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Modeling study of liquid impingement erosion of NiAl alloy

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ABSTRACT

This article presents the theoretical modeling and computation of liquid impingement erosion of solid metallic surface and the response mechanisms, with special interest in study of the liquid impingement erosion behavior of NiAl alloy. Particular attention is paid to investigating the effects of drop velocity and drop size on the damage of the target surface and to predicting and simulating the erosive failures. The models of impact stress wave, mean depth of penetration, and maximum depth of erosion rate (Max DER) are employed to develop various maps for NiAl alloy, including target thickness vs. drop size (diameter), rate of mean depth of penetration (MDRP) vs. drop impact velocity, and damage threshold velocity (DTV) vs. drop size. For comparison, pure Ni target and steel ball erodent are also studied. The computational results are analyzed and discussed.

1. Introduction

Liquid impingement erosion can be described as the collision at high speed of liquid droplets with a solid surface, which results in a form of liquid erosion [1]. It has been observed on many components exposed to high-velocity steam containing moisture droplets such as blades in the low-pressure end of large steam turbines, the aerodynamic surfaces of aircraft and missiles when they fly through rainstorms at high subsonic or supersonic speeds. Liquid impingement erosion is also of concern in nuclear power systems, which operate at lower steam quality than conventional steam systems, and in systems using liquid metals as the working liquid, where corrosiveness of the liquid metal can promote rapid erosion of components. In the early time of encountering with liquid impingement erosion, the damages incurred on various materials and conditions could only be determined through tests; however, the results from these experiments were imperfectly accurate due to complexity and difficulties from uncertainty of surface interactions, liquid drop velocity calculation and geometric variations such the angle of impingement. As a result, scientists have tried to model the erosion process based on material characteristics and other experimental parameters with aims to predict the behavior of different material responses during erosion exposure. These computational models fall into the detection of identifying simultaneous features of damages [2], including change in mean volume or depth of pits, increase in the number of cracks, loss of optical transmission of the target material, and weight loss of the target material. Due to a large number of parameters that influence the erosion process, the development of analytic models that can capture the whole erosion process is a challenge mission. Therefore, only a limited number of models have been highlighted, which provide a basis for the important criteria that are associated with erosion and their respective limitations in the rapid development and advancement of science and technology.

Honegger [3] established the earliest model of liquid impingement erosion process to observe the deformation of the solid target material in the initial stage of damage. He proposed that at the moment of initial impingement, a stress wave generated immediately traveled back from solid–liquid contact into liquid and the liquid exhibited compressible behavior. Cook et al. [4] further suggested that high pressure occurred in liquid impingement erosion and expressed the impact pressure as a function of the density of the liquid, the compressibility of the liquid and the impact velocity of liquid droplet. Engel [5] then modified the pressure equation with the impact of spherical drop and consideration of the elastic deformation of the liquid drop. Lee et al. [6] investigated the improved liquid impact erosion resistance of steam turbine blades that were made of 12Cr steel or Stellite 6B with coating of TiN film for nuclear power plant application. According to the theoretical analysis of stresses generated by liquid impact, TiN coating alleviated the impact stress of 12Cr

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steel or Stellite 6B due to stress attenuation and stress wave reactions such as reflection and transmission at the coating–substrate interface. Lesser [7] developed a computational model based on theoretical approaches, focusing on the surface motion utilizing implementing geometric shock dynamics and guided acoustic shock theory. This model can imitate the material properties, geometrical attributes of the solid target. Later on three-dimensional dynamic finite element analysis and computational fluids dynamics computational models were developed by Adler and Mihora [8] onto a target solid with chosen material properties. They proposed an erosion model based on the frame work of calculating the erosion rate to predict the impact damages, such as crack nucleation, fracture surface intersections, growth of erosion pits, and so on. In order to predict the response of a material in liquid impingement erosion, scientists attempted to find the relationships between erosion resistance and mechanical properties of materials such as hardness, tensile strength, fracture toughness and strain energy. The measurements of erosion resistance of materials can fall into the main aspects such as maximum rate of weight loss, mean depth of penetration, rationalized erosion rate and maximum depth of erosion rate (Max DER).

In this research, the liquid impingement erosion behavior of NiAl alloy was investigated using the analytical models of impact stress wave, mean depth of penetration, and Max DER. The liquid impingement erosion resistance of this alloy was characterized by establishing the relationships between target thickness and drop size (diameter), between rate of mean depth of penetration (MDRP) and drop impact velocity, and between damage threshold velocity (DTV) and drop size. These computational results would provide guiding effect on properly using NiAl alloy in liquid impingement erosion environments and would also recommend effective approach to predicting the liquid impingement erosion resistance of similar alloys.

2. Models of liquid impingement erosion

2.1. Impact stress wave

In the liquid impingement erosion theories given by Honegger [3], Cook et al. [4] and Engel [5], it was suggested that at the moment of initial impingement, a stress wave generated immediately traveled back from solid to liquid contact into liquid at a certain velocity and the liquid exhibited compressible behavior. High pressure occurred in liquid impingement erosion due to water-hammer effect and the impact pressure can be expressed as functions of liquid properties and drop normal impact velocity (V_0). Heymann [9] deemed that in consideration of droplet impacting at 90 degree on a smooth and rigid surface, the impact stress reached the maximum (peak) near the contact area, however, at the exact contact point it remained a relatively small (bottom) value due to the release of the waves that generated the pressure distribution map. This high pressure led to the occurrence of ring cracks and fractures in the area within radius r_0 in the top surface layer of the target, as schematically shown in Fig. 1.

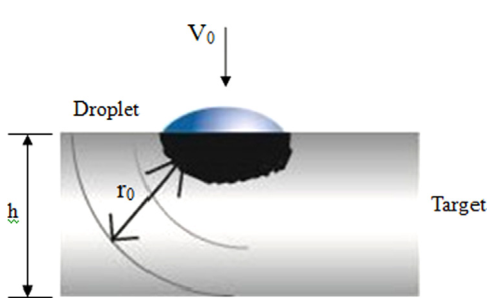

Fig. 1. Ring cracks induced in the top surface layer of the target attacked by liquid drop.

The radius r_0 is expressed as [2]

$$r_0 = \frac{2h}{[(c_d/c_R)^2 - 1]^{1/2}}, \tag{1}$$

where h is the thickness of target, see Fig. 1, c_d and c_R are the dilatational velocity and Rayleigh wave velocity, respectively. Considering the inherent elasticity of the material, the velocity of Rayleigh wave is generally thought to be equal to that of shear wave, and then can be calculated as [10]

$$c_R = \sqrt{\frac{G}{\rho}}, \tag{2}$$

where G and ρ are the shear modulus and density of target material, respectively. The occurrence of erosion damage on target surface depends on the duration of drop incidence time and the duration of the stress wave. When the former is longer than the latter, erosion damage occurs [2], i.e., $(2d/c_L) > (h/c_S)$. Therefore, to avoid erosion damage, the minimum target thickness can be determined by

$$h = \frac{2dc_s}{c_L}, \tag{3}$$

where d is the size (diameter) of liquid drop, c_L and c_S are sound speeds of liquid and solid, respectively, can be calculated by [11,12]

$$c_L = \sqrt{\frac{\kappa_0}{\rho_0}}, \tag{4}$$

$$c_S = \sqrt{\frac{E}{\rho}}, \tag{5}$$

where κ_0 is the bulk modulus of liquid drop and E is the Young's modulus of solid target; ρ_0 and ρ are the densities of liquid drop and solid target, respectively. From Eq. (3) it is evident that for a given target material the minimum thickness h for preventing erosion damage from occurring is solely proportional to the drop size for erosion damage occurring.

2.2. Mean depth of penetration

When a liquid droplet having a diameter d impacts a solid surface at an inclined angle θ with a velocity V, as illustrated in Fig. 2, Hoff et al. [13] described the rate of mean depth of penetration (MDRP), as shown in Fig. 3, by the following equations,

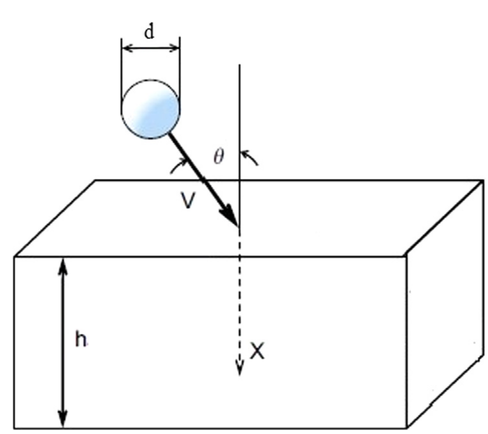

Fig. 2. Incoming liquid drop on solid surface at an incident angle θ.