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CHROMIUM-MANGANESE STEEL SCREW
PROPELLERS

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CHROMIUM-MANGANESE STEEL SCREW PROPELLERS

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CHAPTER I

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CHARACTERISTICS OF FAILURE OF SHIPS' SCREW PROPELLERS AND MATERIALS PRESENTLY USED IN THEIR MANUFACTURE

Research carried out in the Soviet Union and abroad during the past few years has established that failure of screw propellers of all types of ships in use occurs as a result of:

1. collisions with some obstacles (solid objects), which, when propeller material is not sufficiently ductile, lead to the formation of large, branched cracks and eventual fracture of the blades. Propeller blade failure is observed most often in propellers which operate in shallow water and which are not equipped with some shielding devices, as well as in propellers of ships cruising in waters with calved ice.

2. electrochemical corrosion processes. This type of failure takes place in screw propellers of seagoing ships and in ships which serve as a combination of seagoing ship and riverboat. Screw propellers of riverboats are subjected to a lesser degree of corrosion failure.

3. cavitation erosion processes, arising because of friction between the surface of propeller blades and the water stream at high circumferential velocities, as well as because of hydraulic impacts due to the "implosion" of cavitation bubbles.

In addition to the above-mentioned types of failure, which have been thoroughly studied and described in domestic and foreign literature, screw propellers operating

*Numbers in the right margin indicate pagination in the original text.

in water containing suspended abrasive particles wear under the action of these particles. In most cases, failure of ships' propellers occurs under the combined action of several of these factors, for example, corrosion and erosion, cavitation and aorasion, etc.

The principal types of screw propeller failure on seagoing ships and riverboats which have not been adequately described in domestic literature are described below.

1. Hydroabrasive Wear of Screw Propellers on Shallow Draft Ships

Screw propellers on ships which are used in shallow water operate under more severe conditions as compared to those in deep water. River beds of shallow areas of major rivers, as well as of shallow rivers, are contaminated with obstructions which often cause breakage in screw propellers. /8

The most efficient type of ship propulsion for shallow water is water jet propulsion. A 3 or 4-bladed wheel and a 4 or 5-bladed directing apparatus rigidly installed in the shaft of the water supply tunnel are usually used for this purpose. The wheel is protected by a grating to prevent breakage in the event of collision with foreign objects. As a rule, the speed of wheel rotation (500-700 rpm) does not exceed the maximum permissible speed at which the circumferential velocity of peripheral points on the blade (wheel diameter 0.6-0.7 m) reaches the magnitude at which cavitation occurs; therefore, cavitation-erosion breakdown is not observed on working wheels in water jet propulsion.

Failure of water jet wheels is not similar to that occurring as a result of corrosive action of water upon metal. To determine the nature and extent of metal failure, wheels were installed in both water jet and screw propeller ships used under the same conditions in shallow water.

Wheel 1. A wheel 0.64 m in diameter, with a disc ratio of 0.66 and a variable cross-section pitch, was installed in a water-jet propelled pusher tug with a power rating of 150 hp. The wheel's speed was 668 rpm. Material was 25L steel. Average draft of the ship--0.5 m.

This pusher tug was used on the Angara River between Kezhma and Strelka, 624 km apart. The prevailing depth



Fig. 1. Wear of the wheel of the water-jet propelled ship after 400 hours of operation in shallow water (wheel 1).

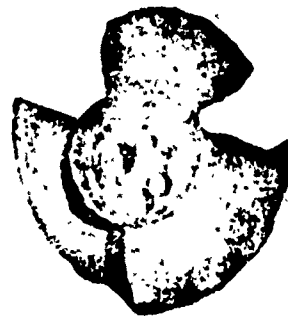


Fig. 2. Wear of the wheel of the water-jet propelled ship after 850 hours of operation in shallow water (wheel 2).

of this part of the river is 0.9-2.5 m.

The condition of wheel surfaces was inspected after 400 hours of service. It was found that the suction and delivery surfaces of blades did not have any traces of failure. The exit and peripheral edges were also in good condition; however, considerable metal failure was observed along the complete length of intake edges of blades, with the exception of a small part of the edge at the blade root. Metal destruction areas 15x250 mm, in size were of the abrasive wear type, with clearly pronounced edge scoring (Fig. 1). Measurement of the thrust change with the worn wheel showed that it decreased by more than 53% as compared with the original thrust.

The wheel was found to be unsuitable for further service and was replaced

Wheel 2. For further study of wheel blade service life under shallow water conditions, a wheel was prepared by welding steel-35 blades to a hub made of 25L steel. This wheel was installed on a water jet propelled passenger ship with 150 hp and 0.5 m draft. The dimensions of the new wheel (pitch, diameter, etc.) were almost the same as those of the first wheel, installed on the pusher tug. Operating conditions were also similar to those in the previous case.

Inspection of the wheel after 850 hours of service showed that delivery and suction surfaces of the blades were in their original state, without noticeable traces of failure. Also, no signs of failure were found on the peripheral and exit edges; however, the intake edge of the blade was subjected to considerable wear (Fig. 2), similar in nature to that described above. The worn areas were 300x75 mm in size and had a progressing nature.

Screw propeller 3. To study the reasons causing ship propeller failure in service in shallow rivers, a study was made of the screw propeller of a 150-hp passenger ship. After only 20 hours of operation in a shallow part of the Yenisey River, failure signs 22x2.5 mm in size were observed at the intake edge of the blade. The suction and delivery surfaces of blades remained in their original state. Because the screw propeller had no protective screen, dents appeared on the intake edges of blades, caused by collisions with foreign objects.

Microstructural analyses were performed with specimens taken directly from the blade of wheel 1 after 400 hours of operation. These specimens did not have signs of cavitation or corrosion failure. Chemical composition of blade material was within the standard composition range of 25L /10 steel. The structure of the analyzed steel contained mainly ferrite and a small amount of perlite.

The intake edge of the blade, directly subjected to strikes of abrasive particles, had a rough, pitted surface (Fig. 3). The depth of individual pits reaches 3-4 mm and their area 18-20 mm².

The peripheral part of the blade is worn to a larger extent than the part adjacent to the hub. This can be explained by the higher circumferential speeds and by the effect of centrifugal separation of solid particles.

Under the continuous action of abrasive particles in areas of high stress, some microscopic cracks appear, which with time become one (Fig. 4). This explains the phenomenon of metal fracture under the wedging action of a stream of hydroabrasive mixture.

The appearance of slip bands on the surface of the suction part of the blade is related to the presence of abrasive wear due to sliding type friction of abrasive particles moving in this area. Inspection of blade thickness showed that the thickness decreased slightly as



Fig. 3. Cross section of the intake edge of the blade at a distance of 0.6 radius from the axis of the hub (x5)



Fig. 4. Cracks in a cross section of the blade edge, developed under the action of a hydroabrasive mixture (x200)

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compared with original dimensions; however, the blade wall thickness decrease did not exceed 1.0-1.5%. In this case, the nature of abrasive wear consists of cutting off microvolumes of metal by moving particles of sand-gravel mixture. /10

The intake edge of the blade is continuously subjected to a large number of concentrated impacts of abrasive particles. As a result, maximal stresses appear on microsections



Fig. 5. Microplastic deformations in a cross section of outer layers of intake edge of the blade (x100)

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of the surface, which causes plastic deformation and strain hardening of the outer layer of metal. Microplastic deformations lead to orientation of metal grains in a direction perpendicular to the motion of solid particles (Fig. 5).

Microhardness of worn intake edges was measured using a PMT-3 device equipped with four sights, located at a distance of 2 mm from each other, with an indenter load of 20 grams. The hardness tests determined that strengthening of the intake edge under the action of abrasive particles reaches high values, increasing from the periphery to the root of the blade. The depth of the strain-hardened layer varies within the range from 0.15 to 0.20 mm. Strengthening of suction and delivery surfaces of the blade did not take place.

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Based on the above analyses, the mechanism of abrasive failure of ship screw propellers and wheels operating in shallow waters is presented as follows: during operation the ship's propeller enters a water stream containing a large number of suspended abrasive particles in the form of sand-gravel mixture. The intake edge of the blade is subjected to a large number of concentrated impacts of

solid particles of turbulent pulsations, the kinetic energy of which converts into deformation strain of blade material. During this phenomenon, considerable plastic deformations develop on separate microsections, accompanied by strain hardening and subsequent embrittlement of the surface layer. Progressive strengthening and embrittlement under the action of a stream leads to the formation of cracks and fatigue failure of the deformed areas and therefore to the removal of microsections of surface layer. The rough surface formed at the initial stage of this process is smoothed by the continuous action of the abrasive stream, as if ground. Later, this process is repeated.

Some very insignificant wear of suction surfaces is a result of the action of abrasive particles, which destroy the surface by scratching and by cutting off microchips of metal as a result of friction and practically do not cause any strengthening of the surface layer.

In conclusion, the operation of ships' propellers under shallow water conditions demonstrated that the main reason for their wear is the mechanical action of the water stream, containing abrasive particles upon the intake edge of the blade, which results in hydroabrasive wear of their surface.

6. Experimental Study of Cavitation-Abrasive Failure of Materials

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As discussed above, failure of ship screw propellers occurs as a result of the combined effect of several factors which are very difficult to reproduce under laboratory conditions for a number of reasons. Therefore, the most expedient method would be one of tests under service conditions. This, however, would require the manufacture and installation on ships of a large number of screw propellers and their use under variable conditions, which would be very expensive. The method of scale modeling also proved to be unacceptable, since it is impossible to determine categories of scale units to convert modeling test results into actual results /22/.

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At the present, some installations have already been created and some are being developed for the investigation of wear resistance of materials under conditions approaching those of actual service tests. In principle, the existing methods of laboratory research provide for separate study of cavitation-erosion, corrosion and hydroabrasive resistance of materials /1, 9, 21, 33, 36, 38, 39/.

Methodology of testing cavitation erosion resistance

The following methods and equipment are used in testing materials for cavitation erosion resistance:

1. Destruction of test specimens by repeated impact against the water stream in a special impact-erosion stand /1, 39/. In this test, a water stream under constant pressure is directed against a revolving disc with specimens fastened to it. The following parameters remain constant during the test: circumferential velocity, shape of specimen, water stream velocity, nozzle diameter, and the distance between the nozzle tip and specimens being tested.

2. Cavitation destruction of materials in testing in a diffuser /6, 30, 36, 38/. Test specimens are placed within a stream, the cross section of which can be varied during the test; as a result, cavitation develops in the area where the specimens are fastened.

3. Destruction of materials in a magnetostriction oscillator. In this case a cavitation zone is created directly under the vibrating specimen.

Evaluation of test results in all these cases is performed by measuring the specimen's weight loss.

Magnetostriction equipment of various systems is widely used; it is superior to other types of equipment, in that it makes it possible to perform miscellaneous experiments, including investigation of destruction kinetics and of the effect of various factors on the rate of the cavitation process. The most important advantage of a magnetostriction device is its high cavitation rate, hence, shorter time needed for the experiment.

The schematic diagram of a magnetostriction oscillator used in the experiments discussed is illustrated in Fig. 15.

Nickel pipe 2--3000 mm long, 18 mm in diameter--serves as a vibrator. Its lower end is screwed into the specimen 1, submerged in fluid. Water temperature during experiments was maintained within the range $20 \pm 2^\circ\text{C}$. For this purpose, ¹⁴⁵ the tank with fluid was cooled by running water.

Longitudinal vibrations in pipe 2 were produced by an electromagnetic field which was created by excitation coil 2. Vibrations were amplified by the field of constant electromagnet 3. This amplifier-magnetostriction oscillator system provides automatic vibration of the specimen

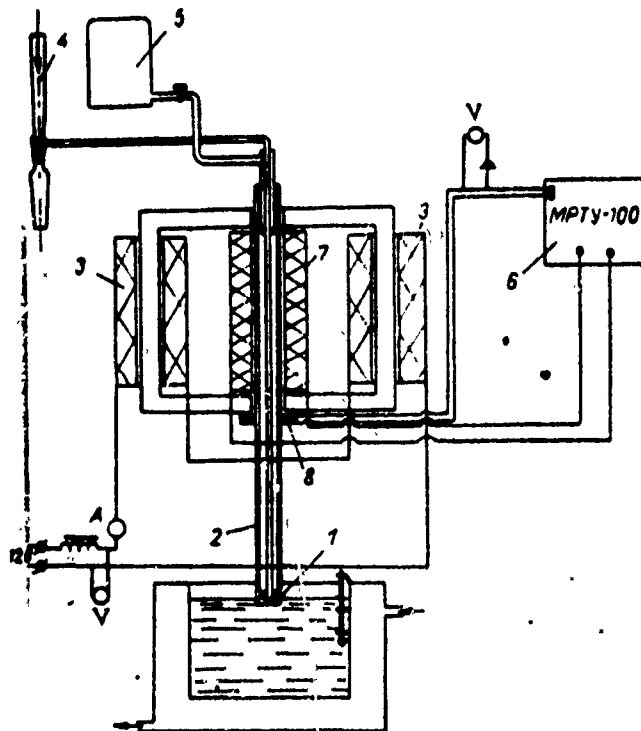


Fig. 15. Schematic representation of a magnetostriction oscillator

being tested. Vibration of pipe 2 occurs under **resonance** conditions, since the frequency of alternate field (**pulses**) is set by the frequency of pipe 2's own vibrations through feedback coil 8. At the same time, electromotive force is induced in the feedback coil and is transmitted to the adapter input of amplifier 6. These vibrations are transmitted to the oscillation circuit consisting of coil 7 and a capacitor.

Pipe vibration frequency is determined by its dimensions and by the weight of specimens being tested and usually is within the range from 7000 to 8000 Hz. To decrease losses to eddy currents, which cause heating of the pipe, a narrow slot 0.5 mm wide is machined along the pipe and then is filled with an adhesive. /46

Pipe 2 is cooled by water flowing along its walls from tank 1 and drawn off by suction pump 4.

During tests, special attention was paid to maintaining constant amplitude of pipe vibration. With an

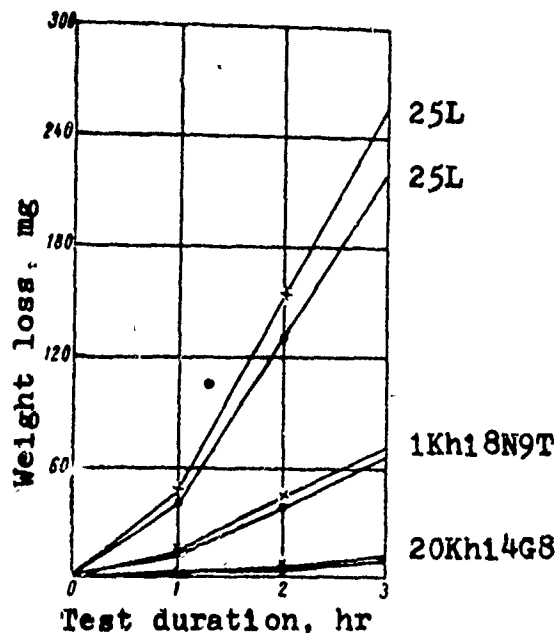


Fig. 16. Aggressiveness of the medium on cavitation erosion in steels.

x-x-x- sea water
 o-o-o- fresh water

increase of vibration amplitude, the rate of weight loss also increases /9/.

In the experiments discussed, the double amplitude of vibration was constant and equalled 0.07 mm. At such an amplitude, accompanying processes such as corrosion and action of abrasive particles are suppressed. This could be the cause of errors in establishing wear resistance of various materials. For example, the cavitation resistance of 18DGSL steel when tested with a magnetostriction oscillator, according to I. P. Kryakin /24/ equals that of 20Kh13NL steel; however, in actual service 18DGSL steel proved to be less resistant than 20Kh13NL steel /33/.

When selecting the test method, we studied the effect of aggressiveness of fluid on cavitation resistance of carbon stainless steel. Synthetic sea water similar in composition to Black Sea water was used as an aggressive medium.

As can be seen from test results (Fig. 16), the aggressive medium has a great effect on carbon steel and

considerably lower effect on stainless steels. In judging cavitation resistance by total weight loss in 3 hours of testing, it was determined that the cavitation failure of materials is caused mainly by mechanical action, the rate of which is enhanced in a corrosive medium.

When processes of cavitation and corrosion are simultaneous, the chemical composition and structure of the metal play a considerable role, particularly under conditions of moderate cavitation action intensity /21/. It is quite possible that a cavitation pulse strength insufficient to remove metal particles might be sufficient to destroy an oxidation film and remove corrosion products, and therefore to enhance the corrosion process. /47

A number of references /21, 33/ indicate the nonconformity of laboratory and service test results because it is impossible to exactly take into account the corrosion factor during the cavitation process.

Consequently, when selecting a method of relative tests, the cavitation resistance of materials in aggressive media should be investigated first and then the selected cavitation-resistant materials should be subjected to additional corrosion tests.

It should be noted that the relative service life of materials determined by testing with various devices, such as an impact-erosion stand, diffuser, or magnetostriction oscillator, coincide pretty closely /1, 9/. Quantitative difference is caused by the varying degree of intensity of mechanical action on metal structure with microloading of material, which is caused by different design features of test equipment.

Experimental study of cavitation abrasive failure of materials on an ultrasonic testing unit

The study of the effect of abrasive particles suspended in water on the cavitation erosion of a screw propeller is of great practical interest.

S. P. Kozyrev /23/ has used in his studies of cavitation erosion wear a unit that is based on the principle of introducing ultrasonic vibrations into a stream of water containing abrasive particles. As was determined in the course of testing, to evaluate the effect of abrasive action on the cavitation wear of metals, it was necessary to decrease the rate of mechanical removal of metal.

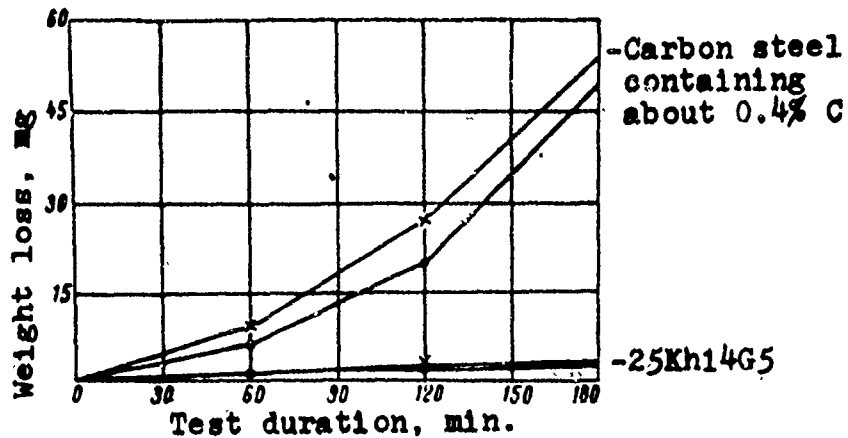


Fig. 17. Effect of abrasive particles on cavitation erosion in steels.
 x-x-x- fresh water containing abrasive particles
 —•— fresh water without abrasive particles

For this purpose a special ultrasonic unit was designed by the authors.

The unit for testing cavitation abrasive wear consists of a magnetostriction converter packet, with a stainless steel concentrator, shaped like a cone, soldered to one end. The testing voltage is transmitted to the winding of the packet from the generator. The specimen being tested is screwed into the butt of the concentrator. /48

The resonant frequency of the converter in the unit is 21.7 kHz. The amplitude of vibrations used in the study was 0.020 mm. Quartz sand with a grain size of 0.1-0.3 mm was used as the abrasive. The amount of wear was evaluated by weight loss of the specimen. Not less than 3 specimens of the same material were tested under the same conditions.

Comparative tests performed in the above unit showed that the presence of abrasive particles in water enhances cavitation erosion wear of carbon steels, but has less effect on chromium and manganese alloy steels.

Fig. 17 illustrates the results of tests on carbon steel (about 0.4% C) and on 25Kh14G5 chromium-manganese steel in water with and without abrasive particles. As shown in Fig. 17, the weight loss of carbon steel in water with abrasive particles increased in 3 hours of testing by 18% and that of chromium-manganese steel by 9%.

The presence of abrasive particles increases the intensity of cavitation erosion wear and also causes a completely different type of specimen wear. This wear occurs deeper into the metal and is in the form of non-uniform pits, as compared with the more uniform wear without the presence of an abrasive.

The worn surface is covered with pits, nonuniform in depth, 0.05-0.08 mm in diameter with hemispheric bottoms. A cracked bead of pressed out metal is formed around these pits. This indicates that the surface of metal in the cavitation zone was subjected to additional mechanical impact by abrasive particles. Abrasive particles which receive additional pulses by the "implosion" of cavitation bubbles increase metal surface wear. /49

As was shown by further research, a qualitative correspondence is observed in tests in a magnetostriction oscillator with a frequency of 7-8 kHz and 0.070 mm amplitude, and in an ultrasonic unit with a frequency of 18-22 kHz and 0.020 mm amplitude.

The quantitative difference in the results of the above tests is caused by the higher frequency and smaller amplitude of specimen vibration in the ultrasonic unit. In addition, an insignificant amount of weight loss, when testing alloy steels in the ultrasonic unit, made it quite difficult to establish the dependence between the weight loss and the amount of alloying elements in steel. Thus, in selecting a test method for determining materials resistant to the combined action of cavitation and abrasive particles, the test in a magnetostriction unit should be used; however, the vibration amplitude should be increased to 0.070 mm, frequency decreased to 7-9 kHz and materials should be additionally tested for hydroabrasive wear.

Hence, the brief analysis of the existing test methods and the comparison of experimental results and actual service data as well as laboratory research, made it possible to select the following methodology for studying wear resistance of materials for ship screw propellers:

1. The most expedient method of study consists of separate investigation of cavitation erosion, hydroabrasive and corrosion resistance of materials;

2. To determine the effect of the corrosion factor on the cavitation erosion wear of metals, tests should be carried out in a magnetostriction oscillator in sea water;

3. The selected materials most resistant to cavitation erosion and hydroabrasive wear should be additionally tested for corrosion resistance in sea water.

7. The Effect of Alloying Elements on Wear Resistance in Steel

In references /1/ and /2/, by I. N. Bogachev and R. I. Mints, data are presented on cavitation resistance of 30Kh10G10 chromium-manganese steel. As a result of experimental and theoretical studies, it was determined that manganese austenite possesses a high resistance to cavitation erosion. However, the above references do not present sufficient substantiation for selecting a chromium-manganese steel composition most suitable for screw propellers operating under particularly severe conditions of cavitation, corrosion and action of abrasive particles. /50

L. S. Malinov and T. D. Eysmond studied the cavitation resistance of chromium-manganese alloys containing less than 0.1% C /27/. They gave recommendations for selecting cavitation-resistant materials with increased corrosion resistance; however, application of steels recommended by the authors for screw propellers may not be expedient due to the difficulties in producing steels with low carbon content. Melting of such steels would require the use of carbonless ferro-alloys, which would increase their cost. Reference /34/, by D. A. Prokoshkin, I. F. Zudin et al., contains little information about wear resistance of chromium-manganese steel. This reference provides only information concerning the effect of alloying elements on the corrosion properties of Kh18G5 steel.

The lack of published data on the effect of alloying elements on cavitation, hydroabrasive and corrosion wear resistance of chromium-manganese steel made it necessary to conduct a special experiment. The results of this research are discussed below.

Cavitation erosion resistance

The results of testing steels with various amounts of alloying elements are given in Table 7 and weight loss kinetics in Fig. 18. The data given in Fig. 18a show that among steels containing 0.2% C (heats No. 2351-2355), the highest cavitation resistance is possessed by steel containing 9.69% Mn and 13.4% Cr (heat No. 2353). With further increase of chromium content, weight losses increase

Table 7 /51

Results of cavitation resistance tests
of chromium-manganese steels

Heat numbers	Content of principal alloying elements, %				Average weight loss (mg) in time (hours)			
	C	Si	Mn	Cr	1	2	3	total for 3 hrs
2351	0.21	0.55	10.71	6.15	0.9	4.1	9.3	14.3
2352	0.21	0.54	10.03	9.75	0.9	1.7	4.1	6.7
2353	0.21	0.52	9.69	13.40	0.2	1.7	3.5	5.4
2354	0.19	0.56	10.64	16.95	2.1	6.1	7.4	15.6
2355	0.19	0.54	9.69	20.65	11.8	21.0	26.0	58.8
162	0.42	0.74	9.75	9.95	0.5	0.6	2.7	3.8
163	0.42	0.73	9.54	11.40	0.7	0.5	2.0	3.2
164	0.47	0.69	9.12	12.95	0.4	0.5	1.5	2.4
165	0.46	0.64	8.90	14.17	0.3	0.5	2.0	2.8
542	0.20	0.42	8.0	13.40	0.3	2.7	4.1	7.1
543	0.21	0.42	10.53	13.13	1.1	3.4	4.2	8.7
544	0.21	0.38	14.0	12.65	3.2	3.3	4.2	10.7
9971/1	0.35	0.69	3.67	13.55	0.6	1.6	2.5	4.7
9971/2	0.34	0.70	8.02	13.22	0.6	1.5	2.4	4.5
9971/3	0.38	0.71	10.74	12.82	0.2	1.5	3.8	5.5
9971/4	0.47	0.71	13.30	12.49	0.6	1.3	3.0	4.9
861	0.30	2.03	3.64	12.70	0.5	0.7	2.4	3.6
340	0.35	1.13	7.83	13.80	0.6	0.6	1.6	2.8
9503	0.23	0.59	8.48	13.65	2.4	2.8	3.8	9.0
9543	0.25	0.88	7.35	13.34	0.4	1.2	3.5	5.1

and with a chromium content of 20.65% Cr weight loss reaches 58.8 mg. Surface wear of specimens made of this steel is the greatest, reaching 0.2-0.3 mm in depth. Wear is nonuniform in the surface area of the specimen. /50

Among steels with increased carbon content (heats 162-165), the highest cavitation resistance is also possessed by steel containing up to 13% Cr (heat No. 164, Fig. 18b).

Our results confirm data obtained by I. R. Kryanin /24/ concerning optimum cavitation resistance of chromium and chromium-nickel steel containing 13% Cr; however, some references give different data. For example, I. N. Bogachev and R. I. Mintz /1, 2/ consider that the optimum amount of chromium to provide cavitation resistance in steel is about 10%.

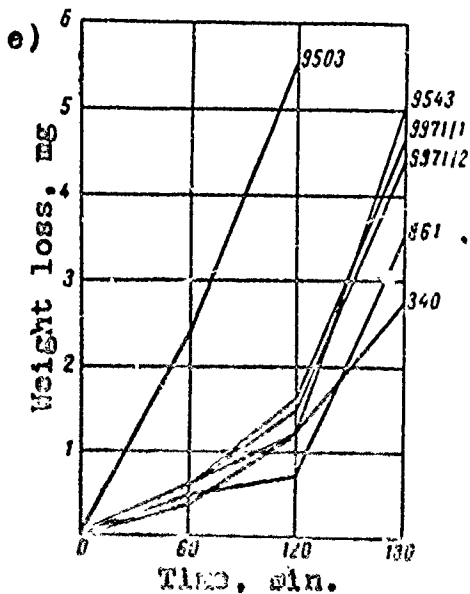
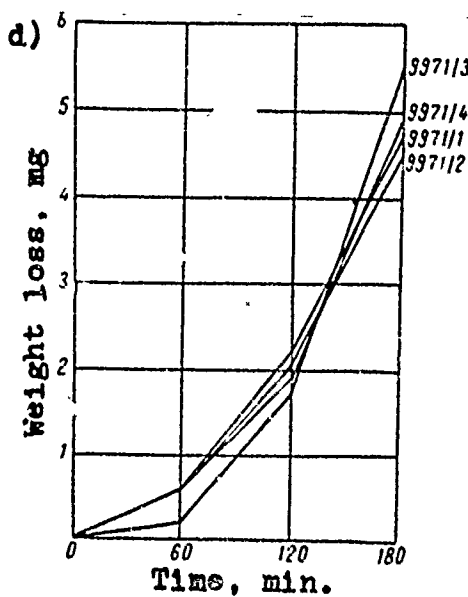
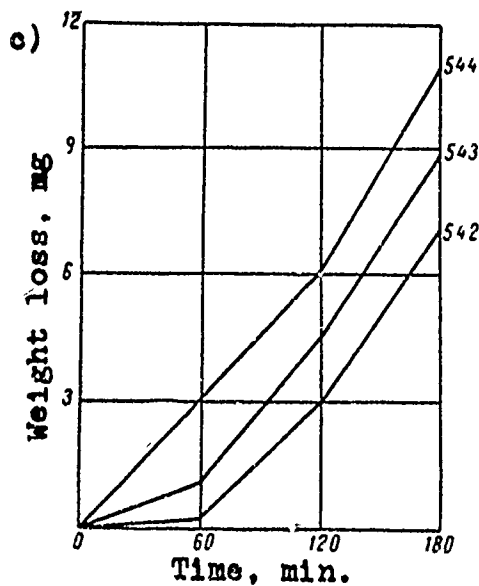
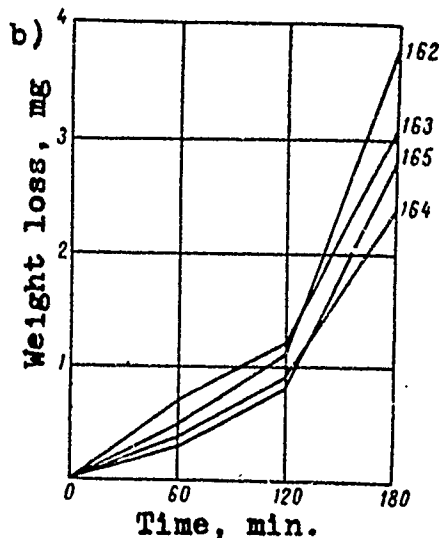
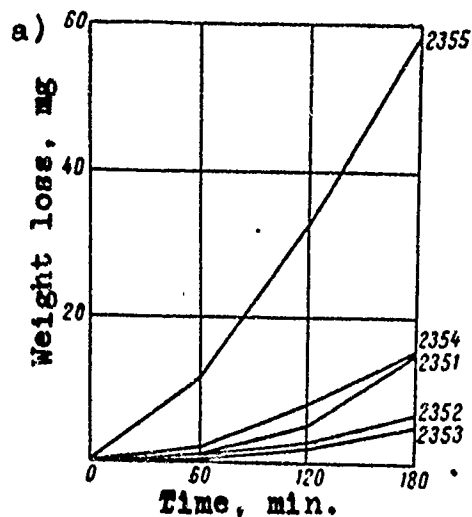


Fig. 18. Effect of alloying elements on cavitation resistance of chromium-manganese steel:

- a, b - chromium
- c, d - manganese
- e - silicon

The greater cavitation resistance of chromium-manganese steel containing up to 14% Cr is explained by the fact that chromium in such amounts provides for the highest degree of alloying without causing structural heterogeneity (i.e. an increase in the amount of structurally free ferrite), which causes the lower cavitation resistance of steel. /51

Figures 18c and d and Table 7 illustrate the results of cavitation resistance tests of chromium-manganese steel with varying manganese content. When steel contains 0.2% C and not more than 14% Cr (heats No. 542-544), an increase in manganese content from 8 to 14% lowers the cavitation resistance of the steel.

In steels containing 0.4% and more carbon (heats No. 9971/1-9971/4) the increase of manganese content does not affect cavitation resistance noticeably. However, also in this case, the steel containing 8.02% Mn and 13.22% Cr (heat No. 9971/2) possesses higher cavitation resistance. This is explained by the fact that as manganese content increases, the austenite's stability is raised. This, on the other hand, decreases the capacity of steel to strengthen during the initial (incubation) period of cavitation, hence weight losses increase. /53

The experiments showed that the optimum manganese content in steel, containing 0.20-0.30% C and 12-14% Cr, is from 7 to 9%.

Reference /27/ states that a decrease of cavitation resistance is observed with an increase of manganese content from 11 to 18% in steel containing 10% Cr and about 0.1% C. As a result of tests it was determined that an increase of carbon content in steel from 0.1 to 0.4% and more (with Mn content 7-9% and chromium content 12-14%) leads to a noticeable increase in cavitation resistance; however, the same tests showed that an increase of carbon content above 0.3% lowers the weldability of chromium-manganese steel. In addition, difficultly soluble complex carbides of the Me_23C_6 type, formed in steel, require heating to a higher temperature, which is difficult to achieve under industrial conditions and also results in a distortion of casting shape during heat treatment. Thus, the optimum carbon content in chromium-manganese steel is considered to be 0.20-0.28%, taking into consideration the combination of technological properties and cavitation erosion resistance.

It is known that of all alloying elements, silicon increases the wear resistance of ferrite in steel most noticeably. Test results for chromium-manganese steel with various silicon contents are shown in Fig. 18e, and the chemical composition of these steels is shown in Table 7.

In steels containing 0.23-0.25% C, with the same manganese and chromium content, an increase of silicon content from 0.59 to 0.88% lowers weight losses in cavitation erosion wear from 9.0 to 5.1 mg (heats No. 9503 and 9543). The highest cavitation resistance is possessed by steel containing 0.35% C, 8.3% Mn, 13.8% Cr and 1.13% Si (heat No. 340). It should be noted that an increase of silicon content in steel above 1% is not desirable, since it leads to an intolerable decrease in notch toughness (below 3.0 kg-m/cm²).

To study the effect of structure on cavitation resistance of chromium-manganese steel in industrial heats, tests were carried out with specimens prepared from large ingots.

Table 8 and Fig. 19 illustrate test results of three heats of steel containing various amounts of manganese (heats No. 8716, 8717 and 8695). Test specimens were prepared from ingots 130 mm in diameter in a basic induction furnace, 150 kg capacity. Prior to testing, specimens were subjected to low annealing at 680°C for three hours to reduce residual stresses and improve machinability. The microstructure of the steels tested is shown in Fig. 20.

From data given in Fig. 19 it can be determined that of all heats, the highest cavitation resistance is possessed by steel of heat No. 8717, containing 0.28% C, 0.36% Si,

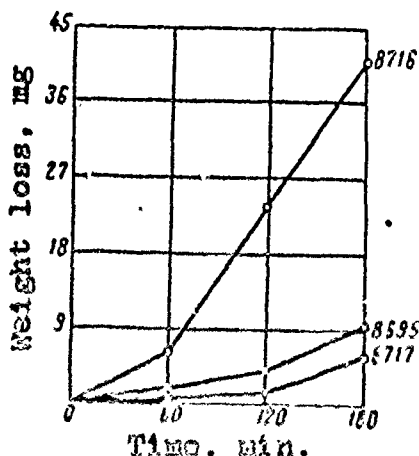


Fig. 19. Results of cavitation tests of chromium-manganese steel in sea water.

Table 8

Results of cavitation resistance tests of chromium-manganese steel

Heat No.	Content of principal elements				Average weight loss (mg) in time (hours)			total (for 3 hours)
	C	Si	Mn	Cr	1	2	3	
8716	0.19	0.31	3.36	12.95	6.4	16.9	17.8	41.1
8717	0.28	0.36	6.85	13.00	4.3	1.1	4.3	5.7
8695	0.18	0.51	11.40	13.78	0.5	3.8	4.9	9.2

Table 9

Results of cavitation resistance tests of chromium-manganese steel in fresh water

Heat No.	Content of principal elements				Average weight loss (mg) in time (hours)			total (for 3 hours)
	C	Si	Mn	Cr	1	2	3	
8694	0.19	0.53	12.2	9.91	0.5	3.8	5.1	9.4
8696	0.16	0.45	6.04	14.10	20.7	47.6	55.5	123.8
8697	0.28	0.35	6.60	18.51	5.9	22.0	26.0	53.9
8713	0.30	0.38	7.45	9.38	0.8	2.6	5.0	8.4
8714	0.27	0.40	8.05	14.30	2.9	2.1	2.1	7.1
8718	0.25	0.35	5.30	19.04	10.0	12.0	14.1	36.1

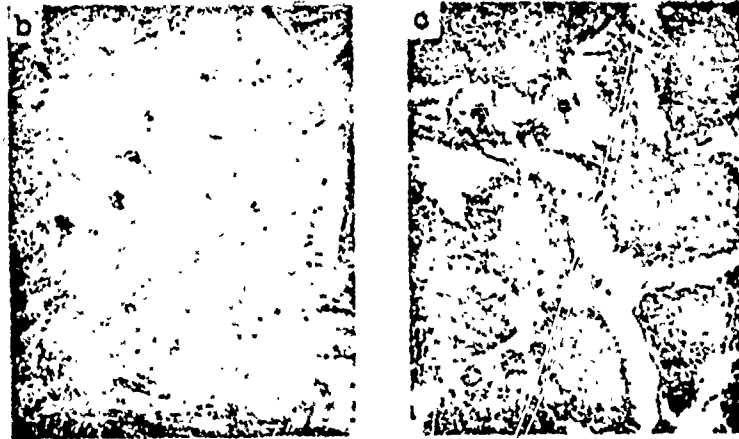
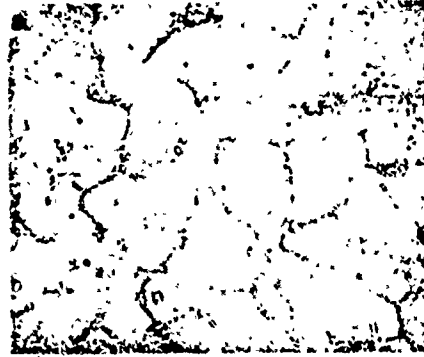


Fig. 20. Microstructure of chromium-manganese steel (x500): a. heat No. 8695; b. heat No. 8717; c. heat No. 8716.

6.85% Mn, and 13% Cr. The structure of this steel consists of gamma-phase, a small amount of alpha-phase and carbides in globular shape (Fig. 20b). /54

The martensitic-ferritic steel of heat No. 8716 (Fig. 20c) had maximum weight losses and the deepest wear, with worn areas nonuniformly distributed on the surface area. The heterogeneous structure of steel in such a state caused the appearance of foci of cavitation erosion wear after 35-40 minutes of testing.

The steel of heat No. 8695 contained a lower amount of carbon than the steel of heat No. 8717; however, the higher manganese content in this steel shifts the steel into the zone of gamma-phase and does not result in a heterogeneous structure. This steel has a large amount of ferrite (Fig. 20a) as compared with steel of heat /56

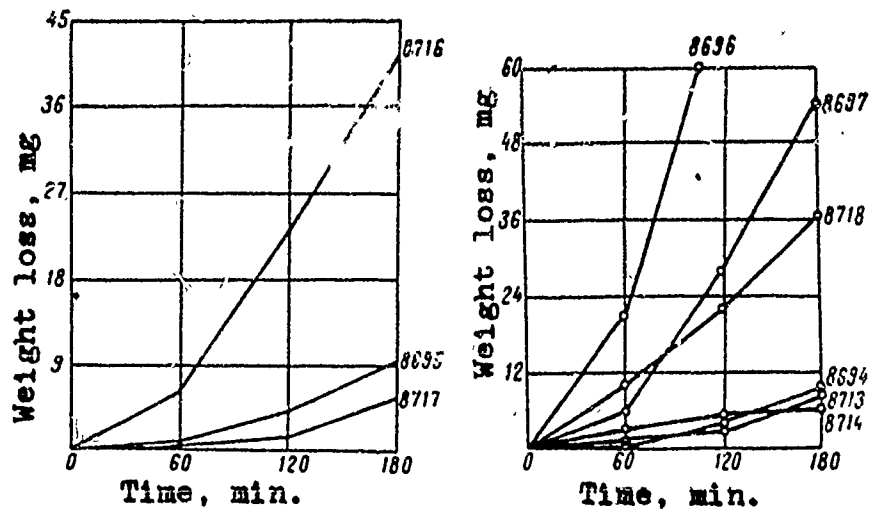


Fig. 21. Results of chromium-manganese cavitation tests in fresh water.

No. 8717 (Fig. 20b) This lowers the cavitation resistance /56 of the steel.

The results of cavitation tests in fresh water of chromium-manganese steel with various content of Cr, Mn and C are shown in Table 9 and Fig. 21.

Test specimens were prepared from ingots 150 mm in diameter. As in the preceding case, specimens were annealed for three hours at 680-700°C before machining.

The results obtained indicate that steel of heat No. 8714, containing 0.27% C, 8.05% Mn and 14.30% Cr, possesses the highest cavitation resistance. Relatively high carbon content provides high cavitation resistance of steel with chromium content above 13.5%. The structure of this steel consists principally of austenite with small areas of ferrite along grain boundaries. /57

As compared with steel of heat No. 8714, specimens of heat No. 8713 possess lower cavitation resistance, in spite of higher carbon content, which contributes to increased gamma-phase formation in steel. This is explained by the higher chromium content of heat No. 8714 (14.30%) as compared with heat No. 8713 (9.38%). Hence, the amount of chromium contained in steel is a determinant for securing high cavitation resistance in both sea and fresh water.

With a decrease in carbon content in steel to 0.19%

(heat No. 8694), the amount of alpha-phase in the metal structure increases, which results in higher weight loss in tests.

From the analysis of test results of steel specimens of heats No. 8697 and 8718 it follows that increasing chromium content to above 18%, with a manganese content of 5.0-6.5% and that of carbon of 0.25-0.28%, results in an increase in weight loss by a factor of more than four.

Some difference in cavitation resistance of steels in heats No. 8697 and 8718 with approximately the same chemical composition is explained by individual characteristics of microstructures of these steels. More favorable, in /58 respect to cavitation resistance, is the structure of steel in heat No. 8718, where carbides are uniformly distributed along grain boundaries and the grains are homogeneous. This provides for higher wear resistance. Steel in heat No. 8697 is characterized by an accumulation of carbides at grain boundaries and nonhomogeneity of grains. Thus, weight losses in cavitation tests exceed that of heat No. 8718 steel by a factor of 1.5.

Highest weight losses were observed in tests of heat No. 8696 steel. These losses are explained by low carbon and manganese content (0.16% and 6.04%). This steel consists mainly of alpha-phase, some amount of gamma-phase and initial carbides.

We also carried out comparative cavitation resistance tests in sea and fresh water of steels with varying contents of chromium and manganese.

As seen in Table 10 and Fig. 22, the difference in the weight loss of corrosion resistant 1Kh18N9T steel in sea and fresh water is insignificant (heat No. 8677).

Similar conclusions can also be made in respect to steel of heat No. 8714, containing 8.05% Mn and 14.3% Cr. /59

In spite of the lower carbon content in steel of heat No. 8694, as compared to steel in heat No. 8714, this steel lost twice as much weight in sea water as it did in fresh water. This is explained by its low chromium content, which is insufficient to provide high cavitation resistance in sea water.

Reference /39/ by V. V. Fomin also states that the optimal content of chromium in austenitic chromium-manganese

The effect of aggressiveness of sea and fresh water on cavitation resistance of steels with various contents of alloying elements

Heat No.	Medium	Content of principal alloying elements				Average weight losses (mg) in time (hr)			
		C	Si	Mn	Cr	1	2	3	total (for 3 hours)
8694	Sea w.	0.19	0.53	12.2	9.91	0.9	9.0	9.6	19.5
	Fresh w.					0.5	3.8	5.1	9.2
8677	Sea w.	Corresponds to standard composition of 1Kh18N9T steel				13.5	30.7	25.5	69.7
	Fresh w.					12.5	25.0	28.4	65.9
8714	Sea w.	0.27	0.40	8.05	14.30	2.4	3.0	2.6	8.0
	Fresh w.					2.9	2.1	2.1	7.1

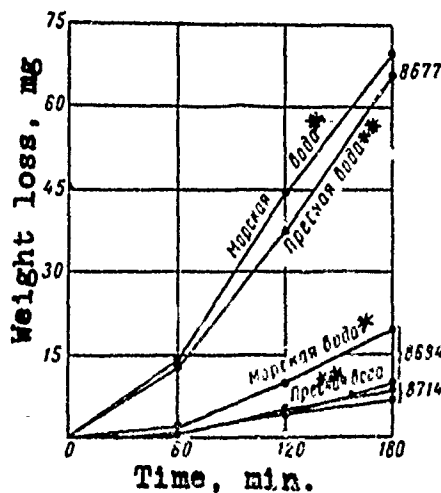


Fig. 22. The effect of an aggressive medium on the cavitation resistance of chromium-manganese steel. *sea water, **fresh water

steel is 14%. With a chromium content below 12% the resistance of steel to electrochemical corrosion decreases, which also lowers resistance of steel to microimpact action during cavitation. /59

As a result of studies of the cavitation resistance of chromium-manganese steel of various composition and structure, it was determined that:

1. with an increase of chromium content from 12 to 14%, the cavitation resistance of chromium-manganese steel also increases. When steel contains more than 14% Cr the amount of ferrite increases, forming an almost continuous network along austenite grains and even separate ferrite areas. This leads to a decrease in cavitation resistance of steel;

The optimal chromium content is about 14%.

2. the highest cavitation resistance is possessed by chromium-manganese steel containing 7-9% Mn;

3. an increase of carbon content in chromium-manganese steel up to 0.38-0.40% results in an increase in cavitation resistance;

4. at a silicon content of up to 1.0% the necessary ductile properties and high cavitation resistance are retained.

Resistance to hydroabrasive wear

The amount of surface wear of screw propeller blades operating in shallow water with a hydroabrasive mixture depends on the following factors:

1. physical-chemical properties of abrasive particles, such as density, hardness and grain shape;

2. the number of hard particles colliding with a surface area unit per time unit and the duration of their action;

3. velocity of the stream containing the hydroabrasive mixture;

4. physical and mechanical properties of blade material;

5. quality of blade surfaces maintained in the course of exploitation, i.e. surface roughness.

Due to the lack of sufficient data on wear resistance of chromium-manganese steels, as well as the lack of quantitative characteristics of the effect of alloying elements on the intensity of hydroabrasive wear, it was necessary to perform a special experiment. In this experiment, units were used which provided for different types of material wear in a hydroabrasive medium.

Unit No. 1 (Fig. 23a), in which specimens revolve in a stationary hydroabrasive medium, is for studying comparative wear resistance of materials. The advantage of this unit, as well as of the units described below, is their small size, hence low consumption of abrasives, and no need for special circulation devices with pumps, tanks and other bulky equipment.

The drawbacks of these units include nodulizing and breaking up of abrasive particles during the test, as well as indeterminacy of the relative velocity of abrasive particles in respect to specimens; therefore, in tests using these units the wear resistance of different materials was determined in relative units.

Unit No. 1 consists of a cylindrical tank, detachable along the diameter, and a chamber, inside of which test specimens 2 are fastened to flanges on the shaft. Specimens are made in the shape of cylinders, 10 mm in diameter, 100 mm long. This specimen shape makes it possible to study hydroabrasive wear under conditions of abrasive particle impact against the cylindrical surfaces and at the same time under conditions of friction along the butt surfaces, which to some degree imitates screw propeller service conditions. The speed of rotation can be changed via multistep pulleys 1.

Based on experimental research, the test methodology was developed and other test conditions determined, such as mixture concentration and test duration. Tests were carried out at a constant rotation speed. Test duration was 3 hours, with the hydroabrasive mixture changed each 30 minutes. Mixture concentration was 180 grams per liter, which prevented its motion together with the specimens. Six to eight specimens were tested simultaneously. One of the specimens, made of type St. 3 steel, was considered to be a standard. Three specimens of each material were tested. Evaluation of wear extent was determined by calculating weight loss with an accuracy of up to 0.1 mg.

The ratio of the weight loss of the standard specimen to that of the specimen being tested, taking into account their initial weights, was considered to be the wear resistance factor. Weight loss was calculated as an average loss from six tests.

Unit No. 1 was also used for studying material wear resistance under conditions of wear due to impacts of specimens against a stream of water containing abrasive /62

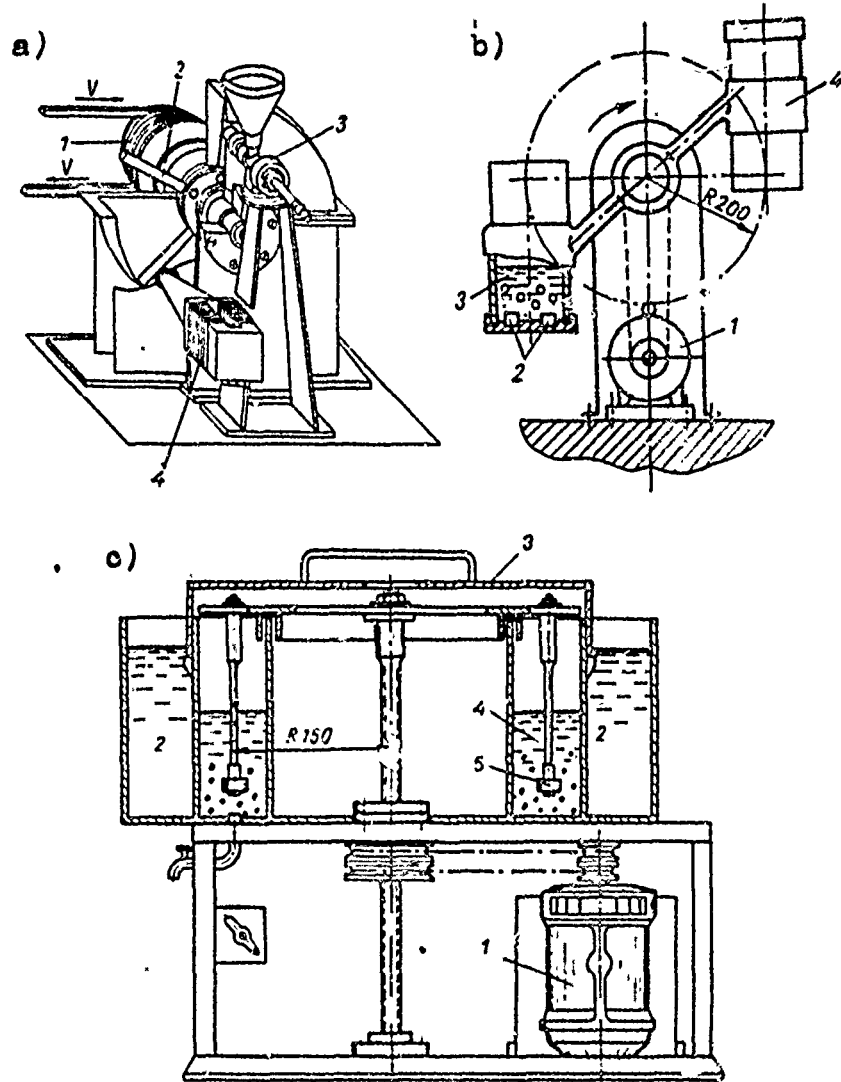


Fig. 23. Units for testing hydroabrasive wear:

a. Unit No. 1:

1. multistep pulley; 2. test specimen; 3. diffuser for feeding hydroabrasive mixture;
4. ultrasonic attachment;

b. Unit No. 2:

1. electric motor; 2. external chamber; 3. lid;
4. internal chamber; 5. test specimen;

c. Unit No. 3:

1. electric motor; 2. test specimens; 3. hydroabrasive mixture; 4. revolving cylinders.

particles (impact erosion wear). For this purpose water was fed under constant pressure to diffuser 3, to which an exact amount of abrasive was fed through a measuring funnel. Then the hydroabrasive mixture was fed to specimens being turned by an electric motor, causing their wear. /62

Unit No. 2 (Fig. 23b) makes it possible to perform tests at various speeds simultaneously. In this unit, cylindrical rods 10 mm in diameter were used, with cylindrical specimens 20 mm in diameter and in height fastened at their ends. The distance between the specimens and the wall of the cylindrical chamber is small, which contributes to the decreased abrasive mixture displacement behind the specimens. In addition, stationary specimens were installed for the same purpose.

The mixture temperature was kept constant by cooling it with water, circulating in external chamber 2. The speed of specimen rotation was changed either by placing specimens into the external chamber (in which case the internal chamber served as a cooler) or by changing the speed of the 3-speed electric motor 1. Up to 12 specimens were tested simultaneously in one chamber. Linear speed of specimen motion in chamber 4 was 11.3 m/sec, and in chamber 2, 16.4 m/sec.

The most intensive wear occurred when the hydroabrasive mixture contained 50% water and 50% quartz sand by volume. Experiments with the same set of specimens were repeated three times and the amount of wear was calculated as an average value of three tests. Each test lasted 4 hours, after which the hydroabrasive mixture was replaced.

Unit No. 3 (Fig. 23c) was designed for testing wear resistance under conditions of impact loading. It can be used with fastened or free specimens. Tests were carried out in four cylinders 4 simultaneously, with a cylinder rotation speed of 60 rpm. All specimens were tested three times. Each test lasted 4 hours. Cylindrical specimens were 20 mm in diameter and height and their edges were rounded off to an edge radius of 5 mm.

Hydroabrasive mixture consisted of rounded gravel 5 to 11 mm in size, quartz sand with a grain size of 0.4-0.42 mm and water, in a proportion of 4:1:5 by volume. The cylinder was filled before the test to 60% of its height and hydroabrasive mixture was replaced after each test.

The effect of abrasion. Test results for cylindrical /63

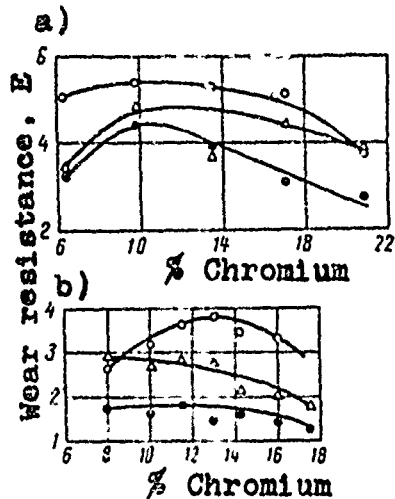


Fig. 24. The effect of chromium on hydroabrasive wear resistance of steel: a. 0.19-0.21% C, 9.7-10.7% Mn, 0.5% Si; b. 0.38-0.47% C, 8.9-9.7% Mn, 0.7% Si. Tests in Unit No. 1.

△ - as cast; ○ - cooling in air from 1100-1150°C; ● - quenching in water from 1100-1150°C.

specimens in Unit No. 1 are shown in Fig. 24. In these tests, quartz sand with a grain size of 0.1-0.25 mm was used. Concentration of hydroabrasive mixture was 180 grams per liter and rotation speed was 1500 rpm. Test specimens were prepared by investment casting. The skin of the specimens formed in casting and heat treatment was removed and the surface was cleaned with fine emery cloth until a metallic luster was obtained.

An analysis of test results shows that among steels containing 0.19-0.21% C and 9.7-10.7% Mn, the highest wear resistance after cooling from 1100°C in air is possessed by specimens with a chromium content within a range from 10 to 14% (Fig. 24a). The same types of steel, either as cast or after quenching in water from 1100°C, possess increased wear resistance with a chromium content of about 10%.

The greater wear resistance of specimens after cooling in air from 1100°C is explained by the fact that with the lower cooling rate, as compared with quenching, the steel contains a greater amount of uniformly distributed carbides, having mostly globular shape. After quenching in water from 1100°C, the amount of austenite in steel increases and the amount of carbides decreases. This results in a decrease in the wear resistance of steel under conditions of hydroabrasive wear.

In the structure of the specimens as cast, an accumulation of coarse-grain carbides and nonhomogeneity of microstructure were observed, which led to decreased wear resistance.

The sharp decrease in wear resistance of steel containing over 15% Cr is explained by the noticeable increase in the amount of free ferrite.

Chromium-manganese steel containing 0.38-0.47% C attains maximum wear resistance with about 13% chromium content, both as cast and after heat treatment (Fig. 24b). With an increase of chromium content to above 14%, a decrease in wear resistance was observed. In such a case, as well as when carbon content is low, the highest wear resistance of steel was attained after cooling in air from 1150°C. /64

Test results also showed that an increase of carbon content in steel from 0.2 to 0.47% results in a decrease in wear resistance. The relative wear resistance of steel with 0.2% C exceeds that of steel containing 0.47% C by a factor of 1.3).

In order to approximate the laboratory test results to tests under actual service conditions, a study of hydro-abrasive wear resistance was carried out using specimens prepared from large castings (industrial melts) in Unit No. 2, with a lower intensity of impact action of hydro-abrasive mixture as compared with the tests in Unit No. 1. Such conditions correspond with the operation of low-draft ships in shallow water with a sandy bottom.

Test specimens were prepared from ingots 60 mm in diameter, cast in sand-clay molds. Cast ingots were quenched in water from 1100°C. After this heat treatment, ingots were machined to the size of specimens for hydro-abrasive testing and investigation of microstructure.

Specimens were tested at a linear speed of 16.4 m/sec.

Figure 25 illustrates the relative wear of steel specimens, with varying chromium content at a carbon content of 0.11-0.31% and manganese content of approximately 7%. Test lasted one hour. As seen from the data in Fig. 25a, specimens containing 0.11% C had maximum wear and specimens containing from 0.22 to 0.24% C had minimum wear. Among steels containing 0.11% C, maximum wear resistance was possessed by steels containing 12-13% Cr; when carbon content was 0.22-0.24%, higher resistance was shown by steels containing 7-8% Cr. In prolonged tests (over 20 hours) this regularity does not change. In measuring hardness in a PHT-3 testing machine, with a 20-gram load on the indenter, it was determined that after testing in Unit No. 2 the microhardness of the surface layer increases less

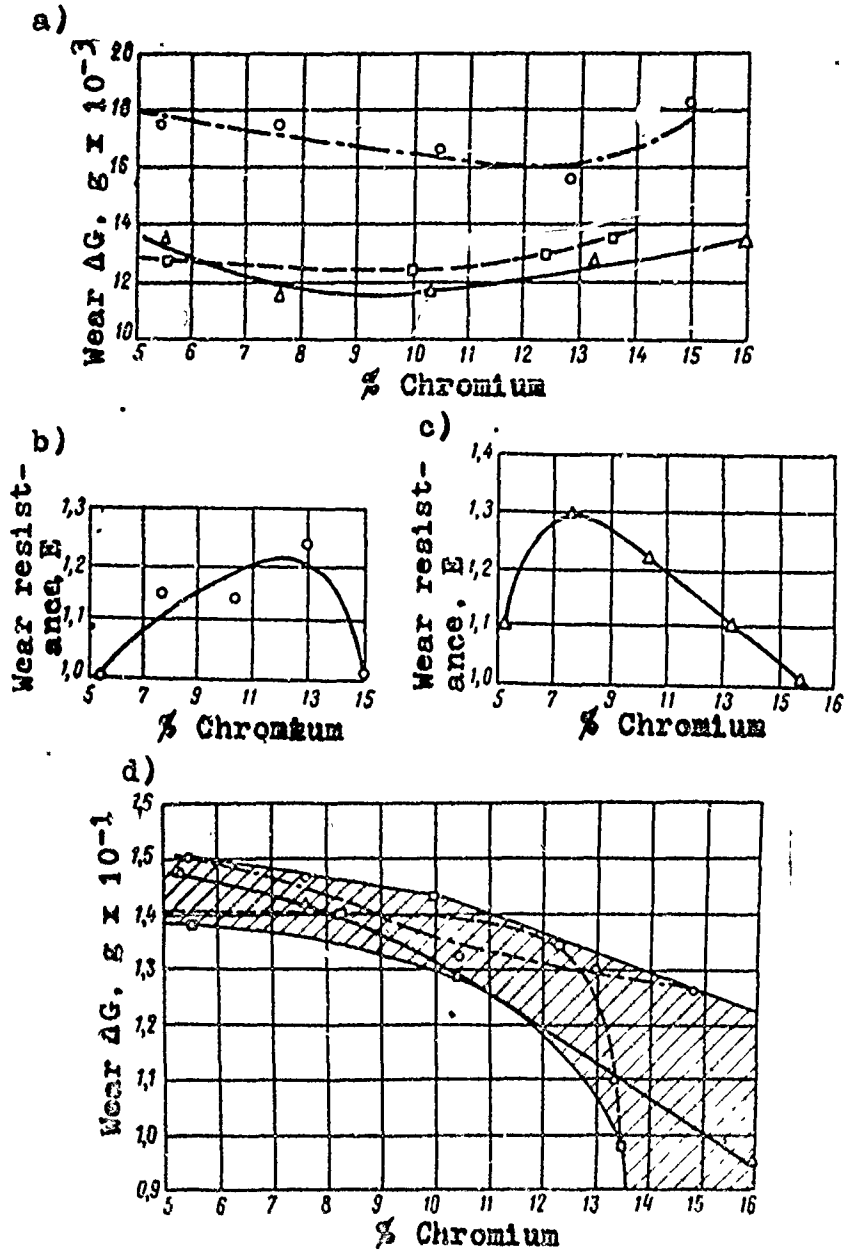


Fig. 25. The effect of chromium on the hydro-abrasive wear resistance of steel.

Tests in Unit No. 2: a. test specimen wear in one hour of testing; b. and c. average value of wear resistance of specimens after 20 hours of testing.

d. tests in Unit No. 3.

○ - 0.11% C; △ - 0.22-0.24% C; □ - 0.26-0.31% C.

than after testing in Unit No. 1. This indicates the lower /64 intensity of abrasive mixture action in Unit No. 2. Thus, under those conditions whereby in the process of hydro-abrasive wear maximum hardening takes place (operation on a sand-gravel bottom), the optimum chromium content (with 0.2% C) will be its lower amount, i.e. 10-12%. Under conditions where the intensity of impact action is low (sandy bottom), it is expedient to increase chromium content to above 12%. The optimum wear resistance will be observed with a chromium content of 12-14%. Further increase of chromium content to above 15% leads, as well as in Unit No. 1, to decreased wear resistance because of the increase in the amount of free ferrite in the microstructure of steel.

After testing in Unit No. 2, the same specimens were /66 tested under conditions of impact load application in Unit No. 3. The specimens were not fastened at the bottom of the cylinders. Tests lasted 20 hours, but the specimens were weighed after each three hours.

As seen from Fig. 25d, test specimen wear decreases with increase in chromium content from 5 to 12%, at the same rate both for steels containing 0.11% C and those containing 0.22-0.24% C. In steels containing 0.26-0.31% C, an increase in chromium content does not affect wear resistance. With further increase in chromium content, specimen wear decreases sharply. This can be explained by the fact that with an increase in carbon content from 0.11 to 0.31%, the amount of gamma-phase in steel structure increases, while the stability of austenite also increases with an increase in chromium content above 12%. This assumption is confirmed by the results of microhardness measurements of surface layers before and after the tests.

Hydroabrasive tests were also performed in Unit No. 3 in synthetic sea water of Black Sea composition. Duration of tests was 60 hours. In each 24 hours of tests the specimens were in motion for 7 hours and stationary the rest of the time.

These tests showed that when the corrosion factor was prevalent, the optimum content of chromium and carbon were 12-14% and up to 0.2%, respectively.

Tests carried out in different units allow us to conclude that the casting skin has a favorable effect on the increase of wear resistance under conditions of hydroabrasive wear. For example, specimens prepared by investment

casting possessed the higher wear resistance in all cases. This is due to the fact that the surface layer of the specimen has a fine-grain microstructure (7-8 in the GOST scale) to a depth of 1.2 mm, while the core of these specimens consisted of larger grains (2-4 on the GOST scale). In addition, the density of the oxidation film of cast specimens is higher than that of machined specimens. This is of considerable importance under service in a corrosive medium.

The effect of carbon. Carbon content in chromium-manganese steel has a substantial effect on its wear resistance under conditions of hydroabrasive wear. It was shown earlier that depending on wear conditions, an increase of carbon content in steel results in individual cases in increase of the relative wear resistance. This is particularly pronounced under conditions of impact load application.

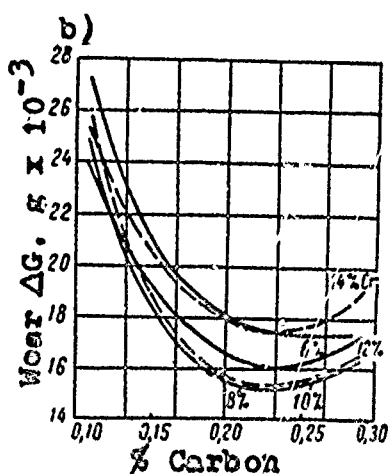
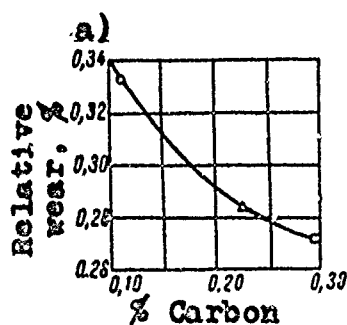


Fig. 26. Effect of carbon on the hydroabrasive resistance of steel: a. tests in Unit No. 2; b. tests in Unit No. 3.

In Fig. 26a, generalized data are presented on the effect of carbon content in tests in Unit No. 2 and in Fig. 26b, in tests in Unit No. 3.

As a result of tests in Unit No. 2 (Fig. 26a), it was determined that the optimum carbon content is: 0.20-0.28% C with 6-14% Cr and with about 7% Mn.

Under conditions of impact load application in Unit No. 3, the relative wear was decreased with an increase in carbon content from 0.1 to 0.3 (Fig. 26b).

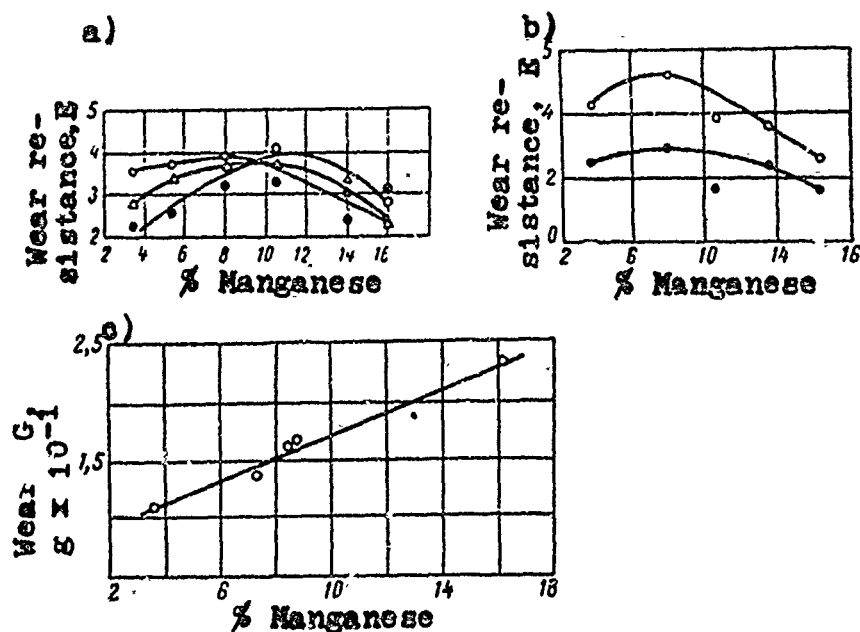


Fig. 27. Effect of manganese on hydroabrasive wear resistance of steel: a. tests on Unit No. 1, specimens of steel with about 0.2% C and about 13% Cr; b. also Unit No. 1, specimens of steel with about 0.42% C and about 13% Cr; c. tests on Unit No. 3, specimens of steel with about 0.2% C and about 12% Cr.

e - as cast; Δ - air cooling from 1100-1150°C;
 o - quenching in water from 1100-1150°C

The effect of manganese. Steels containing 0.2% C, about 13% Cr and 3-16% Mn were tested in Unit No. 1. Steels with higher carbon content (about 0.42%) were also tested. In both cases the wear resistance of steel basically increases as manganese content is increased to 7-9% (Fig. 27a). An exception is steel containing 0.2% C after quenching in water from 1100°C. The wear resistance of this steel increases with an increase of manganese content to 12%.

The increase of austenite stability, related to the increase of manganese content to above 12%, leads to a decrease in wear resistance of chromium-manganese steels. The presence of a large amount of carbides in steel containing 0.42% C after air cooling from 1150°C, leads to the highest resistance of this steel (Fig. 27b).

Tests in Unit No. 3 demonstrated a decrease in wear

resistance of steel containing about 0.2% C and 12% Cr with an increase in manganese content from 3 to 16% (Fig. 27c). This proves once more the assumption made above that manganese austenite stability improves as manganese content increases.

Hence, the test results obtained under various conditions of hydroabrasive wear make it possible to conclude that the optimum manganese content in steel which contains about 0.2% C and 13% Cr is 7-9%. /68

The effect of silicon. The tests of chromium-manganese steel specimens containing about 0.25% C, 14% Cr and 7% Mn in Unit No. 1 established the favorable effect of silicon content increase from 0.3 to 1.4% on hydroabrasive wear resistance of steel specimens (Fig. 28).

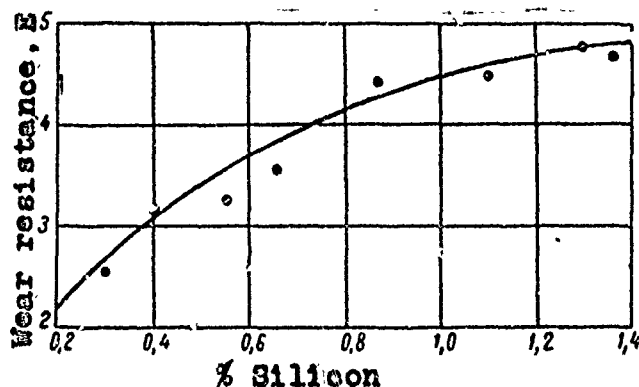


Fig. 28. The effect of silicon on hydroabrasive wear resistance of steel. Tests in Unit No. 1. Specimens of steel with about 0.25% C, about 14% Cr, and 7% Mn.

Corrosion Resistance

/69

The purpose of this research was to determine the corrosion resistance of chromium-manganese steel with varying content of chromium, manganese and carbon. The study of corrosion resistance makes it possible to correctly determine which steel should be selected for screw propellers in service under conditions of combined action of cavitation and corrosion.

Corrosion resistance of steel was determined by changing the electrode potential. This evaluation of corrosion resistance by electrode potential may be used only for

preliminary testing. Sea water of the same composition as Black Sea water was used as an electrolyte. The galvanic circuit was composed of five test specimens made of various steels of the same heat and a saturated calomel comparison electrode, connected, through an intermediate vessel, with a saturated solution of potassium chloride, by electrolytic keys filled with a saturated solution of KCl and sea water.

The steady potential of each of the specimens was measured with a type PPTW-1 high-resistance potentiometer. Measurement precision was within ± 5 Mv.

Chromium-manganese steels were tested, the microstructure of which, after quenching in water from 1100-1150°C, was both two-phase ($\alpha + \gamma$) and austenitic monophase.

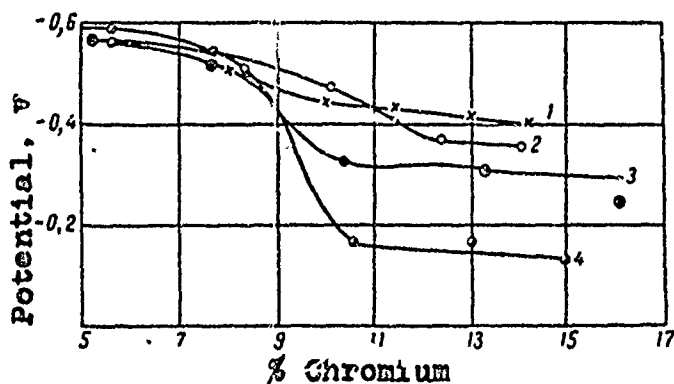


Fig. 29. The effect of chromium on change of the electrode potential of chromium-manganese steels in sea water:
 1. 0.45% C, 9% Mn; 2. 0.28% C, 7% Mn;
 3. 0.24% C, 7% Mn; 4. 0.11% C, 7% Mn.

A study was made of the effect of chromium on change in electrode potential of chromium-manganese steel, relative to a calomel electrode, in sea water (Fig. 29). From this study, it was determined that the corrosion resistance of steels with a constant manganese content depends mainly on the content of chromium and carbon. In all steels studied, when chromium content was increased from 5 to 8%, the corrosion resistance increased to approximately the same extent. At a chromium content above 8%, electrode potential values depend principally on the carbon content in steels.

In steel containing 0.1% C (heat No. 4), the

passivation phenomenon (the attainment by steel of a constant electrode potential value) takes place in sea water at a chromium content of about 10.5%. This steel, by the way, has the highest potential of all steels studied.

Steels containing about 0.45% C possess lower corrosion resistance (heat No. 1). Although their electrode potential becomes constant at a chromium content of about 10%, its value is only one-third that of specimens of heat No. 4, containing 0.1% C.

It should be noted that heating of heat No. 1 specimens during heat treatment was carried to a higher temperature than that of carbide diffusion (1150°C), so practically no carbides were observed, i.e. solid solution impoverishment by chromium did not occur. However, the corrosion resistance of steel with increased carbon content was lower than that of the steels in heats No. 2-4.

The data in Fig. 29 made it possible to establish that chromium-manganese steels attain a stable electrode potential at a chromium content of about 13%, regardless of carbon content; therefore, further increase of chromium content does not change the corrosion resistance of steel. An increase of chromium content to above 18%, with a carbon content of 0.1%, sharply raises the amount of alpha-phase in the structure, which results in the appearance of spot corrosion.

According to F. F. Khimushin /40/, the high content of manganese in type 18-8 chromium-manganese steels impairs corrosion resistance in sea water as compared with type 18-8 chromium-nickel steel. We studied the corrosion resistance of chromium-manganese steel containing 0.20-0.45% C, about 13.5% Cr and 3.5-16% Mn.

Analysis of the change in electrode potential in relation to manganese content (Fig. 30) showed that increasing manganese content up to 10% does not noticeably change the corrosion resistance of chromium-manganese steel. At a manganese content above 10% the corrosion resistance of the steel deteriorates slightly.

As will be shown below, our research /18/ established the favorable effect of adding a slight amount of titanium to steel (0.05-0.1%) on the mechanical properties and cavitation resistance of chromium-manganese steel.

Steels alloyed with titanium also possess relatively high corrosion resistance. /71

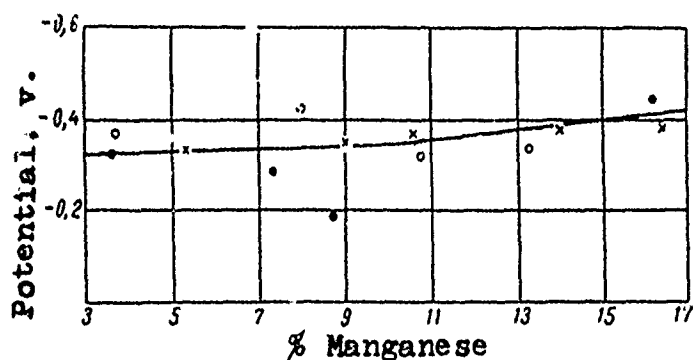


Fig. 30. Effect of manganese on change in the electrode potential of chromium-manganese steel in sea water.

o - 0.35% C, 13.5% Cr; e - 0.32% C, 11% Cr; x - 0.2% C, 13.5% Cr.

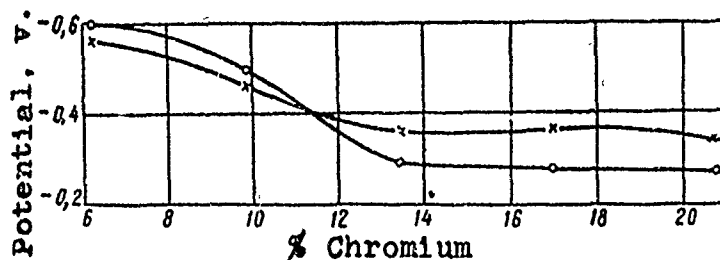
The comparison of data given in Fig. 29 shows that heat No. 3 steel, containing 0.04% Ti and 10.5% Cr, is more resistant to corrosion than steel of heat No. 2, which does not contain titanium (with 12.3% Cr).

The effect of steel structure on corrosion resistance was investigated using specimens in an as-cast state (without heat treatment) and after water quenching from 1100°C. Test specimens were prepared by investment casting. Specimen surfaces were cleaned with emery cloth before testing.

The microstructure of steel, as cast, consisted of alpha- and gamma-phase, with carbides present along grain boundaries. Microstructure of the surface layer of specimens consisted of elongated fine grains. In some areas, clearly expressed structural nonhomogeneity (dendritic segregation) was observed, with large equiaxial grains. /12

As a result of tests, it was established that the fine grain structure of the surface layer of cast specimens favorably affects corrosion resistance of steels containing up to 11% Cr. With further increase in chromium content, to above 11%, the cast steel possesses lower corrosion resistance (Fig. 31) as compared to heat treated steel. This is probably caused by the impoverishment by chromium of the solid solution due to the presence of carbides in cast steel.

As a result of research on the corrosion resistance of steel with various contents of alloying elements, the following conclusions were made:



/71

Fig. 31. Effect of structure on change in electrode potential of chromium-manganese steel in sea water.

- x - 0.21% C, 10.2% Mn, as cast;
- o - the same after quenching in water from 1100°C

1. To secure high corrosion resistance of chromium-manganese steel in sea water, the chromium content should be at least 12%;

/72

2. The optimum carbon content in corrosion-resistant steel is considered to be 0.1-0.2%;

3. Addition of titanium to steel (0.05-0.1%) results in some increase in corrosion resistance;

4. Heat treatment of steel, i.e. quenching in water after annealing at a temperature higher than the temperature of carbide diffusion, also enhances its corrosion resistance.

16. Corrosion Resistance of Steel

/106

Specimens of 25Kh14G8T steel were tested in a stream of synthetic sea water, corresponding in composition to water of the Black Sea.

The sea water was prepared through reactions of chemically pure reagents with distilled water. The overall salinity of the water was 2.2%. The surface area of the samples was about 3 dm², and the volume of the water about 20 liters. The water was changed twice a week.

Corrosion resistance in the stream was measured in terms of weight loss of the samples before and after tests. Testing was done on a spindle apparatus with a specimen velocity in water of 14 m/sec, which resembles to some extent the operating conditions of a screw propeller.

The duration of the corrosion tests in a current was usually 250 hours /8, 9/. Study of the effects of stopping the spindle apparatus showed that the corrosion rate of ferrous metal, and especially of stainless steels, increases significantly when the samples are allowed to remain stationary for some period of time. In order to determine the role of the corrosion factor, the length of comparative experiments was extended up to 1000 hours, with the test specimens being in motion 410 hours.

Studies of the effect of the sea water stream on corrosion resistance of 25Kh14G8T steel were conducted using cast specimens which were cooled in air from 1100°C before machining. Tests were simultaneously conducted on specimens of St. 48 carbon steel, widely used in the manufacture of ships' hulls, and on specimens of 30Kh10G10 cavitation-resistant steel.

The chemical composition of tested steels and the results obtained are given in Table 23. As seen from this table, the 25Kh14G8T steel possesses high corrosion resistance, exceeding that of 30Kh10G10 steel by a factor of 4.3.

The data from tests of corrosion-resistant steels used for screw propellers of sea-going ships (1Kh14ND chromium steel; 1Kh18N9T, 0Kh17N3G4D2T, Kh23Ni8 and other austenitic chromium-nickel steels) show that the corrosion rate of austenitic stainless steel, at various sea-water current velocities, remains practically the same and is independent of current flow velocity within the range from 2 to 16 m/sec. The average corrosion rate of these steels (based on tests of 250 hours) is 0.005 mm/year. /107

The corrosion rate of 0Kh17N3G4D2T austenitic steel is slightly increased when subjected to a stream velocity of 16 m/sec, to 0.008 mm/yr. The corrosion rate of 1Kh14ND steel, when subjected to an increased current velocity from 8 to 16 m/sec, doubles and amounts to 0.013-0.014 mm/yr.

In 25Kh14G8T steel an increase of water stream velocity from 8 to 16 m/sec results in an increase of corrosion rate by 2.2 times, and at a velocity of 16 m/sec the corrosion rate is 0.024 mm/yr.

The results of these experiments confirmed earlier studies of the corrosion resistance of chromium-manganese steels containing over 12% Cr. The relatively high resistance to corrosion of these steels, when subjected to an increase in current velocity within the range 2-16 m/sec, is explained by the rather strong protective surface

Table 23

Results of corrosion-resistance tests of 25Kh14G8T steel in sea water

Steel designation	Chemical composition, %										Weight loss, g	Corrosion rate	
	C	Si	Mn	S	P	Cr	Ni	Ti	K*, g/m ² /hr	P**, mm/yr			
St. 4S	0.21	0.21	0.55	0.004	0.009	---	--	--	--	--	2.53	2.8	3.15
30Kh1G10	0.31	0.52	9.37	0.019	0.021	9.87	0.21	--	--	--	0.065	0.072	0.081
25Kh14G8T	0.25	0.88	7.35	0.018	0.023	13.34	0.24	0.02	0.02	0.02	0.0151	0.0167	0.0188

$$*K = \frac{\Delta P}{S \Delta t}$$

where ΔP - specimen weight loss, g;
 S - specimen surface area, m² ($S=2210 \text{ mm}^2$);
 Δt - duration of tests in the stream, hrs.

$$**P = \frac{K}{d} \cdot 8.76 \text{ mm/yr.}$$

where d - specific gravity of specimen material.

film on steels containing more than 12% Cr. As the sea water stream velocity is increased, this film not only does not break down, but, on the contrary, is quickly re-stored at damaged areas due to the intensified supply of oxygen.

Less resistant to corrosion are steels containing less than 12% chromium, for instance, 30Kh10G10 steel. This is due to an insufficiently strong surface film, formed at a lower chromium content and a higher carbon content. In the experiment, the film was worn more easily by the sea-water stream. /10

Our results confirmed the results obtained by V. A. Delle /5/, in which it was determined that only alloys containing 12% or more chromium had a high corrosion resistance in oxidizing media. Alloys containing less than 12-13% Cr are insufficiently passivated in a sea-water stream, therefore their corrosion resistance is relatively low.

17. Corrosion-Fatigue Strength of Steel

Ship screw propellers operate under conditions of varying stress and corrosion, especially when operating in sea water, so materials used in the manufacture of ship propellers must have adequate corrosion-fatigue strength.

During both normal and corrosion-fatigue failure, microscopic cracks appear which gradually expand, leading to sudden brittle fracture. Corrosion-fatigue failure is characterized by extensive cracking in the area of stress concentration.

The fatigue process in a corrosive medium is characterized by the absence of a fatigue limit; the process depends on the cycle duration, i.e. on the basis for its beginning (a certain number of cycles).

Corrosion-fatigue failure occurs as the result of the simultaneous action of mechanical and corrosive factors, and one may visualize it in the following manner /9/:

Local microplastic deformation leads to lower resistance to oxidation of microvolumes of metal, which is enhanced by the action of the corrosive medium, and which facilitates the escape of ions from the metal into the solution. This leads to the formation and expansion of fatigue cracks of corrosive-mechanical origin. /1

Table 24

Chemical composition and physical properties of 25Kh14G8T steel,
submitted to corrosion-fatigue resistance tests

Heat No.	Chemical composition, %								Mechanical properties		
	C	Si	Mn	S	P	Cr	Ni	Ti	tensile strength kg/mm ²	yield point kg/mm ²	Elongation, %
524/1	0.23	0.73	8.91	0.011	0.023	13.45	0.21	0.05	57.5	28.2	12.0
570	0.21	0.95	10.97	0.008	0.030	14.0	0.20	0.03	55.6	29.0	14.0

The chemical composition of 24Kh14G8T steel and the /109
mechanical properties of specimens subjected to corrosion-
fatigue tests are shown in Table 24.

Experiments were conducted using specimens 8.5-10.0 mm in diameter on MUI-6000 fatigue testing machines at 6000 rpm. The samples were in the shape of bars 25x25x350 mm in size, prepared by investment casting. The metal was melted in a basic induction furnace with a 40 kg capacity. Before machining, the specimens were subjected to heat treatment--quenching from 1100°C in water. The specimens had a groove 15 mm in radius running lengthwise down the middle. This groove provided a smooth transition from the working part of the specimens to the part turned to a diameter of 8.5-10.0 mm; it also prevented the action of stress concentrators during tests.

The corrosive medium was a 3% solution of NaCl in tap water, imitating sea water. The circulation rate of the solution remained constant at about 10 l/hr; tests were based on 10^7 cycles.

The results of the corrosion-fatigue tests of steel are given in Fig. 46. As seen in Fig. 46, the fatigue limit /110 of steel under normal atmospheric conditions is 46-48 kg/mm², while the corrosion-fatigue limit on a base of 10^7 cycles in a 3% saline solution is 18-25 kg/mm².

As a comparison, we include the test results of some steels, according to data in reference /37/ by N. N. Sokolov. The corrosion strength of 1Kh14ND steel, in testing on a basis of 10^7 cycles, was equal in air to 25 kg/mm² and in a 3% NaCl solution to 16 kg/mm². For 2Kh13N steel the corresponding figures are 22 and 14 kg/mm². For 18DGC steel they are 30 and 12 kg/mm².

Thus, experiments have shown that 25Kh14G8T steel has a sufficiently high resistance to corrosion-fatigue failure.

It is known that stress concentrators in the form of keyways, sharp changes in cross-section, etc., result in a decrease in the fatigue resistance of metal parts. The value of the fatigue limit in this case depends on the geometric form of the notch and the sensitivity of the material to stress concentrators. Specimens with a stress concentrator had a sharp, circular, V-shaped notch 2.5 mm in depth and with a corner radius of 0.1 mm.

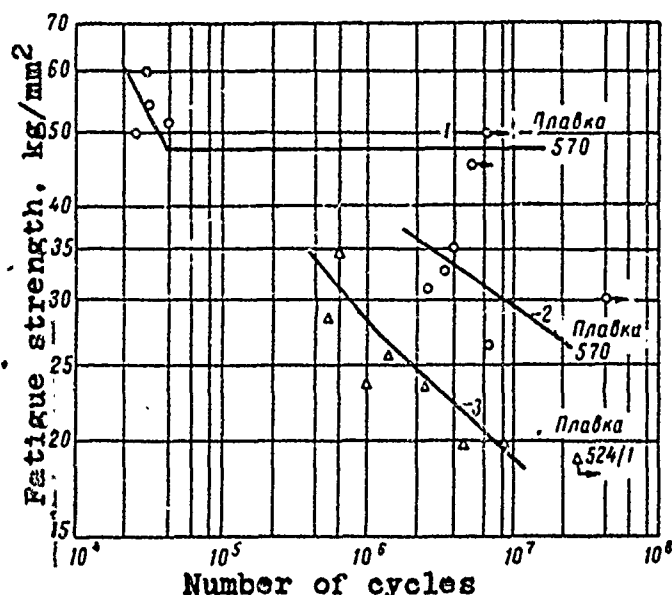


Fig. 46. Corrosion-fatigue strength of steel: 1. tests in air (heat No. 570); 2. tests in a 3% NaCl solution (heat No. 570); 3. same as curve 2 (heat No. 524/1).

Under identical conditions, smooth and notched specimens of 25Kh14G8T steel, 10 mm in diameter, were tested in air and in a 3% solution of NaCl. /110

The results obtained demonstrate that a decrease of fatigue resistance occurs in specimens with stress concentration (sharp notches) when tested in air. The effective stress concentration factor (the ratio of fatigue limit of smooth to notched specimens) is $K_e=2$. A greater decrease in the corrosion-fatigue resistance with notched specimens is observed in salt water. Under these conditions, the value of the corrosion fatigue strength based on 10^7 cycles was only 8-10 kg/mm², whereas for smooth specimens under the same conditions the value of the corrosion-fatigue strength is equal to 18-25 kg/mm².

The decrease in corrosion-fatigue strength of notched specimens is apparently connected with the corrosion processes at the root of the notch as a result of the impeded oxygen supply, necessary for the restoration of a protective oxide film.