Wear 271 (2011) 1397–1403

Contents lists available at ScienceDirect

Wear

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

Evaluation of erosion resistance for metal–ceramic composites and cermets using a water-jet testing apparatus

Y.I. Oka*, H. Hayashi

Department of Chemical Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima 739-8527, Japan

ARTICLE INFO

Article history:
Received 1 September 2010
Received in revised form
25 November 2010
Accepted 25 November 2010

Keywords:
Erosion by water-droplet impingement
Cavitation-erosion resistance
Incubation period
Damage depth rate
Metal–ceramic composite
Cermet

ABSTRACT

High-speed centrifugal water pumps sometimes suffer severe erosion when the cavity generated by the inlet stream collapses. Use of materials with improved fracture toughness and material hardness, such as metal–ceramic composites or ceramic materials, results in a high resistance to cavitation erosion. In the present study, water droplet impingement erosion tests were conducted to evaluate the cavitation-erosion resistance of hard materials, as the process that occurs during water droplet impingement erosion is analogous to that of cavitation. A water-jet testing apparatus, which created robust and reliable testing conditions, was used in the present study. The incubation period and damage-depth rate were used to evaluate the erosion resistance of both metal–ceramic composites, which were generated by precipitation hardening of stainless steel and TiC particles, and WC cermet materials. The metal–ceramic composite showed two phases of erosion damage. The damage-depth rate in the first damage phase was low due to the removal of debris from the TiC particles and the metal substrate. The higher damage-depth rate in the second region was attributed to the removal of either ceramic particles or grains from the surface. Some of the cermet materials showed immediate and remarkable damage with no incubation period due to corrosion of the metallic binder by tap water. Consequently, the erosion resistances of the metal–ceramic composites and the cermets, as evaluated based on the incubation period and the damage-depth rate, were related to the average material hardness in a logarithmic scale. The high erosion resistance was attributed to the increased hardness of the composites and the cermets.

1. Introduction

The chemical components of industrial machinery, which operates at high-speed revolutions and is used in highly efficient production processes, are often exposed to extreme environmental conditions. High-speed centrifugal water pumps sometimes suffer severe cavitation erosion when shock waves generated by turbulent flow or fluctuation in hydrostatic pressure causes the cavity to collapse. There is a need for materials with high-performance characteristics, such as fracture toughness and hardness, which are also highly resistant to cavitation erosion. In general, ceramic materials possess high hardness, but they are limited by their low resilience or toughness. By contrast, metallic materials have ductile and constructive properties, but they lack high hardness. Therefore, the use of metal–ceramic composites offers optimal material resistance to erosion.

It is well known that the behaviours and mechanisms of cavitation erosion are similar to those of droplet impingement erosion [1]. An incubation period with no material removal followed by damage loss (material removal) is observed during both types of erosion [2,3], and the plot of damage versus time is linear during the initial damage phase for both [4,5]. Also, the evolution of shock waves is the origin of the material degradation that occurs during both. However, the pressure, cavitation number and flow velocity on the shock waves generated as a result of cavity collapse are difficult to measure [6], whereas the shock waves generated by the impingement of water droplets can be easily measured and converted into pressure values [1]. We defined the impingement conditions and developed prediction equations using a water-jet testing method in our previous papers [5,7]. Cavitation-erosion resistance can be evaluated by measuring the resistance to droplet impingement erosion using the water-jet method because cavitation and droplet impingement occur via similar mechanisms.

The aim of the present study was to investigate the water-droplet erosion resistance of metal–ceramic composites and cermet materials as an indicator of cavitation-erosion resistance and to confirm the superiority of harder ceramic materials over softer metallic materials. Water-droplet-impingement tests were conducted using a water-jet testing apparatus. The impingement conditions such as impact velocity and the number and size of water droplets have previously been described in detail [5]. The incubation period and subsequent damage-depth rate were deter-

* Corresponding author. Tel.: +81 82424 7845.
E-mail address: iyoshi@hiroshima-u.ac.jp (Y.I. Oka).

0043-1648/$ – see front matter
doi:10.1016/j.wear.2010.11.040

Table 1
Test conditions and rate conversion constant.

Pressure	Velocity (m s^{-1})	Diameter (mm)	Number (μm^{-2} s^{-1})	*k*
20	121	0.095	2.30	969
30	148	0.072	8.50	602
50	191	0.060	36.6	241.7
70	226	0.050	108	141.5
90	256	0.044	225	99.70

k: rate conversion constant.

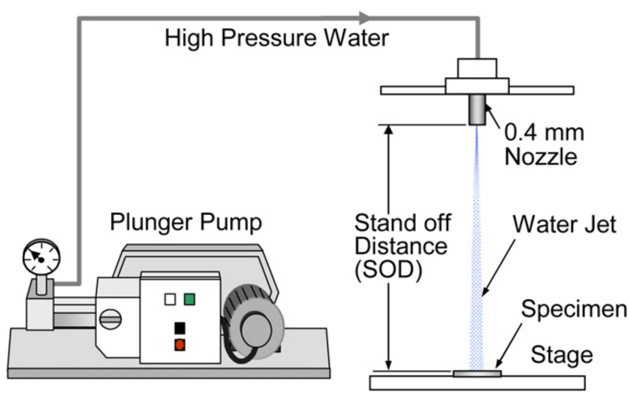

Fig. 1. Schematic illustration of a water-jet testing unit.

Table 2
Materials used in this study.

Materials	Designation	Hardness (GPa)
Mild steel	SS	1.5
Martensitic stainless steel	MS	6.6
Metal–ceramic composite		
Precipitation hardening stainless steel including TiC (30 wt%)		
HT at 843 K	TA1	7.0
	TB1	7.0
HT at 868 K	TA2	7.2
	TB2	6.2
HT at 893 K	TA3	6.5
	TB3	5.6
Cermet		
WC79–NiCr	A	13.0
WC89–NiCrCo	B	12.8
WC85–NiCr	C	11.4
WC–NiCrCo	D	17.4

mined from the damage-depth versus testing time curves. The relationships between incubation period or erosion rate, which was calculated from the damage-depth rate, and the material hardness, were examined as indicators of erosion resistance indicators.

2. Experimental procedures

A schematic illustration of the water-jet apparatus used in the present study is shown in Fig. 1. Pressurized tap water was supplied by a plunger pump and was injected into an orifice nozzle over a test section. The diameter of the nozzle was approximately 0.4 mm. The impingement angle of the water-jet was 90°, and the water pressure was varied from 20 to 90 MPa. The water-jet was gradually reduced to droplets at a certain stand-off distance (SOD) between the nozzle and the specimen. The SOD was held constant at 200 mm in the present study. The other water droplet impingement conditions, such as droplet velocity, diameter and number, which varied with the pressure, were described previously [5] and are summarized in Table 1. The maximal damage-depth on the nozzle axis in the central region was measured using a surface profilometer. Damage-depth curves were obtained for various materials under different impingement conditions. The damage behaviour was characterized by both incubation period and damage-depth rate. The damaged surfaces were observed using scanning electron microscopy (SEM).

The designation and average hardness (GPa) of the test specimens used in the present study are described in Table 2. The metal–ceramic composite composed of precipitation hardening stainless steel containing 30% TiC particles was supplied from two different manufacturers (TA and TB). The material hardness of the composite, particularly the metallic substrate phase of precipitation hardening, was altered by use of three types of heat treatment. Cermet materials with different contents of tungsten carbide (WC) and metallic binders were tested for comparison to the metal–ceramic composite. In addition, the erosion resistances of mild steel (SS) and martensitic stainless steel (MS), which are representative metallic materials, were measured for comparison to the erosion resistances of the metal–ceramic composite and cermet materials.

3. Estimation of lifetime and erosion rate from the experimental data

In reality, erosion damage of industrial components occurs hardly at first, after which the erosion rate increases, resulting in significant damage. Experimentally, these characteristics are expressed by the incubation period with no material removal and the damage-depth rate, which is determined from the slope of the damage-depth versus testing time curves. As both the incubation period and the damage-depth rate are affected by the experimental water impingement conditions, they are not standardized indicators of erosion damage that allow estimation of erosion damage or the lifetime of component materials under real-life conditions. The standard indicators are the droplet mass m_c that initiates the removal of material and the erosion damage rate E, which is expressed as the volume of removed material per unit mass of water droplets (mm^3 kg^{-1}) [5].

The effect of the incubation period I_p (s) on the droplet mass per unit area, i.e., m_c (kg mm^{-2}) is shown in Eq. (1):

$$m_c = N\rho\left(\frac{\pi D^3}{6}\right) I_p = \frac{I_p}{k}, \quad k^{-1} = N\rho\left(\frac{\pi D^3}{6}\right) \tag{1}$$

where N (mm^{-2} s^{-1}) is the impact number per unit area and time, D (mm) is the diameter and ρ (kg mm^{-3}) is the density of the water droplets. $\rho(\pi D^3/6)$ is the mass of a water droplet (kg). k is the constant used to convert the damage-depth rate into the erosion-damage rate, and k^{-1} represents the mass of the water droplets per unit area and time (kg mm^{-2} s^{-1}).

The erosion damage rate E was calculated from the damage depth rate R_d (mm s^{-1}) as shown in Eq. (2):

$$E = \frac{R_d}{N\rho(\pi D^3/6)} = kR_d \tag{2}$$

The impact velocity, impact number, diameter of a water droplet, and k at various pump pressures are listed in Table 1 [7]. The units for the impact number in Table 1 are μm^{-2} s^{-1} (×10^6 mm^{-2} s^{-1}). The impact number in this water-jet apparatus is extraordinary among typical water impingement facilities [8,9].