Wear 269 (2010) 443–448

Contents lists available at ScienceDirect

Wear

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

Analysis of cavitation erosion resistance of cast iron and nonferrous metals based on database and comparison with carbon steel data

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ARTICLE INFO

Article history:
Received 5 December 2007
Received in revised form 28 April 2010
Accepted 30 April 2010
Available online 7 May 2010

Keywords:
Cavitation erosion
Iron and steel
Nonferrous metals
Hardness

ABSTRACT

Cavitation erosion is a form of damage which occurs in many types of fluid machinery such as water turbines, pumps and torque converters, as well as in industrial machines such as cylinder liners of diesel engines, ship propellers and valves. We have constructed a database of cavitation erosion and analyzed carbon steel data. In this study, erosion resistance was analyzed for cast iron, aluminum alloys, copper alloys, and titanium alloys, in comparison with regular carbon steels. The cavitation erosion resistance can be separately evaluated in terms of hardness for these alloys. The resistance is 1/3 to 1/5 lower for gray cast iron and 2/3 to 1/3 lower for ductile cast iron compared with carbon steel of the same hardness, and it is 1/3 to 1/5 lower for aluminum alloys compared with carbon steel. The resistance of copper alloys and titanium alloys is almost the same as that of carbon steel.

1. Introduction

A small number of studies [1,2] have been performed on the statistical evaluation of cavitation erosion. Heymann [1] summarized that the erosion resistance (the reciprocal value of the maximum instantaneous erosion rate) is strongly correlated with hardness for nine kinds of materials (the total number is 119) such as carbon steels, cast irons, stainless steels and many nonferrous alloys, and the erosion resistance increases roughly with the 5/2 power of the hardness excluding stellite (and similar cobalt alloys). However, the analyzed erosion test data included not only cavitation tests but also impingement tests, so that the scattering of the erosion resistance for materials of the same hardness was broad (upper limit/lower limit ~30 times, correlation coefficient: 0.77), and therefore it was still very difficult to evaluate erosion resistance from hardness. Hammitt [2] collected many data of cavitation erosion and obtained the base-fit curve in terms of ultimate resilience.

Hattori and Ishikura [3] constructed a database on cavitation erosion from 1970 to 2002. We concluded that the erosion resistance of carbon steel increases proportionally with 2.4th power of the Vickers hardness with a correlation coefficient of 0.92. Cavitation erosion data obtained from 2003 to 2005 was added to the existing database [4]. Stainless steels have excellent corrosion resistance, and are used for many types of fluid machinery. We found [4] that a very good correlation coefficient of 0.98 for stainless steels was obtained as. Like as for carbon steel, the erosion resistance is in proportion to the 2.4th power of the hardness, when it is evaluated in terms of the Vickers hardness after erosion tests, by introducing an increase ratio of hardness as a material constant F_{mat}. However, the analysis was not made for cast iron and various nonferrous metals that are used for various kinds of fluid machinery components.

In this study, we discuss the erosion resistance of various kinds of cast iron, aluminum alloys, copper alloys, and titanium alloys compared with the results for carbon steels based on the database constructed in our laboratory.

2. Conversion of test data

Since many data under the same condition are required to statistically analyze a database, the method to convert data into the values under standard test conditions specified by the American Society for Testing and Materials, ASTM [5] (amplitude: 50 μm, frequency: 19.5 kHz) was examined. First, data other than 50 μm amplitude (peak to peak) were converted into data values equivalent to 50 μm amplitudes. For the relation between amplitude and erosion rate, Thiruvengadam and Hobbs found that erosion rates increased proportionally to the approximate powers of 1.8 and 1.5 of the amplitude (peak to peak), respectively [6,7]. In this study, the exponent of the amplitude was simply assumed to be 2, in order to convert data with other amplitudes (not 50 μm) into data values equivalent to 50 μm amplitude data. Incidentally, the error between exponent 1.5 and 2 is only 12%, when data of 40 μm amplitude are converted into equivalent 50 μm amplitude data. In this way, all data were converted to a condition equivalent to 50 μm amplitude, and were rearranged into 4 types of 14.7 kHz and 19.5 kHz of both vibratory and stationary specimen methods.

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doi:10.1016/j.wear.2010.04.031

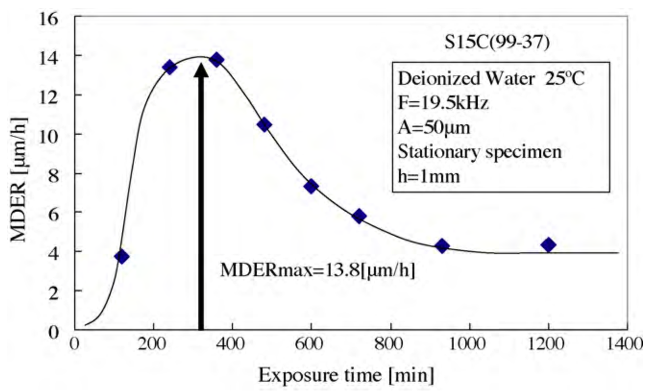

Fig. 1. MDER curve of S15C.

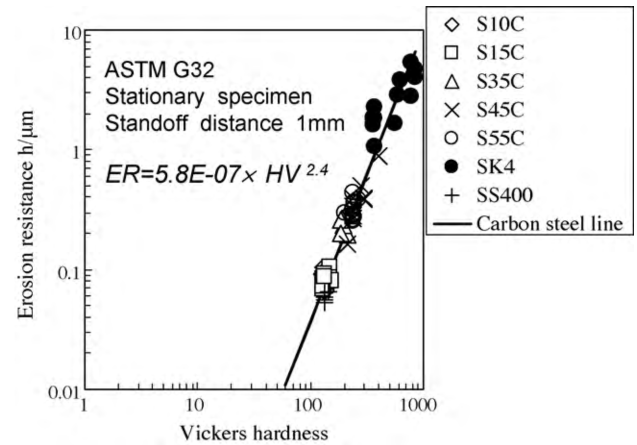

Fig. 2. Relation between hardness and erosion resistance of carbon steel.

The erosion rate can be obtained by converting these data to conditions equivalent to 19.5 kHz and the stationary specimen method (standoff distance: 1 mm). We multiplied the data of vibratory specimen method by 0.28 and the data of 14.7 kHz by 1.2. The erosion resistance of cast iron, aluminum alloys, copper alloys and titanium alloys was evaluated in terms of hardness and compared with the results of carbon steel obtained by Hattori and Ishikura [3].

The results of an erosion test are often expressed by the "mean depth of erosion" (MDE) [5], which is mass loss divided by the material density and the eroded surface area. Another expression is the instantaneous "mean depth of erosion rate" (MDER), that is, the slope of the tangent to the cumulative erosion–time curve at a given point. For example, the MDER–time curve under the condition of 19.5 kHz and the stationary specimen method for S15C (carbon steel) is shown in Fig. 1 The MDER increases gradually and reaches a peak, followed by a gradual decrease. $MDER_{max}$ is the "maximum of the mean depth of the erosion rate", that is, the slope of the straight line that best approximates the steepest linear (or nearly linear) portion of the cumulative MDE–time curve, and it is expressed in μm/h. We define the reciprocal value of $MDER_{max}$ as erosion resistance (ER).

3. Relation between hardness and erosion resistance of carbon steels

Fig. 2 shows the relation between the hardness and the erosion resistance of carbon steels for machine structural use, and carbon tool steels including various heat-treated steels in the database, which was constructed in our laboratory. The relation between hardness and erosion resistance of carbon steel can be expressed as

$$ER = 5.8 \times 10^{-7} \times HV^{2.4} \quad (1)$$

with a coefficient of correlation of 0.92. The erosion resistance has a very high correlation with the hardness. We similarly analyze the data for cast iron, aluminum alloys, copper alloys and titanium alloys in the following chapter.

4. Analysis of cast iron and nonferrous metals

4.1. Cast iron

We analyzed seven types of cast iron, i.e. gray cast iron FC100 and FC200, ductile cast iron FCD400 and FCD700, ferrite phase ductile cast iron FDI, perlite phase ductile cast iron PDI, and austempered ductile cast iron ADI. Table 1 shows the chemical composition and mechanical properties of cast iron. The tensile strength is the value written on the inspection certificate sheet of the test material which we used in the experiments. The Vickers hardness HV is a value measured in our laboratory. HV ranges from 150 to 400 for both gray cast iron and ductile cast iron. Fig. 3 shows the relation between the Vickers hardness of cast iron and the erosion resistance which has been tested in our laboratory. A solid line in this figure shows the base line of carbon steel given in the previous sec-

Table 1
Chemical composition and mechanical properties of cast iron (mass%).

Material	C	Si	Mn	P	S	Cu	Cr	Mo	Mg	Zn
(a) Chemical composition										
FC100	3.38	2.19	0.58	0.021	0.016	–	0.038	–	–	–
FC200	3.38	2.19	0.58	0.021	0.016	–	0.038	–	–	–
FCD400	3.47	2.71	0.31	0.033	0.013	–	–	–	0.035	–
FCD700	3.25	2.68	0.24	0.03	0.01	–	–	–	0.033	–
FDI	3.76	2.15	0.32	0.019	0.042	–	0.04	–	–	0.04
PDI	3.76	2.15	0.32	0.019	0.04	–	–	–	–	0.04
ADI	3.76	2.15	0.32	0.019	0.009	0.62	0.04	0.02	0.042	–

Material	Density (g/cm^3)	E (GPa)	σ_B (MPa)	HV
(b) Mechanical properties				
FC100	7.1	71.5	110	155
FC200	7.1	97	230	350
FCD400	7.1	167	414	201
FCD700	7.1	167	861	385
FDI	7.1	167	414	190
PDI	7.1	167	861	247
ADI	7.1	173	902	370