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Cavitation Erosion of Metallic Materials

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Abstract: Cavitation erosion normally occurs in a fluid dynamic system, which can cause failure of metal parts. It is a complicated process involving the interaction of electrochemical corrosion and mechanical wear. In this paper, various research methods for cavitation erosion behavior are reviewed. The present techniques of cavitation erosion degree measurement and different period determination include mass loss, volume loss, pit number, pit depth and surface roughness. 2D and 3D microstructure characterization observations are applied to discuss the evolution process and micro-zone damage. Hardness, residual stress and ratio of hardness to elastic modulus are good indicators for the degradation of surface mechanical properties. Electrochemical examinations are integrated to investigate the effect of cavitation on passive film and cavitation erosion mechanism. Furthermore, the influencing factors (mechanical properties, material chemical composition and microstructure) and the cavitation erosion characteristics of several metals (i.e. carbon steel, copper, stainless steel and titanium alloy) are introduced and summarized. Normally, the addition of Mn, Co, Cr, C and N can increase the cavitation erosion resistance. High hardness, high yield/tensile and toughness strength, good work-hardening property, fine grains are advantageous to the resistance to cavitation erosion. The cavitation erosion preferentially occurs on the lower intensity phase, which absorbs cavitation impact energy and mitigates the damage degree of a high strength phase. The interface between phases and grain boundary are also the weak spots to be attacked in the initiation and propagation of cavitation erosion. For passive metals, stainless steel and titanium alloy, the passive film is in a metastable state of depssivation/repassivation under cavitation. In a strongly corrosive medium, the synergetic effect of cavitation and corrosion promotes the thinning and semiconducting property change of the passive film.

Keywords: cavitation erosion, corrosion, mechanical properties, electrochemical behavior, passive film, stainless steel, titanium and titanium alloy

1 Introduction

Cavitation is the process of nucleation, growth and collapse of bubbles in a liquid or in an interface of solid-liquid when the local pressure is lower than the saturated vapour pressure. The high impact pressure, that generated by the implosion of bubbles, causes damage on the surface of solid material (Jiang et al 2003, Bardal 2004). This phenomenon is known as cavitation erosion (also called cavitation corrosion). It has been similarly defined as the localized attack that results from the collapse of voids or cavities due to turbulence in a liquid at a metal surface. It normally occurs in a fluid dynamic system, such as a hydraulic turbine, pump, valve, hydrofoil or ship propeller, etc.

Cavitation erosion can cause failure of metal parts, even may result in serious accidents and great economic loss. At the same time, it is a complex phenomenon involving the joint interaction of mechanical, chemical and electrochemical factors (Chen 2010, Davim 2012). Therefore, it is necessary to discuss the characteristics of cavitation erosion from various angles to get a better understanding of the mechanism and controlling parameters. This can provide information and data for the guidance of predicting and preventing cavitation erosion.

This paper gives an overview of research methods and influencing factors of cavitation erosion, as well as the cavitation erosion behavior of several typical metals, including carbon steel, copper, stainless steel, titanium and its alloys.

2 Research Methods for Cavitation Erosion Behavior

Cavitation erosion degree of material is used as an indicator to evaluate the aggressiveness of the flow on the material. In addition, surface morphology, chemical composition, electrochemical properties and surface mechanical properties are also investigated to explore the cavitation erosion characteristics and clarify the cavitation erosion mechanism.

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2.1 Measurement of cavitation erosion degree

There are a series of measurement methods (Lin et al 2016), such as mass loss, volume loss, pit depth and pit number, etc. Mass and volume loss measurements are relatively simple and easy (Brunatto et al 2012). However, both methods are not applicable when the plasticity of the material is large and, after cavitation erosion, the material is plastically deformed only but has no mass loss or with a small volume loss. The depth damaged after cavitation erosion is an important parameter to measure the degree of cavitation erosion. But because the depth varies with position on the surface, the size of each pit is not the same. Accordingly, the average depth of cavitation erosion in a certain area is commonly used. The pit number per unit time and unit area is another parameter which can be used for representing the degree of cavitation erosion. It was proposed by Prof. Knapp (1955). As long as the test duration is not too long and no pits are overlapped, the counting accuracy of the pit number is not affected. Table 1 gives a comparison of different methods.

Based on Knapp's initial idea, cavitation pit counting techniques have been developed using optical method or laser profilometry with the aid of automatic analysis software (Patella et al 2000, Osterman et al 2009). The parameters, volume damage rates V_d and/or pit number rates N_d obtained from pit counting techniques can be related to cavitation erosion damage rate. Among these techniques, three-dimensional (3D) methods are employed to give the pit geometries, such as pit depth, shape, and volume damage rates V_d. In two-dimensional (2D) methods, some assumptions are considered: the pit is a segment of a sphere and the ratio between pit depth and pit radius is constant.

Table 1. Characterization methods of cavitation erosion degree

Method	Measured parameters	Advantage	Disadvantage
Mass loss	Mass difference before and after cavitation erosion (g/h)	Simple and easy for material with large mass loss	Not applicable for materials with large plasticity
Volume loss	Volume difference before and after cavitation erosion (cm^3/h)	Simple and easy for material with large volume loss	Not applicable for materials with large plasticity and small volume loss
Pit depth	Average pit depth in a certain area (cm or μm)	Applicable for material with small mass loss	Difficult to accurately measure if the pit size is not identical
Pit number	Pit number per unit time and unit area	Applicable for material with small mass loss	The test duration cannot be too long

But these techniques are only applied for cavitation erosion analysis during incubation period. After a longer test, the influence of overlapping pits has to be considered. Hence some authors have begun to explore pit separation means to treat superposed impacts. Details have been described in Patella et al (2000).

2.2 Structure characterization of cavitation erosion

1) Morphology examination

2D attack morphologies on the surface or cross-sectional area in large and small scale can be observed by SEM. The damage features, including plastic deformation, pit growth, cracks, crystal grain size change, localized corrosion characteristics, microstructure, corrosion or wear damage traces, can be identified (Zheng et al 2008, Al-Hashem and Riad 2002). Recently, 3D video microscope is used to observe pit distribution, 3D pit shape, microstructure, and corrosion or wear damage traces on the surface and cross-sectional appearance (Lin et al 2017).

2) Damage quantification

The following information: ① 2D and 3D images, ② surface roughness, ③ surface profile and depth measurement, can be provided by AFM. Normally, the maximum scan range is 110 × 110 μm in the X and Y directions and 22 μm in the Z direction. It cannot be applied to observe larger features (Yong et al 2011a). Besides AFM, profilometer can be employed to obtain the profiles of the eroded surface (Chiu et al 2005, Lin et al 2017). According to the profile curves after cavitation erosion of different durations, the roughness values are calculated (Fig. 1). This is helpful to determine the different periods of cavitation erosion.

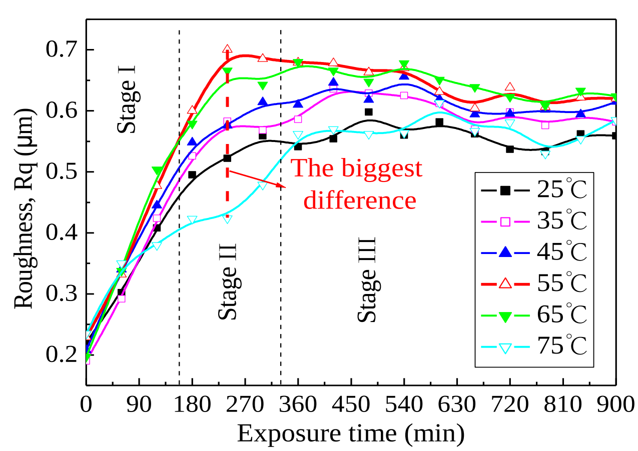

Fig. 1 Variation of surface roughness for Ti-6Al-4V at different temperatures (after Lin et al 2017)

CLSM is an optical imaging technique for increasing optical resolution and contrast of a micrograph by means of adding a spatial pinhole placed at the confocal plane of the lens to eliminate out-of-focus light. 3D structures can be reconstructed from the obtained images by collecting sets of images at different depths within a thick object. This technique has gained popularity in measuring volume, surface area and depth of eroded pits on the electrode surface after polarization test in a cavitation erosion study (Fernández-Domene et al 2010, 2011). This can help determine the cavitation erosion degree from a microscopic point of view.

2.3 Examination of surface mechanical properties and electrochemical behavior

For some materials, hardness (macro and micro) is a good cavitation erosion resistance indicator. The hardness on the surface or the hardness profiles along the depth can be measured by using a nano tester or a Vickers microhardness tester to indicate the effect of impact on the wear resistance of material and work-hardening ability. Corrosion may incur deterioration of mechanical properties of the surface layer. Local elasticity, surface hardness and work-hardening ability are the important controlling factors for cavitation erosion resistance of metallic material. The change of surface mechanical properties of the metallic material has an important relationship with its cavitation erosion behavior. The ratio of nano-hardness to elastic modulus (H/E) of corrosion layer on the metal surface is a dimensionless parameter, which can be used to comprehensively describe the mechanical property of surface layer during cavitation erosion (Li et al 2012). In some cases, an increase in residual stress suggests the occurrence of plastic deformation and phase transformation. It has been employed to analyze the degradation of surface mechanical properties (Lin and Wang 2017). Electrochemical techniques, such as open circuit potential (OCP) monitoring, current at different applied potential, potentiodynamic polarization, electrochemical impedance spectrum (EIS) are useful tools to evaluate the corrosion performance and repassivation tendency of passive materials during cavitation erosion (Zheng et al 2007).

3 Influencing Factors

The cavitation phenomenon is complicated, and there are many factors affecting the cavitation erosion of metallic materials.

3.1 Microstructure and chemical composition

The chemical composition of material usually play an important role in cavitation erosion resistance. The cavitation erosion resistance was improved with a decrease of Ni content and an increase of Mn content in Fe-12Cr-0.4C alloy (Park et al 2013). Austenitic stainless steel containing higher Co and Cr elements has low stacking fault energy. Meanwhile the strain generated in the cavitation erosion process causes the transformation from austenite to martensite, which absorbs the impact energy induced by the bubble collapse. These result in an prolonged incubation period and high cavitation erosion resistance of Cr-Co-Ni-Mn austenitic stainless steel. The surface hardness of CrMnCN austenitic stainless steel increased with C and N concentrations, so was the cavitation erosion resistance (Niederhofer and Huth 2013).

The crystal structure and grain size are also important influential factors for cavitation erosion resistance (Bregliozzi et al 2005). The face centered cubic (*fcc*) metal is prone to plastic deformation under the pressures produced by cavitation shock waves or micro jets, and is not sensitive to high strain rate, which leads to a long incubation period and good cavitation erosion resistance. The body centered cubic (*bcc*) and hexagonal close packed (*hcp*) metals are very sensitive to strain rate, and their cavitation failure mode is generally fast transgranular fracture and cleavage fracture. They are not resistant to cavitation erosion. However, if the martensitic transformation for *hcp* metal occurs during cavitation erosion, the resistance is greatly improved. On one hand, the martensitic transformation consumes a large amount of energy produced by a bubble collapse, on the other hand the strength and hardness of the martensitic phase is relatively high, enhancing the work-hardening ability of the material. In addition, the finer the grain is, the better the cavitation erosion resistance is. The grain refinement may improve the material mechanical properties, produce more uniform deformation, strengthen work-hardening ability.

The cavitation erosion behavior and resistance differ from microstructure. For instance, the order of cavitation erosion resistance of phases in stainless steel is: austenite > martensite > ferrite. The damage of dual phase materials is mainly determined by a low strength phase (Liu and Chen 2009). It absorbs cavitation impact energy and mitigates the damage degree of a high strength phase.

3.2 Mechanical properties

Generally, a metal with high hardness and hardenability has a relatively high cavitation erosion resistance. The experiments of cavitation erosion of CP-Ti and Ti-6Al-4V alloy in 3.5% NaCl solution showed that the cavitation erosion resistance of Ti-6Al-4V with higher hardness was better than that of pure titanium (Mochizuki et al 2007). The studies of cavitation erosion of Cr-Ni-Mo and Cr-Ni-Co alloys in artificial seawater gave similar results. But this is not always true. Some materials with low hardness also show good cavitation erosion resistance. This is ascribed to their good work-hardening property. For example, Cr-Mn-N stainless steel with low hardness in distilled water was more resistant to cavitation erosion compared to 0Cr13Ni5Mo stainless steel which had high hardness (Zheng et al 2008); the cavitation erosion resistance of tin brass with low hardness was significantly superior to that of aluminum bronze in 3.5% NaCl solution. Accordingly, both hardness and work-hardening properties are the main factors affecting the cavitation erosion resistance of materials.

In addition, the cavitation erosion resistance of materials is relevant to the yield and tensile strength. Low yield and tensile strength give rise to a larger cumulative mass loss, and vice versa. High impact work, elongation and elasticity of materials are beneficial to the cavitation erosion resistance, such as 00Cr13Ni5Mo martensitic stainless steel, cast titanium alloy, and TiNiNb alloy. Increasing the relative content of lower bainite in steel can improve the cavitation erosion resistance, mainly because of its high toughness and effective impact resistance in preventing the propagation of pits and cracks. Researchers (Liu et al 2012) have also found that in contrast to the traditional 304 austenitic stainless steel, a new-type, Cr-Co-Ni-Mn austenitic stainless steel, with low plasticity, high yield and tensile strength, has a longer incubation period and better cavitation erosion resistance.

4 Cavitation Erosion Behavior of Metallic Materials

This section provides a review of the research on cavitation erosion behavior for several typical metals.

4.1 Carbon steel and copper

Tables 2 and 3 summarize some research results of cavitation erosion behavior for carbon steel and copper, respectively.

4.2 Passive metals

The passive film on the surface of metal materials (such as stainless steel, titanium alloy, etc.) can prevent it from corrosion in some media. The impact force produced by bubble collapse may destroy the surface passive film and adhered corrosion products, leading to the decrease of corrosion resistance.

4.2.1 Stainless steel

The cavitation erosion resistance has an important relationship with the changes of the surface mechanical properties and passive film, as shown in Table 4. It is also influenced by microstructure, texture, composition, phase transformation (Table 5).

4.2.2 Titanium and its alloys

The present exploration of cavitation erosion mechanism of titanium and its alloys focus on the macroscopic and microscopic cavitation erosion damage measurement, the micro-zone damage characteristics, the evolution of cavitation erosion process, the combined effect of mechanical and electrochemical corrosion (Lin and Du 2014).

Table 2. Cavitation erosion characteristics for carbon steel

Material type	Cavitation erosion characteristics
Low carbon steel	U-shaped pit, work hardening occurring on the surface, deformed layer with deformed twin crystals, and fracture feature of quasi-cleavage and cleavage (Wu et al 2008).
45# steel	The features of morphology were mainly micro-cutting, plowing and spalling (Pang et al 2011).
40Cr steel	A small amount of cavitation pits formed due to the fracture of some grains, not plastic deformation Chen et al (2008). 40Cr steel exhibited better cavitation erosion resistance because of its relatively high toughness, plasticity and fatigue strength (Pang et al 2011).
1Cr13 steel	The cavitation pits occurred mainly in the interface between ferrite and pearlite phases or the area in ferrite phase, which can be explained by lower strength of ferrite phase in contrast with pearlite phase and existence of defects in the two-phase interface (Liu and Chu 2008).
20SiMn steel	The major cavitation erosion failure was intergranular fracture and pits in the grains, possibly resulting from the defects within the material and uneven microstructure (Wang et al 2002).

Table 3. Cavitation erosion characteristics for copper

Material type	Cavitation erosion characteristics
Brass	In distilled water at 25°C, plastic deformation occurred firstly in a very short period of time as a result of low surface hardness. The further erosion produced serious plastic deformation, and the slippage between the grains continued to increase. With the increase of erosion time, the work-hardening made the plastic deformation more and more difficult. At the grain boundaries, cracks initiated and propagated, and the grains started to fall off (Zhang 2008).
Aluminum bronze	In 3.5% NaCl solution, no corrosion existed on the surface of aluminum bronze at the initial stage of cavitation, only local plastic deformation and cracks were observed at the grain boundaries. With the increase of cavitation time, a large number of slip bands appeared in the α phase. Dealuminification corrosion occurred preferentially in the metastable β phase and the small pores appeared at the phase boundary (Deng 2007).
Tin brass	The hardness of tin brass was smaller than that of aluminum bronze, which led to a shorter incubation period. The impact induced by cavitation resulted in rapid plastic deformation and microcracks grew at the grain boundaries in the early stage (Deng 2007). With the continuation of cavitation, the surface cavitation corrosion was promoted by transiting from longitudinal crack propagation to transversal propagation towards cavitation pits (Li et al 2004, Gao et al 2014).

Table 4. Variations of mechanical and electrochemical properties during cavitation erosion of stainless steel

Mechanical properties	Under cavitation the surface mechanical properties significantly (Li et al 2012). In 3.5% NaCl solution, there was a threshold value for the deterioration of surface mechanical properties of austenite stainless steel during cavitation (Yong et al 2011b).
Electrochemical behavior	Cavitation accelerated the diffusion process in the cathode and self-passivation current oscillated in the anode (Zhang et al 2013, Wang and Zhu 2007). The open circuit potential under alternating condition of quiescence and cavitation rapidly shifted towards active direction after cavitation (Luo et al 2003). These phenomena suggested the passive film was in metastable state under cavitation; Kwok et al (2000) and Fernández-Domene et al (2010) found the damage and repassivation of the passive film during cavitation in a heavy LiBr solution. Eventually the substrate was covered with the thinned passive film.

Table 5. Influence of microstructure, texture, composition, phase transformation on cavitation erosion of stainless steel

Microstructure	Luo et al (2003) and García-García et al (2006, 2008) discussed the cavitation erosion behavior difference of ferrite and austenite phases for CrMnN and 1Cr18Mn14N duplex stainless steel. Ferrite phase which is sensitive to the strain. The cavitation erosion and brittle failure appeared in this phase firstly. Then the destruction gradually extended to the austenite phase, and ductile failure occurred subsequently. The plastic deformation caused by slippage and twin crystals consumed the impact energy of bubble collapse, thereby improving the cavitation erosion resistance.
Texture	Grajales et al (2009) applied SEM and EBSD to investigate the effect of texture of 304 austenitic stainless steel on cavitation erosion. The inhomogeneous corrosion of the surface resulted from the inhomogeneous crystal orientation of the grains. The corrosion preferentially occurred in the grains of the (001) and (111) planes with high shear stress and the boundaries between the two grains with big orientation difference.
Composition	The high Cr, Mn, Co and Si contents in Cr-Co-Ni-Mn decreased the fault energy of alloy. Under cavitation, a great deal of fault was easily produced, reducing the occurrence of dislocation cross-slip. This favored the cavitation erosion resistance (Liu et al 2012).
Phase transformation	Cavitation may cause phase transformation in the microstructure of some stainless steels. TEM image of Cr-Co-Ni-Mn stainless steel after 20 h of cavitation indicated that stress induced the transformation from γ-austenite into ε-martensite, then partial ε-martensite into α-martensite, which was beneficial to the cavitation erosion resistance (Liu et al 2012).

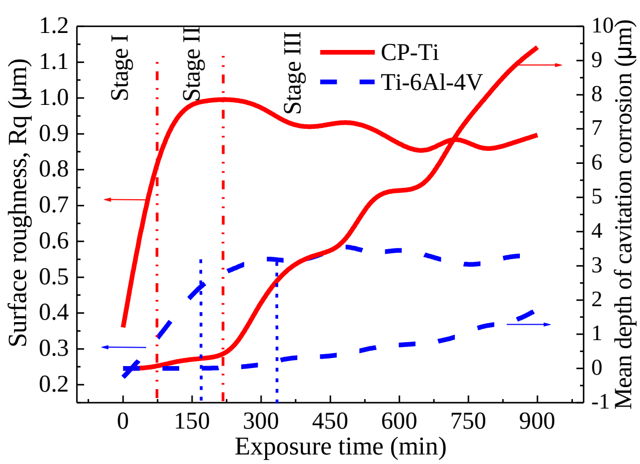

Fig. 2 Variation of surface roughness and mean depth of cavitation erosion for CP-Ti and Ti-6Al-4V (After Lin and Wang 2017)

Cavitation erosion damage measurement. The mass loss, surface roughness and 3D surface profile were used to analyze the cavitation erosion degree of CP-Ti and Ti-6Al-4V (Lin and Wang 2017). The different stages and dynamics of cavitation erosion were obtained (Fig. 2).

Evolution of cavitation erosion. For pure titanium, the constitution is α phase. Neville and McDougall (2011) and Li (2013) observed the morphologies during cavitation erosion of pure titanium. In distilled water, at the initial stage there were small regular annular pits or undulations on the surface. After 30 min, the surface underwent severe plastic deformation and a small amount of surface materials fell off. As cavitation proceeded, the materials in the local areas on the surface further fell off. While there was no slip of grain boundaries and cracks. In 3.5% NaCl solution, in the incubation period plastic deformation occurred. A few pits and cracks grew in local areas. Then they continuously developed, and a lot of surface materials fell off. Yang (2017) investigated the cavitation erosion features in LiBr solution. The surface produced uneven plastic deformation, and as the cavitation test continued, the degree of plastic deformation and the dislocation density of grain boundary increased. This caused slight spalling of materials on the grain boundary, and the production of local cracks. With the extension of cavitation, the cracks propagated along the grain boundary or into the grains, the spalling of materials increased.

In terms of Ti-6Al-4V, it is composed of α and β phase.

Preferential attack occurred at α phase, where the strength was lower than that of β phase. The cracks and pits mainly developed on the phase boundary and the degree of plastic deformation was not obvious. Furthermore, part of β phases fell off from the surface, causing the removal of α phase. Ultimately honeycomb structure formed on the surface. Therefore, the microstructure of titanium alloy had a great impact on the cavitation erosion behavior (Zhang et al 2015, Lin et al 2017).

Interaction of mechanical effect and corrosion. Because titanium is easily passivated, a dense protective film is formed on the surface and there is obvious passivation in the anode polarization of titanium. Fernández-Domene et al (2011) investigated the cavitation erosion behavior of pure titanium in high concentrated lithium bromide solution using polarization curve test and confocal laser scanning microscope. The corrosion potential, the passive region and self-corrosion current were significantly changed. The thinning of the passive film took place. The characteristic potentials were chosen to study the repassivation behavior of titanium by linear current density-time measurement. After cavitation stopped, the regeneration of the passive film dominated at low potentials and no repassivation occurred at high potentials. Zhao (2016) and Yang (2017) discussed the electrochemical behavior of Ti-6Al-4V and pure titanium by means of open circuit potential, polarization curve, EIS, Mott-Schottky curve and current-time curve and micro-zone electrochemical technique. Under cavitation in LiBr solution, the corrosion potential had a significantly negative shift, the corrosion current density and maintaining passive current density remarkably increased. The maintaining passive current density oscillated, suggesting that the passive film on the Ti-6Al-4V electrode surface was in a metastable state of depassivation/repassivation. Besides, the change in the semiconducting property of the passivating film under cavitation was found and cavitation caused the passive film to alter from *n*-type semiconductor to *p*-type semiconductor.

Temperature has an influence on cavitation erosion behavior. Lin et al (2017) analyzed the effect of temperature on cavitation erosion of Ti-6Al-4V in LiBr solution (Fig. 3).

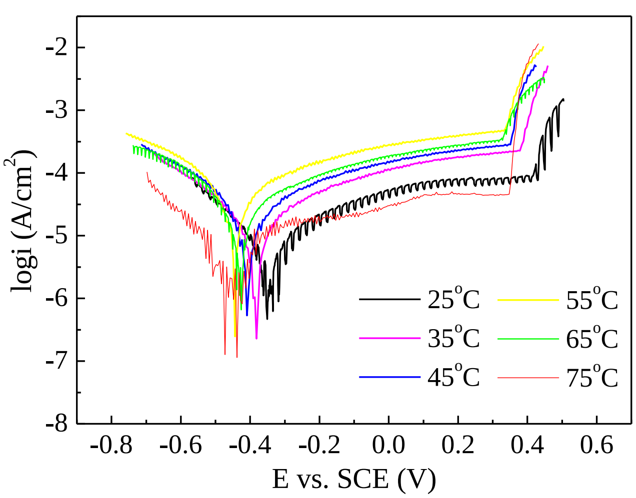

Fig. 3 Potentiodynamic polarization curves of Ti-6Al-4V at varying temperature (After Lin et al 2017)

The increase in temperature enhanced the micro-jet impact strength and accelerated the damage of the passive film on the surface. Moreover, it promoted the corrosion effect. At 55°C the cavitation erosion rate reached a peak. Afterwards, the destruction of the passive film was weakened due to the attenuation of impact strength of micro-jets.

5 Concluding Remarks

1) The main methods for investigating the cavitation erosion of metals include cavitation erosion degree measurement, microstructure characterization observation, surface mechanical properties and electrochemical examination. Mass loss, volume mass, pit depth and number are mainly used in cavitation erosion degree measurement; the cavitation erosion stages and evolution process are explored by the surface analysis techniques and surface roughness test; the surface mechanical properties are analyzed by the microhardness and nano indenter tests, simultaneously the electrochemical tests are combined to discuss the effect of cavitation on the passive film and cavitation erosion behavior.

2) The microstructure, chemical composition and mechanical properties have important effects on the cavitation erosion behavior. Generally, high hardness, good work-hardening property, high yield/tensile and toughness strength, fine grains are beneficial for resistance to cavitation erosion. The content increase of some elements, such as Mn, Co and Cr, C and N, is helpful in improving the cavitation erosion. The cavitation erosion preferentially occurs on the lower intensity phase (such as ferrite phase in carbon steel and stainless steel, α phase in titanium alloy, etc). the interface between phases and grain boundary.

3) For passive metals, the impact force produced by bubble collapse causes the depassivation of the passive film and mechanical properties degradation. During cavitation, the passive film is in a metastable state of depssivation/repassivation. The combined action of mechanical effect and corrosion contributes to the thinning and the semiconducting property change of the passive film.

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