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How common is the steady-state? The implications of wear transitions for materials selection and design

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ABSTRACT

Like other forms of mechanical damage, wear may progress in stages, the length and severity of which depend upon the type of wear and the nature of the tribosystem. Wear rates, wear coefficients, and wear factors are commonly reported as normalized quantities whose units imply a linear relationship with variables such as sliding distance, number of repetitive cycles, elapsed time, and normal force. Unfortunately, such implied linearity can be misleading in design-specific material selection. Examples of non-linear wear characteristics are provided for erosive wear, abrasive wear, fretting wear, and non-abrasive (also known as 'adhesive') wear. The differences between a system-specific, linearized wear rate and the instantaneous wear rate will be discussed, as will the difference between sequential and simultaneous wear transitions. The practice of linear normalization ignores such phenomena as incubation periods, running-in, and post-steady-state transitions, leading to misleading dependencies of wear rates on the sliding distance and sampling interval. Some current ASTM testing standards, notably those on erosion testing, account for the non-linear behavior of wear, but others, such as tests for sliding wear, usually do not. This article discusses non-linear wear behavior of several kinds, how the data can be treated, how wear rate notation can be improved, and how recognizing certain non-steady-state behavior can improve the basic understanding, modeling, and testing of wear.

1. Introduction

The standard definition of 'wear' [1] describes it as the progressive loss or displacement of material as a result of relative motion between surfaces or a surface and another substance; however, that definition does not require that the loss or displacement take place at a constant rate. In fact, there are frequent situations, both in machines and in laboratory experiments, in which the rate of wear changes with time, number of cycles, or sliding distance. For the purposes of this discussion, there are two types of wear transitions: (1) induced transitions, in which the operator or external disturbances to the tribosystem change its operating conditions (e.g., load, speed, acceleration, environment) and (2) natural transitions, in which the materials or tribosystem change without external stimulus. Type 1 transitions can also be induced by external changes in temperature, ingested debris, or vibrations from another piece of equipment that has been turned on. Tribo-corrosion from the surrounding environment can also induce transitions in wear. Examples of Type 2, natural transitions, include running-in, loss of an initial protective film, wear-through of a protective coating, and thermally-induced transitions from the build-up of frictional heat [2]. A common example of a natural transition is scuffing in which gradual loss or degradation of a lubricant leads to solid contact, increased friction, and the onset of wear.

This article addresses Type 2, non-induced transitions. These have significant implications for the calculation of wear rates and the prediction of wear lives. The details of how and why such wear transitions occur is a subject of continuing relevance in tribotesting and material selection. Designers and material developers too often rely on a tabulated wear rates or wear coefficients obtained in tests that do not adequately simulate field conditions in which more than one steady-state wear rate can exist. The discussion that follows will show how wear rates can be annotated, modeled, or limited to specific operating ranges and thus improve their utility.

Most forms of wear can exhibit transitions. They include erosion and abrasion as well as impact wear and rolling contact. In his 1980 handbook article on design considerations related to sliding wear Peterson [3] described a number of non-linear effects of variables such as load and sliding velocity, and time. Mechanistically, the 'wear history' of a tribosystem can behave analogously to the progression of mechanical damage such as fatigue in which a sequence of crack initiation, crack propagation, and failure occurs [4,5]. Also analogous to fatigue, wear rates tend to exhibit statistical behavior, making it advisable to avoid making broad conclusions based on only one or two experiments performed

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Table 1
Comparison of the metrics for reporting wear in two International Wear of Materials (WoM) Conferences (Source: [6,7]).

Form of wear	Unit dimensions	Units of measure (WoM 1987)	Units of measure[a] (WoM 2013)
Abrasive (2, 3 body)	Mass loss	g	g^{-1} (wear resistance) mg
	Scar dimensions	length, mm	depth, nm
			depth, μm
	Volume loss	mm^3	μm^3 [3]
	Combinations of units	cm^3/kg	mm^3/N-m
		mg/N-m	N-m/mm^3 (wear resist.)
		mm^3/m	m^3/m
		mm^3/min	“degree of wear” considers
		mm^3/N-m	displaced versus
		N-m/mm^3 (wear resist.)	removed material in a groove m^2/N
			(reduced from m^3/N-m)
	Non-dimensional combinations	relative to a ref. mat'l.	
		Archard wear coeff. K	
		Product of: (mass[a]density[a]sliding	
		distance[a] contact area) or its inverse	
Cavitation	Mass loss	N/R[b]	mg [3] g
	Mass loss/time	N/R	mg/h
Erosive wear	Mass loss	g	g [3]
		mg	mg [3]
	Mass loss/mass of erodant	g/g	g/g
		mg/g	mg/Kg
	Volume loss	mm^3	mm^3
		cm^3	
	Volume/unit erodant	mm^3/g	mm^3/g
		cm^3/g	g/mm^3 (resistance)
		m^3/g	
	Dimensional change	depth, μm	depth, μm
	Loss/time	g/h	mg/h
		g/m-h	mm^3/s
		mm^3/h	s/mm^3 (resistance)
	Relative loss	relative to a reference material	mass loss normalized to total mass loss
			(% of final wear amount)
Fretting wear	Depth	N/R	mm
			μm
			μm (crack depth)
	Mass loss	N/R	mg
	Volume loss	N/R	μm^3
			mm^3
			m^3 (both test specimens)
	Combined units	N/R	μm^3/N-m
			μm^3/N-μm
			mm^3/N-m
			mm^3/mm
	Other measures of wear	N/R	electric contact resistance normalized pitting
			severity ($_{max}$. depth of pits on both specimens)
Impact wear	Depth	N/R	μm
	Volume loss	N/R	mm^3
Impact with abrasion	Mass loss	N/R	g
	Depth	N/R	μm
	Volume/unit abradant	N/R	mg/Kg
Scuffing	Critical condition	N/R	N (critical load)
			N-m (load and sliding distance for friction
			coeff. to exceed 0.2)
Sliding wear	Mass loss	μg	mg [3]
		mg	% mass loss
		g	
	Volume loss	μm^3	μm^3
		mm^3	mm^3 [12]
	Depth	μm	μm
		mm	mm
			nm
			pin displacement, mm
	Surface roughness due to wear	N/R	μm
			nm
	Loss/distance	g/m	g/m
		mg/cm	mg/m
		mg/m	mm^3/mm
		μg/m	μm^3/mm [2]
		mm^3/cm	mm^3/m [2]
		mm^3/mm	
	Loss/cycle (revolution)	cm^3/kcyc	mm3/cyc [2]
		μg/revolution	
	Loss/time	μm/min	μm/h
		μm/h	
		mm/s	