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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 machines

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PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

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On the effectiveness of fixing cavitation damages with new electrodes featured by a metastable structure of the padding weld

A family of new experimental electrodes with metastable structure of the padding weld have been developed for fixing material damages caused by cavitation impingement in hydraulic machines and devices. High effectiveness of cavitation erosion repair as well as good welding features are found to be rudimentary features of the manufactured electrodes. In the paper the results of laboratory and field tests of the coatings created by means of the new electrodes are presented.

1. Introduction

Padding is a very common method of removing material defects caused by cavitation impingement in hydraulic machines and devices [1,2]. Surface subjected to such a process of renovation gains resistance which depends on technological conditions of the repair as well as the structure and chemical composition of the coating and care material.

In case of water turbines repair neither introductory heating nor the thermal processing after the welding can be applied. Therefore the resistance of a coating and its endurance depend exclusively on the appropriate selection of electrodes due to inapplicability of both.

In search for more efficient fillers of cavitation damages a consortium of partners, namely: the Electrode Manufacture Company – Baildon, the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences and the Institute of the Materials and Welding of the Technical University of Gdańsk have developed a family of experimental electrodes with metastable structure of the padding weld as well as good welding features.

In the present paper the results of laboratory and field tests of padding weld created using new electrodes are presented.

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2. General characteristics of tested electrodes

Until now most post-cavitational repairs in Polish hydro power plants have been conducted using the EN10-10B chromium-manganese electrode [3]. This electrode is characterized by satisfactory welding properties and good cavitation resistance of the padding weld. The fundamental disadvantage of the EN10-10B electrode is emission of a large amount of noxious vapours during the welding process. In eighties there were proposed new electrodes with the chromium steel rod and covering containing ferroalloys, plasticizers, slag-forming ingredients as well as ingredients for ionizing of the arc. These electrodes preserve comparable, or even better cavitation resistance (IMP6 and IMP9) and its use is much less harmful for the human health than that of the EN10-10B electrode. They seem also to be more versatile with respect to their application under different welding conditions. Denotations of the new electrodes as well as their chemical composition are presented in Tab. 1. The technical characteristics of two chosen electrodes IMP 1 and IMP 6 are summarized in Table 2 [4-8].

Table 1. Chemical composition and denotation of the new electrodes

	designation of the electrode	chemical composition %							
		C	Mn	Si	P	S	Cr	Co	Mo
1	IMP 1	0.22	6.08	0.22	0.055	0.003	11.1		
2	IMP 5	0.30	6.42	0.23	0.058	0.012	11.2		
3	IMP 6	0.35	8.31	0.26	0.069	0.012	10.93		
4	IMP 7	0.22	8.28	0.36	0.063	0.013	13.86		
5	IMP 9	0.31	0.55	0.30	0.016	0.010	16.5	6.07	
6	IMP 10	0.25	0.35	0.24	0.022	0.013	13.6	8.00	

3. Padding weld structure

Metallographical investigations

The electrode material is deposited along parallel paths. Chromium steel 2H13 (2Cr13) stands for core material. The thickness of each pad ranges from 1 to 2.5 mm.

Some results of metallographical investigations of the deposited pads are presented in Figs 1-4. The pictures were taken at magnification of 280 times.

The metallographs of the padding structure created by means of the IMP6 electrode are shown in Fig. 1. The sample was not subjected to cavitation erosion in this case. In Fig. 1a the structure of the pad at the sample surface is shown. The martensitic needles, parallel within the grains, accompanied by a large amount of retained austenite are easily visible. Local extrusions of chromium carbides are overspread. The same structure is found 0.5 mm beneath the specimen surface

Table 2. The technical characteristics of IMP 1, IMP 6 and EN10-10B electrodes

Electrode	IMP 1	IMP 6	EN10-10B
type of covering	basic	basic	basic
hardness of deposited metal	35 HRC	25 HRC	250 HB
welding current	constant, positive end to the electrode	constant, positive end to the electrode	constant, positive end to the electrode
position of padding	downward, sideward, vertical	downward, sideward, vertical	downward
dimensions and technological indicators			
– diameter [mm]	3.25 or 4.0	3.25 or 4.0	2.5; 3.25; 4.0; 5.0
– length [mm]	350	350	250; 350; 350; 450
– electrodes per weight unit [100 pcs/kg]	3.4	3.5 or 5.1	4.2; 6.3; 9.9; 14.0
– current intensity [A]	80-120	80-120 or 120-160	110; 150; 190; 230
– deposition intensity [%]		100	100
– melting coefficient [g/Ah]	8.2	8.4	8.6

(Fig. 1b). The grains of dendritic shape are elongated towards the maximum heat removal direction. They meet their end at the in-melt line of the pad into the core material (Fig. 1c). A layer of the core material lying directly under that line is also transformed to martensite with a large amount of carbides localized mainly along the grain boundaries. At the depth of 2.3 mm stripped martensite is cut with the strips of carbide extrusions along the grain boundaries (Fig. 1d). The image of an unaltered structure of the core, 2H13, material is presented in Fig. 1e. The development of cracks on the surface of cavitated sample with a pad produced by means of IMP6 electrode is presented in Figs 2a and 2b. A fine martensitic structure with retained austenite was achieved in the surface layer of the material (Fig. 2c). The similar structure was identified in the surface layer of the sample coated with an EN10-10B electrode (Fig. 3a and 3b). Beneath the in-melt line the assemblies of carbides are visible in the background of martensite (Fig. 3c and 3d). Boundaries of prior austenite are also visible. Somewhat different structure is shown on the layer deposited with the IMP1 electrode. It is presented in Fig. 4a, 4b, 4c and 4d for various depths inside the sample. Almost pure martensite is revealed within the melted zone (Fig. 4a and 4b). Under the in-melt line it changes into martensite with carbides partitioned by the boundaries of prior austenite (Fig. 4c and 4d).

Fig. 1a. The structure of the pad created by means of the IMP 6 electrode – the surface layer of a not cavitated sample. Magnification 280x.

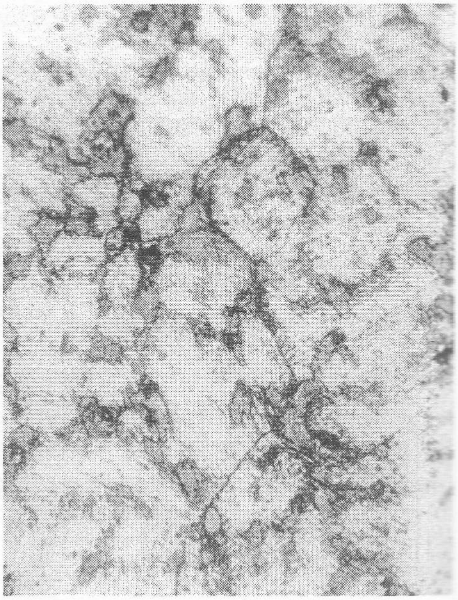

Fig. 1b. The structure of the pad created by means of the IMP 6 electrode – 0.5 mm beneath the specimen surface. Magnification 280x.

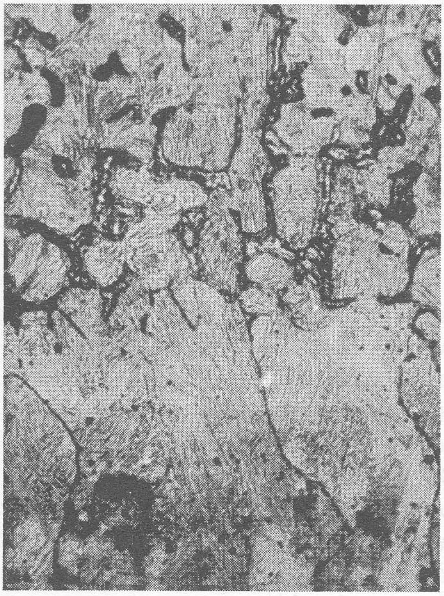

Fig. 1c. The structure of the pad created by means of the IMP 6 electrode – 1.3 mm beneath the specimen surface at junction line with the core material. Magnification 280x.

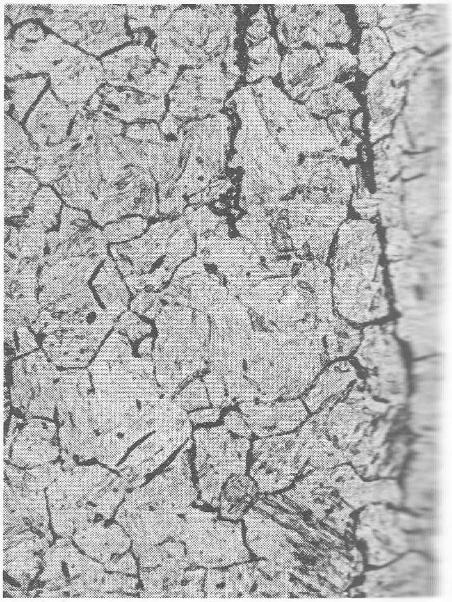

Fig. 1d. The structure of the transformed core material (steel 2H13) – 2.3 mm beneath the specimen surface. Magnification 280x.

4. Erosion resistance

Results of laboratory investigations

The investigations of the cavitation resistance of a padding weld were carried out at the laboratory of the Institute of Fluid-Flow Machinery using the rotating disc facility [9]. Cavitation develops here in the vortex cores behind the cylindrical bolts placed in the disc surface. The test specimens are embedded in the disc downstream to the cavitator. The rotational speed is 2960 rpm, which results in the sample peripheral velocity of approximately 42 m/s. The conditions created at the experimental set-up are similar to the conditions existing in turbomachines where the collapsing vortex cores are the main contributors to cavitation erosion of the streamlined surfaces.

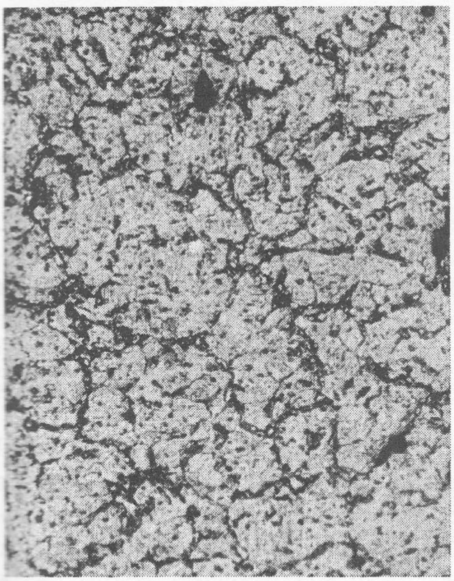

Fig. 1e. An unaltered structure of the core material – 1.3 mm beneath the specimen surface. Magnification 280x.

The erosion curves found for the samples covered with the experimental electrodes coatings are presented in Fig. 1 [6]. The curves indicate that the cavitation erosion rate is different for different padding welds and, hence, the different cavitation resistance can be inferred.

Investigations of cavitation resistance under field conditions

In order to verify the properties of the electrodes under field conditions they were applied during the repairs conducted at some Polish hydro power plants, that is Hydro Power Plant Żur in 1988, in Pumped-Storage Power Plant Żydowo in 1990 and in Hydro Power Plant Żarnowiec in 1996. Commercially available EN10-10B, ES13CrB and EN9CrSiB[2] electrodes were used together with IMP1, IMP6, IMP9 and EN6-10B experimental ones.

The tentative repairs at Żydowo Pumped Storage Plant were conducted on the blades of the Francis turbine runner (electrodes EN6-10 and IMP9) and at the reversible machine hub nearby the line of the hub-blades junction (IMP1, IMP6 i EN6-10 electrodes). Those were the places of particular intensification of the erosion processes. Previously, single pits reaching the diameters of 10 to 12 mm and about 8-10 mm depth were revealed here. Damaged zones of the

[2]Designation after Polish Standards

blades are visible in Fig. 6. During the revision accomplished in 1993 substantial defects were revealed only nearby the blade covered with EN6-10 electrode [10]. No damages were found in places covered with IMP 1 electrode. The area with deposited metal of electrode IMP6 became mat. Apart from that the pits of 1-2 mm depth appeared in heat affected zone. In May 1996 tentative repair of the pump-turbine No 3 rotor at Hydro Power Plant Żarnowiec was accomplished. The IMP6 and EN10-10B electrodes

5. Discussion

Undeniable advantage of the experimental electrodes with respect to those commonly applied in Polish hydropower plants is a considerable reduction of the amount of noxious vapours and decisive reduction of the toxical manganese oxides educed when the electrode EN10-10B is used.

Mechanical properties of the deposits obtained by means of IMP6 and EN10-10B electrodes are similar and differ from the properties of the IMP1 pads. An increase of the microhardness in the case of IMP1 being applied can be the reason for increased chromium content. Simultaneously, a reduction of impact and tensile strength takes place due to the decrease of manganese content in the deposited metal. However, manganese does strengthen the ferritic and stabilizes the austenitic structure.

The investigations indicate, that paddings of both IMP1 or IMP6 and EN10-10B electrodes lead to creation of metastable austenitic structure reinforced with a large amount of frozen martensitic needles. Such structure of the coating guarantees its best endurance, especially because of the transformation of austenite into martensite under the cavitation loading. The structure is preserved despite of the annealing heating in course of wekling the subsequent pads. The latter exerts its influence only on the amount and sort of the undiluted carbides.

Mutual relationships between the cavitation erosion curves (Fig. 5) indicate that the rate of damage development of the EN10-10B electrode padding is much greater than that of the IMP 1 and IMP 6 electrodes. It can be also seen that under laboratory conditions the erosion of the deposited IMP 1 material is more intense than that of the deposited IMP 6 material.

It is sometimes noticeable, that the relative intensity of erosion of some steels changes with time and it happens that after a certain period of time the previously worse steel (e.g. austenitic one) becames better compared to the previously superior one (e.g. martensitic steel) [12]. It could be explained with that the martensitic structure or the phase is created under the cavitation loading [13]. As a result a considerable increase of the duration of incubation period takes place [14].

Some alloy additives, especially in the case of austenitic steel, can increase cavitation resistance of the material [15]. Such phenomena seem to take place in coatings produced by means of the IMP9 electrode which show substantial amount of Co. The reason for that is that some alloy components introduce less

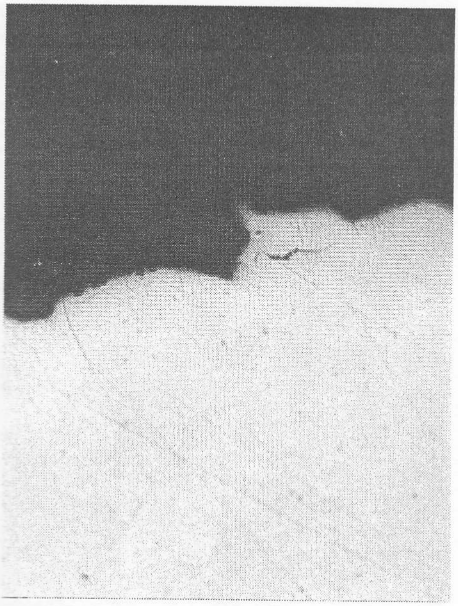

Fig. 2a. The crack development at the surface of cavitated sample with a pad produced by means of the IMP 6 electrode.

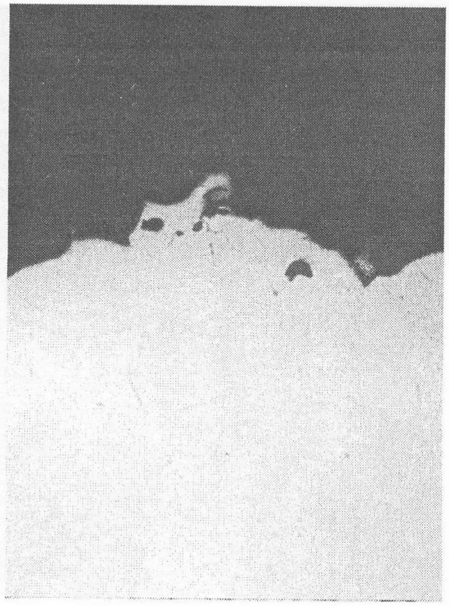

Fig. 2b. The crack development at the surface of cavitated sample with a pad produced by means of the IMP 6 electrode.

Fig. 2c. The structure of the pad created by means of the IMP 6 electrode – 1.5 mm beneath the cavitated specimen surface. Magnification 400x.

were used. In spite of the fact that the cavitation intensity in Żarnowiec is much greater than that in Żydowo [11] the expected damages were practically not measurable. The overall view of the blade – after the one year of operation – is presented in Fig. 7. The areas covered with coatings are marked with chalk. Subsequent figures (Figs 8 and 9) present exemplary places covered with padding weld and their state in August 1997. The isolated assemblies of cavitation pits appear beyond the mended area – in heat affected zone.

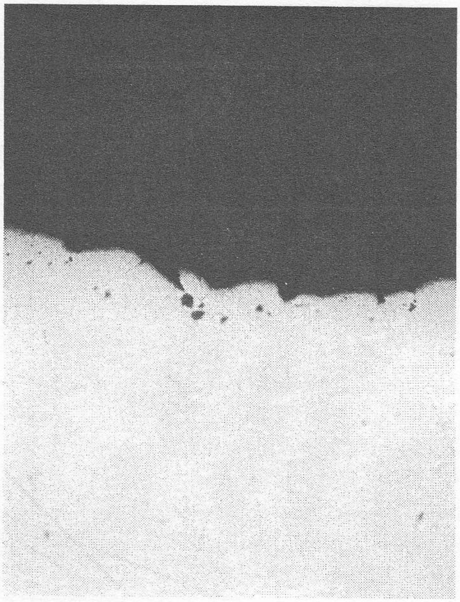

Fig. 3a. The structure of the pad created by means of the EN10-10B electrode – the surface layer of a not cavitated sample. Magnification 280x.

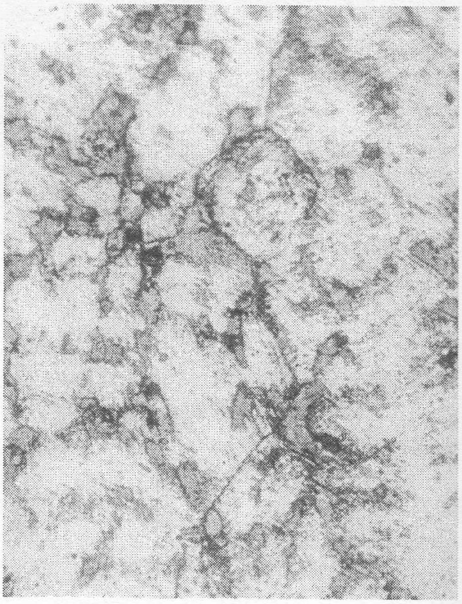

Fig. 3b. The structure of the pad created by means of the EN10-10B electrode – 0.5 mm beneath the cavitated specimen surface. Magnification 280x.

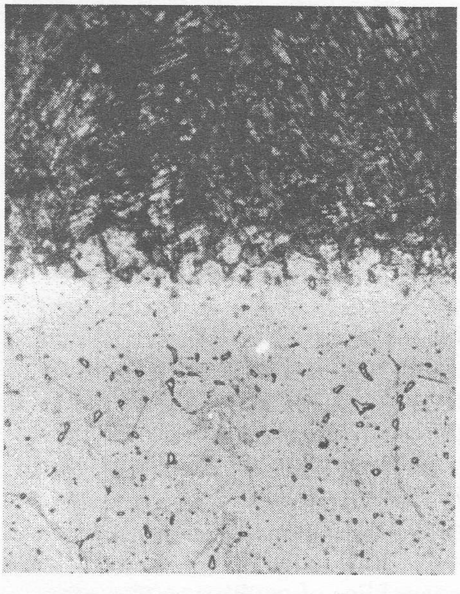

Fig. 3c. The structure of the pad (made by the EN10-10B electrode) and the core material (2H13) beneath the in-melt line – 2.2 mm beneath the specimen surface. Magnification 280x.

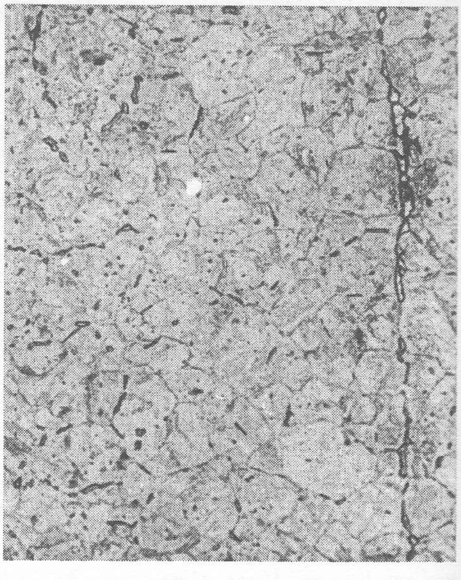

Fig. 3d. The structure of the transformed core material (steel 2H13) – 2.6 mm beneath the specimen surface. Magnification 280x.

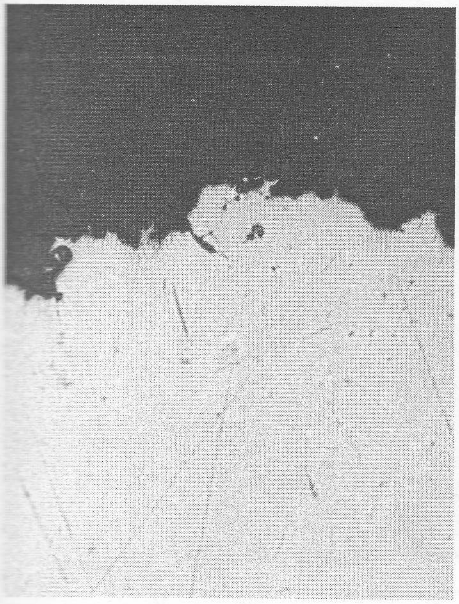

Fig. 4a. The structure of the pad created by means of the IMP 1 electrode – the surface layer of a cavitated sample. Magnification 280x.

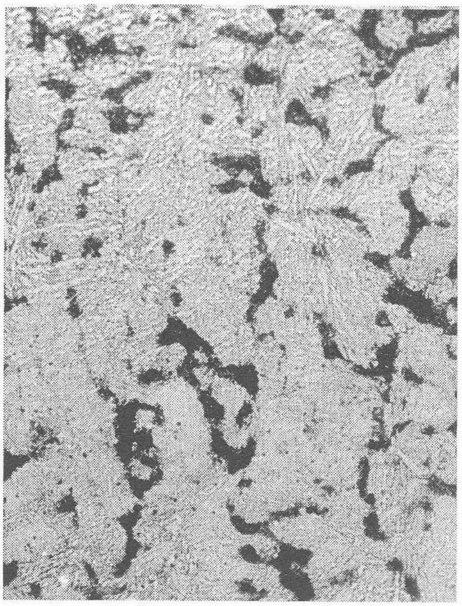

Fig. 4b. The structure of the pad created by means of the IMP 1 electrode – 0.5 mm beneath the cavitated specimen surface. Magnification 280x.

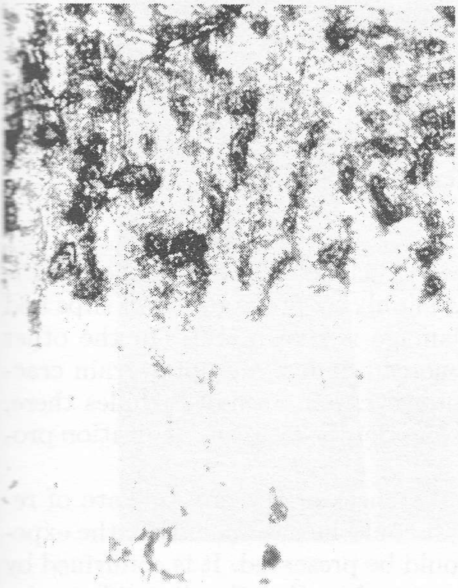

Fig. 4c. The structure of the pad (made by the IMP 1 electrode) and the core material (2H13) beneath the in-melt line. Magnification 280x.

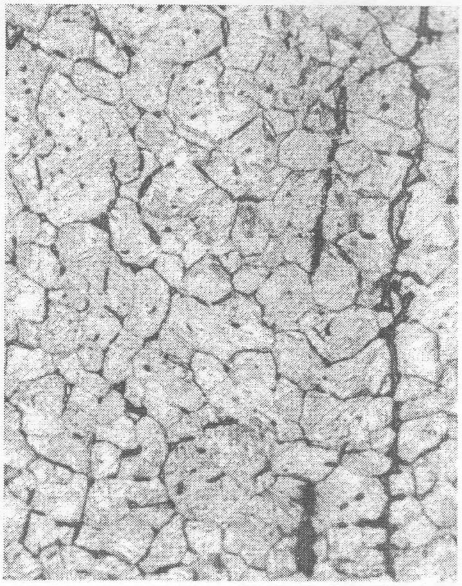

Fig. 4d. The structure of the transformed core material (steel 2H13) – 1.5 mm beneath the specimen surface. Magnification 280x.

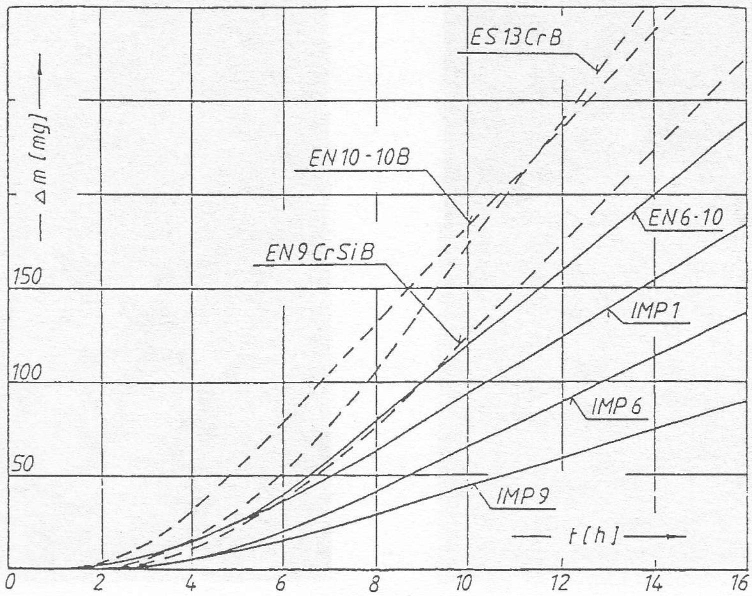

Fig. 5. The erosion curves (mass loss versus in time) for samples covered with padding welds of the experimental and commercial electrodes.

deformations in Fe_α than in Fe_γ. It is profitable as far as the internal stresses growth does not prompt the development of cracks [16].

It seems that the type of crystalographical structure achieved in the pads is regular and compact. Its destruction proceeds mainly by propagation of slips and therefore high resistance to the cavitation damage is shown [17]. On the other hand, in the zone beneath the in-melt line one can expect the inter-grain cracking along the grain boundaries due to the intense cumulation of carbides there. The extrusion of alloy elements at the grain edges deteriorates the cavitation properties of the material.

Under the field conditions the detected differences of the erosion rate of respective paddings are much smaller. However, it could be assumed, that the experimentally found rating of the erosion rates would be preserved. It is confirmed by the results of tentative repairs carried out at power plant Żur. Smaller differencies of erosion rates detected under field conditions can be ascribed to a greater share of weak cavitation implosions which cause the work-hardening of each material in the same way.

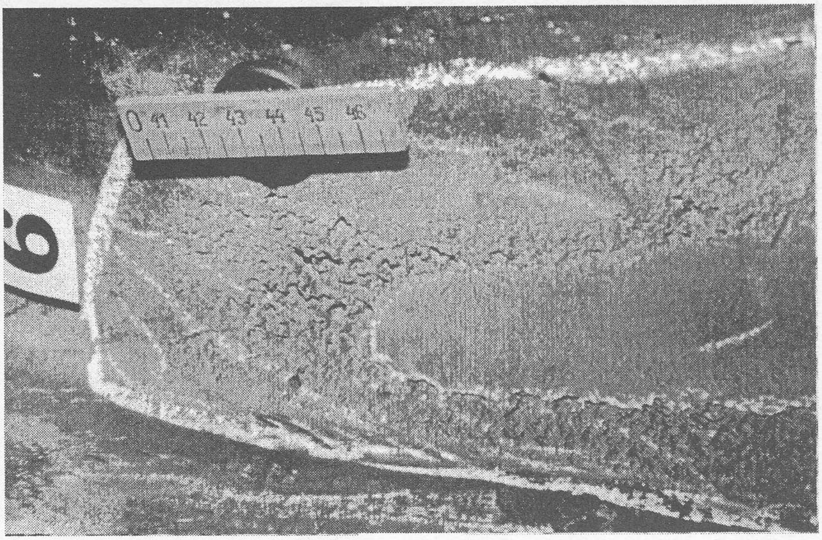

Fig. 6. The damaged zones of the blades of the Francis turbine in Żydowo Pumped Storage Plant.

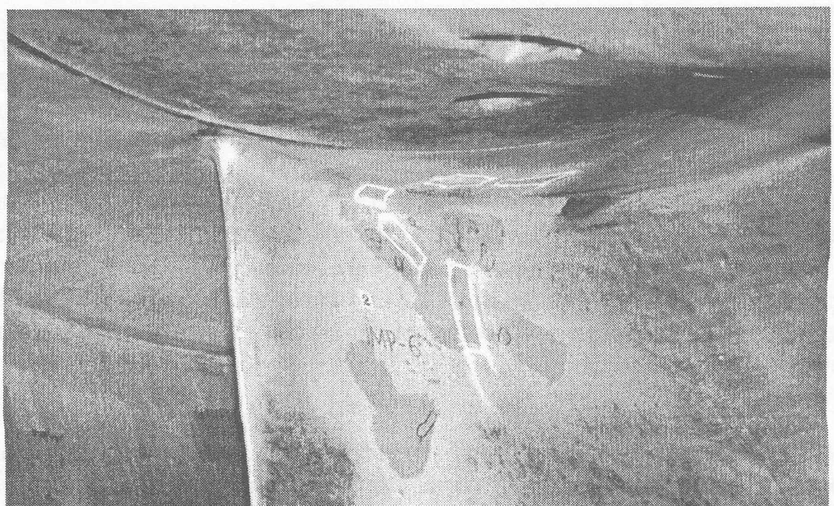

Fig. 7. The overall view of the blade of the pump-turbine rotor in Hydro Power Plant Żarnowiec – one year of operation after the tentative repair with IMP 6 and EN10-10B electrodes.

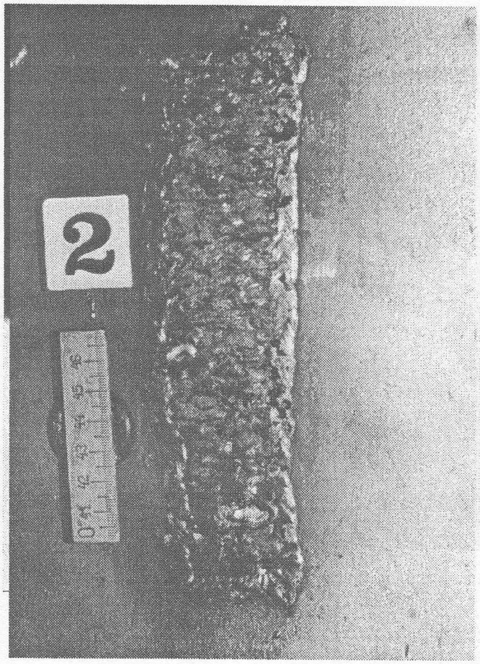

Fig. 8a. The exemplary places of the pump-turbine rotor covered with padding weld created by IMP 6 electrode.

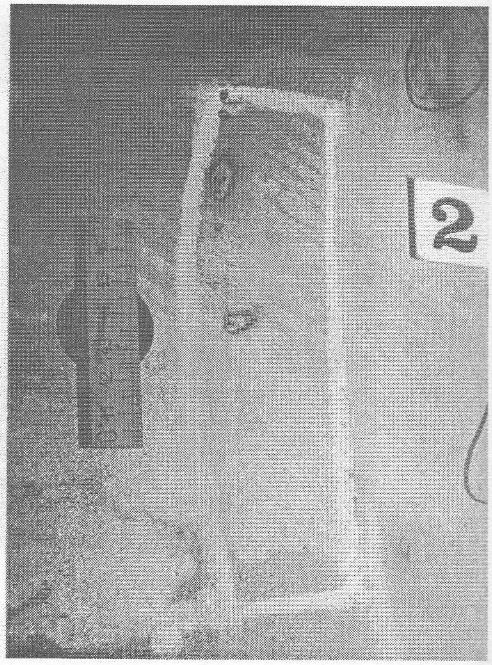

Fig. 8b. The state of the same places after 16 months of operation.

6. Conclusions

The results indicate that creation of metastable austenitic structure reinforced with martensite yields positive effect on the cavitation resistance of the material. From this point of view the new experimental electrodes can be efficiently used for repair of cavitation damages in hydraulic turbines. Moreover, they also shows profitable welding properties in comparison to the electrodes applied in Poland till now.

Acknowlegements Experimental electrodes discussed in this paper have been developed under the Central Research & Development Programme 5.1 which sponsored also laboratory and field tests till the end of the eighties.
Tentative repairs were conducted by the Zakłady Remontowe Energetyki Gdańsk (Power Industry Repair Works Gdańsk) and HYDROMEX companies.
Research Programme after 1990 has been supported jointly by the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences and the "Elektrody Baildon" Sp. z o.o. (Baildon Electrodes Ltd).
Contribution of the above subjects to the results obtained and kind collaboration of the Towarzystwo Elektrowni Wodnych (Hydro Power Plants Society) and po-

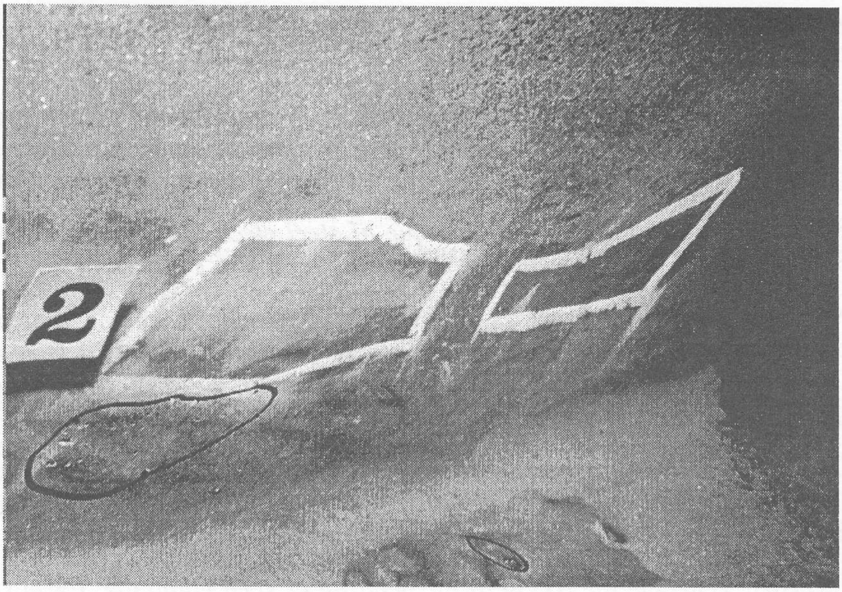

Fig. 9. The state of the exemplary places covered with padding weld created by IMP 6 electrode after 16 months of operation.

wer plants mentioned are acknowledged herewith.
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O skuteczności napraw uszkodzeń kawitacyjnych za pomocą nowych elektrod tworzących metastabilną strukturę napoin

Streszczenie

W pracy scharakteryzowano rodzinę nowych elektrod tworzących metastabilną strukturę napoin przeznaczonych do napraw uszkodzeń kawitacyjnych maszyn i urządzeń hydraulicznych. Przedstawiono wyniki badań laboratoryjnych i wyniki trwałości napraw pokawitacyjnych turbin wodnych w elektrowniach Żydowo i Żarnowiec.