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Analytical modeling of solid-particle erosion of Stellite alloys in combination with experimental investigation

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ABSTRACT

This article presents the analytical modeling of erosion behavior of Stellite alloys under solid-particle impact. The erosion rates of five selected Stellite alloys, which are currently or potentially applied in an environment condition involving erosion, are investigated experimentally at two particle impact velocities of 84 and 98 ms^{-1}, and at two impingement angles of 30° and 90°. The Sheldon–Kanhere (S–K) model that utilizes the indentation hardness theory to derive a particle penetration equation is modified to fit the experimental data of Stellite alloys. The most significant improvement of this modified model is to include the effect of particle impingement angle. This introduces two parameters in the model, which are determined by fitting the experimental data of the five Stellite alloys. With this modified model, for Stellite alloys that have similar chemical compositions to the alloys studied in this research, the erosion rates at the particle impact velocity of 84 $\mathrm{m\,s}^{-1}$ or 98 $\mathrm{m\,s}^{-1}$ can be predicted for any particle impingement angles less than 30°. The limitations of this model are discussed.

1. Introduction

Erosive wear, as one of wear degradations, is the multitudinous phenomena characterized by a progressive deterioration of materials. There are a couple of parameters that influence the erosion rate of materials. The extent to which each parameter contributes to the erosion rate would depend on the environmental conditions together with the type of material under investigation. The main impact parameters are impact angle, particle velocity, particle size, shape and properties of both the abrasive particles and the target material under consideration [1]. Due to high cost and long duration involved in erosion testing, physics-based and statistics-based erosion models have been developed to predict/reveal the erosion resistance/mechanisms of materials. These models could also be used to predict the life of metals in erosive environments. A number of studies have proposed a variety of correlative equations between impact parameters and erosion damage caused by solid particle impact.

Finnie [2] developed the first erosion model for ductile materials where he considered erosion as a micro-machining process. His model was based on an ideal ductile, non-work hardening solid target material eroded by rigid particles. Finnie [3] further expanded his original model and proposed an erosion formulation derived from analyzing the motion equations of a single particle impacting a ductile surface. Although the calculations of the equations agreed with experimental data for low impact angles (between 15° and 30°), it however contradicted experimental results for impact angles greater than 60° and even predicts zero erosion rate at near 90° impact angles. Tilly [4] studied ductile material erosion, and proposed a removal mechanism involving a scrapping and extrusion of materials to form ridges that were vulnerable when attacked by particles moving at a high velocity. Tilly [5] further developed a two-stage model of the erosion process for ductile materials. Bitter [6,7] proposed a model for single-particle erosion of metals with an assumption that both types of erosion mechanisms (cutting and deformation) occurred simultaneously but further noted that “deformation wear” would be the dominant wear mechanism at normal incidence while “cutting wear” would be dominant at shallow angles. The erosion theory given by Bitter [6,7] showed complex forms in terms of expression and implementation, which were concerned by Neilson and Gilchrist [8] to seek a simpler analytical solution. Hutchings and Winter [9] investigated the work hardening and annealing effects on the erosion mechanism of ductile materials. In their studies, they used a large steel sphere attacking on an aluminum surface to investigate single particle erosion, and postulated that the material removal mechanism was the shearing of the surface layer of the ductile metal target in the direction of motion of the projectile and an overhanging lip was formed and removed during the erosion process. Hutchings [10] developed a model

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of multiple-particle erosion of metals using spherical particles impacting at normal angle and represented their results as mass loss per unit mass of impinging particles. He postulated that the mechanism of material removal was the formation and detachment of platelets of the material, and assumed that only after a critical strain was attained in the material would this detachment occur. Sundararajan and Shewmon [11] proposed a model for multiple-particle erosion of metals using the same criterion of a critical strain needed for material removal; their findings agreed better with experimental erosion data compared to Hutching's model [10]. Sheldon and Kanhere (S–K) developed an erosion model to study large single particle impact on 6061-TO aluminum surface [12]. In this model, a particle penetration equation was derived using the indentation hardness theory; the erosion rate was formulated including particle diameter, density and impact velocity, as well as target surface hardness.

Stellite alloys are a family of cobalt-based alloys containing a large amount of chromium, Cr (20–30 wt%), also tungsten, W (4–18 wt%) or molybdenum, Mo (up to 28 wt%) and a small amount (<3 wt%) of carbon, C [13]. These alloys are generally strengthened by the precipitation of various carbides in the cobalt solid solution matrix, which provides a unique combination of mechanical and tribological properties such as high hardness and strength, superior adhesive and abrasive wear resistance and excellent solid particle and cavitation erosion resistance. They also display excellent corrosion and oxidation resistance due to the high Cr content. These superior properties to other alloys make Stellite alloys widely employed in various applications, typically in gas turbine engines, oil production and refining, and mechanical manufacturing that involve metal to metal wear, fretting, hot corrosion, particle erosion plus others. Although some experimental studies in erosion behavior of Stellite alloys have been reported [14,15], the reported data are very limited, which has retarded the application of these alloys in erosive environments. Since modeling can reduce the high cost and long duration involved in erosion testing, material researchers have been resorting to this approach in the erosion study. However, among the erosion models none can be used to effectively predict the erosion damage or loss of Stellite alloys. To this end, the present research attempted to create an erosion model for Stellite alloys. The S–K model [12], originally developed for 6061-TO aluminum, was modified by fitting the experimental data of five selected Stellite alloys under solid-particle erosion, and further improved by taking into account the particle impinging angle, which was neglected in the S–K model. Using this model, the erosion resistance of a Stellite alloy which has a similar chemical composition to one of the alloys studied in this research at the particle impact velocity of 84 ms^{-1} or 98 ms^{-1} can be predicted for different particle impingement angles. However, this model has limitations; therefore, it is more suitable for comparative study of erosion resistance between Stellite alloys.

2. Formulation of erosion model

In studying the hardness of metals by means of indenting a test surface with a sphere, Meyer (1908) found that the diameter of the recovered indentation, d, for a given hard sphere is related to the applied load, F, by the relation

$$F = pd^n, \tag{1}$$

where p is the load for unit diameter and n is the logarithmic index. The S–K model was derived from the energy balance consideration involving Meyers's relation on velocity-indentation. The associated kinetic energy (KE) for a normally impacting spherical particle with velocity, V, diameter, D, and mass density, ρ_p, is given by [12]

$$KE = \frac{1}{2}\left[\frac{3}{4}\pi\left(\frac{D}{2}\right)^3\right]\rho_p V^2. \tag{2}$$

The work done W, by the indenting sphere in a direction, x, normal to the surface from the time of surface contact until penetration stops at a depth, q, is [12]

$$W = \int_0^q F dx \tag{3}$$

replacing F in Eq. (3) with Meyer's relation, the following can be obtained:

$$W = \int_0^q pd^n dx. \tag{4}$$

Based on these relations, Sheldon and Kanhere [12] went further and proposed that the material removal per particle or per gram of particles of the same size would be proportional to the cube of the penetration depth, q

$$w \sim q^3 = \frac{D^3 V^3 \rho_p^{3/2}}{H_v^{3/2}} \tag{5}$$

where w is the volume of material removed per gram of particles, i.e., erosion rate (m^3/g); D is the particle diameter (m); V is the impact velocity (m/s); ρ_p is the particle density (kg/m^3); and H_v is the Vickers hardness of the target material (Pa).

3. Solid-particle erosion test

To testify the validity of Eq. (5) for Stellite alloys, the solid-particle erosion test was conducted on five selected Stellite alloys, which are commonly or potentially used for erosion resistance in various fields. The chemical compositions of these alloys are listed in Table 1. The first three alloys contain high carbon content, thus a large volume fraction of carbides, as shown in Fig. 1. Alloy C also contains very high tungsten content, which results in a large amount of $(W,Co)_6C$ carbide in addition to Cr_7C_3 carbide. The last two alloys contain very low carbon content, but high molybdenum, which induces a large amount of intermetallic compounds Co_3Mo and $CoMo_6$ in the microstructures, as shown in Fig. 1. Alloy D also has precipitated $Cr_{23}C_6$ due to higher carbon content, compared to alloy E.

The hardness of these alloys was measured on a Microhardness Tester Unit, Model SMT-X7 Dual Indenter, under an indentation load of 2 kg. Ten tests were made on each alloy and the average hardness values are reported in Table 2, with the measurement error within 4.23%. The density data of the alloys were provided by the alloy supplier and are also reported in Table 2.

The erosion tests of the Stellite alloys were conducted on an S.S. WHITE Airbrasive Micro-Blasting Jet Machine, Model 6500 Erosion Chamber, according to the ASTM G76-02 Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets [16]. The specimen holder contains a screw which allows the

Table 1
Chemical compositions (wt%, Co in balance) of Stellite alloys.

Alloy	Element							
	Cr	W	Mo	C	Fe	Ni	Si	Mn	Others
Alloy A	30	4.5	1.5	1.6	3	3	2	2	
Alloy B	30	4	1.5	1	3	2.5	0.7	1.4	
Alloy C	22	32	0	1.5	0	0	0	0	
Alloy D	24.2	0	11.8	0.35	1	3.8	0.45	0.52	2.07Nb
Alloy E	27	0	11	0.25	3	2.75	1	1	