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Effect of Entropy Generation on Wear Mechanics and System Reliability

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Abstract. Wear is an irreversible phenomenon. Processes such as mutual sliding and rolling between materials involve entropy generation. These processes are monotonic with respect to time. The concept of entropy generation is further quantified using *Degradation Entropy Generation theorem* formulated by Michael D. Bryant. The sliding-wear model can be extrapolated to different instances in order to further provide a potential analysis of machine prognostics as well as system and process reliability for various processes besides even mere mechanical processes. In other words, using the concept of 'entropy generation' and wear, one can quantify the reliability of a system with respect to time using a thermodynamic variable, which is the basis of this paper. Thus in the present investigation, a unique attempt has been made to establish correlation between entropy-wear-reliability which can be useful technique in preventive maintenance.

1. Introduction

Quality control methods over many years have been statistical in nature with reliability prediction models of systems being distribution based. Estimation and analysis of system failures has always been a primary concern in design of systems and risk assessment [1]. Previously, a hypothesized distribution with a constant failure rate that entailed an exponential distribution of the object's lifetime would not be sufficient for today's dynamic and complex systems as shown by Zhang et. al [1]. The authors used the time – varying failure rate Weibull model instead of the constant failure rate model, that could understate system reliability in some cases, and overstate it for others [1].

However, as the complexity of the systems dealt with by mankind continues to increase with each decade, it becomes imperative to design reliability models that become even more accurate with time, to the extent of even simulating instantaneous system reliability models in order to predict the critical failure period of the system. On the microscopic level, a small crack in a bridge structure would not seem to be a cause for any problem, however, factors such as thermal, cyclic stresses and material ageing would be detrimental in converting a small- sized crack to a large-scale failure that would cause financial losses and most importantly, human lives. In systems such as rockets, even a one- time failure would result in massive losses.

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A more cumbersome yet a newer and accurate prediction of system reliability lies in the fact that the irreversibilities that every system is subject to cause it to age with time, irrespective of the system.

For example, a cutting tool flank wearing out with time or a shoe sole wearing out with friction due to walking obey the same universal basic principle: dissipative processes that 'age' or 'degrade' the system, in this case being friction, cause a loss of reliability in function and sustenance with respect to time. Therefore, it becomes an inherent assumption that system reliability is an inverse consequence of an increase with the wear of the system.

Looking at the models of wear that have been postulated so far, a common and popular wear principle was put forth by Archard in the form of his famous sliding wear equation for frictional wear:

$$w = \frac{kLx}{H} \tag{1}$$

Here k is a wear coefficient(dimensionless), H the hardness pressure, L the normal load, and x the distance undergone during the sliding process.

However, the assumption of wear as a fundamental variable in reliability prediction poses problems. Archard's wear law takes care of friction wear across sliding surfaces and governs purely *physical* wear. However, for different tribological instances that cause wear in different forms such as oxidation, chemical reactions, abrasion or simple ageing, the fundamental equations governing wear differ, and the concept of 'wear' becomes more abstract. It hence becomes imperative to come to a more characteristic fundamental variable than wear.

It is a known fact that all dissipative processes are a consequence of irreversible thermodynamics, *independent of the nature of the dissipative process*. In other words, the fundamental variable governing wear trends and hence reliability over time is nothing, but the irreversible entropy generated due to dissipative processes involved in ageing that causes the system's *departure from equilibrium*.

Considering the fact that every system tries to attain equilibrium, wear occurs as a *response* to equilibrium departure in order to keep pace with the *rate* of departure from equilibrium by trying to re – establish entropic equilibrium at the expense of mass or physical property loss. This wear is what causes exactly the observable loss of function of the system by decreasing its reliability.

According to the Second Law of Thermodynamics:

$$dS = dS' + dSe \tag{2}$$

where Se is entropy associated with heat flow, S' is entropy generated, and S is system entropy.

For a reversible process, the entropy generation is zero. However, for an irreversible process, entropy generation is mandatorily greater than zero.

Michael D. Bryant proposed that all wear processes are a function of entropy generated that arise due to dissipative functions [2]. In other words:

$$dw \propto dS \tag{3}$$

Entropy flow due to heat can be neglected in most practical purposes for steady state sliding or steady state processes. Besides this assumption, non-equilibrium thermodynamics has a greater role to play in irreversibility of the wear mechanism[4]. Therefore, the equation now changes to:

$$dw \propto dS' \tag{4}$$

Previous literature on entropic- based damage approach to reliability and integrity characterization has been put forward by Anahita et. al [4] wherein reliability assessment of aluminium 7075-T651 samples was done through tensile testing, one sample subject to corrosion fatigue in a corrosive 3.5% wt. NaCl solution, while the other not being subject to any dissipative function [4]. It was found that the sample subject to corrosion had a lower ultimate tensile strength due to its closer proximity to the *entropic endurance limit* as compared to the sample not subject to dissipative functions.

The problem hence reduces to finding the entropy generation due to each dissipative process and summing them discretely to obtain the total entropy generated over the combined set of processes. This is offered by the *Degradation Entropy Generation theorem* proposed by Bryant in the third section. After obtaining all the generated 'entropic' sources that contribute to 'noise' in the system, we put forward a model in the form of our 'Reliability- Entropy' hypothesis that gives a thermodynamic correlation to our reliability – computation model, that seeks to incorporate aberrations in distribution – based models followed by its use in the fundamental concept of sliding wear in this paper to illustrate our concept.

We first use the DEG theorem proposed by Bryant to find the total entropy generated and the wear, and then proceed to find the reliability variation of the system with time via our proposed Reliability – Entropy hypothesis.

2. Quantifying Entropy Generation due to Dissipative Processes

Michael D. Bryant listed the entropy generated due to various processes that occur on tribological interfaces. These are primarily the various processes that take place during generalized wear. [2]

2.1. Dissipative Processes

- Adhesion of surfaces and films due to adhesive wear and adhesive friction [2]:

$$dS' = \left(\frac{\gamma}{T_m}\right) \times dA \tag{5}$$

γ is the work/unit area to create new surface area dA and T_m is the mean temperature of the medium.

- Plastic deformation due to friction, given by [2]:

$$dS' = \left(\frac{U}{T_m}\right) \times dV \tag{6}$$

U is work due to plastic deformation/cutting expended per unit volume dV and T_m is the mean temperature of the affected media.

- Fracture due to mechanical processes, commonly associated with fatigue [2]:

$$dS' = \frac{(G-2\gamma)}{T_{cr}} \times dV \tag{7}$$

where a is crack length, $G = -dU/da$ is the energy release rate dependent on strain energy U, γ is surface energy and T_{cr} is the temperature at the cracked material tip.

- Phase change associated with surface melting/ re- crystallization, given by [2]:

$$dS' = \frac{dH}{T_{Phase}} \tag{8}$$

where dH is the latent heat absorbed or shed, and T_{phase} is the temperature associated with the phase change process.

- Chemical reactions, associated with chemical and oxidation wear with entropy change [2]:

$$dS' = (\frac{\breve{A}}{T})d\zeta \tag{9}$$

where $\breve{A}$ is chemical affinity and ζ is extent of reaction.

- Diffusion, associated with gradient induced migration of material, with entropy change similar to that of chemical reactions [2].

- Mixing wherein mixing of material between surfaces takes place with molar entropy change

$$dS' = -R\Sigma(\frac{Ni}{N}) \times ln\,(\frac{Ni}{N}) \tag{10}$$

Ni denotes molar masses of n species and *Ni/N* denote molar fractions [2].

- Heat transfer (entropy flow) associated with diffusion of heat dQ from region of higher temperature T_h to lower temperature T_l, with entropy change [2]:

$$dS' = (\frac{1}{T_l} - \frac{1}{T_h}) \times dQ \tag{11}$$

3. Degradation-Entropy Generation Theorem

Manufacturing converts raw materials into organized finished components. Ageing and deterioration, or wear of these components while subjected to dissipative processes irreversibly changes the composition of the material [5] by increasing the entropy generation with time.

The outcome of the understanding resulted in the Degradation Entropy Generation (DEG) Theorem put forward by Michael D. Bryant "wherein the rate of degradation was related to the irreversible entropies produced by the underlying dissipative physical processes that age and degrade components. The DEG Theorem leads to a differential equation in a variable that describes the degradation. The equation depends on the operational and environmental variables that characterize the system. Integration of the equation accumulates the degradation over time." [2]

$$\frac{dS'}{dt} = \sum_{i,j}\left(\frac{dS'}{d\rho i}\frac{d\rho}{\mathrm{d}\zeta}\right)\frac{\mathrm{d}\zeta}{\mathrm{dt}} = \sum\frac{dS'}{dt} \tag{12}$$

$$\frac{dw}{dt}=\sum_{i,j}\left(\frac{dw}{d\rho}\frac{d\rho}{\mathrm{d}\zeta}\right)\frac{\mathrm{d}\zeta}{\mathrm{dt}} \tag{13}$$

$$=\sum_{i,j}\frac{\left(\frac{dw}{d\rho}\frac{d\rho}{\mathrm{d}S'}\right)\left(\frac{\frac{dS'}{d\rho}d\rho}{\mathrm{d}\zeta}\right)\mathrm{d}\zeta}{\mathrm{dt}}=\sum B\frac{dS'}{dt} \tag{14}$$

Where $Bi = dw/ds$ for the ith process.

Bryant showed through the equation that the rate of degradation can be expressed as a linear combination of the rates of production of irreversible entropy by dissipative processes of a degradation mechanism. When a process dissipates power dpi/dt where pi is the energy associated with that particular process i, the irreversible entropy S' generated and the degradation w depend on process temperature Ti, generalized force ($\partial pi/\partial\zeta\, j\, i$) where $\zeta\, j\, i$ denotes the jth phenomenological variable of the ith process having m such time dependent variables and generalized velocity ($\partial\zeta\, j\, i/\partial t$) [2].

The current trend in maintenance engineering is either preventive or breakdown maintenance. On-the-job maintenance is an upcoming concept where conditions are continually monitored and problems are fixed immediately as they arise. The calculation of *damage index* is highly advantageous when the best estimated time of failure is known, so that the material can be worn to the closest safe point of usage. This sees several effective applications in virtually any industry where time, labour and profit margins are critical and in short supply.

4. Wear Time Curve and Reliability Correlation

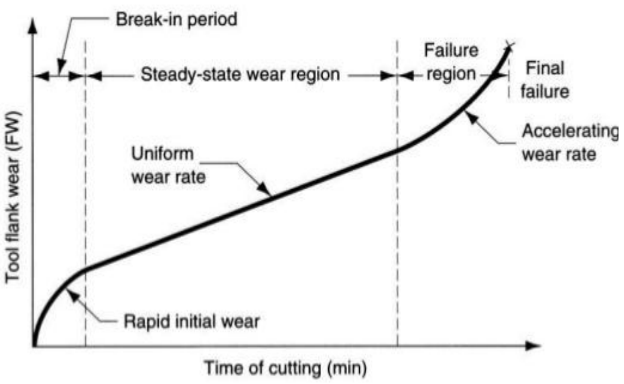

Figure 1: Tool flank wear vs Time of Cutting (min)

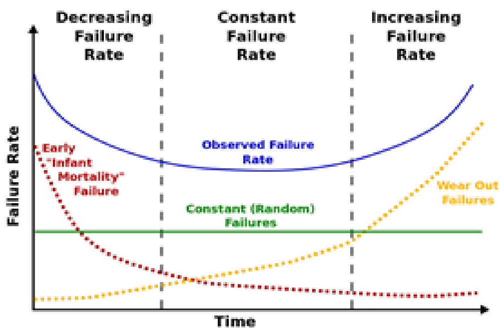

Figure 2: Failure Rate vs Time as a Bathtub curve

The above schematic depicts a turning operation. Initially, wear is rapid due to a large entropy flow due to heat. Consider the asperity contact layer of the tool to be in contact with the workpiece. Consider a control volume wherein friction between the asperity contact layer and the workpiece takes place [3]. Heat flows into the asperity contact layer, and some if it reaches the sub-surface contact layer. Initially, due to a large temperature gradient between these two layers, there is a large entropy flow due to heat. The rate of wear increase then stabilises in the middle region. This is because the entropy flow due to heat reduces upon decreasing temperature gradient with time (due to Fourier conduction between the layers) [3]. However, wear still continues to increase because of entropy generation owing to accumulation of thermal flux within the mechanically affected zone, thus making the net system entropy change higher. When there is a further increase in time, the accumulated thermal flux increases exorbitantly due to dissipative processes, leading to excessive wear due to chemical processes, diffusion, plastic deformation and oxidation.

The concept of extrapolating the general wear time curve to reliability of any system/component gives it a physical meaning by linking the decrease of reliability to 'irreversibility' and 'damage' [4] due to 'foul play' by sources that generate entropy within the system.

Our aim is to find the reliability of a component in a system at any time *t*. From the bath tub curve of quality control, it is observed that the maximum probabilities of failure of components occur at the 'infant' and 'close to lifetime' areas. However, the bath tub curve illustrates the probability of failure of a bulk number of components out of a given set; whereas the wear – time curve applies to a particular component only. Therefore, instead of looking at failure probabilities of a number of components, we scale down the failure probabilities to 'sub- failures' within one component.

The 'sub- failures' within a component could be: plastic deformation, adhesion, friction or even rupture. However, sub failures of a component have no meaning as they cannot be quantified easily. Therefore, expressing these 'sub – failures' as a ratio of the total cumulative damage *D* intuitively makes more sense.

Therefore, the local damage index[4] of a particular component at a time *t* is given by *d(t)/D,* which is initially high at infancy, low in between and once again high in value close to its lifetime.

A more useful measure is one wherein one can find out the cumulative damage that has occurred till a time *t* as a percentage of the total damage *D.* This is obtained by the following expression:

Cumulative Damage index =

$$\int \frac{d(t)dt}{D} \tag{15}$$

At *t* = lifetime (L), the cumulative damage index becomes one. This is when the component ceases to perform in any function, completely gives way or reaches its manufacturing/rated limit.

Now, correlating the observations from the general wear-time curve and bath tub curve, we have, at any time:

$$\frac{d(t)}{D} \propto \frac{dw(t)}{dt} \tag{16}$$

or:

$$\frac{d(t)}{D} = K\frac{dw(t)}{dt} \tag{17}$$

where K = 1/ *w(l)* or the reciprocal of wear at lifetime.

Reliability will be the amount of life remaining from the fraction of life that has undergone damage, or:

$$Re(t) = 1 - \int_0^T \left(\frac{d(t)}{D}\right) dt \tag{18}$$

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At time t = L, the numerator and denominator will cancel, giving the reliability as zero. We can hence write;

$$Re(t) = 1 - \frac{1}{w(l)}\int_0^T \frac{dw}{dt} \tag{19}$$

Further simplifying the expression using the Degradation Entropy Generation Theorem:

$$1 - \int_0^T \frac{d(t)}{D}dt = 1 - \frac{1}{w(l)}\int_0^T B\frac{dSdt}{dt} \tag{20}$$

where, $B = (dw/ds)$ for a particular process. This equation sums up the Reliability - Entropy hypothesis that is proposed in this paper.

5. Sliding Wear

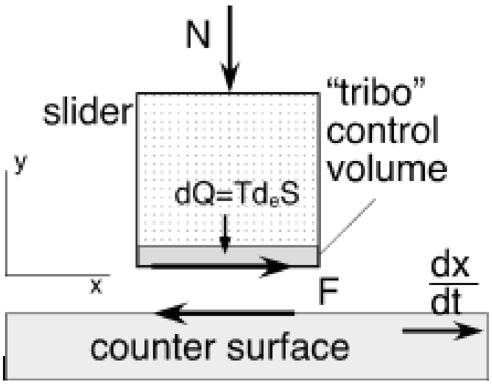


Figure 3: Slider on a counter surface[2]

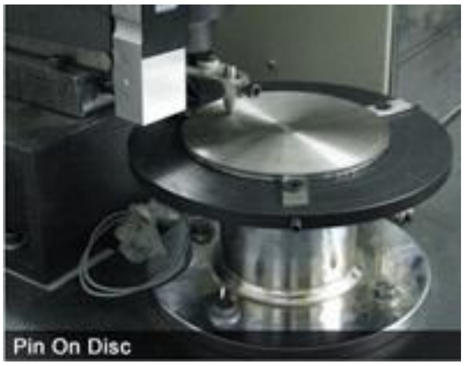


Figure 4: Pin on disc wear apparatus

In order to illustrate the Reliability- Entropy Hypothesis, a simple wear test experiment has been conducted to test the reliability of two tools made respectively of aluminium and brass. We have to validate that the more 'reliable' of these two materials, would be the best choice for use in making small gears. From this, we can infer if anodized aluminium or brass is preferred in making small gears.

According to our Reliability- Entropy Hypothesis,

$$\int \frac{d(t)dt}{D} = \int K\frac{dwdt}{dt} \tag{21}$$

Where $\frac{d(t)}{D}$ is the local damage index at time *t* and $\int \frac{d(t)dt}{D}$ is the cumulative damage index from time *t*=0 upto a point *t*=*t.* When the upper limit *t*=L, or the **entropic endurance limit** [4]**,** the cumulative damage index equals one. However, for practical purposes, lifetime is always set by a factor below the entropic endurance limit. Also:

$$\frac{dw}{dt} = B\frac{ds}{dt} \tag{22}$$

Considering steady state sliding with non-equilibrium thermodynamics,

$$\frac{dw}{dt} = \sum B \frac{dS'}{dt} \tag{23}$$

where only the irreversible component of entropy is considered.

In this experiment, the primary source of dissipative power is the frictional force, which generates the control volume entropy. From the apparatus, the entropy generated has been obtained by placing the temperature thermocouple in the specimen gripper where the heat generated by the friction gets conducted throughout the aluminium and brass bullet specimens.

Clearly, the power generated by friction is:

$$P \;= F \times v \tag{24}$$

Dividing the power by the temperature of the specimen and gripper at each point, we get the approximate entropy generated per unit time.

$$\frac{dS'}{dt} = \frac{F \times v}{T} \tag{25}$$

Now, the apparatus that we have consists of a rotary spinning disc that brings about wear on our stationary bullet samples at a wear track diameter of 70 mm.

Therefore, the velocity of sliding can be expressed as:

$$v = \frac{\pi D N}{60000} \tag{26}$$

The following data was obtained for aluminium and brass respectively (3.5 kg load, wear track dia 70mm, specimen dia 10mm, 642 rpm)

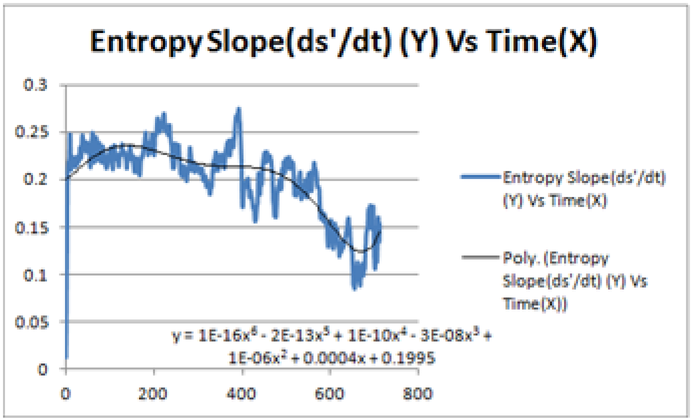


Figure 5: Entropy generation slope vs time (for aluminium specimen)

Integrating the above obtained equation with time, and substituting the ideal boundary condition at time t=0, using the assumption entropy generated= 0, we get:

$$s'(t) = \frac{t(3\times10^7t^2-7t^5+4200t^4-1575000t^3+7\times10^7t^2+10^9\times42t+41895\times10^9)}{21\times10^{13}} \tag{27}$$

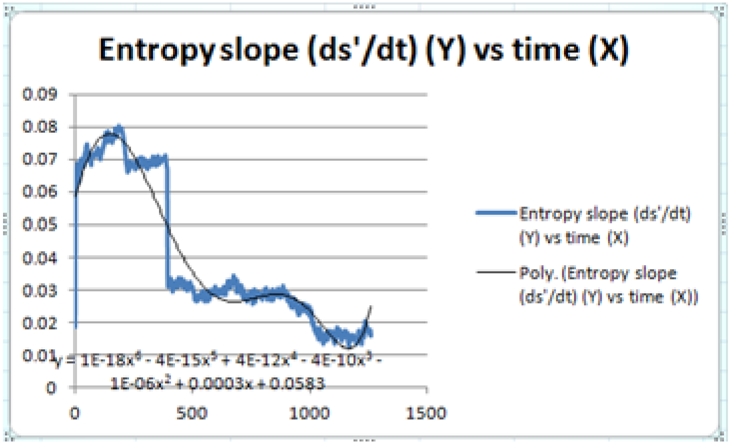


Figure 6: Entropy generation slope vs time (for brass specimen)

For the brass specimen:

$$s'(t) = \frac{\frac{t^7}{7}-\frac{2000t^6}{3}+8\times10^5t^5-10^8t^4+\frac{10^{12}t^3}{3}+15\times10^{14}t^2+583\times10^{14}t}{10^{18}} \tag{28}$$

at any time t and after substituting the same boundary conditions.

From the information provided in the two graphs and from the Degradation- Entropy Generation theorem, it would be correct to infer that aluminum has more entropy generated as compared to brass and hence more wear occurs in aluminum. The experimental results validate that as follows:

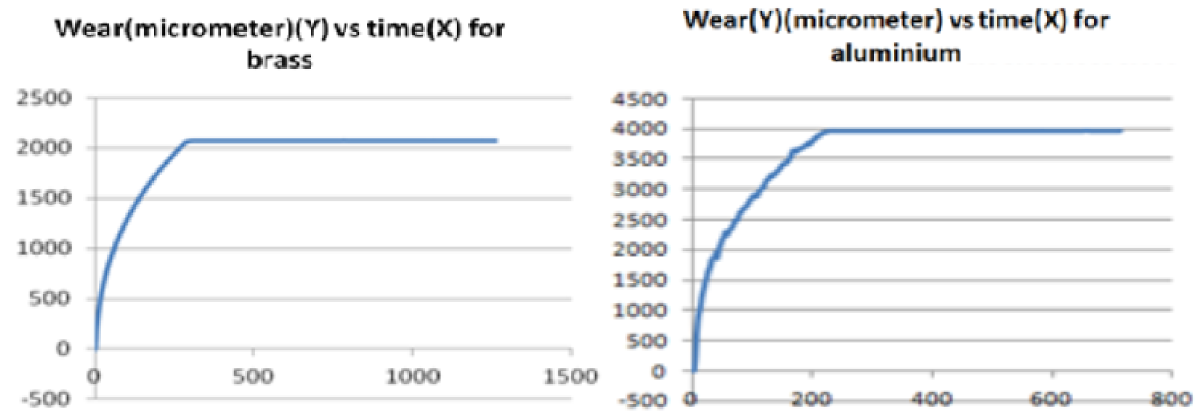


Figure 7: Wear (in mm) vs time (s) for **a)** (left) brass specimen, **b)** (right) aluminium specimen

We can hence say that brass would be a better material for making small gears as compared to anodized aluminium.

Let us say that the manufacturer of the gears keeps a time limit of 3 hours continuous usage on the gears.

The objective is to find the reliability of these two gears at a time of 2 hours 30 minutes. In order to do this, we use the formula:

$$1-\int\frac{d(t)dt}{D} = 1-\int K\frac{dwdt}{dt} \tag{29}$$

where $1-\int\frac{d(t)dt}{D}$ gives the reliability at any time *t*.

The equation can be further written as:

$$1-\int\frac{d(t)dt}{D} = 1-\frac{1}{Bs}\int B\frac{ds}{dt} \tag{30}$$

using the DEG theorem to express wear in terms of entropy. Further simplifying the expression:

$$1-\int\frac{d(t)dt}{D} = 1-\frac{1}{s}\int\frac{ds}{dt} \tag{31}$$

where *s* in the denominator is entropy at the designated lifetime.

Substituting the values, we obtain that the reliability of the brass gears after 2 hours 30 minutes exceeds that of the aluminium gears. The reliability of the aluminium gears comes out to be 72.09% and the reliability of the brass gears is 75.06%. This is consistent with the fact that brass, being a stronger material wears out less easily than aluminium. The relative closeness of the values shows that there could be better alternatives than brass, but out of the two, brass would be a better option for making the small gears. Thus, the above method proves successful in conceptualizing reliability with the help of the DEG theorem via our proposed Reliability- Entropy Hypothesis.

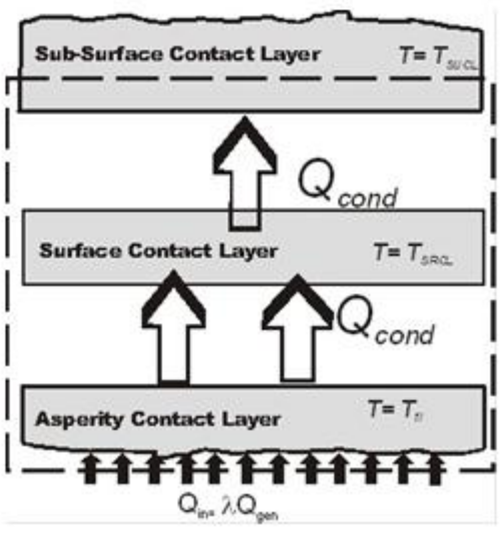


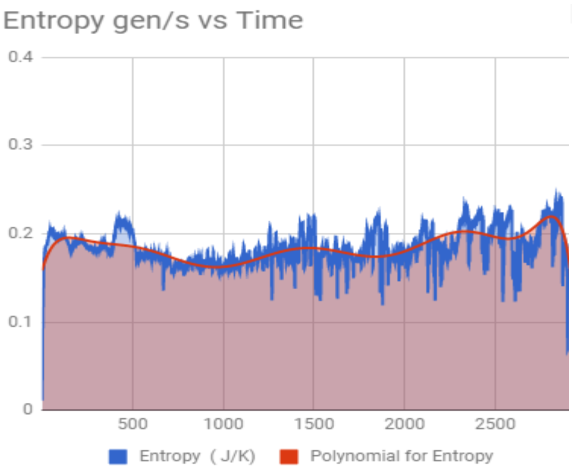
Figure 8: Heat and temperature distribution within material subject to sliding[3]

6. Effect of Cryogenic Treatment on Tool Wear and Reliability

The generation of entropy as a phenomenon in a dissipative process reduces the quality of energy, or ***exergy*** extracted from the process and lowers its ***efficiency***. If the rate of entropy generation is lowered, it naturally follows that more exergy or work can be extracted out of the process (here, machining process). Cryogenic treatment of tools prior to machining processes for long has been a preferred solution for achieving this by increasing tool life [6] and decreasing entropy by reducing the magnitude of tangential cutting forces. For tool steel, cryogenic treatment converts the austenite to brittle martensite that is seen to have positive effects on tool life increase. However, martensite by no means provides a stable equilibrium. Martensite is formed by rapid quenching of austenite so that carbon atoms have no time to diffuse out and form cementite. This is the reason why supersaturated martensite due to shear deformations creates dislocations that increases strength in steels. Martensite at exposure to heat however destructs. As a result, cryogenic treatments are accompanied are often accompanied by complementary heat treatments or *tempering treatments* that reduces the brittle nature.

To prove the robust nature of the Reliability - Entropy Hypothesis across the same material: one sample of tool steel treated cryogenically and the other sample without cryogenic treatment were tested on the same sliding wear apparatus. Both steel samples consisted of 0.8% carbon, the latter material being cryogenically treated for three hours and then tempered by heat treatment (Austenisation at 1323K for 30 minutes followed by air cooling, 83K cryogenic treatment for 4 hours followed by tempering at 673K for 30 minutes) whereas the former was not treated.

For tool steel specimens (3.5 kg load, wear track dia 80mm, specimen dia 10mm, 642 rpm), the following entropy curves were obtained from data.



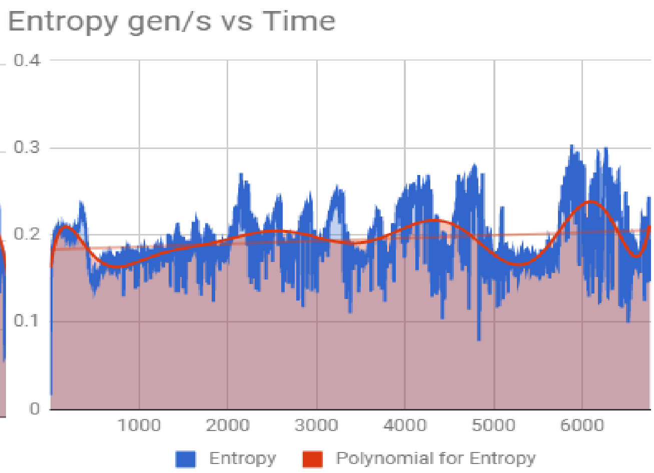


Figure 9: Entropy generation slope vs time for Carbon Steel **a)** (left) without CT, **b)** (right) with CT

Since both the specimens are made of the same material entropy generation stays in the same range but the one without cryogenic treatment reaches its endurance limit first. Secondly, greater the corresponding duration of downward slope or fall in the entropy generation/s versus time graph, greater would be the subsequent wear at those points in order to satisfy the second law of thermodynamics through compensation in the form of physical mass loss as an attempt to re-establish entropic equilibrium. This can be further backed up by the corresponding wear data as presented below along with the microstructures.

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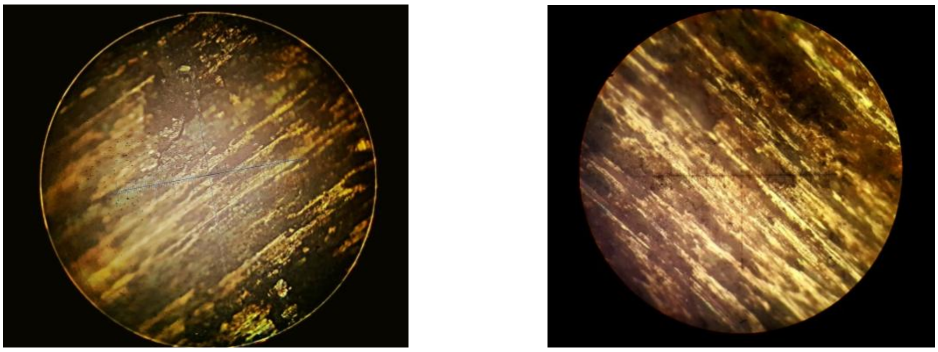

Figure 10: Microstructure of worn material **a)** (left) without CT **b)** (right) with CT

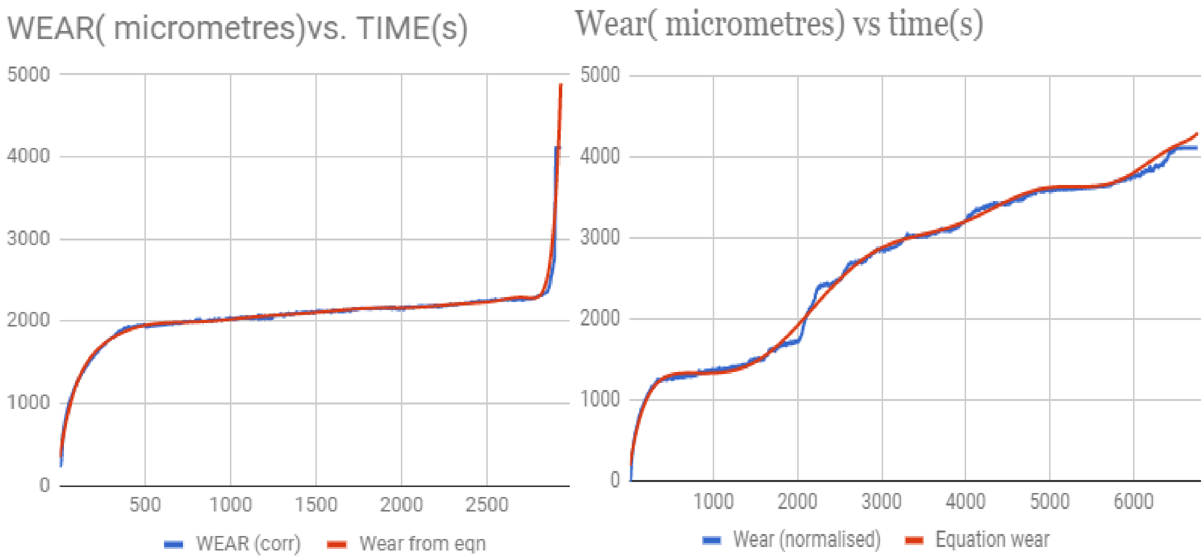

Figure 11: Wear (in mm) vs time (s) for Carbon Steel **a)** (left) without CT, **b)** (right) with CT

This clearly exhibits that cryogenic treatment has made the specimen more resistant to wear due to dissipative processes. This can be noted from the microstructure as the material with CT has carbon diffused through the martensite structure due to heat treatment that followed the process. Comparing the microstructures, there is more abrasion in that of the sample that is non-cryogenically treated as evident by the area ratio of darkened portions. Grains of martensite are clearly visible in the central region of the microstructure of the sample that is cryogenically treated. This has hence made the CT specimen more reliable than non-CT specimen over the first thirty three minutes of usage. However, after the thirty three minutes until the failure of the non-CT sample, the relative wear of the cryogenic tool is higher. This could be due to the initiation of a series of ductile-brittle sub-failures within the cryogenically treated tool due to a very low percentage of retained austenite along with the martensite. It is however a point to be noted that the cryogenically treated sample is sustained over a longer life cycle for the same endurance wear as compared to the non- CT sample. Computing the reliability variations with the given data (using the Reliability Entropy Hypothesis), we get:

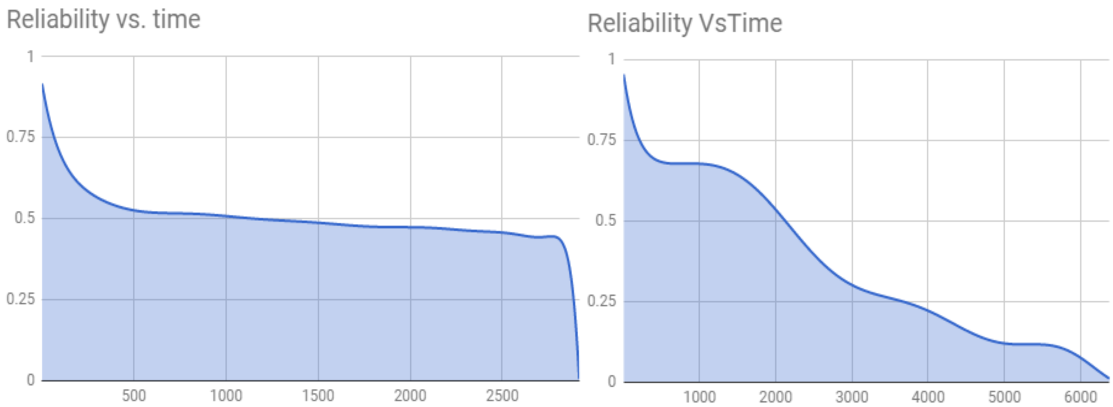

Figure 12: Reliability vs. time for tool **a)** (left) without CT, **b)** (right) with CT

This can have huge implications in industries because increased reliability and wear time directly affects the tool change interval, thereby effectively reducing machine downtime and maintenance costs.

7. Conclusion

The Reliability – Entropy Hypothesis proposed in this paper seeks to give the concept or system reliability meaning by obtaining its damage fraction as a percentage of the total entropic endurance damage. This will serve as a fresh method of preventive maintenance; although being more cumbersome, the accuracy of reliability prediction will increase several – fold, and has the potential to have large implications in machine prognostics and failure analysis. It is yet to further develop the hypothesis by determining ways to calculate *dw/ds* for different situations and multiple dissipative mechanisms occurring at the same time. For systems with subsystems, the entropy generation for a single component of each subsystem can be found out, then the series parallel relations of reliability can be used to apply them to the complete system. The Reliability - Entropy hypothesis can pave way for predictive maintenance using exhaustive digitalization techniques through automation and save costs.

8. Acknowledgements

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9. Appendices

Nomenclature

ds'	Entropy change
γ	Work/unit area
dA	Surface Area
T_m	Mean Temperature
U	Work due to plastic deformation
dV	Unit volume
G	Energy release rate
T_{cr}	Temperature at cracked material tip
dH	Latent heat absorbed
$T_{phase\ change}$	Temperature associated with phase change
A	Chemical Affinity
ζ	Extent of Reaction
Ni	Molar masses
Ni/N	Molar fractions
$(\partial pi/\partial\zeta\, j\, i)$	Generalized force
t	Life time
K	Reciprocal of wear at lifetime
d(t)/D	Local Damage index
v	Velocity of sliding
s	Entropy at designated lifetime
B	Change in wear with respect to entropy
$\int_0^t \mathrm{d(t)dt/D}$	Cumulative damage index (integral)
1-$\int_0^t \mathrm{d(t)dt/D}$	Reliability at any time 't'
DEG	Degradation Entropy Generation

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