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On the role of intrinsic material response in failure of tribo systems

Hisham A. Abdel-Aal*

Department of General Engineering, University of Wisconsin-Platteville, 1 University Plaza, Platteville, 53818-3099 WI, USA

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Abstract

This paper studies the intrinsic material response (IMR), to energy accumulation in sliding. The underlaying hypotheses is that any material has an intrinsic limit that bounds the rate of dissipation of externally applied energy (work/thermal flux). Whenever, the rate of application of external energy is less than that of the intrinsic dissipation rate, a material catastrophic event may be avoided and vice versa. It is shown that while wear may be correlated to the structures developed in compression of a given material, the structures are correlated to the response of the material to the interaction between thermal conduction and thermal storage. This parameter in turn is influenced by the combination of strain rates and rate of entropy generation. When such analysis is applied to the sliding of pure copper, wear is found to be correlated to two parameters: the thermo-mechanical coupling factor whereas, the second represents the rate of mechanical strains to thermal strains.

Keywords: Thermodynamics of wear-sliding of copper-strain rate effects thermo-mechanical coupling in sliding; Entropy generation in wear

1. Introduction

Sliding of materials entail energy dissipation that is subject to thermodynamic limitations. These represent the amount and rate of entropy production in a sliding solid. Attempts to study the thermodynamic links between wear and entropy generation scarcely surface in tribology literature. Klamecki [1–4] developed a non-linear model of the thermodynamic behavior of a sliding system that is based on entropy production, for near-equilibrium conditions, and on conservation of energy, for far-from-equilibrium conditions. The model predicts the possibility of cyclic energy dissipation in sliding bodies. However, application of the model to practical systems was hindered by the lack of material characterization within a thermodynamic frame. As such, a direct link between wear and entropy generation and thermal energy dissipation was not explored.

Biswas and co-workers [5–7] demonstrated that, at least, for metals in specific regimes of strain rate and temperature, material response is unique to initial micro-structure. This offered the possibility of explaining structural instabilities based on thermodynamics reasoning. Consequent work, [8–14] investigated the behaviour of a number of metals (titanium, copper, and cadmium) within the framework of strain rate response, and questioned the view that wear is inversely related to hardness. The results promoted the fundamental idea that wear of metals is a consequence of stable–unstable material response that is triggered by the strain rate and temperature states. These works did not, however, offer a direct correlation between energy transfer in sliding and the evolution of structural deformation.

An attempt to formulate a parametric relation between the strain rate and the change in thermal energy flow in a sliding material [15–20], correlated the change in energy flow, which is equivalent to the change in entropy per unit temperature rise, to the transition in wear regimes for several materials. Explicit correlation between wear rate in lubricated contacts and the flow of entropy was experimentally verified by Ling and co-workers [21,22]. However, the question of how wear is related to micro-structure evolution,

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Abbreviations: HDC, heat dissipation (diffusion) capacity; MAZ, mechanically affected zone; NCS, nominal contact surface; ARRH, actual ratio of residual heat; RRH, ratio of residual heat; SWR, specific wear rate

* Tel.: +1 608 342155; fax: +1 608 3421566.
E-mail address: haabdela@excite.com.

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Nomenclature

A	is the surface area
B	thermal effusivity ($\mathrm{W\,m^2\,K^{-1}\,S^{1/2}}$)
C_v	specific heat at constant volume ($\mathrm{kJ\,kg^{-1}\,K^{-1}}$)
C_k	specific heat measuring isothermal volumetric change ($\mathrm{W\,m^{-1}\,K^{-1}}$)
C_p	specific heat at constant pressure ($\mathrm{J\,m^{-3}\,K}$)
D	thermal diffusivity ($\mathrm{m^2\,S^{-1}\,GPa}$)
H	hardness expressed as pressure (GPa)
K	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
K^*	apparent (effective) thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
K_b	bulk modulus (GPa)
K_m	mechanical dilatation contribution to thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
K_ε	coefficient of thermal expansion ($\mathrm{m\,m^{-1}\,K^{-1}}$)
K_σ	coefficient of thermal expansion in stress ($\mathrm{J\,m^{-3}\,K}$)
Q_a	actual amount of heat conducted through a contact spot ($\mathrm{W\,m^{-2}}$)
Q_gen	heat generated due to friction ($\mathrm{W\,m^{-2}}$)
Q_w	heat generated due to wear particle shedding
T	temperature (K)
T^0	rate of temperature rise of the surface ($\mathrm{K\,S^{-1}}$)
V_slid	sliding speed ($\mathrm{m\,S^{-1}\,m^3}$)

Greek symbols

β	temperature coefficient of conductivity ($\mathrm{K^{-1}}$)
δ	temperature coefficient of diffusivity ($\mathrm{K^{-1}}$)
η	thermo-mechanical coupling factor
μ	coefficient of friction

and the energetic of that relation was not addressed by the authors.

A major obstacle in understanding the thermodynamics of wear, is that the analysis of tribology problems is based on separating the mechanical from the thermal states. In sliding, however, thermal and mechanical states are coupled. This situation is mathematically described by the so-called Jeffrey's heat equation (JHE) [23], which despite being complex offers an in-depth perspective of the interaction between thermal and mechanical influences in a strained sliding solid. The JHE defines an "apparent thermal conductivity", which physically represents the effect of the mechanical strain on the flow of thermal energy in the solid. The correlation of that parameter to wear transition of titanium within a thermal transport frame was explored in [24], and was linked to protective layer formation in steels [20]. It was postulated that wear may occur as a response to the accumulation of energy within the surface or subsurface contacting layers. A natural progression of that idea is to explore possible paths to failure given thermodynamical constraints. That is, if entropy generation is related to wear, and wear, in turn, is related to the evolution of micro-structures, so, would the evolution of micro-structures be linked to entropy generation? and to energy path blockage? If so, is wear, also, a manifestation of entropy generation?

This work attempts to answer such questions. It is shown that energy accumulation is triggered by the influence of strain rate on thermal conduction. This accumulation is correlated to the evolution of the micro-structure of the material especially at a sublayer that acts as an incubator for wear particles. Wear rate is found to be correlated to the variation of two factors within this sublayer: the thermo-mechanical coupling factor, and the rate of mechanical strain to the rate of subsurface heating.

2. System modeling

Consider an open system, Fig. 1, that represents the mechanically affected zone (MAZ) in a sliding metal. This system is subject to a thermal load, representing the work of the friction force,

$$Q_\mathrm{gen} = \mu V_\mathrm{slid}\ H(T) \tag{1}$$

The energy leaving the system has two contributions: the first arises because of heat conduction and is given by:

$$Q_\mathrm{cond} = (\nabla(K_i(T)T_i)A \tag{2}$$

The second component, however, arises from the thermal energy leaving the system because of wear particle shedding. This is given by:

$$Q_\mathrm{w} = m_\mathrm{w} C_\mathrm{p} \Delta T \tag{3}$$

Now balancing the energy passing through the system we may write:

$$Q_\mathrm{net} = Q_\mathrm{gen} - Q_\mathrm{cond} - Q_\mathrm{w} \tag{4}$$

Abdel-Aal [19] have shown that the first two terms in the left hand side of Eq. (9) ($Q_\mathrm{gen} - Q_\mathrm{cond}$), is equivalent to:

$$Q_\mathrm{gen} - Q_\mathrm{cond} = \frac{B^*}{\sqrt{t_c}} \tag{5}$$

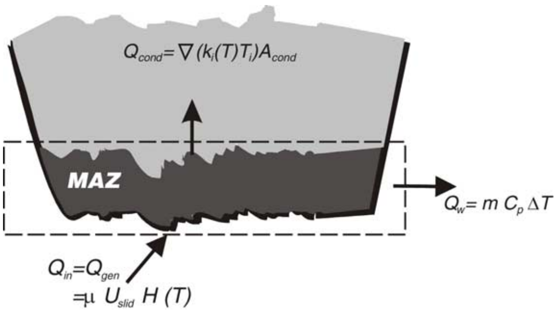

Fig. 1. System model for the mechanically affected zone in a sliding metal.