ARCHIVES OF METALLURGY AND MATERIALS
Volume 59 2014 Issue 1
DOI: 10.2478/amm-2014-0039

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CAVITATION EROSION RESISTANCE OF ALLOYS USED IN CATHODIC PROTECTION OF HULLS OF SHIPS

ODPORNOŚĆ NA EROZJĘ KAWITACYJNĄ STOPÓW STOSOWANYCH DO OCHRONY KATODOWEJ KADŁUBÓW STATKÓW

Seawater is an aggressive environment which causes the necessity of using corrosion protection of hulls of ships. Cathodic protection is an effective prevention method which has been applied in this area for many years. In this method, potential of the ship's hull is reduced by using galvanic anodes (so-called protectors), which are additionally exposed to cavitation erosion.

Results of cavitation erosion resistance investigation of alloys commonly used in cathodic protection of hulls of ships, are presented in this paper. The tests were carried out on the three, most often applied materials which are zinc, aluminium and magnesium alloys. The investigated samples were subjected to cavitation conditions in a jet-impact laboratory stand. Destruction mechanism of the surface layer affected by working liquid was described. The highest cavitational erosion resistance among all studied alloys was exhibited by AlMg alloy.

Keywords: cavitation, cavitation erosion, cathodic protection, galvanic anodes

Agresywne środowisko wody morskiej powoduje konieczność ochronny przed korozją kadłubów statków. Skuteczną metodą jest od wielu lat stosowana ochrona katodowa. Polega ona na obniżeniu potencjału kadłuba poprzez stosowanie anod galwanicznych (protektorów), które są dodatkowo narażone na erozję kawitacyjną.

W pracy przedstawiono wyniki badań odporności na erozję kawitacyjną stopów stosowanych do ochrony katodowej kadłubów statków. Do badań wybrano trzy najczęściej stosowane stopy: cynku, aluminium i magnezu. Próbki poddawano obciążeniom kawitacyjnym na stanowisku strumieniowo-uderzeniowym. Opisano mechanizm niszczenia warstwy wierzchniej materiału pod wpływem oddziaływania cieczy roboczej.

Wykazano, iż największą odporność na erozję kawitacyjną wśród badanych stopów wykazuje stop aluminium AlMg.

1. Introduction

The cathodic protection with protector anodes is one of the simplest and most effective way to preserve metal hulls of ships against corrosion. In this method, potential of the ship's hull is reduced by adding galvanic anode (so-called protector), with more electro-negative potential than hull's base material. The potential difference between hull of ship and anode leads to formation of a current flow from protector to protected metal immersed in seawater. This process is accompanied by the gradual degradation of protector anode - which in the case of its total destruction - is replaced by the new one. Due to a number of advantages which are: the low cost of protectors manufacturing and installation, ease of obtaining a uniform current distribution on the protected construction and lack of current sources, this method of corrosion prevention is widely applied. The effectiveness of cathodic protection depends mainly on type and chemical composition of the protector, its shape as well as specific conductivity of corrosive environment. Aluminium and zinc based alloys are most commonly applied materials for galvanic anodes in hulls of ships protection. Additionally, magnesium alloys are used for some short-term, temporary preserving applications. Moreover, more complex protectors consisting of several layers of different materials (e.g. with core made of zinc and the outer layer made of aluminium [1-4]) are also applied in some special cases.

The characteristics of the anode materials used in shipbuilding industry are shown in Table 1.

TABLE 1
The characteristics of the anode materials used in shipbuilding industry

Properties	Protector		
	Zinc-based	Aluminium-based	Magnesium-based
Potential in seawater [V]	-1.1	-1.5÷-1.7	-1.0÷-1.2
Current efficiency [Ah/kg]	780÷810	1100÷1200	1500÷2420
Current output of anode [%]	to 95	50÷55	50÷80
Material wear [kg/(A∗year)]	12.0	8.0	3.6÷5.6

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Zinc-based protectors are characterized by high current efficiency (approximately 95%) and -1.1 V potential in seawater relative to Cu/CuSO4 electrodes. However, zinc protectors have high current efficiency only when the resistivity of corrosive environment does not exceed 20 Ωm.

Aluminium-based protectors exhibit potential from -1.0 to -1.2 V in sea water and their current efficiency is in range from 50 to 80%. Aluminium alloys with zinc (3-6% Zn) or zinc and tin (1.5-8% Zn and 0.08-0.2% Sn) are mainly applied as protectors.

Magnesium-based protectors are characterized by high negative potential from -1.5 to -1.7 V in seawater. In the other hand, their main disadvantage is low current efficiency (approximatelly 50%) originated from its substantial own corrosion, which is particularly observed in presence of impurities such as iron, nickel, copper, silicon and lead. Harmful effects of pollutants may be successfully eliminated by additions of aluminium (5-7%), zinc (2-4%) and manganese (0.15%) to the magnesium.

Cathodic anodes in the propeller and flap rudder areas are also additionally exposed to the cavitation erosion. Formation of vortical cavitation phenomenon in propellers area accelerates the destruction of ship's hull protectors installed on these parts. In order to properly protect surrounding of the stern of ship against corrosion, it is recommended to install more cathodic anodes. The arrangement of protectors on ship's flap rudder, is presented on Fig. 1.

Fig. 1. The arrangement of protectors on ship's flap rudder

The aim of this work was to determine the cavitation erosion resistance of selected alloys, which are applied as protectors in cathodic protection of hulls of ships.

2. Investigated materials

Following materials were examined in the present paper: ZnAl4, AlMg and MgAl2Si.

ZnAl4 zinc-based alloy is characterized by good castability, good corrosion resistance and the dimensions invariability upon aging treatment. Is primarily used as pressure casts with high dimensional accuracy for precision industry, automotive, electrical and mechanical engineering. The structure of ZnAl4 alloy is characterized by η solid solution dendrites and $\eta + \alpha$ eutectic located in inter-dendrite spaces [5] (Fig. 2).

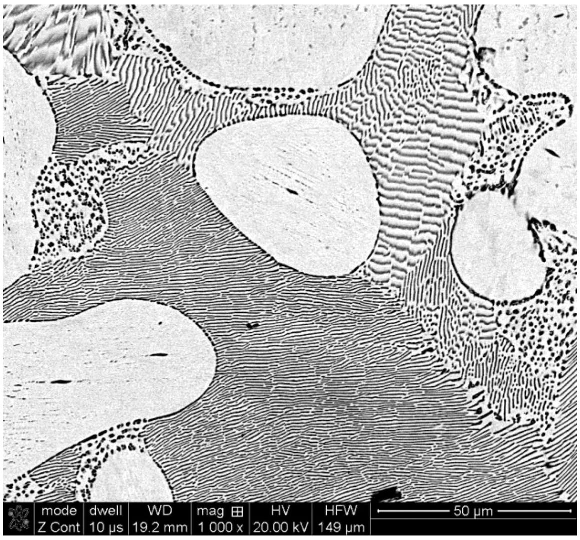

Fig. 2. Microstructure of ZnAl4 alloy

Aluminium alloy with magnesium has a high corrosion resistance in seawater and good machinability. It is also highly weldable with additional lack of corrosion susceptibility in joint area. AlMg alloy is used in the construction of vehicles and ships, chemical apparatus and decorations. Presence of AlSiMnFe phase was observed in the structure of this alloy (Fig. 3) [6].

MgAl2Si magnesium-based alloy exhibits small density and good castability with low cramp. The alloy has a good corrosion resistance, good workability, and may be used in complex shape casting. MgAl2Si alloy has already found wide application in transport, aircraft, military and textile industries. Microstructure of MgAl2Si alloy has α-Mg solid phase and intermetallic Mg_2Si phase (Fig. 4) [7-9].

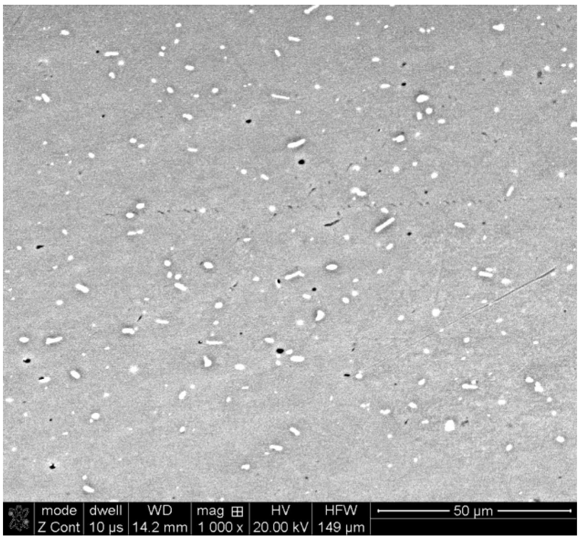

Fig. 3. Microstructure of AlMg alloy

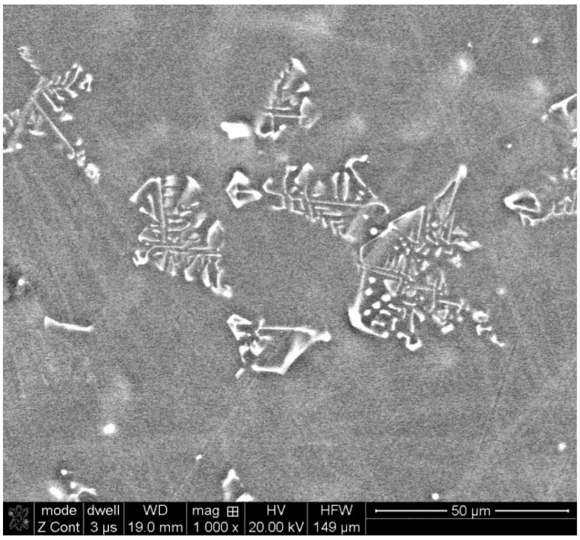

Fig. 4. Microstructure of MgAl2Si alloy and Mg_2Si Chinese script phase

Chemical composition and mechanical properties of tested alloys are shown in Table 2.

TABLE 2
Chemical composition and mechanical properties of tested materials [5]

Chemical element	Alloy		
	ZnAl4	AlMg	MgAl2Si
Al	3.80÷4.20	bal.	1.80÷2.60
Mg	0.045	0.80÷1.20	bal.
Zn	bal.	0.20	0.20
Si	-	0.40	0.70÷1.20
Fe	0.020	0.15	0.005
Cu	0.030	0.10	0.010
Mn	-	0.10	0.20
R_m min [MPa]	280	180	170
$R_{e0.2}$ min [MPa]	200	100	110
A_5 min [%]	10.0	4.0	4.0

3. Methods of investigation

The examination of cavitational erosion was carried out on a jet-impact device located at Institute of Basic Technical Sciences, Maritime University in Szczecin [10]. Examinated samples had cylindrical shape with 20 mm diameter and $6^{\pm 0.5}$ mm height. Surface roughness of samples, measured by PGM-1C profilometer, was in range of 0.010÷0.015 μm. The samples were vertically mounted in rotor arms, parallel to the axis of water stream pumped continuously at 0,06 MPa through a 10 mm diameter nozzle located 1.6 mm away from the sample edge. The rotating samples were hitting by the water stream. Water flow of 1.55 m^3/h was constant during entire experiment. The samples were examined up to 120 minutes. After 5, 15, 30, 60, 90 and 120 minutes samples were taken out from rotor arms, degreased in an ultrasonic cleaner for 10 minutes at 30°C, dried in a laboratory drier for 15 minutes at 120°C and finally weighted as well as its surface observed on microscope. After that, specimens were mounted again in the rotor arms with maintaining their initial position in relation to the water stream.

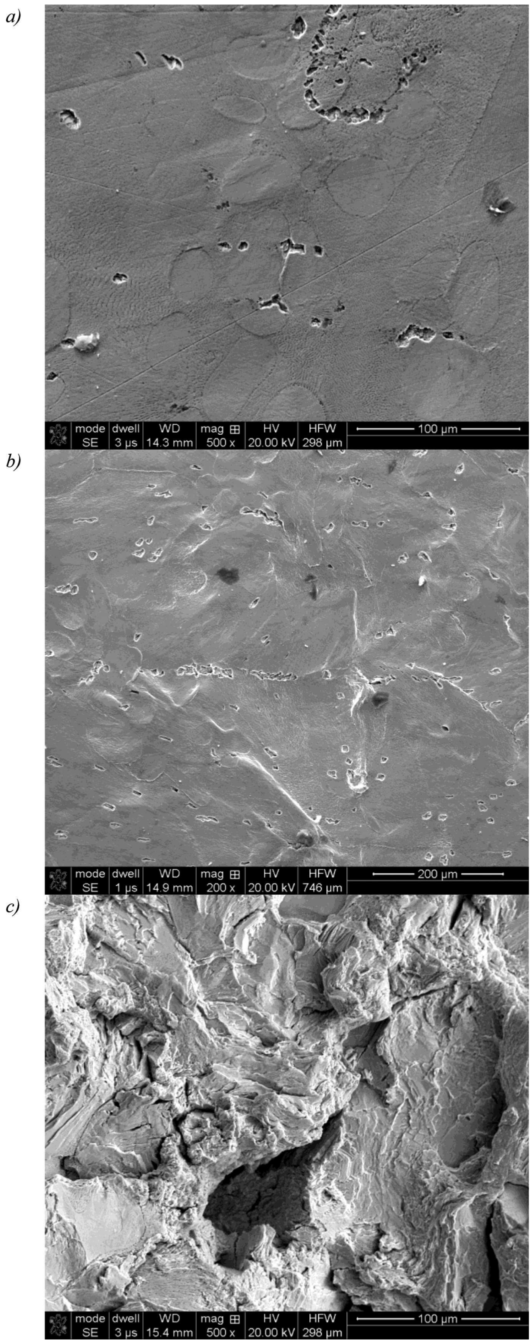

Fig. 5. Effects of cavitational erosion of ZnAl4 alloy after: a) 5 minutes, b) 15 minutes, c) 60 minutes

4. Study results and their analysis

ZnAl4 zinc-based alloy is a material with the highest mechanical properties, but with the lowest resistance on cavitation erosion among all tested alloys. The process of destruction initiates on phase boundaries between η solid solution dendrites and $\eta + \alpha$ eutectic. First single losses of material are visible after 5 minutes of the water stream hitting (Fig. 5a). Further exposition on liquid stream leads to coalescence of individual pits and thus formation of craters located in phase boundaries, as well as prominent plastic deformation of the surface (Fig. 5b). Depth of the craters is subsequently increased during the accelerated erosion period, through a process of gradual destroying of whole grains or their crushing (Fig. 5c).

Such mechanism of cavitation wear in ZnAl4 alloy is affected mayby by orientation of grain. After 60 minutes of testing, surface fatigue striations were observed on craters walls, what confirms the presence of fatigue stresses in the material.

Aluminium alloy with magnesium addition showed the higher resistance to cavitation erosion. After 120 min of examination the alloy was only slightly affected by erosion process, which progressed evenly in place of water stream impact. Destruction mechanism of AlMg alloy is characterized by uniform crushing of grains. The effects of cavitation erosion after 60 and 120 minutes are presented in Figure 6.

The cavitation erosion mechanism of MgAl2Si alloy is closely related with the structure of this material. In the early stages, uplifting of harder areas of the Mg_2Si phase due to the "washout effect" of the α phase (with lower hardness and plasticity), was observed on the surface of the sample (Fig. 7a).

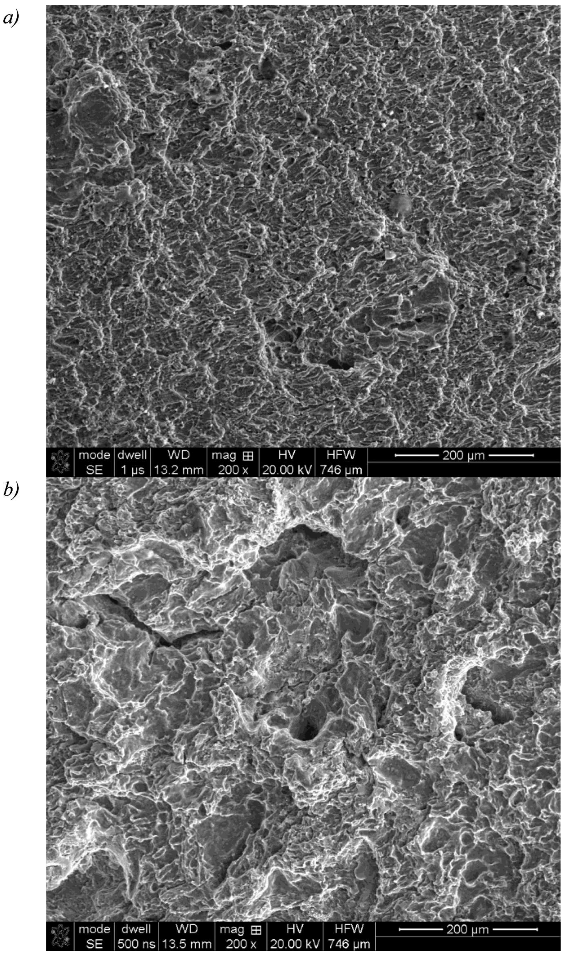

Fig. 6. Effects of cavitational erosion of AlMg alloy after: a) 60 minutes, b) 120 minutes

Further exposition of the alloy surface on water stream causes the formation of craters on the boundaries between α and Mg_2Si phases (Fig. 7b).

The presence of craters on the surface of the sample causes accelerated erosion of material due to crushing of harder Mg_2Si phase grains. This leads to enlargement of craters and pits on material surface and consequently – crushing the whole grains of both α and Mg_2Si phases (Fig. 7c).

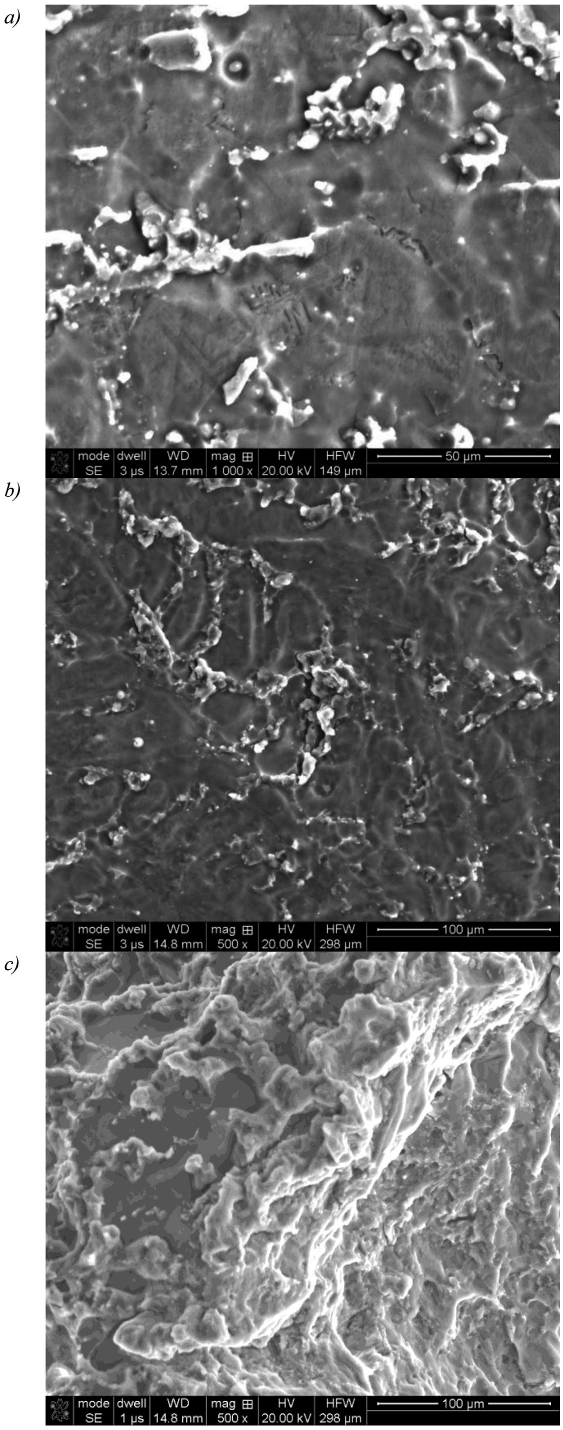

Fig. 7. Effects of cavitational erosion of MgAl2Si alloy after: a) 5 minutes, b) 15 minutes, b) 120 minutes

Figure 8 shows the curves of the volume loss as the function of time obtained for investigated alloys.

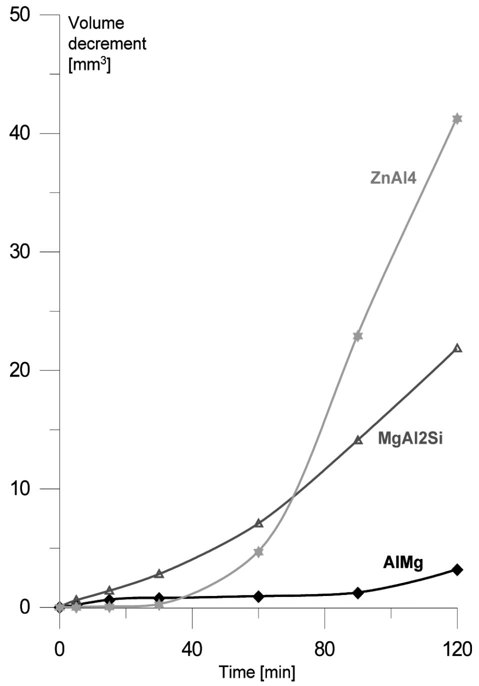

Fig. 8. Comparison of the test results of cavitational erosion of investigated alloys

5. Summary

The cathodic protection is the most popular method of protecting the hulls of ships against corrosion. Effectiveness of this method is determined by an appropriate selection of the material for the anode protectors, quantity of protectors, their shape and size and appropriate placement. The anode is located in the mostly exposed to corrosion sites, which are under the waterline and in place of different metals contact. The stern of ship deserves special attention, due to the propeller material (0.1V potential in seawater) and the cavitation phenomenon. Results of conducted investigations of cavitation erosion resistance on a jet-impact measuring device, suggest that among all tested alloys (which are applied on cathodic anodes protectors), the AlMg alloy should by used in places mostly subjected to cavitation phenomenon. This material posseses approximately 5 times higher cavitation erosion resistance than the magnesium-based alloy and 10 times higher than the ZnAl4 alloy. The uniform surface erosion of AlMg alloy caused by the cavitation phenomenon, the highest potential in seawater and the satisfactory current efficiency, allows concluding that the aluminium-base protector will be effective and economic solution.

Received: 10 March 2013.

Acknowledgements

Scientific work funded by the Ministry of Education and Science in the years 2011÷2014 as a research project No. N N507 231 040.

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