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exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machinery

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ГИДРОФОРУМ

НАУЧНО-ТЕХНИЧЕСКАЯ КОНФЕРЕНЦИЯ

на тему

ПРОБЛЕМЫ ГИДРАВЛИЧЕСКИХ ТУРБОМАШИН

Гданьск-Владыславово, 24-27 сентября 1985 г.

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KAZIMIERZ STELLER, TADEUSZ KRZYSZTOFOWICZ

Instytut Maszyn Przepływowych PAN, Gdańsk (Institute of Fluid-Flow Machinery, Polish Academy of Sciences)
Zakład Metaloznawstwa i Obróbki Cieplnej Politechniki Gdańskiej (Department of Structural Metallurgy and Heat Treatment of the Technical University of Gdańsk)

Selection of Materials for Hydraulic Power Machines Exposed to Cavitation

Attention is drawn to factors influencing performance of materials when exposed to cavitation. Information is given on methods of evaluating the resistance of materials basing on their mechanical properties and erosion tests. Special attention is given to the principles of selecting structural materials for machine elements which are exposed to cavitation.

1. Introduction

The durability and reliability of fluid-flow machines are mainly influenced by:
— design and operating conditions,
— technology of manufacture, especially the structural materials applied.

An important barrier, which makes increasing performance parameters of fluid-flow machines difficult, is cavitation. Effects of cavitation are of two kinds. On one hand side, cavitation changes operation characteristics of the machines, on the other it is the cause of dynamic influences on their structural elements; it causes vibrations, wear cracks and erosion of material.

Experience gained by the Polish water power industry indicates that damages of machine elements caused by cavitation become increasingly frequent. In effect inter-repair periods become shorter and duration of repairs increases. The size of the problem and the need for limiting it are proved by examples from the following water power plants (Fig. 1): a) — Gródek, b) — Koronowo, c) — Solina, d) and e) — Żydowo, f) — Żarnowiec.

Erosion may be counteracted among others by using proper materials. In this paper, physical and chemical properties of materials guaranteeing good resistance to cavitation are indicated, methods of evaluating materials are discussed and directions for designers and users concerning selection of structural materials are given.

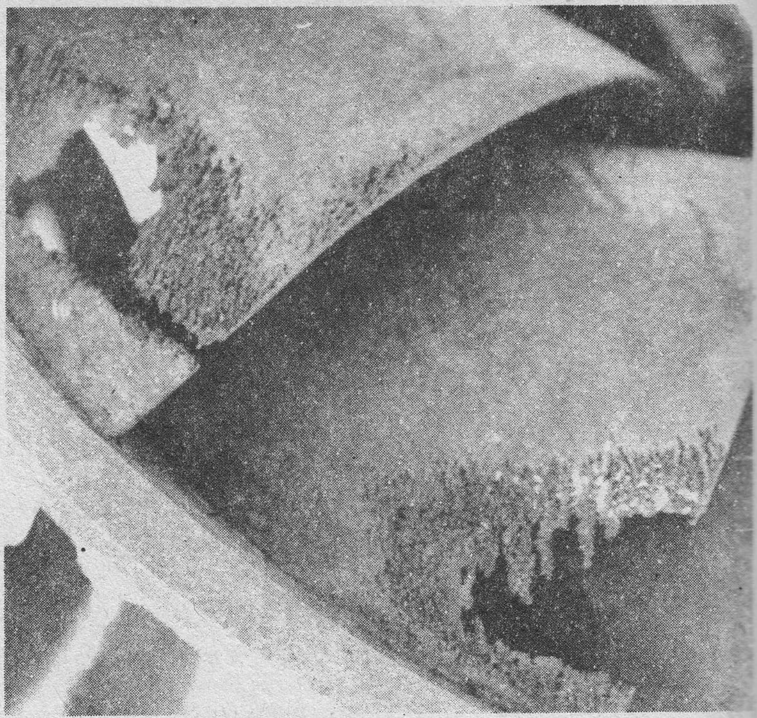

Fig. 1a. Damages to carbon steel runner blades after 7 years operation (Francis turbine, hydro power plant at Gródek)

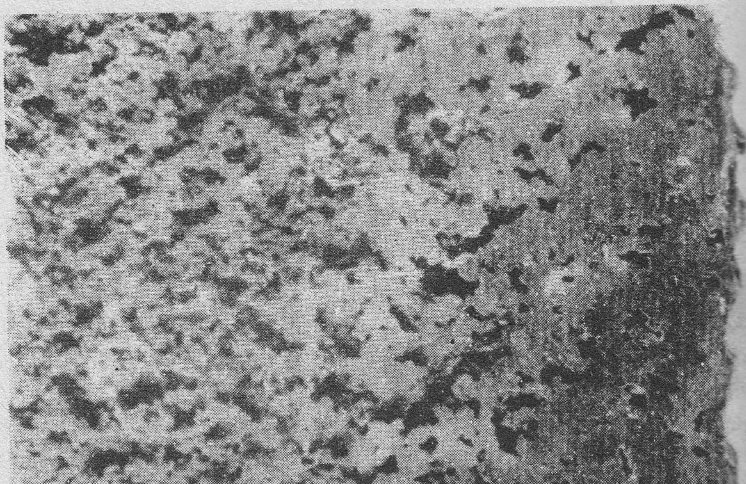

Fig. 1b. Damages to cast carbon steel runner casing (Kaplan turbine of hydro power plant at Koronowo)

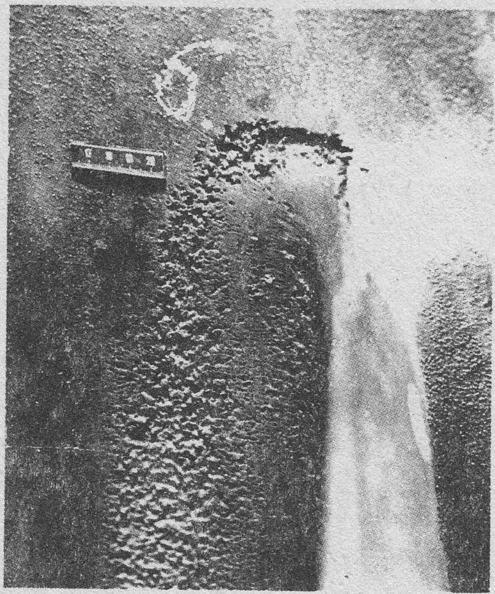

Fig. 1c. Damage of the hub at the runner outlet (Francis turbine, hydro power plant at Solina)

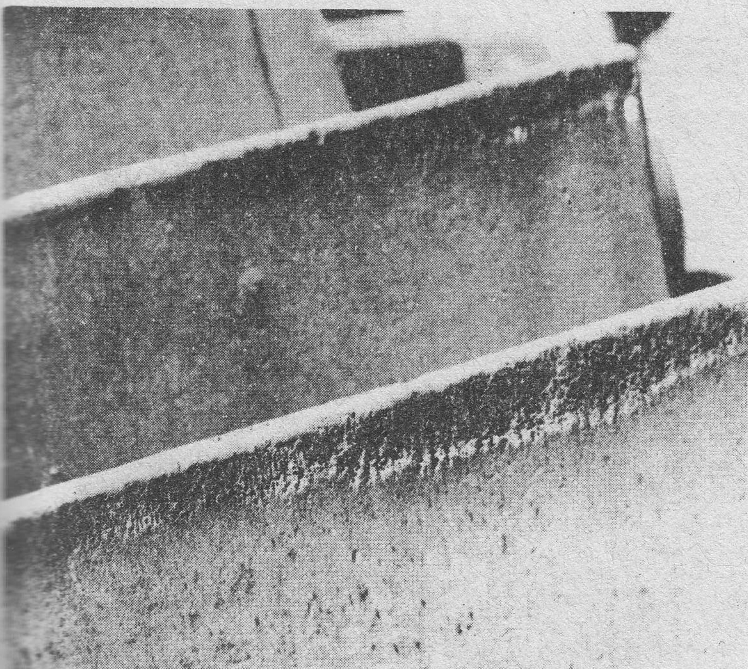

Fig. 1d. Damage of cast manganese steel guide ring vanes (reversible machine, pumped-storage power plant at Żydowo)

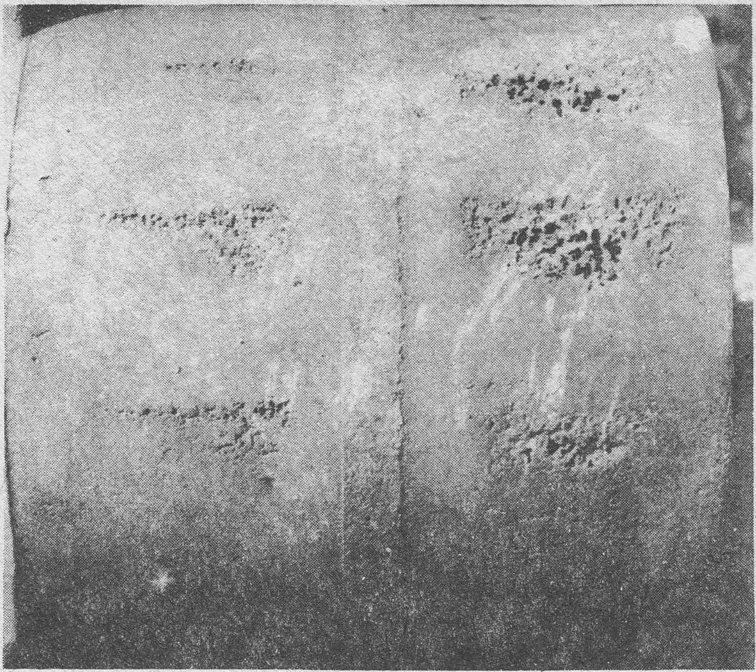

Fig. 1e. Cavitation pitting in the guide ring vane journal (reversible machine, pumped--storage power plant at Żydowo)

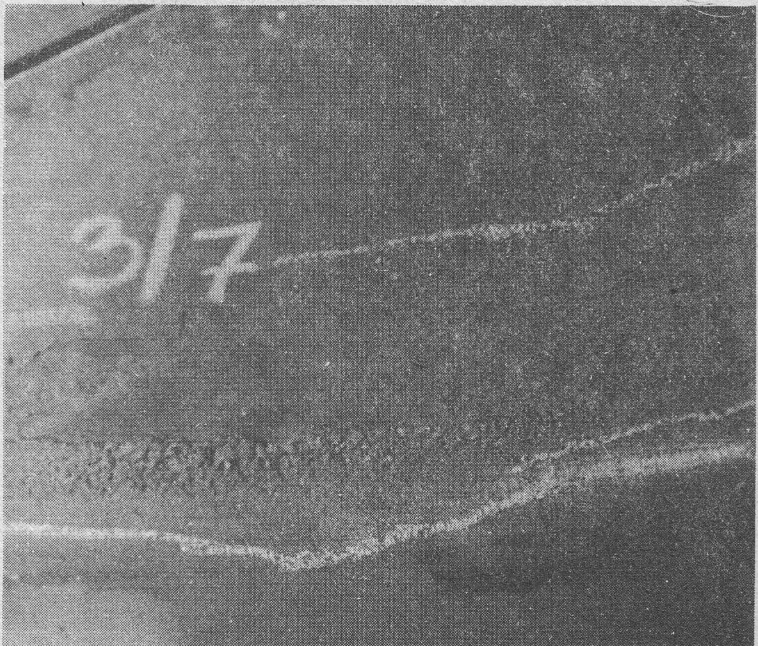

Fig. 1f. Damage of runner hub padded with stainless steel (reversible machine, pumped-storage power plant at Żarnowiec)

2. Factors Influencing Performance of Materials Exposed to Cavitation

The cavitation erosion process depends on the kind and condition of material, type and intensity of cavitation, type and state of liquid, especially its chemical activity. Influence of material factors on erosion is illustrated in Fig. 2. It may be concluded that materials characterized by good mechanical properties, resistant to corrosion, with uniform and fine grained structure and a limited number of defects have high resistance to cavitation.

Material performance under cavitation impingement is connected with the energy of cavitation pulses. The relation between erosion intensity I_e [W/cm^2], i.e. energy absorbed by a unit material surface in unit time, and the mean damage penetration rate MDPR has been defined by A. P. Thiruvengadam [7] in the following form:

$$\mathrm{MDPR} = \frac{I_e}{\mathrm{SE}} \left[\frac{\mathrm{cm}}{\mathrm{s}}\right] \tag{1}$$

where: SE [MPa] — is the resistance of the material to erosion, understood as the maximum unit energy accumulated in the material before it gets separated. The same author pointed out [8] that erosion intensity can be determined from the formula

$$I_e = \frac{1}{2}\rho v_\infty^3 \frac{L}{2R} \sigma_\infty \Delta\sigma \exp\left(-\frac{2.67}{\mathrm{We}\Delta\sigma}\right) \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \tag{2}$$

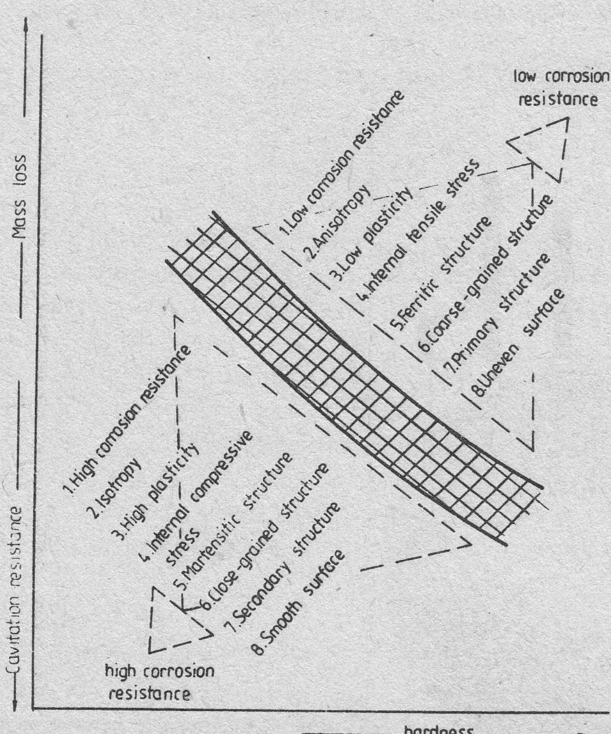

Fig. 2. Influence of the properties of material on its erosion resistance [3]

where ρ — density of liquid in kg/m^3, v_∞ — undisturbed flow velocity in m/s, L— characteristic linear dimension in mm, $\overline{R}$ — mean cavitation nucleus radius in mm, σ_∞ — cavitation number in undisturbed flow, $\Delta\sigma = \sigma_i - \sigma_\infty$ (σ_i is the cavitation number corresponding to initial cavitation), We — Weber number. It results from formula (2) that erosion intensity is a function of many arguments often difficult to determine.

The cavitation number σ is often assumed as a measure of cavitation intensity. Depending on the value of this number the machine performance parameters and dynamic characteristics as well as the cavitation erosion course are defined. The last

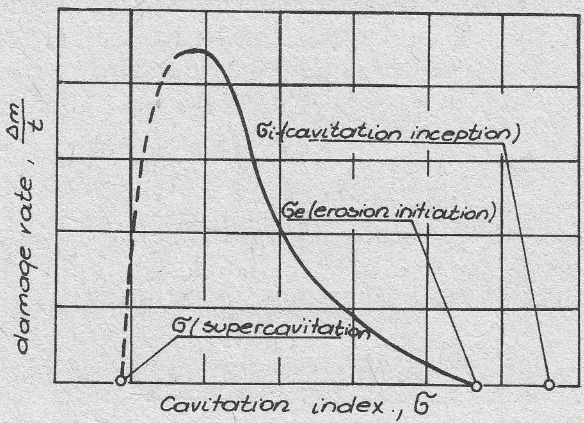

Fig. 3. Rate of material damage in dependence of cavitation index

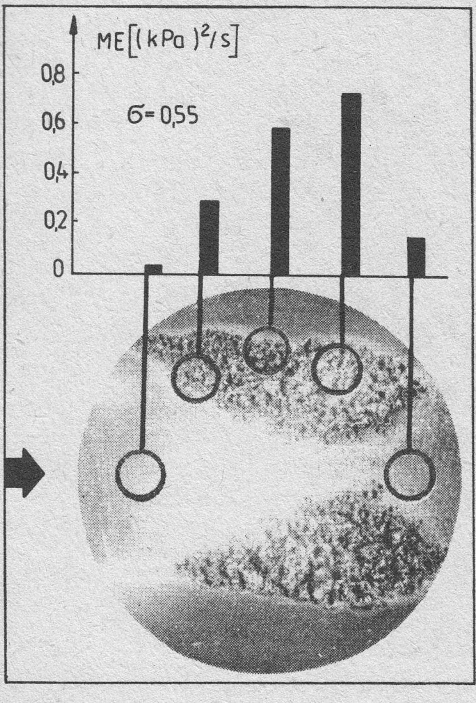

Fig. 4. Relationship between index ME and the damage degree of a lead sample

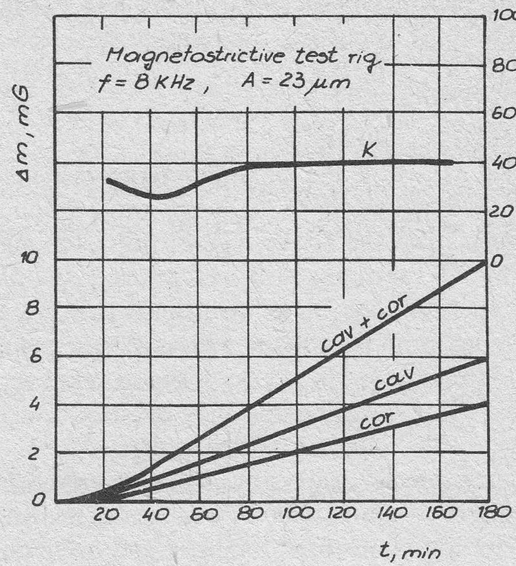

Fig. 5. Carbon steel exposed to cavitation and corrosion; cavitation cycles every 20 min, corrosion cycles every 22.8 h

relationship is shown in Fig. 3. It can be seen that the relationship $\Delta m/t = f(\sigma)$ is not a simple one and therefore forecasting cavitation damages from the value of σ is not possible. However, as a measure of erosion danger may be used the intensity of action of cavitation on the material, i.e. the value of loads resulting from cavitation bubble implosions. This phenomenon may be characterized by the following index of cavitation intensity:

$$\mathrm{ME} = \frac{1}{T}\sum n_i p_i^2 \quad \left[\frac{(\mathrm{kPa})^2}{\mathrm{s}}\right] \tag{3}$$

where: n_i — number of pulses in the i-th interval corresponding to pressure p_i in kPa, T — time of pulse counting measured in seconds. This observation is confirmed by Fig. 4 in which the relationship between the ME index and the degree of a lead sample destruction is shown.

With respect to the liquid, its influence on cavitation erosion is determined by: chemical composition, temperature, gas content, pH value, viscosity, conductance. The most important is the chemical activity of the liquid, which has a stimulating effect on the damage process of metals, especially of cast iron and carbon steel. Hence the joint action of cavitation and corrosion quickens damage occuring under the influence of the cavitation phenomenon itself. This statement is illustrated in Fig. 5.

3. Evaluation of Resistance of Materials to Cavitation

By cavitation erosion resistance of materials we understand the ability to resist the damaging effect of cavitation. Evaluation of this ability is only relative, and is supported by more or less accurate grounds. To the less accurate ones belong various strength parameters such as e.g. hardness, elasticity or strain energy at distortion; for example those occurring the relationships determined by F. G. Hammitt et al. [2]:

$$1/MDPR = C\cdot UR^{0.998} \qquad 1/MDPR = C\,(UR\,HB)^{0.72}$$
$$1/MDPR = C\,(UR\,E^2)^{0.659} \qquad 1/MDPR = C\cdot HB^{1.8} \tag{4}$$
$$1/MDPR = C\cdot SE^{0.738}$$

in which MDPR is the maximum damage penetration rate, i.e. the ratio of the depth of pits, corresponding to the maximum erosion rate, to the time of cavitation action. As results from the above relationships, the materials with higher UR (ultimate resilience), HB (hardness in Brinell units), E (modulus of elasticity) and SE (destructive strain energy) have better resistance to cavitation. These relationships have been determined from tests made with a certain group of materials on a magnetostriction stand. However, it should be borne in mind that a change of conditions of damage (not excluding the materials) may cause not only a change of the value of constant C, but also of the value of indices in formulas (4).

A more precise evaluation of the material is based on erosion tests. They consist in a quantitative comparison of changes in the materials (samples of materials) caused by cavitation of constant intensity and occurring under the same conditions.

Most often, erosion tests, are performed under laboratory conditions with the use of flow, vibration and impact devices. The laboratory of the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences in Gdańsk is equipped with such apparatus. With its use the curves indicating the loss of sample mass or volume and erosion rate in time are determined. In Fig. 6 an example of curves indicating destruction of

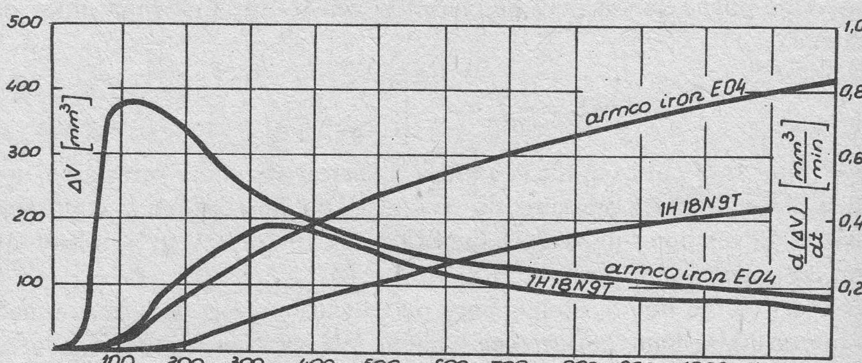

Fig. 6. Damage characteristics of "Armco" iron and acid resistant steel 1H18N9T determined at a rotating disc stand (Laboratory of the Institute of Fluid-Flow Machinery, P.A.Sci.)

commercially pure iron and acid resistant steel at a stand with a rotating disc is presented. Smaller, or more slowly occurring changes in one material (in this case in the acid resistant steel) as related to changes in the other one (armco iron) indicate that the first material is more resistant than the second one.

Evaluation made under laboratory conditions does not always coincide with the behaviour of the material in field. The reason for this is the reaction of material to the change of level, form and number of pressure pulses resulting from cavitation bubble implosions.

If it is assumed that the energy of an impact absorbed by the material is constant and proportional to the supplied energy, then knowing the results of laboratory tests of corresponding samples (of known cavitation intensity) and the corresponding cavitation intensity index under operating conditions, the average durability of the material in a full scale machine can be evaluated. It can be written that the average material durability is approximately [4]:

$$\delta_N = \delta_L \frac{R_{cav,F}}{R_{cav,L}} \frac{(\eta \mathrm{ME})_L}{(\eta \mathrm{ME})_F}, \qquad [\mathrm{min/mm^3}] \tag{5}$$

where $R_{cav,F}$ and $R_{cav,L}$ is the resistance of the same material under field (F) and laboratory (L) conditions, $\eta < 1$ is the efficiency with which the material absorbes energy, ME is the cavitation intensity index (equation 3). The method of experimental determination of resistance R_{cav} is described in [5]. Assuming the approximation that $\eta_F = \eta_L$ and $R_{cav,F} = R_{cav,L}$ equation (5) becomes:

$$\delta_F = \delta_L \frac{\mathrm{ME}_L}{\mathrm{ME}_F}. \tag{6}$$

Since the average material durability δ may be assumed as inversely proportional to the mean damage penetration rate MDPR, it can be written that:

$$\mathrm{MDPR}_F = \mathrm{MDPR}_L \frac{\mathrm{ME}_F}{\mathrm{ME}_L}. \tag{7}$$

4. Classification of Materials in Respect to Their Cavitation Properties

From among various factors influencing the resistance of materials to cavitation, the chemical composition and structure of the material should be distinguished. For example, the most desired structure for steel is the martensitic structure, which ensures far higher cavitation resistance than the ferritic-pearlitic structure (Fig. 7).

Erosion curves of steels varying both in chemical composition and structure are shown in Fig. 8. It may be concluded that the chemical composition and structure influence the incubation period and material durability.

A classification of some Polish materials with regard to cavitation erosion resistance was carried out at the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences. For the evaluation materials often used in hydraulic machines were selected. The evaluation was based on erosion tests performed on a device with rotating disc. Test results are shown in Table 1. The classification may be helpful in selecting the material for machine elements exposed to cavitation.

The following materials of foreign origin have good "anticavitation" properties. British, martensitic steels En56A, En56C and austenitic ones 304S15 and 321S12 which have chemical composition similar to steels designated in the Polish Standards

Table I

Evaluation of some Polish materials with regard to their cavitation erosion resistance

Resistance	Material, characteristics according to the Polish Standards or name
Very good	stellite
Good	23H12MNF, E Stel CoW, ES13Cr, 2H13 quenched and tempered
Fairly good	ES 18-8-2, LH17N2, ES 18-8, ES 18-8-6, BM12733, Superston, ZICr28, ES 24-18, 1H18N9T, OH18N9
Moderate	BAM2, 2H13 annealed, St5, BK331, LI1500, 1H13, L1H13N, EO4, St3, MM55, LI1400
Poor	15G, M70, ZI300, ZI250, ZI200, PA2 very poor

a)

b)

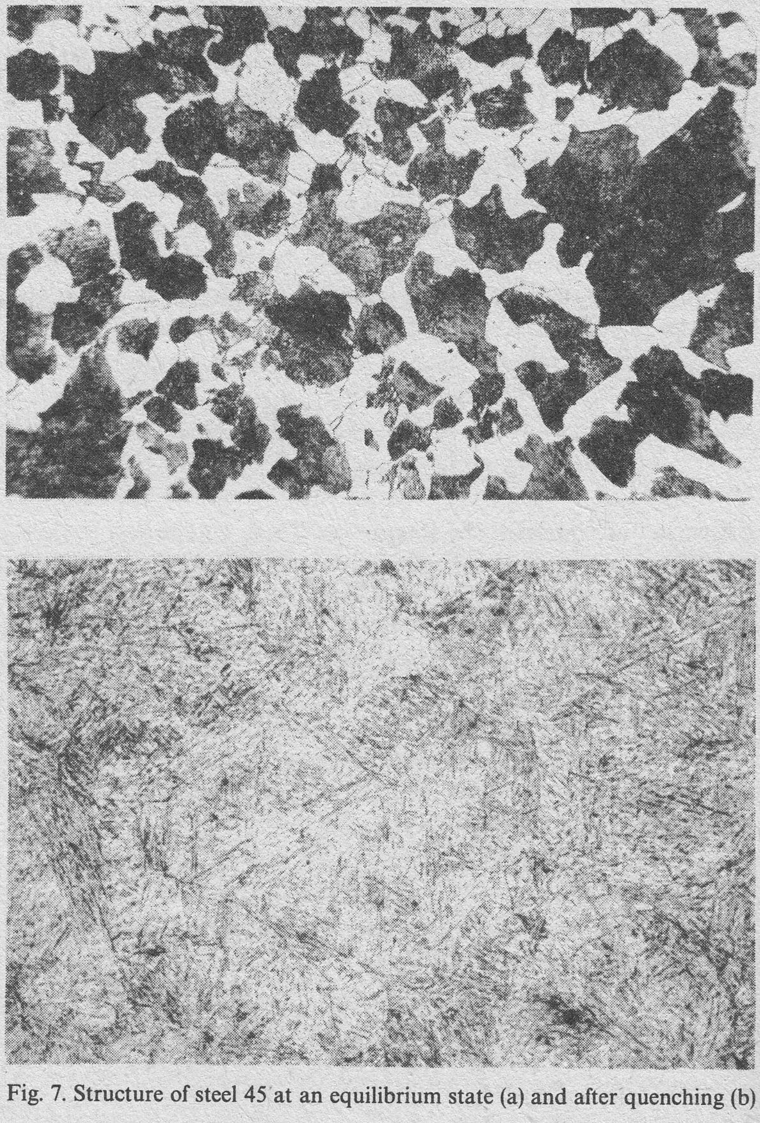

Fig. 7. Structure of steel 45 at an equilibrium state (a) and after quenching (b)

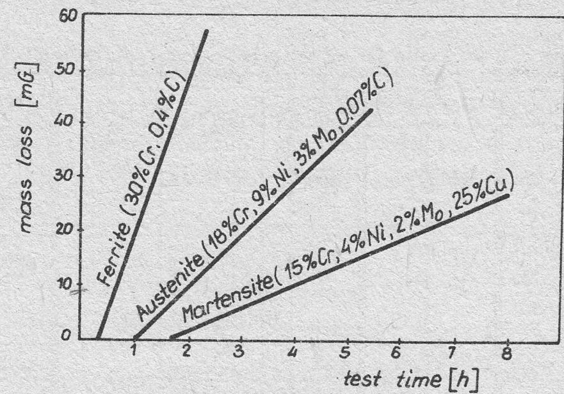

Fig. 8. Erosion curves for various steels

as 1H13, 3H13 and OH18N9, 1H18N9T; also martensitic steels for precipitation hardening Nimar 110, Nimar 125 corresponding to the Polish N18K8M5TPr, N18K9M5TPr, or Ultrafort 401 — corresponding to H10N7K9M5Pr (in accordance with the 1977 draft of the branch standard);

Czechoslovakian, martensitic steels type Cr13, Cr13Ni4, and austenitic steels type Cr13Ni6 with chemical composition similar to steels designated by the Polish Standard as 2H13, H13N4, and H13N6;

French, martensitic steels Z12C13, Z35C13, and austenitic steels Z5CN 18-08, Z8CB 18-08, Z8CBT 18-08 with chemical composition similar to steels designated by the Polish Standard as 1H13, 2H13-4H13, OH18N9, 1H18N9, 1H18N9T;

Soviet, martensitic steels 3X13, 25X14H, 0012H3A, austenitic steels 30X10Г10, ...H3Г3A 2, X14Г30HP, X14Г12M, X18H12Б P.

It is well known that the most endangered by mechanical overloads and cavitation are water turbine runners, pump impellers and rotors of reversible machines. Arriving at the best solutions for these elements requires of course close cooperation of the designer (rotor geometry), physical metallurgist (selection of material) and production engineer (manufacturing). Depending on the requirements and production facilities, the rotors are cast or are composed of cast, rolled or welded elements. At present, martensitic cast steel (low-carbon) with an addition of nickel and molybdenum are used for casting. Information on structural materials used for hydraulic machine rotors by VOEST-ALPINE is presented in Table 2.

Lately, VOEST-ALPINE has developed new martensitic cast steels, of improved hardness, designed for special applications (parts exposed to cavitation, erosion and those working in marine environment), e.g. cast steel type G-X5CrNiCuMoNb 13/6/2/2 and the double-phase (martensitic-austenitic) type G-X6CrNoMo 24/8.

Large runners or impellers, which consist most often of cast elements (hubs, skirts, blades), rolled (skirts) and those made from sheet steel (unshaped blades), are connected mechanically or by welding. In the last case, the type G-X5CrNiMo 13/4 material has good weldability.

Table

Typical stainless cast steel used for water turbine runners by VOEST-ALPINE [1]

Kind of cast steel	Chemical composition, %				Heat treatment °C	Mechanical properties			
	C	Cr	Ni	Mo		$R_{0.2}$ (MPa)	R_m (MPa)	A_s (%)	KV 20°C (J)
G-X10CrNi 13/1	0.07–0.11	12.0–13.5	1.4–1.5	—	Solutioning 1000—1050 Ageing 650—700	440	640–790	15	27
G-X5CrNi 13/4	0.07	12.0–13.5	3.5–4.5	0.4–0.6	Solutioning 980—1050 Ageing 580—620	540	760–960	15	60
G-X5CrNiMo 13/4	0.07	12.0–13.5	4.0–5.0	1.4–1.6	Solutioning 980—1050 Ageing 580—620	540	760–960	15	40
G-X5CrNiMo 16/5	0.07	15.0–16.0	4.5–6.0	0.5–2.0	Solutioning 980—1050 Ageing 580—620	540	760–960	15	40

More information on materials used by VOEST-ALPINE is contained in the paper of H. Enöckl and others presented at the International Seminar in Vienna [1].

The problem of improving structural materials exposed to cavitation is the centre of attention of both the research centres involved in materials technology and the manufacturers of water turbines, impeller pumps, ship propellers, hydraulic fittings etc. For instance, the Institute of Power Engineering in Warsaw and the Baildon Ironworks in Katowice have developed new electrodes EN10-10B designed mainly for regenerating water turbine elements damaged by cavitation. Investigations of padding welds from other electrodes made in Poland showed [6] (Fig. 9) that the ES13Cr and EStelCoNi electrodes have higher resistance to cavitation than the con-

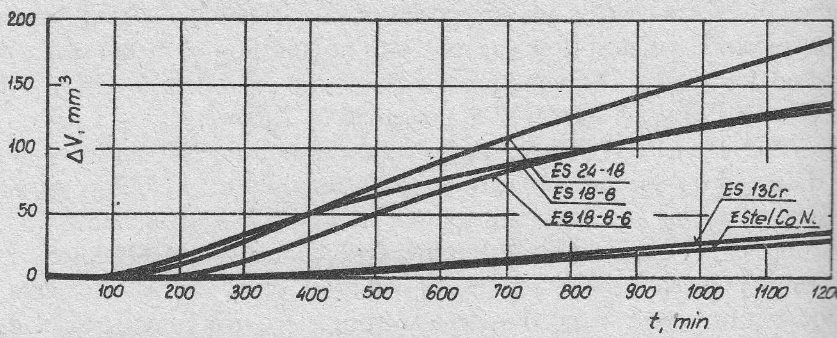

Fig. 9. Erosion test results for samples padded with various electrodes (Laboratory of the Institute of Fluid-Flow Machinery, P.A.Sci.)

only used chromium-nickel-manganese electrodes. This observation was confirmed the results of repairs carried out at the Żydowo Pumped-Storage Power Plant.

It should be mentioned here that the selection of electrodes and development of ew electrodes for hydro power installations is not only connected with regenerating damaged parts but also with protective paddings for machine elements made from rbon steel.

5. General Indications

Increasingly frequent occurrence of cavitation in hydraulic machines requires king this phenomenon under consideration when selecting structural materials. rst of all, cavitation conditions of designed machines should be investigated. These estigations should supply information on cavitation intensity and the places where occurs. They may be based on theoretical prediction (analyses of pressure distri- tions and velocities in the flow system), model tests* (cavitation characteristics of chines and recordings of cavitation symptoms) or comparative evaluations (com-

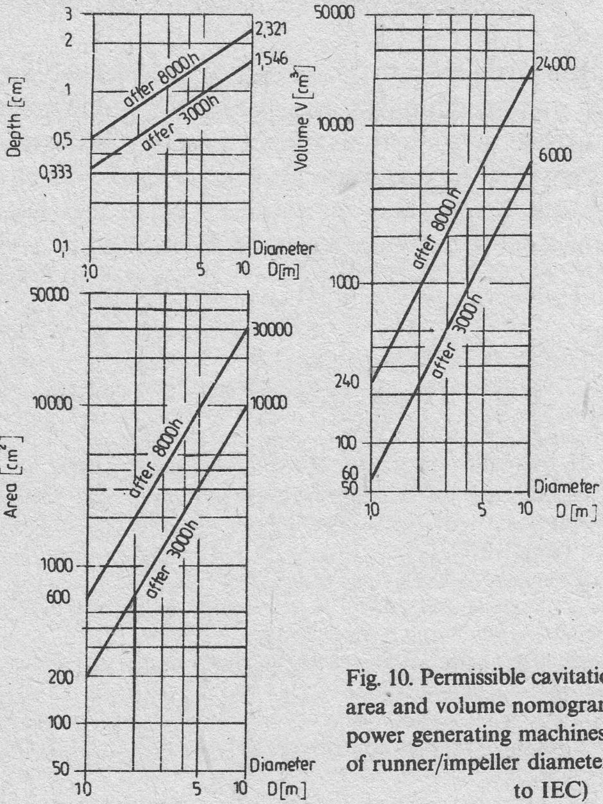

Fig. 10. Permissible cavitation pitting depth, area and volume nomograms for hydraulic power generating machines, in dependence of runner/impeller diameter (examples acc. to IEC)

* If model tests are used, the scale effects should be taken into account, especially the influence of nsions, velocities and pressure on the course of cavitation phenomena.

parisons of performance of similar machines). This information and the knowledge of cavitation resistance of various materials should be used in actual designing.

When machine elements are repaired or replaced, it is worthwhile to examine cavitation phenomena under field conditions. To gain this objective, an evaluation of cavitation loads should be made using diagnostic methods presented also in one of the papers at this conference. Only the results of such investigations, together with the results of tests of appropriate samples of materials, can ensure proper selection of a structural material or a method of repairing machine elements damaged by cavitation.

When selecting structural materials, also the IEC recommendations should be taken into account (International Electrotechnical Commission, Publication [illegible] 1978: Cavitation pitting evaluation in hydraulic turbines, storage pumps and pump-turbines). In Fig. 10 are shown the nomograms from the IEC publication determining permissible values of maximum pitting (g) in cm, damaged surface area (A) in cm^2, and volume loss (V) in cm^3, depending on runner or impeller diameter D. These recommendations refer to the guarantee period of 8000 h (water turbines) and 3000 h (storage pumps and reversible machines). The IEC recommendations are not compulsory. Nevertheless, they are a valuable indication for designers and users of hydraulic machines.

The indications presented here are not always explicit and precisely stated. Further work on these problems and on durability and availability improvement of power generating machines is carried out in various research centers. Research on building and repairing machines exposed to cavitation also serves these objectives. It seems that progress in this field can be promoted by gaining a better understanding of the erosion mechanism, knowledge of cavitation erosion forecasting and through cavitation diagnostics.

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Dobór materiałów do budowy hydraulicznych maszyn energetycznych narażonych na działanie kawitacji

Streszczenie

Na wstępie przedstawiono przykłady elementów maszyn hydraulicznych uszkodzonych wskutek kawitacji (rys. 1a...f). Na tym tle omówiono czynniki wpływające na niszczenie materiałów (rys. 2) oraz wskazano na przebieg erozji kawitacyjnej w zależności od parametrów charakteryzujących przepływ z kawitacją (rys. 3, 4 i 5).

Szczególną uwagę poświęcono ocenie odporności materiałów na działanie kawitacji. Przytoczono związki empiryczne (4) między maksymalną szybkością penetracji erozji i różnymi cechami wytrzymałościowymi materiałów oraz wskazano na testy erozyjne służące ocenie (rys. 6) i przewidywaniu trwałości materiałów w różnych warunkach kawitacyjnych (wzór 5).

W dalszym ciągu przytoczono wyniki badań materiałów (rys. 7, 8 i 9), przedstawiono klasyfikację niektórych materiałów krajowych pod względem ich odporności na erozję kawitacyjną (tabela 1) oraz zamieszczono informacje o materiałach angielskich, czeskich, francuskich, radzieckich i austriackich charakteryzujących się dużą odpornością na działanie kawitacji przepływowej.

Na zakończenie zamieszczono wskazówki ogólne dotyczące wyboru materiałów do budowy maszyn narażonych na działanie kawitacji oraz zalecenia międzynarodowej komisji elektrotechnicznej IEC w sprawie erozji kawitacyjnej w turbinach wodnych, pompach zasobnikowych i maszynach odwracalnych.

Подбор материалов для строения гидравлических энергетических машин подвергающихся действию кавитации

Резюме

Во вступлении представлены примеры элементов гидравлических машин, повреждённых ввиду действия кавитации (рис. 1a...f). На этом фоне обсуждаются факторы влияющие на разрушение материалов (рис. 2), а также указывается на ход кавитационной эрозии в зависимости от параметров характеризующих течение с кавитацией (рис. 3, 4 и 5).

Особое внимание уделяется оценке сопротивляемости материалов действию кавитации. Приведены эмпирические зависимости (4) между максимальной скоростью проникновения эрозии и различными признаками сопротивления материалов, а также указывается на эрозионные испытания служащие оценке (рис. 6) и предвидыванию прочности материалов в различных кавитационных условиях (формула 5).

В дальнейшем приводятся результаты исследований материалов (рис. 7, 8 и 9), представлена классификация некоторых отечественных материалов с точки зрения их сопротивляемости действию кавитационной эрозии (таблица 1), а также помещаются информации о английских, чешских, французских, советских и австрийских материалах характеризующихся большой сопротивляемостью действию проточной кавитации.

В заключении даны общие указания относительно отбора материалов для строения машин подвергающихся действию кавитации, а также рекомендации международной электротехнической комиссии IEC по делу кавитационной эрозии в гидротурбинах, аккумуляторных насосах и обратимых машинах.