Wear 398–399 (2018) 178–182

Contents lists available at ScienceDirect

Wear

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

Erosive wear resistance evaluation with the hardness after strain-hardening and its application for a high-entropy alloy

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ARTICLE INFO

Keywords:
Wear resistance
Slurry erosion
High-entropy alloy
Hardness
Strain-hardening

ABSTRACT

Hardness has been regarded as a primary parameter for the wear resistance evaluation of metals for a long time. However, because of work-hardening induced by wear, sometimes there is a big difference between the actual wear resistance and the evaluation with the original hardness (H_1). So an experimental hardness test after strain-hardening was suggested, and the effect of this experimental hardness on the evaluation of erosive wear resistance was investigated. Based on the slurry erosion tests of 8 kinds of metals under 90° impingement, a significant positive linear correlation between the erosive wear resistance and the ratio of strain-hardened hardness (H_2) and compressive elastic modulus (E) was obtained. And the correlation coefficient (R^2) between the value of erosive wear resistance and H_2/E ratio increases from 0.61 to 0.89 when the original hardness is substituted by the strain-hardened hardness. Furthermore, the erosive wear resistance of AlCrFeCoNiCu HEA was evaluated by the empirical expression and the difference between the experimental and predicted values is less than 10%. Therefore, the proposed evaluation method with the strain-hardened hardness is practical and effective for the erosive wear resistance evaluation of a candidate metallic material.

1. Introduction

The erosive wear which occurs when solid particles entrained in a fluid stream strike a surface has been a serious and continuing problem in many industrial operations [1]. For a safe and economic design, an appropriate erosive wear evaluation or erosion rate prediction must be obtained for those components which are used in hydro applications like pump impellers, turbine blades, mining pipelines etc. Investigations into the field of erosion are typically daunted by the huge number of experimental parameters which may have an effect on this damage mechanism, including flow conditions, the composition of the structural material, slurry material and even temperature. Normally, erosive wear evaluation has two steps as follows, (1) to compute the two-phase flow field in the relevant component (impeller, liner, and casing), and (2) relating the computed flow field to the local wear rate via experimentally determined wear coefficients [2]. Based on computational fluid dynamics (CFD) providing local evaluation of the mechanical action of the fluid flow and mechanical parameters of the impacting solids suspended in the flow [3], numerical prediction of erosion wear trends in centrifugal pump casing pumping dilute slurries is obtained in terms of the impact wear parameters i.e. pump flow rate, pump speed (RPM), particle diameter and various geometry conditions [2]. Moreover, the erosion evaluation via numerical simulation with CFD is also applied in the erosion of flue-dust change-over valves (FDCVs) by impingement of coke particles [4] and even the erosion-corrosion phenomena in four-phase flows [3]. However, the numerical simulation to estimate the erosion of pump components using available erosion models showed deficiency with actual wear measurement [5]. One of the reasons is a lack of a fundamental understanding of the erosion phenomenon.

The erosion mechanism has been investigated for many years. An erosive wear problem involves an eroding surface, the particles producing erosion, and the fluid flow conditions which bring the particles into contact with the surface [1]. Research focused on understanding erosion phenomena can be characterized into three distinct areas of study which include the role of solid particles, the nature of fluid flow and the understanding of material characteristics [6]. From the viewpoint of material characteristics, Bitter developed a model combining the two erosion mechanisms of deformation wear and cutting wear, which occur simultaneously in ductile materials [7], and these two mechanisms have become the basis for model development and have been well accepted until now [6]. Although there is no linear

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https://doi.org/10.1016/j.wear.2017.12.006
Received 27 July 2017; Received in revised form 6 December 2017; Accepted 6 December 2017
Available online 09 December 2017
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relationship between hardness and erosion wear resistance, and sometimes the material microstructure has a greater influence on wear resistance than the bulk hardness [8], it is reasonable that high hardness is beneficial to resist deformation and cutting in a certain situation. Thus, classical theories of wear often tend to emphasize hardness in defining the wear resistance of a surface [9]. Although hardness has been regarded as a primary material property affecting wear resistance for a long time, the ratio of hardness to elastic modulus, *H/E* ratio, is a more suitable parameter for predicting wear resistance [10]. The *H/E* ratio expresses a measure of the elastic limit of strain, which is an indicator of material durability since this parameter essentially describes the elastic strain to failure capability (and resilience) of a candidate material [9]. Actually, the *H/E* ratio has already been a very important parameter in gear design where it is used as a plasticity index. Thus, this ratio is used to interpret the wear resistance of *nc-TiC/a-C:H* nanocomposite coatings [11] and also is present in the numerical models for wear rate prediction [12].

Erosion of metallic materials causes wear and work-hardening simultaneously. For example, the erosion mechanisms of stainless steels consist of plastic deformation, work-hardening, and initiation of cracks [13]. So, the hardness of a target surface actually changes and normally increases with erosion because of work-hardening. Indeed, owing to obvious work-hardening effect, spheroidal carbide cast iron has higher erosive wear resistance than high chromium cast irons [14]. Since work-hardening is a common phenomenon of metals during erosion, only real surface hardness obtained after work-hardening can reveal the actual wear resistance. Furthermore, because elastic modulus is not a sensitive parameter to microstructure, real surface hardness substituted for the original hardness of metals is eligible to improve the predictive reliability of erosive wear resistance. Therefore, a so-called strain-hardened hardness test containing a dual indentation method is suggested for wear resistance evaluation in this paper. Based on the strain-hardened hardness, a roughly linear relationship between *H/E* ratio and the experimental erosive wear resistance is obtained under 90° impingement angle. Furthermore, the erosive wear resistance of a new developed high-entropy alloy (HEA) is estimated by this evaluation method.

2. Experimental

2.1. Materials

To obtain a new *H/E* ratio with the strain-hardened hardness, eight kinds of metallic materials were used in this work, including steels (ZGMn13, 30CrMo, 1Cr13, Q235, 0Cr19Ni9), aluminum alloy (6061) and titanium alloys (TC4, TC11). Table 1 presents chemical compositions, densities and elastic moduli of the test materials.

AlCrFeCoNiCu HEA ingots were prepared by arc-melting a mixture of pure elements with purity of 99.9% under a Ti-gettered argon atmosphere in a water-cooled copper crucible. Each ingot was melted four times to ensure uniformity in composition. Sample rods with a diameter of 6 mm were synthesized by suction casting into a copper mold under a purified Ar atmosphere. For erosive wear tests, plate samples with 3 mm × 10 mm × 80 mm size were also fabricated by suction casting.

2.2. Material characterization

Hardness tests were performed on a standard Brinell hardness tester (HBE-300, Shanghai, China), which includes two steps to get the hardness after strain-hardening. Firstly, fix the steel sample on the loading platform and then make an indentation on the surface using 10 mm hardened steel indenter at 29.4 kN load with 15 s loading duration. To show the strain-hardening effect, the second indentation was made at the center of the first indentation. Therefore, keep the position of the sample on the loading platform to ensure an overlap of two indentations. Secondly, change the indenter and load to 2.5 mm hardened steel indenter and 1.839 kN respectively, and then measure the hardness with 15 s loading duration. This hardness value obtained after pre-compression is the strain-hardened hardness. Meanwhile, the original hardness of materials were also measured with 2.5 mm indenter and 1.839 kN load. Same hardness measurements were performed for the titanium alloys as well as the as-cast HEA alloy. As an example, the indentations for the hardness measurements of titanium alloy TC4 are illustrated in Fig. 1. The largest indentation is related to the pre-compression. And the indentations located at position A and B refer to the hardness tests for the original hardness and the hardness after strain-hardening. Since aluminum alloys are much softer than steel, 10 mm hardened steel indenter and 9.8 kN load were used for pre-compression. Then, 5 mm indenter and 2.45 kN load were used to obtain the strain-hardened hardness with 15 s loading duration. The measurements of the original and strain-hardened hardness were repeated at least three times and the average values were used for each sample.

To apply the evaluation method, the elastic modulus of the HEA is needed as well as the hardness. As-cast AlCrFeCoNiCu rods with a diameter of 6 mm were cut to 10 mm long. Uniaxial compressive testing was performed on the as-cast AlCrFeCoNiCu rod with a polished cylindrical surface at a strain rate of $1 \times 10^{-3}\ \mathrm{s}^{-1}$ on SANS 5504 testing machine at room temperature.

2.3. Slurry erosion testing

Samples for erosive wear tests were cut to dimensions of 10 mm × 10 mm × 10 mm and then polished with 1,000-grit SiC paper in order to assure an average surface roughness (R_a) below 0.1 mm. Slurry erosion tests were performed in a jet erosion testing machine, as shown in our previous work [15]. This erosion test does not involve recirculating slurry but uses a fresh slurry flow comprised of water and 1 wt% SiO_2 particles with a diameter of 350–600 μm. The morphology

Table 1
Metals and their mechanical properties.

Metals		Compositions	Density	Elastic Modulus
GB	ASTM	(mass fraction/%)	(g/cm^3)	(GPa)
ZGMn13–1	B – 3	C 0.90–1.50, Mn 10.0–15.0, Si 0.30–1.0, S ≤ 0.05, P ≤ 0.10, Fe balance	7.93	200
30CrMo	4130	C 0.26–0.34, Si 0.17–0.37, Mn 0.40–0.70, Cr 0.80–1.10, Mo 0.15–0.25, P ≤ 0.035, S ≤ 0.035, Ni ≤ 0.030, Cu ≤ 0.030, Fe balance	7.89	210
1Cr13	S41000	C ≤ 0.15, Cr 11.50–13.50, Mn ≤ 1.00, Ni ≤ 0.60, Si ≤ 1.00, P ≤ 0.035, S ≤ 0.030, Fe balance	7.87	200
Q235A	A283M-Gr. D (OS230MPa)	C 0.14–0.22, Si 0.12–0.30, Mn 0.30–0.65, P ≤ 0.045, S ≤ 0.050, Fe balance	7.80	200
0Cr19Ni9	S30403	C ≤ 0.08, Si ≤ 1.0, Mn ≤ 2.0, Cr 18.0–20.0, Ni 8.0–10.0, P ≤ 0.045, S ≤ 0.03, Fe balance	7.93	206
6061	6061	Si 0.4–0.8, Mg 0.8–1.2, Fe ≤ 0.7, Cu 0.15–0.4, Mn ≤ 0.15, Cr 0.04–0.35, Zn ≤ 0.25, Ti ≤ 0.15, Al balance	2.69	71
TC4	GradeF5	Al 5.8–7.0, Zr 0.8–2.0, Mo 2.8–3.8, Si 0.2–0.35, Fe ≤ 0.25, C ≤ 0.1, O ≤ 0.15, N ≤ 0.05, H ≤ 0.012, Ti balance	4.45	110
TC11	/	Al 5.8–6.8, V 3.5–4.5, Si ≤ 0.15, Fe ≤ 0.30, C ≤ 0.1, O ≤ 0.20, N ≤ 0.05, H ≤ 0.0125, Ti balance	4.48	123

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