Wear 267 (2009) 2033–2038

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Effect of liquid metal composition and hydrodynamic parameters on cavitation erosion

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ARTICLE INFO

Article history:
Received 9 September 2008
Received in revised form 17 April 2009
Accepted 4 August 2009
Available online 13 August 2009

Keywords:
Cavitation erosion
Cavitation
Liquid metal
Hardness
Flow velocity
Cavitation number

ABSTRACT

Cavitation erosion testing machine for low-temperature melting alloy liquid was developed by using a vibratory apparatus. The erosion tests of SUS304 were carried out in three kinds of lead–bismuth and deionized water. We defined a relative temperature as the percentage between freezing and boiling points. At relative temperature at 14 °C, the erosion rate is 10–12 times in various lead–bismuth alloys, and 2–5 times in sodium, as compared with that in deionized water. When SUS304 was exposed to a cavitation in PbBi, the surface was work hardened 20% harder compared with original surface. In deionized water, SUS304 was work hardened by 5%. Therefore, we can conclude that larger collapse pressure can be estimated to act on the specimen surface in lead–bismuth, as compared with that in water.

We discussed the effect of hydrodynamic properties on cavitation erosion in a flowing system. It is considered that the erosion rate in sodium is in proportion to 1st to 6th power of flow velocity similarly to that in mercury. The incipient cavitation number is approximately unity irrespective of test liquids. Furthermore, the relation between MDER and cavitation number is expressed as power low of function with an exponent of 2.5.

1. Introduction

Research on cavitation erosion in liquid metals is very important to confirm the safety of fast breeder reactors using sodium coolant and to understand cavitation erosion in the liquid–mercury target system of the neutron spallation source [1]. The effect of cavitation erosion in liquid metals includes liquid properties (temperature, density of the liquid, sound velocity, etc.) and flow properties (flow velocity, cavitation number, etc.). A liquid property is based on characteristics of the liquid itself and is not changed by apparatus such as vibratory and flow systems. Especially, Hattori et al. [2] found that the erosion rates of the cavitating liquid jet method and the vibratory method show similar temperature dependencies after defining a relative temperature.

Regarding cavitation erosion in liquid metal, Thiruvengadam et al. examined the temperature dependencies of the erosion rates of pure titanium [3] and SUS316 [4] in sodium using a vibratory apparatus. They reported that the erosion rate of pure titanium has a maximum at 750 °F, and that the erosion rate of SUS316 decreases with increasing temperature. But, they only used the terminal erosion rate of the last stage. Since terminal erosion rates are optional in the ASTM (American Society for Testing and Materials) standard, it has the disadvantage of not comparing well with other test results. Garcia and Hammitt [5] carried out vibratory cavitation erosion test of SUS304 in water, mercury, lithium, and lead–bismuth alloy. They referred to the sodium data by Thiruvengadam, and reported that the erosion rate in sodium at 260 °C is about nine times larger than in water of 18 °C. Moreover, they [5] found that heat transfer controlled collapse occurs only near the boiling point and inertia controlled collapse occurs at temperatures below the boiling point. Young and Johnson [6] carried out vibratory cavitation erosion tests of a cobalt alloy (L-605) in sodium at various pressures and temperatures. They found that the erosion rate increased with increasing pressure, and they obtained a peak for temperature dependence. The peak occurs at the approximate average of freezing and boiling temperatures (as shown in later Fig. 4). However, a detailed study of the temperature effect has not yet been performed. Hattori et al. [7] previously developed a cavitation erosion test apparatus and carried out erosion tests in deionized water and liquid metal. The influence of both liquids on instantaneous MDER (Mean Depth of Erosion Rate) was discussed. Moreover, they discussed the effect of liquid properties and temperature effects on the erosion rate. They previously proposed a new parameter to evaluate the erosion rate in various test liquids, and clarified that in the low relative temperature region an increase in the temperature affects the erosion rate by an increase in the

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0043-1648/$ – see front matter
doi:10.1016/j.wear.2009.08.002

Table 1
Chemical composition of lead–bismuth mass%.

	Bi	Pb	Sn	Cd	In
PbBi-47	44.7	22.6	8.3	5.3	19.1
PbBi-68	50	26.7	13.3	10	–
PbBi-94	50	28	22	–	–

Table 2
Physical and mechanical properties of lead–bismuth.

	PbBi-47	PbBi-68	PbBi-94
Freezing point [°C]	47	68	94
Boiling point [°C]	654	460	560
Density at 20 °C [g/cm^3]	8.86	9.38	9.69
Tensile strength [kPa]	373	421	530
Brinell hardness	12	9.2	12.8

vapor pressure, resulting in an increase in the number of cavitation bubbles.

Regarding the flow dependence of the erosion rate in liquid metal, Belahadji et al. [8] carried out an erosion test in a venturi tube to obtain a relation between flow velocity and pitting rate (the density of pits per unit surface area and per unit time of exposure) during the flow. They reported that in mercury, the pitting rate is increased with the 6th power of the flow velocity for velocities between 2 and 6 m/s and with the 1st power of the flow velocity for velocities between 6 and 10 m/s. However, they did not discuss the relation between the flow velocity and the pitting rate in water in order to compare it with the experimental results in mercury. Kamiyama and Yamazaki [9] measured incipient cavitation numbers in mercury and in water in venturi tubes. They reported that the incipient cavitation numbers in mercury and in water are almost unity. However, they did not discuss the cavitation number of erosion.

In this study, erosion tests were carried out in three kinds of liquid lead–bismuth alloys and in deionized water to discuss the influence of the kind of metal on the erosion rate. The hardness increase of the test specimen by work hardening due to cavitation is also examined. Moreover, the effect of flow velocity and the cavitation number on the erosion rate is discussed. We discuss the effect of the liquid properties with results of a vibratory method obtained in this study and take the effect of the flow properties from references.

2. Test material and experimental procedures

2.1. Test material and test apparatus

Three kinds of low melting point lead–bismuth alloys and deionized water were used as test liquids. The chemical composition and the physical and mechanical properties of the lead–bismuth alloys are listed in Tables 1 and 2, respectively. The numbers for the material identification in Table 1 are the freezing points of the test liquids. The freezing point of lead–bismuth alloys can be widely changed from 20 to 180 °C with the addition of Sn and Cd.

The chemical composition and the physical and mechanical properties of the erosion test specimen are listed in Tables 3 and 4, respectively. Since SUS304 stainless steel is used for pipes of sodium in a fast breeder reactor plant, SUS304 was used as test specimen in this study. The Brinell hardness was measured in this study, and was converted into the Vickers hardness using a conversion table based on SAE J417b [10].

Table 3
Chemical composition of test material mass %.

	C	Si	Mn	P	S	Ni	Cr
SUS304	0.05	0.33	1.76	0.36	0.22	8.49	18.18

Table 4
Mechanical properties of test material.

Tensile strength [MPa]	HB	HV
672	180	189

Fig. 1 shows the vibratory test apparatus for liquid metals which was developed in our previous study [7]. The test apparatus consists of a vibratory apparatus as specified in the ASTM G32-03 standard [11] and a liquid metal reservoir kept at constant temperature.

2.2. Experimental procedure

Cavitation erosion tests were carried out with the vibratory specimen method by using a vibratory apparatus. The exposed area of 201 mm^2 corresponds to a circular test specimen area with a diameter of 16 mm. The facility was operated at a frequency of 19.5 kHz and a double amplitude of 50 μm. The test temperatures were 55, 100 and 150 °C for PbBi-47, 75 °C, 100 and 150 °C for PbBi-68, and 100 and 150 °C for PbBi-94. The temperatures of deionized water were 10, 25 and 40 °C. The immersion depth of the specimen was 5 mm at every temperature. Test specimen in liquid metal was removed after every time interval and washed in boiled deionized water. Then, the specimen was washed in acetone with an ultrasonic cleaner and the erosion mass was measured with a precision balance with a sensitivity of 0.01 mg. The cavitation erosion was evaluated in terms of mass loss and instantaneous MDER (Mean Depth of Erosion Rate) of the test specimen. The MDER was defined as the mass loss divided by the material density, the eroded area and the exposure time interval. The tests specimens after testing were cut to measure their Vickers hardness on the cross section with a microhardness testing machine.

3. Experimental results and discussion

3.1. Cavitation test results

Fig. 2 shows the mass loss curves in the lead–bismuth alloys and deionized water at each temperature. The data points of PbBi-68 were obtained by Hattori et al. [7]. The mass loss passes through an incubation period of low mass loss and then increases linearly at each temperature in the various test liquids. The incubation period

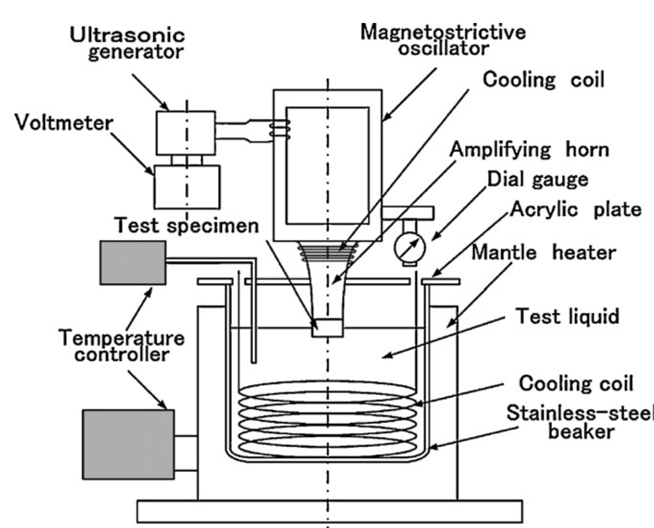

Fig. 1. Vibratory test apparatus.