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# WEAR UNDER LUBRICATED SLIDING CONTACTS - A DIMENSIONAL ANALYSIS MODEL

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## ABSTRACT

The aim of this research was to investigate and analyze the wear of commonly used die material (AISI 4140) under lubricated sliding contact with low carbon steel sheet. Mineral based oil blended with sulfur and ester was used. A mathematical model considering lump parameters was developed using dimensional analysis technique. Tribo-experiments were conducted on a dedicated test set-up which simulates the actual contact conditions as in sheet metal drawing operation. This paper highlighted the wear characteristics of a lubricant containing specific additives under sliding contact conditions to anticipate the wear so as to render it a suitable lubricant for deep drawing operation.

**Keywords:** *Wear, Dimensional Analysis, Deep drawing and Additives.*

## 1. Introduction

The resulting wear characteristics in a tribo-system could be linked with a group of parameters such as structural parameters, operational parameters and interaction parameters. Structural parameters, which characterize the components (i.e. materials, lubricants involved in the process), operational parameters (i.e. load/pressure, speed, sliding distance/duration) and interaction parameters which characterize, in particular, the effect of operating parameters on the structural components of a tribo-system that define its contact conditions [1]. Furthermore, tribo-systems are classified as 'closed system' and 'open system'. In closed system components are continuously involved in friction and wear, and in 'open system' flow of material occur as in deep drawing operation.

In a deep drawing tribo-system, wear is not an intrinsic material property; rather it depends on operating variables, type of lubricants and the contact conditions and regimes of lubrication. The regimes of lubrication in metal forming process are studied by various researchers and boundary as well as mixed lubrication is observed [2-4].

Friction, wear and lubrication attributes significantly in deep drawing process. Friction determines the required force and energy needed for the process along-with the flow of the metal. Reducing friction to a very low level may not be essential, but preferable to avoid adhesive wear, or galling in most cases like forming of steels [3]. The main role of the lubricant is to control the friction, to reduce the wear, to prevent seizure and to preserve as long as the possible integrity of the tools and work pieces with optimum frictional energy [4].

The friction and wear characteristics of mineral based oil having sulfur and ester as an EP/AW additive were evaluated with the help of Pin-on-disc and four ball tribo-testers under sliding conditions [5, 6].

Various models representing wear volume as a function of either operating variables or material properties were developed but they are limited to dry sliding contact conditions only. Archard type of wear equation, here represented in the form as,

$$\psi = K_w \left(\frac{F_N . V}{H_{soft}}\right) \qquad (1)$$

In above equation, $\psi$ is the time rate of wear, $F_N$ is the applied load, $H_{soft}$ is the hardness of the softest contact partner and V is the sliding speed. Above equation found to be inadequate for lubricated sliding contact because it incorporates only three parameters. The imprecision of this equation may be seen in the very large range of the values of $K_w$, extending from $10^{-4}$ to $10^{-9}$. No one is able to predict $K_w$ for any particular application to better accuracy [7].

The aim of the present work is to investigate and analyze the wear of die material under lubricated sliding contacts with the help of a simulated test conditions. A mathematical model is developed with the help of a dimensional analysis. In order to study wear characteristics, a low cost, laboratory scale dedicated test set-up is developed by adopting a special attachment on shaper machine and experiments were conducted on this set-up.

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## 2. Dimensional Analysis Model

Dimensional Analysis (DA) is based on the hypothesis that the solution of the problem is expressible by means of a dimensionally homogeneous equation in terms of specified variables. Dimensional Analysis offers a method of reducing complexity of experimental variables which affect a given phenomenon. The principal use of DA is to reduce from a study of dimensions of the variables in any physical system in the form of any possible relationship between those variables. There are many methods of dimensional analysis. The authors tried to investigate the amount of wear of die/punch material used in deep drawing operation on a simulative type novel tribo-tester, under boundary lubrication condition, using a dimensional analysis (DA) Buckingham Π theorem method. As discussed earlier, structural parameters are Elastic modulus (E) of tool material, Hardness (H) and Surface roughness ($R_a$) of steel sheet; interaction parameters are kinematic viscosity (η) of lubricant; and operational parameters are Load ($F_N$), Sliding speed (*v*), test duration or time (T) and/or sliding distance. Wear (as a weight loss) was measured as the main dependent variable.

### 2.1 Steps in dimensional analysis

### 2.1.1 The independent variables

The tribological variables involved in the process are taken as W, $E, H, R_a, \eta, F_N, v, T$. The set of variables under consideration with their dimensions are shown in Table 1.

**Table 1: Variables under Consideration**

| Variables | Symbol | Unit | Dimension |
|---|---|---|---|
| Wear (Wt. loss) | W | gm (wt.) | $M^1L^1T^{-2}$ |
| Elastic Modulus | E | $N/m^2$ | $M^1L^{-1}T^{-2}$ |
| Hardness | H | $N/mm^2$ | $M^1L^{-1}T^{-2}$ |
| Surface roughness | $R_a$ | µm | $M^0L^1T^0$ |
| Kinematic viscosity | η | $mm^2/s$ | $M^0L^2T^{-1}$ |
| Load | $F_N$ | N | $M^1L^1T^{-2}$ |
| Speed | v | m/s | $M^0L^1T^{-1}$ |
| Duration | T | hrs | $M^0L^0T^1$ |

The functional equation for wear (W) may be expressed as,

$$W = f\,(E, H, R_a, \eta, F_N, v, T) \tag{2}$$

This in its most general form may be written as,

$$\psi\left(W, E, H, R_a, \eta, F_N, v, T\right) = C \tag{3}$$

### 2.1.2 Dimensional Variables

Thus the total number of variables $m = 8$, and all the variables may be completely described by the three fundamental dimensions M-L-T. Hence $n = 3$, there are $(m - n)$= 5 dimensionless π- terms, so that

$$\psi(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5) = C_1 \tag{4}$$

### 2.1.3 Dimensionless variables:

In order to form these π terms, there is need to choose repeating variables. These variables should be such that:-

a) None of them should be dimensionless,
b) No two variables have the same dimensions,
c) They themselves do not form a dimensionless parameter, and
d) All the fundamental dimensions are included collectively in them.

Moreover, as far as possible, the dependent variable should not be taken as a repeating variable as otherwise it will not be possible to obtain a explicit relationship. Since in this case $n = 3$, the repeating variables chosen are Load ($F_N$), Speed (v), and Duration (T). By applying Buckingham's dimensional analysis,

$$\pi_1 = F_N^{a_1}, v^{b_1}, T^{c_1}, W \tag{5}$$
$$\pi_2 = F_N^{a_2}, v^{b_2}, T^{c_2}, E \tag{6}$$
$$\pi_3 = F_N^{a_3}, v^{b_3}, T^{c_3}, H \tag{7}$$
$$\pi_4 = F_N^{a_4}, v^{b_4}, T^{c_4}, R_a \tag{8}$$
$$\pi_5 = F_N^{a_5}, v^{b_5}, T^{c_5}, \eta \tag{9}$$

### 2.1.4 Construction of dimensionless group

Substituting the proper dimensions for each variable in this exponential equation in MLT system.

$$\pi_1 = M^0L^0T^0 = (M^1L^1T^{-2})^{a_1}(L^1T^{-1})^{b_1}(T^1)^{c_1}(M^1L^1T^{-2}) \tag{10}$$

Equating the exponents of M, L and T ,

For M: $a_1 + 1 = 0$

for L: $a_1 + b_1 + 1 = 0$

for T: $-2a_1 - b_1 + c_1 - 2 = 0$

From this, $a_1 = -1$, $b_1 = 0$ and $c_1 = 0$

Hence, $$\pi_1 = \frac{W}{F_N}, \tag{11}$$

 

Similarly, solving for $\pi_2$, $\pi_3$, $\pi_4$ and $\pi_5$,

$$\pi_2 = \frac{v^2T^2E}{F_N} \quad (12)$$

$$\pi_3 = \frac{v^2T^2H}{F_N} \quad (13)$$

$$\pi_4 = \frac{R_a}{v\,T} \quad (14)$$

and, $$\pi_5 = \frac{\eta}{v^2T} \quad (15)$$

Now, expressing in terms of Eq.(4).

$$\frac{W}{F_N} = \psi\left(\frac{v^2T^2E}{F_N}, \frac{v^2T^2H}{F_N}, \frac{R_a}{v\,T}, \frac{\eta}{v^2T}\right) \quad (16)$$

In order to obtain the final expression in a desired manner, $\pi_2$ and $\pi_3$ can be replaced by a new term, as

$$\pi_a = \frac{\pi_2}{\pi_3} = \left(\frac{E}{H}\right) \quad (17)$$

And $\pi_5$ can be replaced by,

$$\frac{\pi_4}{\pi_5} = \frac{v.R_{a.}}{\eta} \quad (18)$$

Also, $v.T = s$, sliding distance, Hence,

$$\frac{W}{F_N} = \psi\left(\frac{E}{H}, \frac{R_a}{s}, \frac{R_a\,v}{\eta}\right) \quad (19)$$

For a more generalized relationship, Eq. (19) is rewritten with exponents α and β, is expressed as

$$\frac{W}{F_N} \propto \left(\frac{E}{H}\right)\left(\frac{R_a}{s}\right)^{\alpha}\left(\frac{R_a\,v}{\eta}\right)^{\beta} \quad (20)$$

The above equation is simplified and wear equation is written with $K_w$ as a proportionality constant.

$$\frac{W}{F_N} = K_W\left(\frac{E}{H}\right)\left(\frac{R_a}{s}\right)^{\alpha}\left(\frac{R_a\,v}{\eta}\right)^{\beta} \quad (21)$$

The response $(\frac{W}{F_N})$ is expressed in terms of operating variables such as sliding distance (s), and sliding speed (v) which were controlled during the experiments. The material properties such as modulus of elasticity of die material (E), Hardness of sheet material (H), surface roughness of sheet ($R_a$) and viscosity of an oil (η) were kept constant. The number of experiments were planned to evaluate the function by varying only one operating variable at a time. The undetermined function ψ is evaluated from the experiments and then a relationship is established between the main $(\frac{W}{F_N})$ and the variables influencing the wear under a boundary set of lubricating conditions.

## 3 Experimental Details

### 3.1 A wear test set-up

The tribo-system in sheet metal forming is characterized as an open system, where the sheet material in contact should stay fresh and the tool is allowed to run in for long distances. Therefore, for investigating the wear characteristics of die materials under boundary/mixed lubricated condition, explicitly designed test set-up are needed.

Following requirements need to be satisfied in order to reproduce the possibility of a deep drawing open tribo-system.

i) To have a well defined simulated contact conditions, a sheet has to be in limited contact and should stay fresh and the tools has to be run-in continuously.
ii) The operational parameters should depict the industrially adopted scenario.
iii) Tests should be performed as functions of varied parameters as load, velocity, time or distance etc.

In order to fulfill above requirements, author developed a dedicated test set-up by adopting a special attachment to an existing shaper machine on which it is allowed to slide a tool on a sheet at different speed to keep the tool in continuous contact and the sheet in fresh state for every pass. This configuration is schematically shown in Fig. 1. A tool of radius 2.5 mm is slides along a sheet material clamped on a perfectly flat plate ground on both sides and mounted on a table, with a normal force $F_N$, and slide with a velocity v in ‘x’ direction. At the end of a stroke, the tool is slightly lifted and slides back to the starting position and table moves a selected distance in ‘y’ direction (Fig.1). The process is continued till to cover the required sliding distance. In this way, it is assured that, the sheet material in contact is always stay fresh and the tool is in continuous contact, as corresponds to the open tribo-system. The applicable load is in the range of 50-2000 N, with a sliding speed from 20-500 mm/s. During testing, normal load was measured in-situ by a load cell. The amount of wear was measured by weight loss method. The normal load is measured by using a load cell. The load cell is mounted on a shaper tool head assembly as shown in Fig. 2. To ensure flatness of a sheet during the experiment, a flat plate of hard material is first mounted on a shaper table and then a sheet is clamped over it. Fig. 2 shows the pictorial view of test set-up.

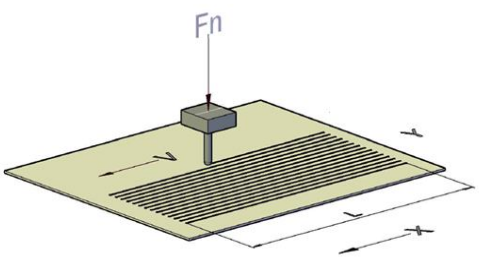


**Fig. 1 Schematic drawing of a Wear Test set-up**

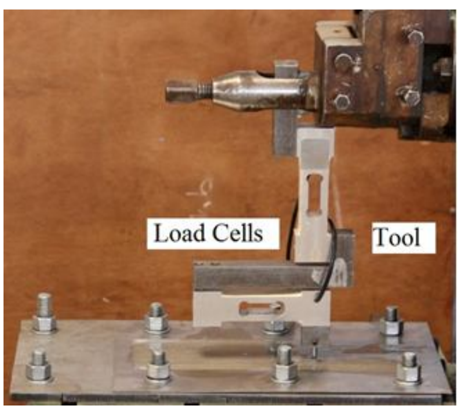


**Fig. 2 Pictorial View of a Wear Test Set-up**

### 3.2 Materials

A material selected for experimentation was 1.6 mm cold rolled low carbon steel (CR4) sheet of extra deep drawing (EDD) grade. The chemical composition of sheet material is 0.08 wt. % C, 0.40 wt. % Mn, 0.030 wt. % S and 0.020 wt. % P. All sheets were taken from the same batch. The roughness values of these sheets were measured by a stylus type instrument and average Ra value is 0.9 to 1.1 µm. The sheets of required size were cut in order to perform the experiments perpendicular to the rolling direction. The hardness value of the sheet is 218 Kgf/mm$^2$, measured on a Vickers' Hardness Tester.

AISI 4140 is selected as a tool material. The chemical composition is (wt %) (0.38-0.45 C, 0.75-1.00 Mn, 0.035 P, 0.040 S, 0.15-0.35 Si, 0.80-1.10 Cr, 0.15-0.25 Mo. and balance is Fe). The modulus of elasticity of this material is (E) is 2.14 x 10$^4$ Kgf/mm$^2$.

A general tribological evaluation of a mineral based lubricants containing ester and sulfur additives were done on four ball tester and additives were found to be synergistic in nature [8]. Authors were intended to study wear characteristics of such oil. Mineral based oil blended with Sulfur (2%) and Ester (5.25%) was chosen. The description of a lubricant is given in Table 2.

**Table 2: Lubricant under Study**

| Lube Type | Additive Concentration (% by Wt.) | | Viscosity (cP) | Specific gravity |
|---|---|---|---|---|
| | Sulfur | Ester | | |
| Mineral Based (SN 150) Oil | 2 | 5.25 | 96.60 | 0.882 |

## 4. Experimental Results

The slope of the plot ($\frac{W}{F_N}$) against the operating variables determines the exponents for an equation (Eq. 21) obtained by dimensional analysis. The normal load of 200 N and sliding speeds ($v$) ( 75 mm/s to 350 mm/s), sliding distance ($s$) of (1100 m to 3300 m), were selected as test parameters. All sheets were cleaned with acetone before applying the lubricant to a sheet. A lubricant of viscosity 0.0966 Pa-s, (Table 3) was chosen. The amount of lubricant (4-5 ml/m$^2$) applied and spread uniformly on the surface using a clean piece of reinforced paper. The tribological experiments were performed perpendicular to the rolling direction. At the end of the test the corresponding weight loss of the tool was measured using a fine balance having least count of 0.1 mg. A new tool is set for next run. Table 3 depicts the experimental results.

**Table 3: Experimental Results**

| S. No. | $\frac{R_a}{s}$ | $\left(\frac{R_a\, v}{\eta}\right)$ | Weight Loss (mg) | $\frac{W}{F_N}$ |
|---|---|---|---|---|
| 1 | 9.09E-10 | 6.84E-04 | 0.5 | 2.50E-08 |
| 2 | 4.54E-10 | | 1.0 | 5.00E-08 |
| 3 | 3.03E-10 | | 1.8 | 9.00E-08 |
| 4 | 9.09E-10 | 12.84E-04 | 1.7 | 8.50E-08 |
| 5 | 4.54E-10 | | 2.8 | 14.0E-08 |
| 6 | 3.03E-10 | | 5.1 | 2.55E-07 |
| 7 | 9.09E-10 | 18.94E-04 | 5.1 | 2.55E-07 |
| 8 | 4.54E-10 | | 9.5 | 4.75E-07 |
| 9 | 3.03E-10 | | 16.5 | 8.25E-07 |

 

## 5. Derivation of Exponents for Wear Equation

The Graphs for ($R_a$/s) verses ($\frac{W}{F_N}$) and for ($R_a$.ν/η)] verses ($\frac{W}{F_N}$) were plotted on logarithmic co-ordinates, as shown in Fig. 3 and Fig. 4 respectively.

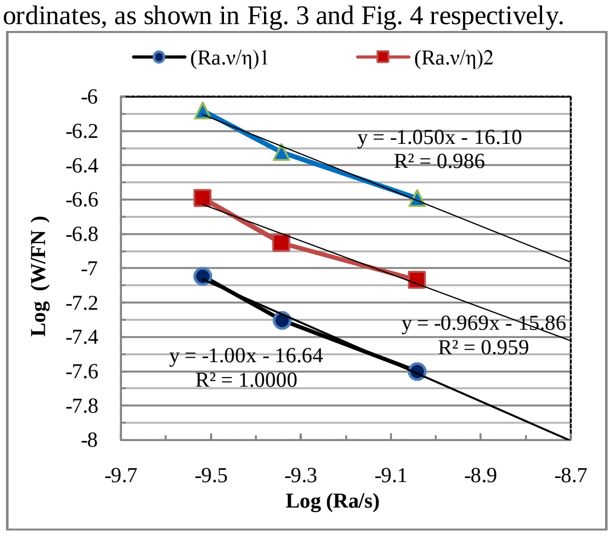


**Fig. 3 Log ($R_a$/s) Vs Log ($\frac{W}{F_N}$)**

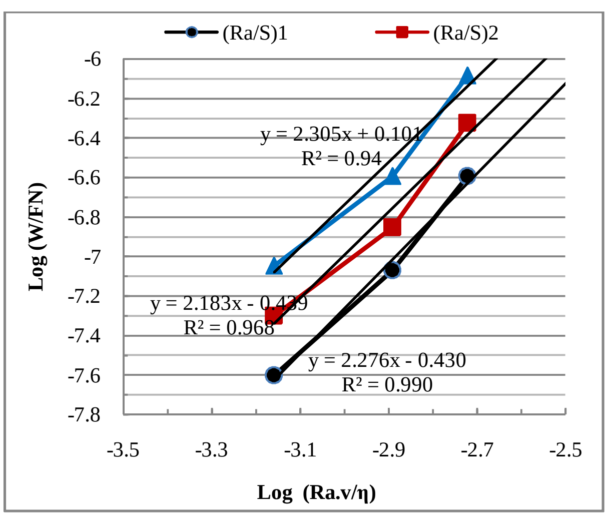


**Fig. 4 Log ($R_a$.ν/η) Vs Log ($\frac{W}{F_N}$)**

The mean slope of the straight lines is the exponents used in the model. The wear equation is written the following form.

$$\frac{W}{F_N} = K_W \left(\frac{E}{H}\right)\left(\frac{R_a}{s}\right)^{-1.0063}\left(\frac{R_a\,v}{\eta}\right)^{2.2546} \qquad (22)$$

By substituting the material properties, i.e, E= 2.14 x $10^4$ Kgf/mm$^2$ and hardness H= 218 Kgf/mm$^2$ in the above equation the wear coefficient was evaluated.

$$\frac{W}{F_N} = 98.165\,Kw \left(\frac{R_a}{s}\right)^{-1.0063}\left(\frac{R_a\,v}{\eta}\right)^{2.2546} \qquad (23)$$

Where, $K_w$ is 2.61673 x $10^{-12}$.

Hence, above equation can be rewritten as

$$\frac{W}{F_N} = 2.568 \times 10^{-10}\left(\frac{R_a}{s}\right)^{-1.0063}\left(\frac{R_a\,v}{\eta}\right)^{2.2546} \qquad (24)$$

## 6. Conclusions

This study suggested an approach to determine the wear (of die materials) under lubricated sliding contacts corresponding to deep drawing operation. Experiments were conducted on a dedicated test set-up developed by adopting a special attachment to shaper machine, which depicts actual contact conditions and sliding speed as in deep drawing operation. A mathematical model considering lump parameters was developed using dimensional analysis technique for commonly used die materials and cold rolled low carbon steel sheet material under lubricated condition. However, detail research involving other influencing parameters (such as in-process temperature rise) have to be undertaken in order to predict the optimality of use of this equation in a specific deep drawing operation.

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