temperature range of operation of heat exchange equipment. In order to exclude mutual

influence, samples from different materials were tested separately in different autoclaves, for each temperature tests were carried out on three samples. When testing conditions of mode of contact with the air atmosphere and mode of contact with water vapor were simulated:

Before testing, the samples were degreased, then washed with distilled water, dried in a drying

**Figure 2.** Samples of ПТ-7М alloy after testing in a mixture of crystalline salts in contact with the air atmosphere



**Figure 3.** Samples of ПТ-7М alloy after testing in a mixture of crystalline salts at a pressure of saturated water vapor.

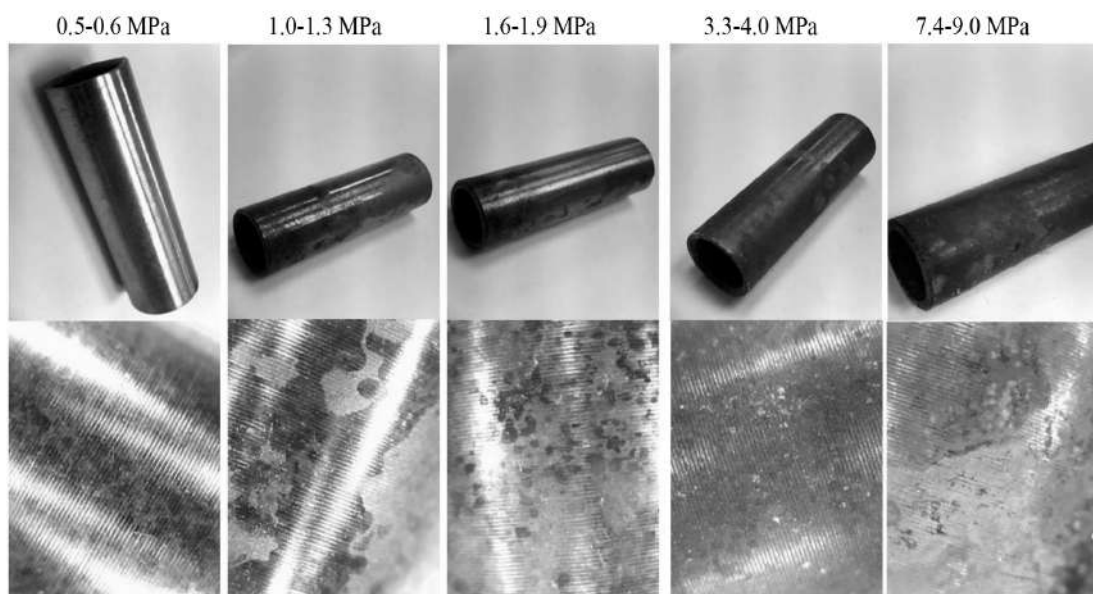


Figure 4. Samples of 42XHM alloy after testing in a mixture of crystalline salts in contact with the air atmosphere

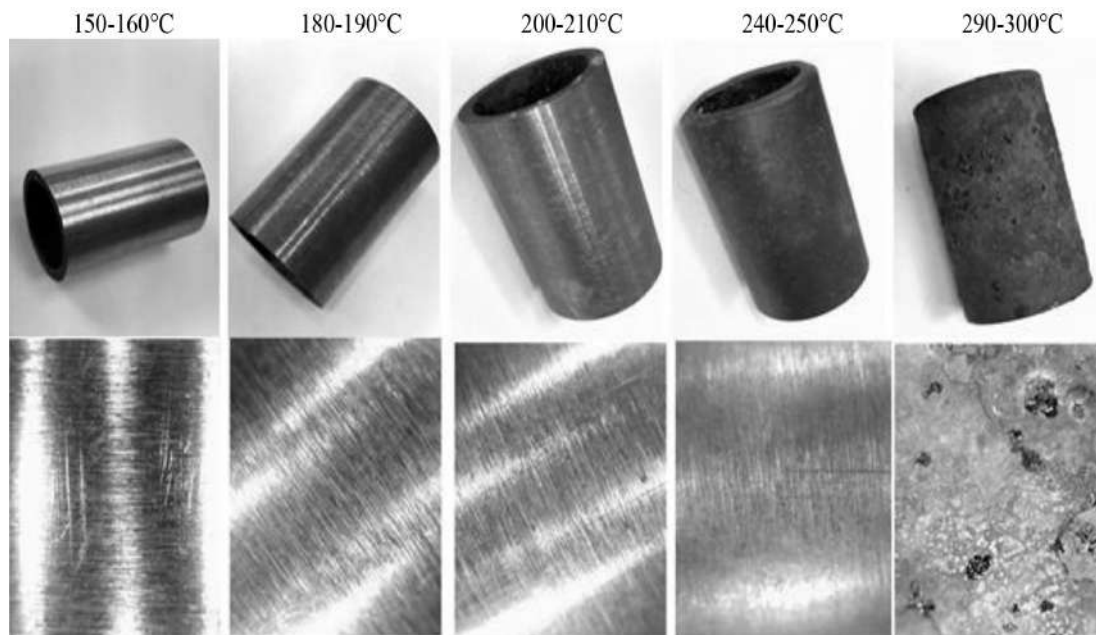


Figure 5. Samples from an 42XHM alloy after testing in a mixture of crystalline salts at a pressure of saturated water vapor

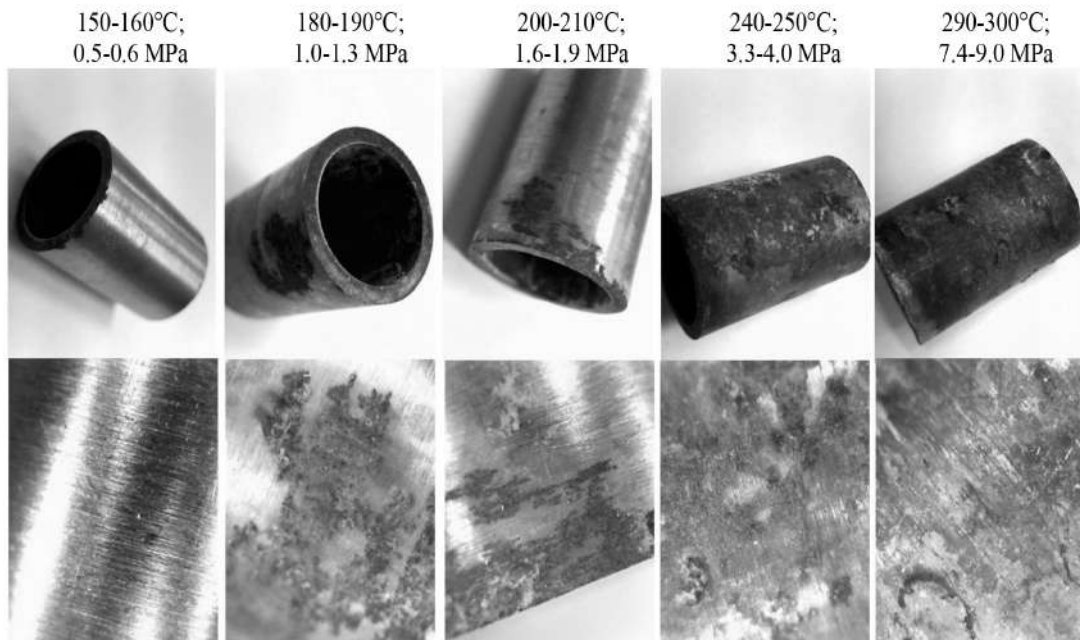




Figure 6. Samples of Inconel 690 alloy after testing in a mixture of crystalline salts in contact with the air atmosphere.

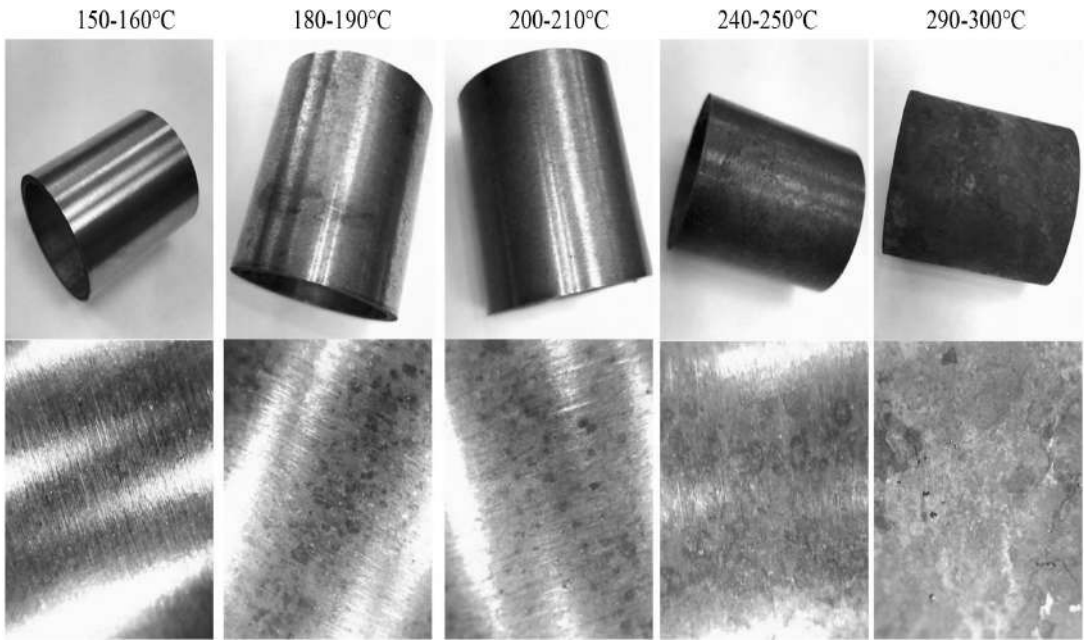


Figure 7. Samples of Inconel 690 alloy after testing in a mixture of crystalline salts at a pressure of saturated water vapor

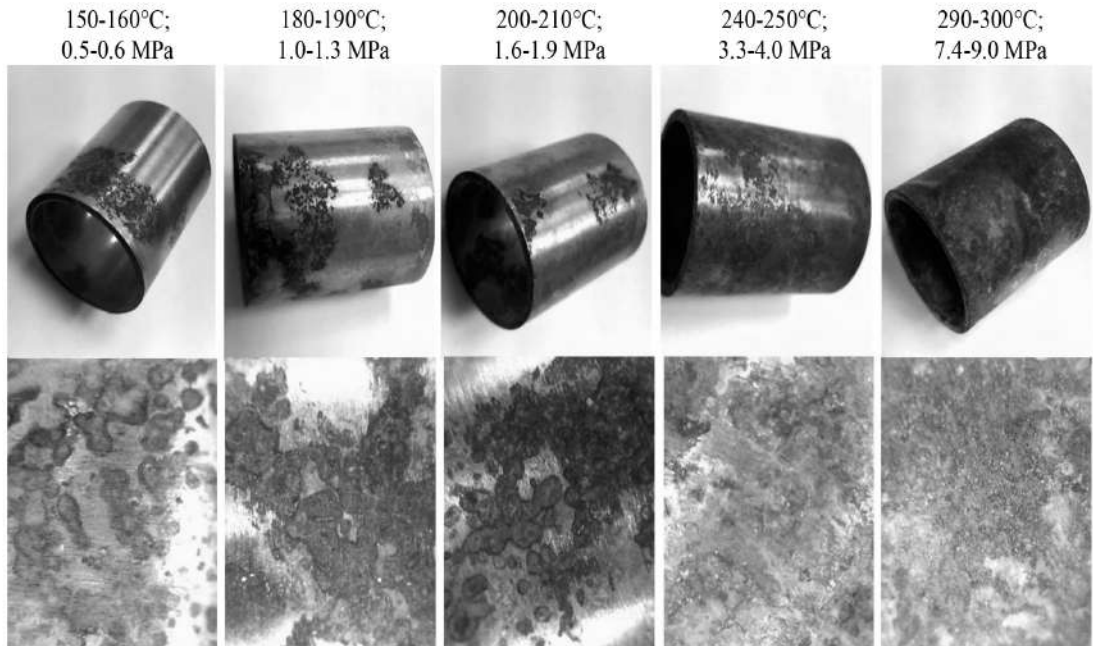


Figure 8. Samples from Incoloy 800 alloy after testing in a mixture of crystalline salts when in contact with an air atmosphere

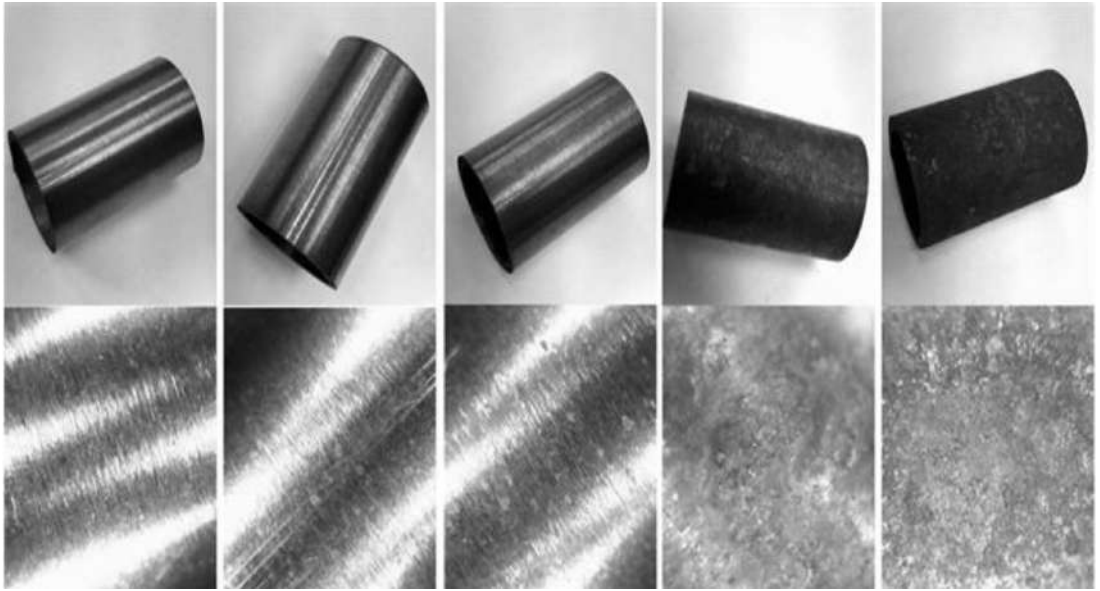
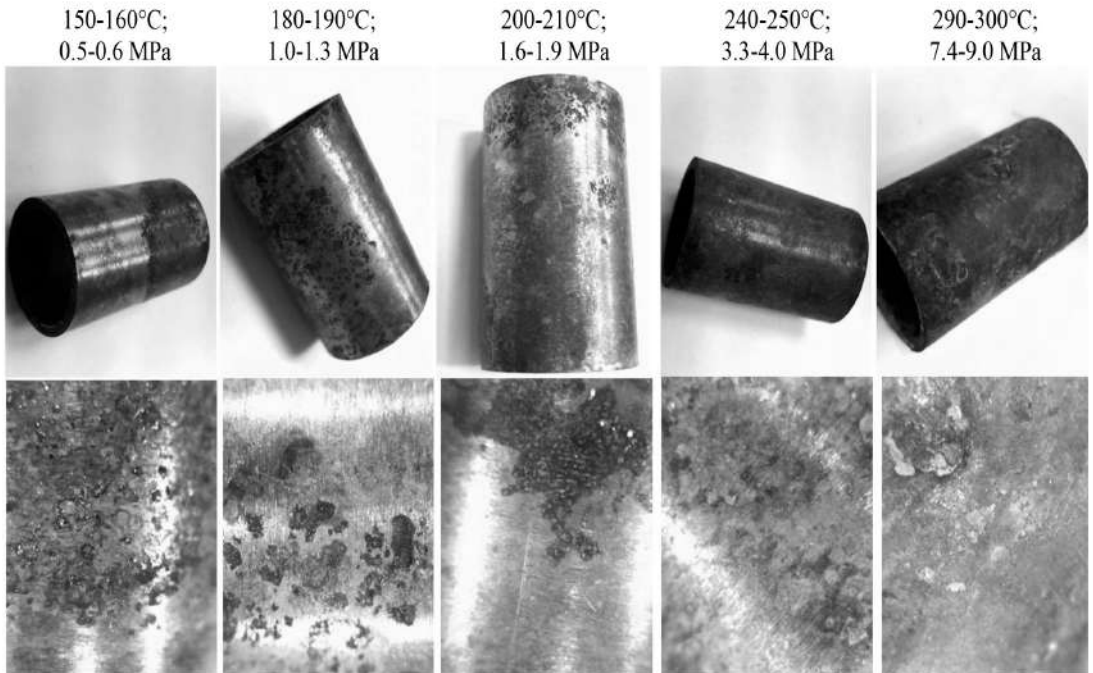


Figure 9. Samples from Incoloy 800 alloy after testing in a mixture of crystalline salts at saturated water vapor pressure



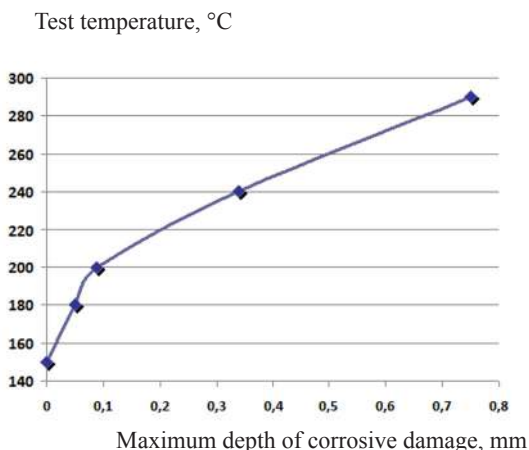
chamber at a temperature of 100°C. Then they were placed in a mixture of salts poured into a ceramic beaker, which was installed in an autoclave. When tested in conditions of contact with the air atmosphere, the autoclave cover was not sealed, water was not poured into the autoclave.

#### 4. Results of comparative corrosion tests of samples

Photographs of samples from PT-7M alloy, 42XHM, Inconel 690, Incoloy 800 alloys after testing in a mixture of crystalline salts at atmospheric pressure and at water vapor pressure in the temperature range of 150-290°C (Fig. 2 - 9). Photographs of sample surfaces were taken at a magnification of 50x.

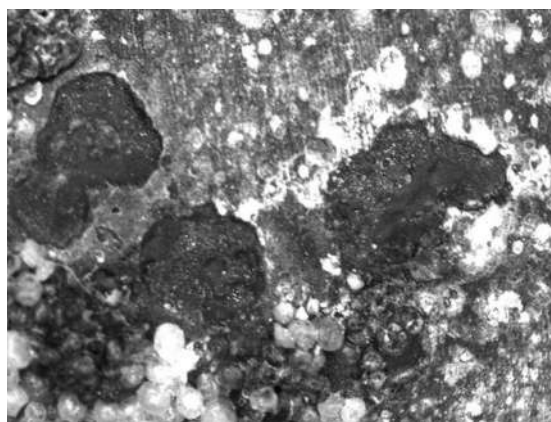
From fig. 2 shows that the rate of hot-salt corrosion of the PT-7M alloy upon contact with atmospheric air increases with increasing temperature. Traces of hot-salt corrosion were found at temperatures of 180-190°C, with increasing temperature the depth of local lesions - ulcers, increases. On the surface of samples of alloy PT-7M, tested at temperatures of 290-300°C, the most deep local corrosion lesions are observed. According to the results of metallographic research, it can be stated that their depth varies on average in the range from 0.2 mm to 0.3 mm, maximum depth is 0.75 mm. The graph of the maximum depth of the recorded corrosive damages - ulcers versus test temperature is shown in fig. 10. It should be noted

**Figure 10.** Dependence of the maximum depth of corrosive damages - ulcers on pipes made of PT-7M alloy on the temperature of testing, medium is air atmosphere, test duration 500 hours

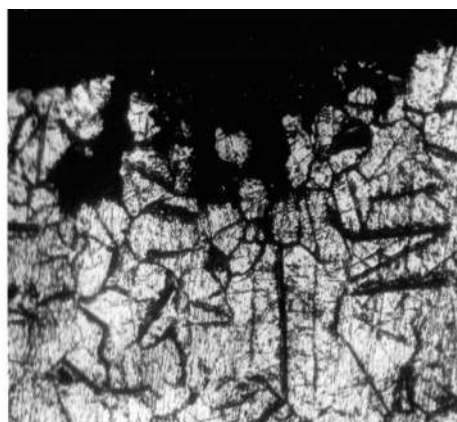


the intergranular character of the flow of hot-salt corrosion (Fig. 11). The hydrogen content in the metal of the samples tested at temperatures of 290-300°C, measured by a spectral method in the area of corrosive damages after appropriate preparation of the sample surface, ranged from 0.010% mass to 0.014% mass, which exceeds the initial hydrogen content in the sample — 0.006% mass.

**Figure 11.** - a) local corrosion damages on the surface of a sample of alloy PT-7M after testing in contact with an air atmosphere, at a temperature of 290-300°C (50x). b) the state of the surface layers in the area of local damages at 150x magnification (intergranular destruction).



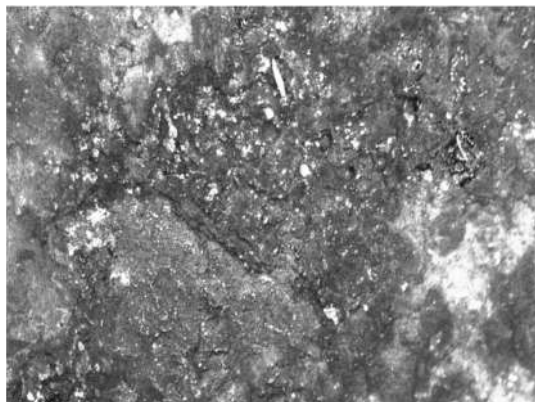
a)



b)



**Figure 12.** Local corrosion damages to a sample of alloy 42XHM after testing in contact with an air atmosphere at a temperature of 290-300°C (50x).



As can be seen from fig. 3, when tested in an atmosphere of saturated water vapor, with an increase in temperature and pressure, the surface of specimens made of PT-7M alloy lost metallic luster. There were no traces of hot-salt corrosion under these conditions, the passive state of the sample surfaces is maintained at all test temperatures.

After testing in crystalline salts, the surfaces of the 42XHM alloy specimens (Fig. 4) lost metallic luster upon contact with the air atmosphere at temperatures from 150°C to 250°C. Local surfaces of corrosion damages in the form of ulcers with deposits of corrosion products of green color - a mixture of chromium and nickel oxides and chlorides (Fig. 12) were detected on the surfaces of 42XHM alloy samples tested at a temperature of 290-300°C. When tested in an medium of saturated water vapor, local corrosion damages in the form of ulcers were found on the surfaces of samples from alloy 42XHM (Fig. 5). According to the results of the metallographic study, the depth of the damages, both when tested in the medium of atmospheric air and in the atmosphere of water vapor, averaged 0.1 mm. Intergranular damages are not marked.

The surfaces of samples made of Inconel 690 alloy (Fig. 6), after testing in contact with an air atmosphere at temperatures from 150°C to 250°C, have lost their metallic luster. The surfaces of Inconel 690 alloy sample tested at temperatures of 240-250°C, 290-300°C are completely covered with deposits of products of general corrosion of the alloy. Local corrosion damages on the surfaces of the samples was not detected. When tested in an medium

of saturated water vapor (Fig. 7), local corrosive damages in the form of extensive ulcers were detected on the surfaces of the samples. According to the results of metallographic studies, their depth averaged 0.1 mm.

Samples of Incoloy 800 alloy (Fig. 8) after testing in contact with the air atmosphere lost metallic luster. After testing, a dense layer of products of general corrosion of the alloy was fixed on the surfaces of the samples after testing at temperatures of 240-250°C, 290-300°C. When tested in an medium of saturated water vapor (Fig. 9) at temperatures 150-160°C, 180-190°C, 200-210°C on the surfaces of all samples from Incoloy 800 alloy, separate corrosion spots are fixed, the surface area of which increases with increasing temperature. The surface of the samples tested at temperatures from 240-250°C, 290-300°C is covered with a layer of corrosion products of the alloy. According to the results of metallographic studies of local corrosion damages on the surfaces of the samples after testing in ambient air and water vapor was not detected.

### 5. Results and discussion

The course of hot-salt corrosion of samples made of PT-7M alloy in contact with an air atmosphere was recorded at a test temperature of 180-190°C and higher. It seems that for heat exchange equipment made of PT-7M alloy, the most dangerous mode is contact with crystalline alkali metal chlorides and bromides in an air atmosphere at a temperature of 300°C. Saturated water vapor provides a passive state of the surfaces and prevents the occurrence of hot-salt corrosion in the entire operating temperature range.

It should be noted that it is possible to increase the resistance of titanium alloys to hot-salt corrosion by reducing the concentration of impurities at the grain boundaries. Thus, an increase in resistance to hot-salt corrosion was observed on submicrocrystalline modifications of titanium alloys with grain sizes in the range from 0.2  $\mu\text{m}$  to 1  $\mu\text{m}$  obtained by the method of equal-channel angular pressing [8.9].

Separately, it should be noted that the samples from 42XHM, Inconel 690, Incoloy 800 alloys showed higher corrosion resistance under the test conditions compared to samples from PT-7M alloy.

### 6. Conclusion

1. The temperature limit for the onset of hot-salt corrosion in contact with the air atmosphere for the



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titanium PT-7M alloy according to the test results is 180°C.

2. For PT-7M alloy, the most dangerous mode in terms of the development of hot-salt corrosion is contact with crystalline salts, alkali metal chlorides and bromides, in air at 300°C.

3. Humidification of the atmosphere prevents the occurrence of hot-salt corrosion PT-7M in the entire temperature range of the tests performed.

4. Samples from alloys 42XHM, Inconel 690, Incoloy 800 showed higher corrosion resistance under test conditions compared with samples from alloy PT-7M.

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