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Analysis of mechanical and chemical mechanisms on cavitation erosion-corrosion of steels in salt water using electrochemical methods

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ABSTRACT

Cavitation erosion-corrosion causes damage and removal of material especially in rotors of centrifugal pumps, water turbines, as well as in control valves and in motors. Based on a dynamic corrosion model the pure mechanical erosion amount of different steel alloys was identified using an indirect cavitation test method combined with an electrochemical cell. We demonstrate that cavitation erosion can be enormously reduced by application of external cathodic potentials. The cavitation rate was in-situ determined using atomic emission spectrometry during the cavitation test. Due to the separately identified pure mechanical and the combined corrosive and synergistic cavitation erosion-corrosion correlation with hardness and arising charge densities during cathodic potentials were found for the mechanical part.

1. Introduction

Cavitation is the formation and dissolution of vapour or gas filled pockets inside the flow of liquids [1,2]. The collapse of bubbles on a surface causes fluid microjets that are directed against the surface and lead to severe deterioration and surface material loss as these microjets generate extreme pressure and temperature peaks. The most common sources of cavitation in technical applications are fast moving objects in a fluid such as rotors of centrifugal pumps, water turbines, lubricants in piston rings and bearings, control valves, spillways, engines, propellers and in the renewable energy sector at tidal stream turbines [3]. In addition, cavitation can be responsible for the occurrence of noise due to vibrations and a loss of energy efficiency. Due to its economic impact prevention and control of cavitation erosion has been studied extensively [4–8].

In this context the cavitation erosion of stainless steel [5] and the effect of temperature, pH and sulphide [6] were investigated. It was found that the cavitation erosion behaviour strongly correlates with mechanical properties of metals [7]. An overview of scientific work in this field is given by Karimi and Martin [8].

Furthermore the superposition of mechanical erosion and electrochemical corrosion is assumed as a main degradation mechanism for cavitation engineering alloys in corrosive environment [9]. Therefore synergistic mechanisms of cavitation and corrosion have to be taken into account. Erosion-corrosion interactions have been studied for carbon steel [10], pure iron [11] and cast iron [12]. Many publications focus on the investigation of synergistic effects of erosion and corrosion for different fluids (acidic slurry medium, seawater) and materials (various engineering alloys, copper, cuprous-nickel, marine and offshore materials) [13–19]. The role of different parameters influencing erosion-corrosion was identified by the work of Rajahram et al. [20,21]. Cavitation erosion-corrosion tests to identify inhibitory mechanisms for iron in a 3% sodium chloride solution were conducted by Oka and Ohkubo [22]. In addition, laser surface modification of stainless steels was used to increase their electrochemical corrosion resistance and cavitation erosion-corrosion resistance [23], [24].

Electrochemical measurements are applicable to investigate specific material parameters as the passivation of stainless steel in more detail [25]. In-situ electrochemical measurements during solid particle impingement were carried out to investigate the influence of passivation and repassivation [26]. It was found that higher measured current levels were associated with damage of the passivating film which limits repassivation and contributes to enhanced corrosion. Also dynamic impedance spectroscopy was used to evaluate the cavitation erosion-corrosion degradation of mild steel [27]. The effect of applied potential on passivation and erosion–corrosion of a Fe-based amorphous metallic coating under slurry impingement was evaluated by Zheng et al. [28]. The impact of oxide films on a steel surface on wear was also investigated using an impact-fretting tribometer in combination with electrochemical methods [29]. Nie et al. [30] investigated the corrosion behaviour of metallic materials in ethanol-gasoline alternative fuels using cyclic potentiodynamic tests. They found a higher anodic Tafel slope using ethanol as electrolyte as than using NaCl. This behaviour is caused by a film formation on the surface, which is less permeable and

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can even obstruct the metal dissolution reaction, but still permits the electrochemical reaction. Differences in the corrosion kinetic of the different steel materials arise in connection to the microstructure. For example large Si particles cause more cathodic reaction on the surface and involve higher corrosion current density and lower polarization resistance. It was pointed out that the corrosion resistance increases with the measurement of a more positive corrosion potential (better passivity) and a higher polarization resistance (R_p).

Burson-Thomas and Wood [31] reviewed the developments in erosion–corrosion over the past 10 years and found that the research focus was the investigation of synergistic effects of erosion and corrosion, application-specific studies (marine, oil and gas engines and automobile industry) and Fe-based materials, Ni-based alloys and hard metal coatings. But they also mentioned the current lack in understanding the fundamental mechanisms in erosion–corrosion which should be examined using mechano-electro-chemical techniques. A review about physical mechanisms for cavitation erosion loads and an overview of cavitation erosion models is given by Terwisga et al. [32]. This work is based on this problem as the approach consists of the coupled investigation of cavitation erosion and electrochemical methods. The hypothesis of this work is that the influence of corrosion on cavitation erosion can be evaluated and reduced by applying electrochemical potentials. In particular, electrochemically applied cathodic electrochemical potentials lead to a suppression of corrosion reactions thus enabling the quantification of the corrosive attack in cavitation. Preliminary work using ionic liquids (ILs) [33], aqueous solutions of ILs [34] and sodium chloride [35], demonstrated the effect of electrochemical potentials, applied in a three-electrode configuration [36], on the tribological behaviour. Therefore the objective of this work is to characterise erosion mechanisms of corrosion and cavitation erosion using electrochemical methods.

2. Experimental

2.1. Materials

The cavitation erosion behaviour of steel 1.3505 (DIN 100Cr6, AISI 52100), tempered 1.3505T (heat treatment according to DIN EN ISO 683–17) and 1.4125 (DIN ×105CrMo17, AISI 440C, annealed condition) was analysed using different techniques. The samples had a circular cross-section of 24 mm in diameter and a height of 7.9 mm. Surface near micro-hardness (nanoindenter Fischerscope H100C, Helmut Fischer GmbH, according to ISO 14577) and macro-hardness (Vickers HV2) of the three different steels were measured (Table 1). Roughness and after cavitation tests erosion profiles were characterised using profilometry (Hommel Tester T8000, Co. Jenoptik). Mass loss due to cavitation was measured using precision balance (Sartorius R160 P). Sample topology after cavitation was analysed with scanning electron microscope equipped with energy dispersive X-ray spectroscopy for determination of oxygen content (SEM, S-3400 N, Co Hitachi). In addition, chemical composition on the surface and the bulk material was measured using XPS (X-ray photoelectron spectroscopy, Leybold MAX 100; argon ion sputtering, sputter rate: 2 nm/min; 1 kV; 500 nA). The microstructure was analysed by structural analysis after polishing and etching of the steels using light microscope.

Table 1
Chemical composition and mechanical properties of specimen materials.

Material	1.3505	1.3505T[a]	1.4125
R_a (µm)	0.03	0.04	0.04
R_z (µm)	0.36	0.37	0.46
Specimen area, A_0 (mm^2)	452	452	452
Vickers-hardness HV2	167	631	226
Micro-hardness HV0.031	245	995	380
Micro-Young's Modulus (GPa)	218	228	235
Electrochemical equivalent, K (g/A s)[b]	2.85×10^{-4}	2.85×10^{-4}	2.68×10^{-4}
Density, ρ (g/cm^3)	7.79	7.68	7.65
C1s.Carb (wt.%)[c]	9.38	2.95	2.85
O (wt.%)[c]	2.28	5.25	0.69
Si (wt.%)[c]	–	3.3	–
Cr (wt.%)[c]	3.16	1.59	31.26
Mn (wt.%)[c]	0.24	0.33	0.4
Mo (wt.%)[c]	–	–	1.04

[a] Tempered according to DIN EN ISO 683–17.
[b] Calculated using formula from Ref. [37].
[c] Measured with XPS at a sputter depth of 50 nm.

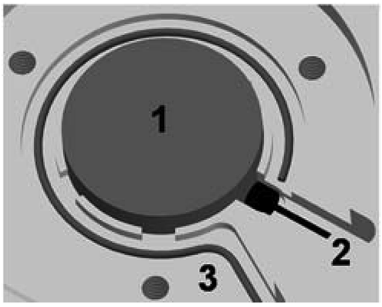

Fig. 1. Technical drawing of the electrically insulated 3-electrode test setup: 1. Working electrode (WE, testing specimen); 2. Ag/AgCl-reference electrode (RE); 3. Platinum ring counter electrode (CE).

2.2. Electrochemical measurements

Electrochemical measurements were carried out with an electrically insulated 3-electrode test setup using a potentiostat Parstat4000 (Co. Ametek) in 0.6 M NaCl (≈seawater) solution (Fig. 1). As reference electrode (RE) Ag/AgCl (Ø 4 mm, standard potential against a standard hydrogen electrode: −194 mV, Co. Warner Instruments) and counter electrode (CE) platinum were used. The particular examined steel specimen was set as working electrode (WE) with a contact area A_0 with the electrolyte of 452 mm^2. Three different measuring methods were applied to analyse the static and dynamic corrosive behaviour of the steel types. At first the open circuit potential (OCP) was measured before starting the cavitation tests. The dynamic potential method (DPM) was used to characterise the static corrosion coefficient C_0 which describes the conditions without external mechanical impact. It was found by Iwabushi et al. [38] that the corrosion rate at the fresh surface (without passive layer), as it occurs under mechanical action (i.e. sliding friction), is higher than at static conditions. This corrosion behaviour can be estimated by the current density obtained from the potential pulse method PPM. Dynamic corrosion, the predominated damage mechanism during cavitation erosion, was therefore analysed using PPM, as this measurement represents the corrosion behaviour for the fresh surface [38]. The test procedure was conducted as following:

1. DPM: 60 min measuring OCP, polarization curve between −500 mV to 500 mV vs. OCP, scan rate: 0.1 mV
2. PPM: 60 min measuring OCP, polarization curve between −500 mV to 500 mV vs. OCP, scan rate: 1000 mV/s

The most important electrochemical parameters obtained from the polarization curves (Tafel plots) were the corrosion potential (E_{corr}), corrosion current density (I_{corr}) and the anodic and cathodic Tafel slopes (β_a and βc). On the basis of these values the corrosion rate per year (m_y in mm/year, eq. (1)) was calculated. Whereas the molar mass (M), the number of electrons which participate at the chemical reaction (z), the Faraday constant (F = 96485.309 A s/M), the time (one year, $t = 3.15 \times 10^7$ s) and the density (ρ in g/cm^3, values see Table 1) are given parameters. The equivalent weight (Q, eq. (2)) for alloys which is the ratio of atomic weight of the element and the number of electrons