

Material Wear Evaluation using Temperature Controlled Wear Testing

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ABSTRACT

One of the commonly used methods for evaluating friction and wear behavior of hard plastics is described in ASTM 3702 test specification. Wear tests conducted using this test method show that friction coefficient is dependent on temperature (generated due to friction), especially for filled plastics. Tests with high load and / or speed result in melting of the plastic due to excessive temperature build up. In the present study, a method has been developed to conduct dry and lubricated wear tests while controlling test temperature. Controlling temperature ensures that the failure mode of the test specimen is due to wear and not due to melting resulting from excessive temperature build up. The details of temperature control for both dry and lubricated wear tests are outlined and wear rate / friction for different combinations of loads and speeds are presented. The wear rates and friction coefficients obtained from temperature controlled tests can directly be used to rate materials for wear / friction performance.

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INTRODUCTION

Several methods currently exist to characterize wear and friction behavior of materials. "Wear Rate and Coefficient of Friction in Self lubricated Rubbing Contact using a Thrust Washer Machine" outlined in ASTM 3702, is one of the commonly used methods for wear and friction characterization [1]. This test method uses a rotating sample on a counter surface of a specific initial roughness. The test is usually conducted at a constant value of applied pressure and a fixed rotational speed. Figure 1 shows the schematic of a typical test set-up used to conduct the ASTM 3702 standardized test. Load is applied on the sample using dead weights via a lever arm. Rotation is imparted to the test specimen via a motor geared appropriately to achieve desired torque and rotation speed. The spindle from the motor is coupled to sample holder via two pins and a ball bearing. The ball bearing enables the test sample to adjust dynamically to ensure that the load is applied uniformly on the contacting face, especially in case of non-uniform wear. The data acquisition system consists of an LVDT (Linear Variable Differential Transformer) to measure displacement, a thermocouple to measure temperature, and a load cell to measure torque. The friction coefficient is calculated from the torque and the applied load on the test sample. In the current study, a machine developed by Lewis Research, Inc. incorporating the above features was used. The test procedure

involves conducting pre-test measurements (test sample weight and dimensions, counter surface weight / roughness) and mounting the test sample on the sample holder. The sample holder and the counter surface are installed on the test machine. The thermocouple is then installed on the counter surface. Weights are added to achieve desired pressure. The test is started by initiating rotation of the motor/spindle at the desired speed. The data acquisition system periodically collects temperature, displacement and torque information. After completion of the test, posttest measurements are conducted and the weight/dimensions of the test sample are recorded. The weight of the counter surface is also recorded to evaluate weight loss due to wear of the counter surface. Roughness measurements of the counter surface can also be conducted after completion of the test to estimate change in counter surface characteristics resulting from wear. It has been observed that for large values of applied loads and/or speeds, the heat generated due to friction tends to soften/melt the test sample rather than create failure due to wear. Due to this limitation, it is very often not possible to evaluate friction / wear characteristics at large values of loads and / or speeds which may very well be close to the actual operating conditions.

Extensive research has been carried out by researchers to understand tribological behavior of engineering materials. Amiri and Khonsari compiled research studies pertaining to

application of the thermodynamic approach to friction and wear for modeling sliding contacts [2]. Zmitrowicz, in his review article summarized wear patterns from experimental observations, discussed laws of wear, and presented theoretical calculations to estimate abraded mass and temperature fields in pin-on-disc test rig [3]. Brostow et al. showed that a parabolic relation exists between penetration depth and the energy dissipation ($\tan \delta$) for polymeric materials [4]. Khedkar et al. conducted DSC measurements and tribological tests on PTFE composite with various types of fillers [5]. A pin-on-disc type tribometer was used for conducting tribological tests. A correlation between heat of fusion and wear resistance was observed. They also concluded that the wear process in PTFE composites depend mainly on thermal stability, thermal conductivity, and characteristics of filler materials. Briscoe and Sinha, in their extensive review article concluded that wear of polymers is influenced by three major groups of parameters; (1) sliding contact conditions such as surface roughness and contact kinematics, (2) temperature (and other environmental conditions) dependent bulk mechanical properties of polymer, and (3) role and properties of the 'third body' which is defined by the first two groups [6].

In the present study, to better understand effect of temperature on wear and friction, add-on fixtures to the Lewis test machine have been designed and built to control temperature during the test for both dry and lubricated wear tests. The details of the fixture designs are outlined in this paper. Dry and lubricated wear tests have been conducted for a glass and MoS₂ filled PTFE material. The effect of temperature on wear rate and friction coefficients for different combinations of 'PV' (where P is the applied pressure on the test sample and V is the average linear sliding velocity) is presented. Also, wear and friction data while maintaining constant value of PV for two different combinations of pressure and velocity is presented. Despite controlling test temperature (by removal of heat using the temperature control fixtures), fluctuations in temperature still occur. It has been observed that these temperature fluctuations correlate with the displacement measured by the LVDT. A method of extracting wear/wear rate information from the test data by compensating for these temperature fluctuations is also detailed. The wear/wear rate thus extracted from LVDT measurements are compared to those calculated from measured weight loss and possible causes of discrepancies between the two measurements are listed.

Test data shows that the temperature control fixtures satisfactorily maintain a desired test temperature. Test results indicate that wear rate has a dependence on temperature. For a glass and MoS₂ filled PTFE compound, an increase in wear rate is observed with an increase in temperature. The coefficient of friction for the glass and MoS₂ filled PTFE did not seem to show dependence on temperature, however, analyzing the data using Minitab® statistical analysis software showed that there is statistically significant

dependence of friction on temperature. Lubricated wear tests show good temperature control; however, the test durations to produce wear in a lubricated test set-up were lengthy, possibly due to low friction coefficients resulting from mixed hydrodynamic lubrication conditions at the interface.

FIXTURE DESIGNS

Two fixtures have been designed and built to control interface temperature for dry and lubricated wear tests. These fixtures can be added to the existing test machine when temperature control is desirable, and removed to conduct tests as per ASTM 3702 test specifications. The test fixtures are designed so that there are no rigid connection between the fixture (on which the test specimen is mounted) and the cooling system (air cooling for dry tests and oil for lubricated tests). This ensures that the reaction torque measured by the load cell is not affected.

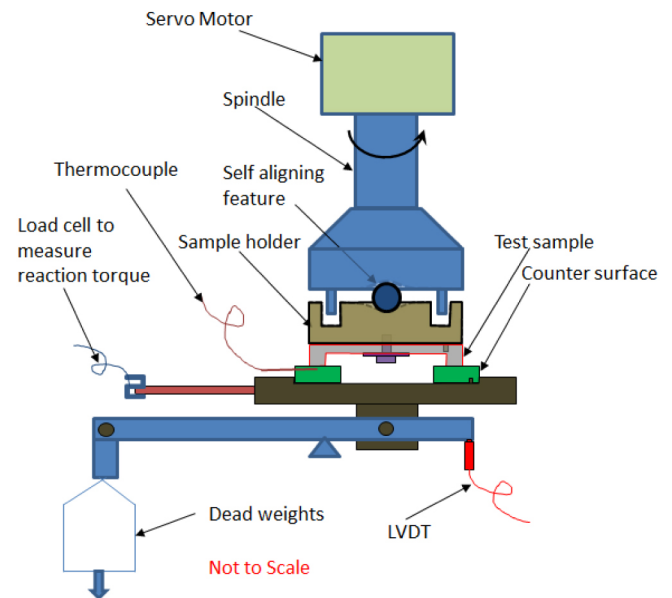


Figure 1. Schematic of Test Set-up

Temperature Control Fixture for Dry Wear Test

Figure 2 shows the schematic of the temperature control fixture for dry wear test. The fixture consists of a copper counter surface base that mounts onto the test machine. The copper counter surface base is attached to a hollow copper enclosure. The hollow copper enclosure has fins to promote heat removal. Temperature control in dry wear tests is achieved by controlled removal of heat generated at the interface of the test sample and the counter surface. Heat generated at the interface is conducted to the hollow copper enclosure and the fins. Air at a fixed temperature supplied via vortex tubes is passed through the fins and around the hollow enclosure to remove heat generated at the interface. The

temperature of the air is controlled by controlling the inlet air pressure supplied to the Vortex tubes [7].

ASTM 3702 specifies the use of AISI-C 1018 steel with a roughness of $16 \pm 2 \mu\text{in}$ Ra for the counter surface. In the current study, CMW®3, an alloy of Copper (99.10% Cu and 0.90% CR), with Ra of $16 \pm 2 \mu\text{in}$ has been used as the counter surface due its higher thermal conductivity.

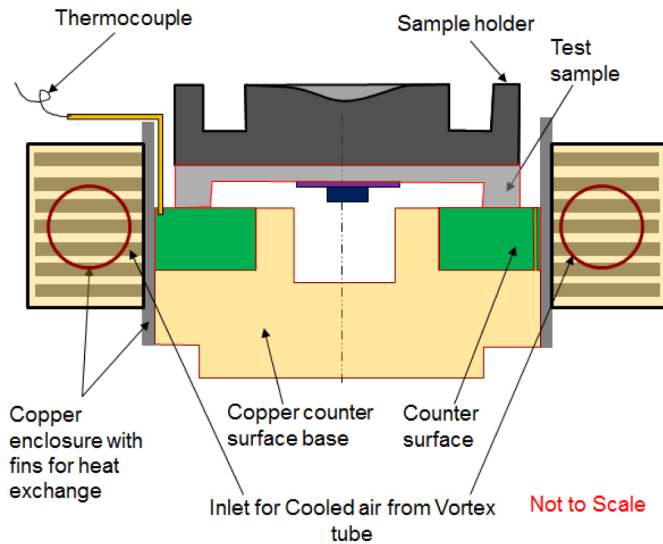


Figure 2. Schematic of Temperature Control System for Dry Wear Tests

Table 1 compares the thermal conductivity, hardness and linear expansion coefficient of the two counter surface materials. This particular alloy of copper was chosen as it has hardness close to that of AISI-C1018 steel, but with a much higher thermal conductivity (which promotes heat removal). A steel washer as described in ASTM3702 can also be used in this temperature control fixture, if preferred.

Table 1. Comparison of Properties of AISI-C 1018 steel with CMW®3 Copper Alloy [8]

	AISI C-1018 Steel	CMW®3 Copper Alloy
Thermal Conductivity (W/m/°C)	51.9	324
Hardness (Rockwell B)	73.0	75.0
CTE, linear (m/m/°C)	12.2×10^{-6}	17.6×10^{-6}

Heat transfer analysis

The design of the temperature control fixture for dry wear tests was optimized by conducting heat transfer analysis using finite element technique. The finite element model was created and analyzed in Abaqus commercial finite element package [9]. In the analysis, it is assumed that all of the power generated by the motor is converted to frictional heat. The motor has a power of 1.5 kW which corresponds to a heat flux of $11,628 \text{ kW/m}^2$ on a test sample with a surface area of 129 mm^2 . Figure 3 shows the geometry, loads and

boundary conditions used in the finite element analysis. Heat transfer from the counter surface to the copper base and the copper enclosure with fins was modeled as conductive heat transfer. The removal of heat from the fins by blowing air was modeled as convective heat transfer using a film coefficient. The film coefficient for convective heat transfer was estimated using Sieder Tate equation [10] for turbulent flow and Hausen correlation [11] in the laminar regime.

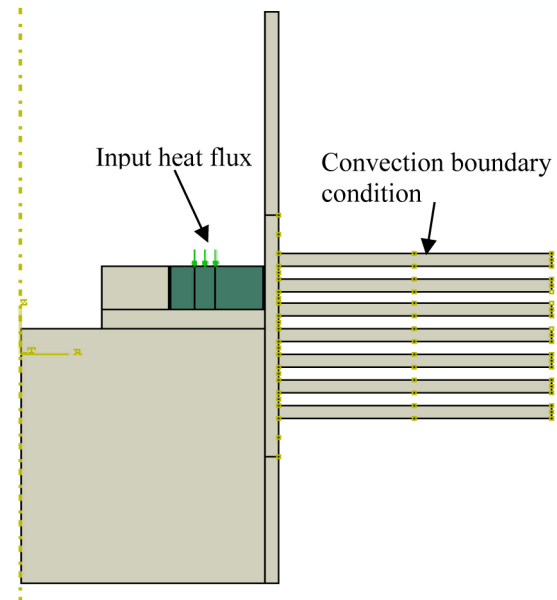


Figure 3. Loads and Boundary Conditions used in Heat Transfer Analysis

An axisymmetric model was used for the heat transfer analysis and the domain was discretized using four node, linear axisymmetric heat transfer elements. Various geometric parameters (number of fins, location of fins and dimensions) and materials (for the base, hollow enclosure with fins and counter surface) were considered in the analysis. Also, scenarios where there is loss of contact between the counter surface and hollow enclosure were considered. The final design was optimized to achieve optimal temperature distribution at the interface. In the analysis, heat transfer occurring through the test sample itself was not considered.

Figure 4 shows the temperature distribution (in Kelvins) from one of the analyses cases where an aluminum counter surface is used together with a copper base and a copper enclosure with fins. With a film coefficient corresponding to maximum velocity of air from the vortex tubes and an air temperature of 5°C , the maximum temperature at the interface was about 100°C .

Temperature Control Fixture for Lubricated Wear Tests

A schematic of the set-up for the temperature control unit in a lubricated wear test is shown in Figure 5. The