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A CONSIDERATION OF THERMODYNAMIC ASPECTS OF WEAR: ENERGY AND ENTROPY

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To establish a thermodynamic basis for degradation, a hypothesis was made on the potential correlation between entropy and degradation for wear of machinery components. This paper reports an experimental study of wear of model machinery component pairs, on an accelerated testing basis. Measured were wear, friction, temperatures, and entropy flow. Results show a strong correlation between the referenced wear and the production of entropy flow. The hypothesis linking wear to entropy led to formulations consistent with the Archard/Holm wear law.

Keywords : Wear, Entropy, Thermodynamics, Degradation, Energy

1. INTRODUCTION

Manufacture, which transforms nature's raw materials into highly organized finished components, reduces entropy and increases thermodynamic energies of worked materials. Aging or degradation, which tends to return these components' materials back to natural states, must increase entropy and reduce thermodynamic energies, to be consistent with the second and third laws of thermodynamics. This recognition led to creation of a Thermodynamic Degradation Paradigm, wherein experimentally it was shown that degradation in the form of wear correlated with entropy flow [1] produced by accompanying irreversible processes occurring at the wearing surface. In effect, entropy or thermodynamic energies can function as an aging "time base," and energetics of the irreversible processes that drive degradation can be incorporated into predictive formulations involving entropy or thermodynamic energies.

Thermodynamic energy and entropy can predict the direction and reaction rate of chemical processes, heat and energy transfer, and the efficiency of engines, among other phenomena. Machine component degradation involves physical effects similar to these processes, i.e., degradation is also a thermodynamically driven process. A natural question is, can entropy predict the direction and rate of degradation processes in machinery components?

Recent work [1-3] concerned thermodynamic treatment of degradation. Reference [3] discussed thermodynamic reliability engineering and derived "key physics-of-failure time-compression equations stemming from Minor's hypothesis, the Coffin-Manson power law, Peck's humidity model, and diffusion methods." References [1,2] studied correlation between wear and entropy flow in machinery components and showed normalized wear a function of normalized entropy flow. This paper reviews these concepts.

2. APPARATUS AND PROCEDURE

In Fig. 1, a copper rider (E) slides against a steel slider surface (D), under carefully maintained boundary lubricated conditions. Arm (B), free to rotate in the horizontal plane, allows friction force to be measured. Also, (C) is a magnetic tachometer; (F) is a simple calorimeter with the rider component as an integral part; (G) is a pipe fitting where lubricant, which wets the interface of the component-pair, can be drawn for ferrographic analysis; (H) is the probe of a photonic sensor which measures the surface recession of the rider. Oil is circulated by a peristaltic pump. A DC motor drives the rotating shaft on which the slider is mounted. Not shown is a built-in transducer, which restrains the arm (B) from moving and measures the friction force. The cylindrical end of the rider component is encased in a cylindrical insulator (F). The cylindrical end of the rider and the insulator form the basic part of a simple calorimeter. To complete the calorimeter function, very fine iron-constantine thermocouples were inserted into drilled holes to the center of the rider to allow three temperatures along the insulated length to be measured.

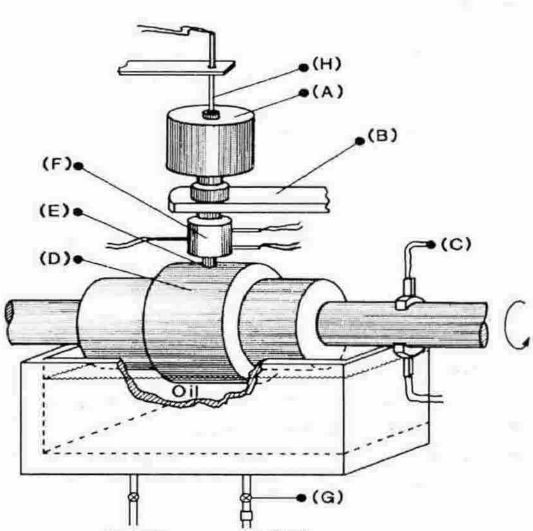

Fig. 1 Slider test apparatus.

To accelerate testing, a 9.1 kg dead weight (A) pressed bodies together. The 1,000 rpm rotational speed corresponded to a 3.3 ms^{-1} surface speed. During runs, the surface temperature reached steady state within an hour. The surface temperature (bottom thermocouple at F), surface recession due to wear (photonic gap displacement sensor H), and entropy flow (insulated rider with thermocouples, at F) were carefully measured vs. time. Entropy flow was calculated from measured temperatures via $S_n = \sum^{n} \frac{\Delta Q^{(n)}}{T^{(n)}}$ where $\Delta Q^{(n)}$ is the increment of heat to the rider during the n^{th} time interval, and $T^{(n)}$ is the average absolute surface temperature. The entropy flow originates from irreversible processes caused by rubbing–-plastic work in asperities and subsurface layers, fracture, etc–-occurring in a very thin, constantly wearing layer on the rider's surface. After obtaining thermal steady state, an initial five-minute run smoothed out and equilibrated the specimen.

3. RESULTS

Temperatures, surface recession due to wear, and entropy flow were measured (as previously described) and plotted versus time [1, 2] for a series of six tests. Data for each test consisted of 13 readings at five-minute intervals. Maximum error of measurements and calculations was 2.5%. From the aforementioned data, ordered pairs of wear and entropy flow (at identical times) were constructed. Plotted in Fig. 2 are normalized wear vs. normalized entropy, where values of wear and entropy flow were normalized by the maximum wear and entropy flow value measured for each test. Different symbols denote data points from the six different test runs.

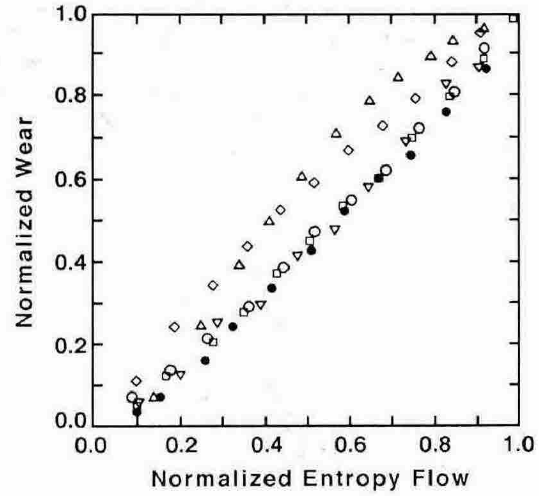

Fig. 2 Normalized wear vs. normalized entropy.

4. DISCUSSION

Fig. 2 shows Normalized Wear approximately equal to Normalized Entropy Flow, to first order. The correlation links the irreversible degradation by wear to the production of irreversible entropy flow. We believe this to be a general principle of machinery component wear: irreversible degradation is always accompanied by concomitant production of irreversible entropy.

We recall the Archard/Holm Wear Law [4, 5]

$$w = kLx/H \tag{1a}$$

where w is the volume lost by wear, k is a dimensionless wear coefficient, H is hardness pressure, L is normal load, and x is distance slid. Upon differentiating Eq. (1a) and introducing friction coefficient $\mu = f/L$, where f is friction force,

$$dw/dt = kP/\mu H.. \tag{1b}$$

Here power

$$P = \mu L(dx/dt) \tag{2}$$

dissipated by friction as heat generates irreversible entropy at rate $P/T = dS/dt$, giving

$$dw/dt = kT/\mu H \; dS/dt \tag{3}$$

via Eq. (1b). We now assume wear

$$w = F_w(S) \tag{4}$$

depends upon entropy S, the *degradation base.*. Differentiating Eq. (4) gives $dw/dt = (dF_w/dS)(dS/dt)$. Comparing this result to Eq. (3) gives

$$k = \frac{dF_W}{dS}\frac{\mu H}{T}. \tag{5}$$

The slope of our Fig. 2 data estimates dF_w/dS: Concomitant measured values for μ and T, and handbook values for H, when inserted into Eq. (5) yielded $k=1.2x10^{-4}$, $k=8.6x10^{-5}$, $k=10^{-4}$, $k=10^{-4}$, with average $k=1.01x10^{-4}$. This compares within 1% to values measured by Rabinowicz [6] for compatible metals under poor lubrication, i.e., 10^{-4}.

Where Archard's Wear Law, Eq. (1a) requires measured normal force L, wear volume w, and distance slid x, to obtain k, our thermodynamic based formulation measured w, friction μ, and temperatures. We consider Archard/Holm's Wear Law to be subsumed in Eq. (4). Also, wear formulations based on Eq. (4) can be made consistent with laws of thermodynamics, and the energetics of sliding, e.g., Eq. (2).

4. CONCLUSIONS

We found a strong correlation between degradation by wear and entropy flow, derived a wear law from this, and showed this law consistent with Archard/Holm's wear law, Eq. (1a).

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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