ABRASIVE WEAR AND CAVITATION

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On parts of hydraulic machines subjected to abrasive wear, along with surfaces of uniform wavy wear, local wear in the form of relatively deep grooves is also often found. The formation of local wear is usually associated with some obstacles to the flow over the surface of the part (irregularities from rough machining of the part, cavities in the metal, weld deposits, bolt holes, etc.) or with bluff forms of parts. There is reason to suspect that the cause of local wear, in addition to abrasion, is also separation-type cavitation (^{1}), arising in the vortex-formation zone. At present, however, opinions on the role of cavitation in abrasive wear ($^{2-5}$) are contradictory, which is explained by the absence of experimental studies of this problem, which is of substantial importance in choosing the metal for hydraulic machines.

The experiments described were carried out in hydrodynamic tube No. 2 of the Institute of Mechanics of the Academy of Sciences of the USSR jointly with the Institute of Mechanical Engineering of the Academy of Sciences of the USSR under the direction of K. K. Shalnev. The cross section of the working chamber of the tube was 6×25 mm^2; the diameter of the model exciting separation-type cavitation, $d = 6$ mm, and the flow velocity $v = 17$ msec^{-1} remained constant in the experiments. Plates of rolled lead were used as reference specimens, and the abrasive medium was water with sand of grain size 0.05–0.4 mm. The arrangement of experiments with cavitation erosion behind a cylinder has been described previously (^{6}); other details of the present investigation and the results are given in Table 1, where $\lambda = l_z/d$, l_z is the length of the cavitation zone; c is the sand concentration; h is the duration of the experiments; ΔG is the loss of weight of the specimens over the whole test period.

The wear experiments were supplemented by high-speed motion-picture recording* of the cavitation zone at a frequency of $6 \cdot 10^4$ frames $\cdot$ sec^{-1}, carried out in reflected light (Fig. 1).

Experiment 1, the control experiment, was carried out with pure water. The surface of cavitation erosion (Fig. 2a) consists of two tail-shaped regions corresponding to the position of the end of the cavitation zone behind the cylinder. The erosion regions are pitted with ulcers extending into the depth of the metal.

Experiment 2, with wear from the combined action of cavitation and abrasion, gave a different picture of wear (Fig. 2b). Even during the experiment there

Figure 1

Figure 1: Figure 1

Figure 2

Figure 2: Figure 2

was observed, above all, the appearance of a groove of local wear encircling the cylinder on the pressure side like a necklace with open ends. The surface of the groove on the bend is smooth, toward its ends passing into the wavy surface characteristic of abrasive wear. In the trace of the ends of the groove, pits of cavitation erosion are noticeable, arising, probably, from cavitation of the irregularities of the groove surface. The surface region between the ends of the groove, corresponding to the location of the tail erosion in experiment 1, is almost completely free of cavitation erosion. Downstream, outside the cavitation zone, the surface of the specimen has a wavy appearance; the crests of the waves are located normal to the direction of flow, the distance between them tends to a constant value, and their heights increase toward the end of the specimen.

* The motion-picture recording was performed by A. A. Milovidov.

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Fig. 1. Individual successive frames from high-speed cinematography of the cavitation zone behind a circular cylinder, taken at a frequency of $60 \cdot 10^3$ frames $\cdot$ sec^{-1}

Fig. 2. Photographs of specimens tested for different types of wear. Designations *a*–*d*, see Table 1; *e*—wavy erosion, specimen 2; *zh*—the same, specimen 3

Experiment 3, conducted with suppressed cavitation, showed that the wear consists of a groove of local wear around the cylinder and wave-like wear over the remaining surface, with the exception of the region between the ends of the groove, which this time was free of wear (Fig. 2e).

Experiment 4 was intended to test the protective action of the groove against erosion on the surface region between the ends of the groove. The specimen was made composite: of a brass frame and a lead plate pressed into it, placed in the zone where cavitation was located (Fig. 2e). The groove of local wear could form only toward the end of the test period because of the greater resistance of brass to abrasion than that of lead. In the initial period of the test, the lead surface was subjected to the combined action of cavitation and abrasion and bears traces of intense wear from both abrasion and cavitation, with the difference from cavitation erosion that the walls of some pits are polished by sand particles.

Fig. 3. Diagram of vortex flows that caused abrasion. 1 —model of a circular cylinder; 2 —walls of the working chamber; 3 —rear vortices (Bénard—Kármán); 4 —front vortices (Zhukovsky); 5 —boundary vortices (Prandtl)

Figure 3: Fig. 3. Diagram of vortex flows that caused abrasion. 1 —model of a circular cylinder; 2 —walls of the working chamber; 3 —rear vortices (Bénard—Kármán); 4 —front vortices (Zhukovsky); 5 —boundary vortices (Prandtl)

Experiment 5 was carried out with a composite specimen in order to determine the intensity of abrasive wear in the absence of cavitation. The groove of local wear formed later; its ends pass into abrasive wear, but of lower intensity, in the zone of vortex separation. The brass part of the specimen was worn, but to a lesser degree than the lead in experiments 2 and 3. The brass part of the specimens behind the cylinder had not yet acquired a wave-like appearance, but its roughness is noticeable; the front end of the specimen was even polished.

Fig. 3. Diagram of vortex flows that caused abrasion.
1 —model of a circular cylinder; 2 —walls of the working chamber; 3 —rear vortices (Bénard—Kármán); 4 —front vortices (Zhukovsky); 5 —boundary vortices (Prandtl)

From a comparison of the results of experiments 4 and 5 it follows that, under the combined action of cavitation and abrasion, the intensity of local wear in the zone of separation cavitation and of abrasive wave-like wear in the zone free of cavitation increases (Fig. 2e, g), which leads to a greater loss of weight of the specimen in experiment 4 (see Table 1).

Table 1

No. of experiments	Designation in Fig. 1	λ	C, vol. %	h, hours	ΔG, mg
1	a	3	–	12	50
2	b	0	0.5	12	428
3	c	0	0.5	12	135
5	g	3	0.5	6	810
5	d	0	0.5	6	150

The origin of the different kinds of wear in our experiments is explained by the flow patterns (Fig. 3).

The location of the cavitation-erosion regions corresponds to the location of periodic cavities in the stage of their growth, or to the location of rear vortices (Bénard—Kármán) in the absence of cavitation (7). The location of the groove of abrasive wear corresponds to the arrangement of the front vortices (Zhukovsky) (8), which form in the transverse sections of the flow at a bend (9), in this case in jets flowing around the cylinder from the front pressure side. The vortex

Fig. 4. Development of the cavitation zone with time.

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–helical structure of the transverse flows is demonstrated by observations of the inception of cavitation on the axis of the flows. Here there occurs a wear phenomenon analogous to the drifting of snow in front of isolated obstacles in a strong wind and to the scouring of bulls from the pressure side (^{8}), and described also-

also in works (10, 11). Since the diameter of the front vortices must be at least two times smaller than the diameter of the cylinder, the erosive force of the sand grains in the vortex must be greater than that in the main flow bending around the cylinder in planes normal to its axis (12). The origin of the wavelike abrasive wear formed on the smooth surface of the lead specimens is explained by the erosive action of sand grains located in the boundary vortices (Prandtl) (13, 14). The wavelike wear in the zone of the rear vortices, according to experiment 5, and the absence of any traces of wear corresponding to the rotational motion of the liquid in the vortex zone, indicate that the sand grains either are ejected from the zone of the rear vortices, or the force pressing them against the wear surface is negligibly small in comparison with the pressing force in the boundary vortices.

High-speed cinematography of the cavitation zone explains both the retarding action of the groove on combined wear from cavitation and abrasion, and the condition of abrasive wavelike wear. In the presence of grooves of local wear, the cavitation cavity changes from periodic (7), pulsating, into a stationary one, thereby excluding the penetration of sand particles into this "stagnant" flow zone, which occurs at high speed when the groove has not yet arisen.

Fig. 4. Development of the cavitation zone with time. 1 –length of the cavitation zone $l_z/d = f(\tau/\tau_0)$, τ –stages of time, τ_0 –period of cavity shedding; 2 –length of an individual cavity $l_c/d = f(\tau/\tau_0)$; 3 –distance of the center of gravity of the cavity from the cylinder axis $l_{cg}/d = f(\tau/\tau_0)$.

In the absence of grooves of local wear, the cavitation zone consists of cavities periodically arising and being carried away by the flow, with a fundamental frequency $f = 1000$ Hz. The periodicity of cavity development obeys the Strouhal law at the value $\mathrm{Sh} = 0.23$, similarly to that described earlier (7). If one considers the change in length of the entire cavitation zone with time (and not of an individual cavity), then the pulsation of its tail is represented by a stepwise curve (Fig. 4, 1). At the moment of cavity separation, every 0.001 sec, a rapid jump-like shortening of its length occurs at a speed of 50 m sec^{-1}. From the moment of formation and after separation of the cavity, it pulsates in the direction of the flow with a frequency $f_c = 7000$ Hz (Fig. 4, 2); its complete shortening to disappearance occurs away from the model. The pulsation of the cavity is also reflected in the motion of its center of gravity, measured from the model axis (Fig. 4, 3).

As a result, with the appearance in the flow of a zone of separation cavitation, the turbulence of the boundary layer must increase, which is identical with an increase in the Reynolds number. In this case, according to (15), the distance between the boun-

by secondary vortices remains constant, but the velocity at the boundary of the main flow and the boundary layer increases or, in other words, the velocity at the periphery of the vortex. The force of abrasion of the sand grains then increases in proportion to the square of the velocity ratio.

Conclusions

1. When a circular cylinder in a tube of rectangular cross section is flowed around by a plane-parallel stream carrying abrasive particles at a medium concentration, the following types of wear are formed: 1) grooved (local) wear, encircling the cylinder on the pressure side and associated with the presence of front vortices; 2) wavy wear, associated with the vortex structure of the boundary layer. In the region of rear vortices, wavy wear is observed that does not reflect the vortex structure of the flow.
2. When cavitation zones are present in the flow, the intensity of wear increases both in the cavitation zone and outside it. The increase in wear in the cavitation zone is explained by the combined action of abrasion and cavitation. The increase in the intensity of abrasive wavy wear is explained by the increase in flow turbulence in the presence of cavitation.
3. Cavitation of the cylinder has no effect on the intensity of grooved wear due to abrasion. Irregularities of the surface of grooved wear may cause local cavitation and cavitation erosion.
4. A common property of abrasive and cavitation wear is that, in the case of separated flow, both types of wear, mutually intensified, are located in the zone of growth of cavitation cavities behind the cylinder, in the region of rear vortices. The difference is that cavitation and cavitation erosion do not form on a smooth flat surface, whereas abrasive (wavy) wear does arise.
5. The choice of metal for hydraulic machines operating under conditions of cavitation in water containing sediment should be made on the basis of testing them under the combined action of cavitation and abrasion.

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