

Nonlinear Kinetic Modeling of Sliding Wear Evolution in Vanadium Microalloyed Hadfield Steel

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Abstract

In this study, the effect of vanadium addition on the sliding wear behavior of austenitic high-manganese (Hadfield) steel was experimentally investigated and a nonlinear kinetic wear model was proposed. Pin-on-disk wear tests were conducted according to ASTM G99 under constant load and sliding conditions for three compositions: base steel (0 wt.% V), 0.6 wt.% V, and 0.9 wt.% V. The results showed that vanadium addition significantly improved wear resistance, with the 0.6 wt.% V alloy exhibiting the lowest wear rate. Further increase to 0.9 wt.% V did not produce a considerable improvement, indicating an optimum vanadium content. Experimental observations revealed a nonlinear decrease in wear rate with increasing sliding distance, which could not be fully described by the classical Archard model. Therefore, a nonlinear kinetic model was developed to describe the transition from the initial running-in stage to steady-state wear. Model parameters were extracted from experimental data and showed good agreement with measured results (high R^2 values). The transition parameter reflected the evolution of wear mechanisms and the stabilization of surface conditions during sliding. Compared with the Archard model, the proposed model provided a more accurate prediction of wear behavior, especially in the later stages of sliding. The results demonstrate that vanadium improves both the initial and steady-state wear performance of Hadfield steel and that the proposed nonlinear kinetic model can effectively describe the wear evolution of vanadium-alloyed high-manganese steels.

Keywords: Wear, Hadfield steel, Vanadium, Sliding wear, Nonlinear model, Archard law, Wear kinetics

1. Introduction

Wear is one of the major degradation mechanisms in engineering components operating under sliding and abrasive conditions, particularly in mining and material-handling systems where severe contact stresses are present [1]. Austenitic high-manganese (Hadfield) steels are widely used in such environments due to their excellent toughness and strong strain-hardening capability; however, their wear resistance strongly depends on microstructure evolution, hardness, and contact conditions during sliding [2].

Microalloying with carbide-forming elements such as chromium, molybdenum, and vanadium has been widely explored to improve the wear performance of high-manganese steels. Among these elements, vanadium promotes the formation of fine V-rich carbides, enhances hardness, and improves resistance to plastic deformation and material removal during sliding wear [3]. Recent studies also indicate that the effect of alloying elements on wear resistance is often nonlinear and may exhibit an optimum composition depending on microstructural stability and deformation behavior [3,4].

The classical Archard wear law is commonly used to describe sliding wear; however, its assumption of a constant wear coefficient limits its ability to capture the nonlinear evolution of wear observed in high-manganese steels [5]. Experimental studies show that wear rate typically decreases from an initial running-in stage toward a steady-state regime due to work hardening, surface stabilization, and tribolayer formation, highlighting the importance of nonlinear wear modeling [4,6].

Therefore, the aim of this study is to investigate the effect of vanadium addition on the sliding wear behavior of Hadfield steel and to develop a nonlinear kinetic wear model capable of describing the evolution of wear rate with sliding distance. The novelty of this work lies in the development of a nonlinear model that quantitatively captures the transition from the running-in stage to steady-state wear based on experimental data. The proposed model is evaluated and compared with the classical Archard approach.