Novelty Statement

A unique high speed electromagnetic tribometer based on a minor caliber electromagnetic launcher has been designed and implemented to characterize wear of an Al alloy at sliding speeds and pressures that cannot be achieved by conventional tribometers.

This study expands on a companion paper submitted previously to Wear journal by investigating the influence of the guider material on transition from severe plastic deformation to melt lubrication wear region. The study shows that the guider thermal properties influence this transition condition.

The Effect of Tribomaterial Pairings on Wear of an Aluminum Slider under High Sliding Speeds and High Contact Pressure

M. J. Siopis¹ and R. W. Neu^{1,2}

¹George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA

²School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA

Abstract –A unique high-speed electromagnetic tribometer based on a minor caliber electromagnetic launcher was used to study metal on metal wear under high sliding speeds and high contact pressures. Large scale melting of the slider occurred and was correlated to the sliding conditions, pressure and velocity, as well as slider – guider material properties. A series of experiments were conducted to study the response of a 6061-T6 aluminum slider on four different guider materials, C11000-H2 copper, 1018 steel, 1045 steel and CP titanium (grade 2) at sliding speeds from 0 – 1,200 m/s and contact pressures from 100 – 225 MPa. A transition from a severe plastic deformation to melt lubrication wear region occurred under a critical combination of sliding speed and contact pressure. Test results showed that the guider thermal properties influenced this transition condition, such that a guider with a higher volumetric thermal mass resulted in a higher transition condition than one with a lower volumetric thermal mass. The overall impact of the different guider materials tested on the transition condition is within 6% of the baseline C11000-H2 copper.

Index Terms – High-speed tribometer, Aluminum, Copper, Titanium, Steel, High Velocity, High Contact Pressure, Melt Lubrication

Nomenclature

α	Heat partition coefficient	Pe	Peclet Number
A_n	Nominal contact area (mm ²)	ρ	Mass density (kg / m ³)
β	Normalized volumetric thermal mass	σ	Contact pressure (MPa)
χ	Thermal diffusivity (m ² / s)	τ_d	Dwell time (s)
c	Specific heat capacity (J / kg · K)	τ_h	Diffusion time (s)
$\dot{E}_{gen}$	Energy dissipation rate (W)	v	Sliding speed (m/s)
$\dot{E}_{storage}$	Energy storage rate (W)	v_c	Critical velocity (m/s)
K	Thermal conductivity (W / m · K)	V	Volumetric wear (mm ³)
l	Slider half length (m)	$\bar{W}$	Normalized wear rate (mm/mm)
Φ	Dimensionless time ratio	x	Distance slid (mm)
ψ	Proportionality constant (s / m · MPa ^{1/4})	z	Diffusion depth (m)

M. J. Siopis is a PhD graduate from the George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA (e-mail: msiopis3@gatech.edu)

R. W. Neu is a professor with the George W. Woodruff School of Mechanical Engineering and School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA (e-mail: rick.neu@gatech.edu)

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1. Introduction

Metal on metal sliding contact at high speeds and high contact pressures can result in wear of one or both of the contacting bodies. Typical engineering systems subjected to high sliding speeds and high contact pressures include ultrahigh speed machining[1], rocket sleds[2], large caliber cannon[3], and electromagnetic launchers[4]. Operating conditions with sliding speeds on the order of 100 – 1,000 m/s and contact pressures in excess of 100 MPa are common in these systems. Under these sliding conditions three distinct wear regions may appear: plasticity – dominated wear, severe plastic deformation and melt lubrication.

Characterization of slider wear under high sliding speeds and high contact pressures is important to designing more efficient and robust engineering system components. Wear is a system response dependent on the operating conditions, pressure and velocity, and tribomaterial pairing of the slider and guider. Lim and Ashby [5] constructed wear – mechanism maps by compiling data from steel pin (slider) on steel disc (guider) experiments to provide insight into the dominant wear mechanisms, wear rates and coefficients of friction for a wide range of operating conditions. Using the same methodology, a wear mechanism map for Al alloys was also generated [6]. Al alloys are of particular interest as they are relevant to electromagnetic launchers. The wear mechanisms of Al alloys at high sliding speeds and high contact pressures are not well established due to the challenge of attaining these operating conditions with conventional tribometers. For high sliding speeds the general wear mechanism identified is referred to as melt wear, which involves a broad class of wear mechanisms ranging from localized melting at the asperity level to large scale melting, referred to as melt lubrication. Using conventional tribometers, melt lubrication is typically only observed with metals of lesser thermal capability (i.e., lower melting temperature) [7].

For high sliding speeds, greater than 100 m/s, and low contact pressures, less than 100 MPa, the general wear mechanism identified is localized melting. The localized melt provides lubrication resulting in a low coefficient of friction [8]. Under higher contact pressures, greater than 100 MPa, the Al alloy wear mechanism map [6] suggests that seizure will occur. However, there is no experimental evidence of seizure at these higher sliding speeds. A prior study of wear of Al alloy on copper [9] showed that seizure does not occur and instead for sliding speeds between 100 and 800 m/s, a form of plasticity-dominated wear, characteristic of adhesion, occurs. As the sliding speed is increased further to 800 – 1,000 m/s, the wear is characteristic of severe plastic deformation exhibiting significant plastic flow promoted by thermal softening. Under extreme sliding speeds, greater than 1,000 m/s, a third wear regime, referred to as melt lubrication, is present. This region is characteristic of large scale melting, such that the entire slider interface is molten. Under melt lubrication the dominant heat dissipation mechanism is viscous in nature and wear rates tend to be significantly larger than the plasticity-dominated wear regime. Often times it is ideal to operate in the plasticity-dominated wear region as the wear coefficient is an order or two lower than the severe plastic deformation and melt lubrication regions.

The transition from severe plastic deformation to melt lubrication occurs at a critical combination of sliding speed and contact pressure and is referred to as PV product for melt lubrication. When the product of the contact pressure raised to $1/4$ power and sliding speed ($\sigma^{1/4} \cdot v$) equals $3,350 \text{ MPa}^{1/4} \text{ m/s}$, a shift from severe plastic deformation to melt lubrication occurs [9]. It has been shown that by selecting a slider material with a higher melting point that the transition condition can be increased [7]. The objective of this study is to understand the effect of guider material properties on the transition between wear regions. For this study a 6061-T6 aluminum

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4 slider was tested on four different guiders materials of varying thermal and mechanical
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6 properties using a unique electromagnetic tribometer at Georgia Tech [9]. In particular, a set of
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8 experiments was designed to explore the effects of the guider material properties on the
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10 conditions necessary to generate melt lubrication.
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15 **2. Experimental Methodology**

16 17 18 *2.1 Experimental Setup*

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20 The electromagnetic tribometer used to achieve sliding speeds on the order of 1,000 m/s and
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22 contact pressures on the order of 100 MPa is comprised of a specialized tribo-slider shown in
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24 Fig. 1 that is accelerated in an electromagnetic launcher (EML). The design of the tribo-slider is
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26 based on earlier work conducted by Stefani and Parker [10]. The electromagnetic tribometer
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28 utilizes a minor caliber EML at Georgia Tech to generate a propulsive force capable of
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30 accelerating a 10 gram projectile from rest to 1,200 m/s in 750 μ s. The tribo-slider is composed
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32 of an armature, which provides the electrical connection between the rails resulting in a
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34 propulsive force, a non-conductive G-10 glass fiber composite ramp, two wedges with wear tabs,
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36 and two nylon bore riders to constrain the vertical movement of the wedges. The wedges are
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38 allowed to move freely up and down the ramp. A half open view of a loaded tribo-slider in the
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40 EML bore is also shown in Fig. 1. A near constant acceleration is held during the first 0.45 m of
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42 travel. The acceleration coupled with the wedge mass and ramp geometry provides an inertial
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44 load on each wedge. Each wedge slides down the ramp and engages with a guider embedded in
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46 the sidewall insulator. Each wedge contains a wear tab, effectively called the slider, which has a
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48 3.18 mm square contact area, except for test number two, where the contact area was varied to a
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50 2.41 mm square. The guiders, with dimensions 6.35 mm x 6.35 mm x 1.56 m, are embedded into
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52 the two sidewall insulators so they are isolated from the high electrical current in the rails.
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Fig. 1 – Fully assembled tribo-slider (left) and half open view of a loaded tribo-slider and EML bore (right).

2.2 Experimental Procedure

The total mass of the tribo-slider and the electrical current profile are held near constant for each test. A peak electrical current of 280 kA is maintained for approximately 750 μs . During this time the tribo-slider accelerates from rest to 1,200 m/s resulting in a near constant tribo-slider acceleration of approximately $1.60 \times 10^6 \text{ m/s}^2$ over a sliding distance of 0.45 m. The combination of the inertia load, due to the tribo-slider acceleration and wedge mass coupled with the ramp geometry, generates a normal load between the wedge wear tab (slider) and the guider at the contact interface. The desired contact pressure is achieved by adjusting the individual wedge mass via an embedded tungsten pin. Instrumentation in the form of b-dot sensors [11-13] and Rogowski coils [14] are used to obtain the tribo-slider acceleration, velocity, and position as a function of time. A total of eight tests of varying contact pressure and guider material with a

peak sliding speed of approximately 1,200 m/s were conducted. The test conditions are summarized in Table 1.

Table 1 – Summary of test conditions to study the effects of guider material properties on slider wear.

Test No.	Guider		Contact Pressure (MPa)	Peak Velocity (m/s)	Contact Area (mm ²)
	Material	Hardness (HV)			
1	C11000-H2 Cu	105	101	1210	10.1
2	C11000-H2 Cu	105	122	1180	5.8
3	C11000-H2 Cu	106	124	1210	10.1
4	C11000-H2 Cu	106	130	1190	10.1
5	C11000-H2 Cu	108	225	1180	10.1
6	1045 Steel	281	135	1140	10.1
7	1018 Steel	238	134	1150	10.1
8	CP Ti (Grade 2)	183	144	1170	10.1

During each test the contact pressure at the slider-guider interface is held near constant (since acceleration is near constant) until a peak velocity of approximately 1,200 m/s is attained, while the sliding speed is increasing at a constant rate. This results in a different combination of pressure and velocity as a function of time or distance slid. As the slider wears it deposits material onto the guider. The slider deposition takes on the form of a visible and distinct “track” of material. The track is approximately the width of the slider. The appearance and amount of slider deposition varies as a function of the pressure and velocity. Analysis of the deposition provides insight into the interface physics, which is important when selecting materials or designing tribological systems subjected to these extreme sliding conditions.

Following each test the guiders were removed from the EML bore. The guiders were first viewed under a Leica DM 4000 optical microscope to identify changes in the appearance of the slider deposition as a function of pressure and velocity. After the qualitative assessment, the specimens were then prepared for non-contact optical profilometry. Volumetric deposition measurements were taken at discrete locations and correlated to sliding speed and pressure. Each location was segmented into three different areas, left, middle and right. The middle area was masked and deposition was removed from the left and right areas by “flaking” off the deposition followed by a sodium hydroxide swab to remove any residual aluminum. Sodium hydroxide was used as it reacts with aluminum in a corrosive manner but does not affect the guider materials in this study. The deposition in the middle area was then measured using a Zygo NewView 6k scanning white light interferometer. The left and right areas were used to define a reference plane to determine the volume of deposited slider material in the middle area. A 10 mm x 5 mm scan was taken to capture the left, middle and right areas. The scan setting resulted in a pixel-to-pixel resolution of 2.18 μm with a vertical resolution of 0.02 μm . Average deposition thickness, in the severe plastic deformation and melt lubrication regions is on the order of 10 μm , making the error introduced due to vertical resolution of the scanning white light interferometer approximately 0.2% of the measurement.

2.3 Data Analysis

Volumetric measurements of the worn slider material on the guider were taken at different locations along the guider. For comparison and analysis purposes the volumetric wear data was put into a rate form and then normalized by the slider nominal area of contact. The normalized wear rate is defined as

$$\tilde{W} = \frac{V}{A_n \cdot x} \quad (1)$$

Where V is the volume of deposited material, A_n is the nominal contact area of the slider and x is the distance slid.

As an example, a normalized wear rate plot for a 6061-T6 aluminum slider on a C11000-H2 copper guider at a contact pressure of 101 MPa as a function of sliding speed is shown in Fig. 2. Three different wear regions were identified and correlated to images from optical microscopy. The plasticity – dominated wear region occurred at lower sliding speeds and is representative of normalized wear rates less than 1.0×10^{-4} . The volume of deposited slider material in the plasticity – dominated wear region was relatively low and difficult to precisely measure using the method employed, as it fell within the noise of the guider surface roughness. For this reason only an upper bound could be obtained. The second wear region, severe plastic deformation, increased sharply and then decreased steadily until a critical velocity was attained. The increase in the normalized wear rate is due to a bulk temperature rise at the slider interface that results in thermal softening and shearing / plastic deformation on a large scale. The heat dissipation from this large scale shearing / plastic deformation eventually results in bulk melting of the slider interface and partial lubrication, marked by the steady decrease in normalized wear rate. The normalized wear rates in the third wear region, melt lubrication, increase linearly with velocity. This increase is a result of the viscous drag due to the shearing of a functional melt film capable of supporting the applied contact load. This shift from severe plastic deformation to melt lubrication is demarcated by a critical velocity and is sensitive to both pressure and velocity, such that a higher contact pressure results in a lower critical velocity. The combination of

pressure and velocity, which results in this shift, defines the lower end of the melt lubrication boundary.

Figure 2 - Wear regions and normalized wear rates as a function of velocity for 6061-T6 aluminum on C11000-H2 copper at 101 MPa.

For this study the primary focus is to understand the influence of guider materials on normalized wear rates of a 6061-T6 slider in the melt lubrication region. It has been shown through melt lubrication theory [15] that the melt film is turbulent under the conditions tested in this study and the normalized wear rate is proportional to $\sigma^{1/4} \cdot v$ [9]. By plotting the normalized wear data as a function of $\sigma^{1/4} \cdot v$ the effects of contact pressure are removed allowing for specific parameters, such as guider material properties, to be isolated and studied.

2.4 Error Analysis

For plotting clarity the experimental data does not include error bars. The uncertainty, for a 95% confidence interval, for the data presented is between 5 – 10% of the calculated value. The primary source of error in the measurement process can be attributed to the surface topography of the guider. Surface roughness due to how the guider was formed and deformation due to the interaction of the slider – guider contact resulted in an average arithmetic mean surface roughness of $\leq 1 \mu\text{m}$. Slider deposition, when averaged over the measurement area, is on the order of $10 \mu\text{m}$. The MetroPro 8.1.5 software package, which is a component of the scanning white light interferometer system, takes a best fit plane of the left and right areas on each side of the middle test area so as to average out the effects of the guider topography. The volume of the material in the middle / test area is taken from this best fit plane. Both the slider deposition and some portion of the guider topography are included in this volume calculation. In doing so, error is introduced due to the statistical distribution of the guider topographical features (peaks and valleys). For an arithmetic mean surface roughness of $1 \mu\text{m}$ and an average deposition thickness of $10 \mu\text{m}$, the resultant error in the volumetric measurement can be up to 10%. This is significantly larger than the resolution error introduced by the scanning white light interferometer. The error due to the surface topography is considered to be the primary or dominant source of error in the volumetric wear measurements.

3. Design of Experiments

3.1 Influence of Guider Mechanical Properties

Before exploring the effects of guider thermal properties on normalized wear rates, it was necessary to understand the effects of guider mechanical properties (i.e., hardness), as it was difficult to acquire guider materials in the correct form with differing thermal properties and

similar mechanical properties. A survey was conducted to identify a group of materials that had similar thermal properties (thermal conductivity, density and specific heat), but different mechanical properties. A group of low to medium plain carbon steels was identified as the ideal candidate materials to investigate the effects of mechanical properties on normalized wear rates in the melt lubrication region. Two different plain carbon steels, a 1018 low plain carbon steel and a 1045 medium plain carbon steel, were selected. Hardness values, surface roughness measurements and material compositions are provided in Table 2 [16-18]. Hardness measurements were taken using a portable Riehlebulk hardness tester per ASTM E18-14 and E110 – 10 and the hardness values were converted to a Vickers hardness number for comparison purposes using ASTM E140 – 07 hardness conversion tables. The resultant hardness of the 1018 and 1045 plain carbon steel is 238 HV and 281 HV, respectively. The Ra surface roughness of the steel guider experiments was larger than the average Ra (approximately 1 μm) of the other six experiments. The higher surface roughness of the steel guiders resulted in an increase in the error from 5 – 10%, as stated previously in the Section 2.4, to 10 – 20 %. The increase in error did not have a significant impact on the data trends discussed in the following sections.

Table 2 – Comparison of the steel guiders tested to evaluate the effect of mechanical properties.

Test No.	Guider Material	Alloying Element Composition (%wt)				Ra (μm)	Hardness (HV)
		C	Mn	P (max)	S (max)		
6	1018 Steel	0.15 – 0.2	0.6 – 0.9	0.04	0.05	4.7	238
7	1045 Steel	0.43 – 0.5	0.6 – 0.9	0.04	0.05	4.3	281

The normalized wear rates for a 6061-T6 aluminum slider on two different steels in the melt lubrication region as a function $\sigma^{1/4} \cdot v$ is plotted in Fig. 3. By plotting the normalized wear data as

a function of $\sigma^{1/4} \cdot v$ the effects of contact pressure are removed allowing for the effects of guider mechanical properties to be isolated for comparison[9]. The results in Fig. 3 show negligible difference between the two tests as both lines lay on top of each other. It was concluded that that the effects of guider hardness on slider normalized wear rates in the melt lubrication region are negligible. The negligible effect of guider mechanical properties on the slider normalized wear rates can be attributed to the condition of the slider interface. At higher sliding speeds, such as in the severe plastic deformation wear region, the slider has undergone thermal softening due to a rise in bulk temperature and accordingly the strength is reduced as the interface temperature approaches the melting point of the 6061-T6 aluminum. After the wear mechanism has shifted to melt lubrication, the slider and guider surfaces are fully separated by a melt lubrication film. For this reason the guider hardness has negligible influence at these higher sliding speeds.

Figure 3 - Normalized wear rate dependence on $\sigma^{1/4}v$ for a 6061-T6 slider on a 1018 steel and 1045 steel guider in the melt lubrication region.

3.2 Influence of Guider Thermal Properties

Traditional heat transfer theory was utilized during the guider material selection process in identifying the thermal properties of significance. For sliding contacts where the primary heat source is frictional dissipation and the mode of heat transfer is thermal conduction, well-established heat partition theory published by Jaeger[19] was used to identify relevant thermal properties for selecting potential guider materials. A dimensionless heat transfer parameter referred to as the Peclet Number was used to evaluate the conditions at the sliding contact interface. The Peclet number represents the ratio of advective to diffusive heat transport,

meaning for small Peclet numbers, <0.1 , diffusion dominates and for larger Peclet numbers, >10 , advection dominates [20]. The Peclet number is defined as follows

$$Pe = \frac{v \cdot 2l}{\chi_1} \quad (2)$$

where v is the velocity, $2l$ is the length of the slider in the direction of travel and χ_1 is the thermal diffusivity of the guider. For a 6061-T6 aluminum slider on a C11000-H2 copper guider, with a sliding speed of 1,000 m/s, a slider length ($2l$) of 3.18 mm, and a guider thermal diffusivity of $1.13\text{E-}04 \text{ m}^2/\text{s}$, a Peclet number of 28,000 is calculated. This value is three orders of magnitude larger than the value of 10 used to define large Peclet numbers, in traditional heat partition theory.

For large Peclet numbers, Jaeger's heat partition theory is presented in the following analytical form

$$\alpha = \frac{K_1(v \cdot l)^{\frac{1}{2}}}{1.125K_2\chi_1^{\frac{1}{2}} + K_1(v \cdot l)^{\frac{1}{2}}} \quad (3)$$

where α is the heat partition coefficient for the guider, K_l is the thermal conductivity of the guider, K_2 is the thermal conductivity of the slider, χ_1 is the thermal diffusivity of the guider, $2l$ is the length of the slider in the direction of travel, and v is the velocity. The heat partition coefficient represents the fraction of the heat dissipated at the contact interface that is partitioned into the slider.

Several simplifications are made to Equation 3 to put it into a form that can be used for screening potential guider materials. The first simplification requires fixing the slider length and velocity. For this study the slider geometry is fixed and the effects of velocity in the severe plastic deformation and melt lubrication regions have minimal impact on the heat partition coefficient, in which case Equation 3 can be simplified to the following form

$$\alpha = \frac{K_1 C_1}{1.125 K_2 \chi_1^{\frac{1}{2}} + K_1 C_1} \quad (4)$$

where C_1 represents $(v \cdot l)^{1/2}$. The second simplification requires fixing the slider thermal conductivity K_2 . A slider material of 6061-T6 aluminum was used for all experiments. This allows for Equation 4 to be simplified further to the form

$$\alpha = \frac{K_1 C_1}{C_2 \chi_1^{\frac{1}{2}} + K_1 C_1} \quad (5)$$

where C_2 represents $(1.125 \cdot K_2)$. Dividing the numerator and denominator by K_1 gives the following form

$$\alpha = \frac{C_1}{C_2 \frac{\chi_1^{\frac{1}{2}}}{K_1} + C_1} \quad (6)$$

Substituting the relationship for thermal diffusivity χ in terms of density, ρ , specific heat, c , and thermal conductivity, K , gives

$$\alpha = \frac{C_1}{C_2 \left(\frac{1}{\rho_1 \cdot c_1 \cdot K_1} \right)^{\frac{1}{2}} + C_1} \quad (7)$$

This provides a material index in the form

$$M_1 = \rho \cdot c \cdot K \quad (8)$$

where the index depends entirely on the properties of the guider material.

Maximization of the material index M_1 results in a larger heat partition coefficient and minimization of the material index M_1 results in a smaller heat partition coefficient. Additionally, it is of interest to find an intermediary heat partition value as to better characterize the sensitivity of the melt lubrication transition conditions to guider thermal properties. A group of materials that were readily available in the proper form were evaluated utilizing the material index M_1 . A maximum material index value of $13.3 \times 10^8 \text{J}^2 / (\text{m}^4 - \text{K}^2 - \text{s})$ was identified for copper. This means using a copper guider will result in a larger heat partition coefficient and provides the upper bound for the guider thermal study. A minimum material index value of $0.4 \times 10^8 \text{J}^2 / (\text{m}^4 - \text{K}^2 - \text{s})$ was identified for titanium. The use of titanium results in a lower heat partition coefficient and provides the lower bound. A good intermediate material index of approximately $4.0 \times 10^8 \text{J}^2 / (\text{m}^4 - \text{K}^2 - \text{s})$ was identified for molybdenum and tungsten. However,

acquisition of molybdenum and tungsten proved costly. Several other potential material candidates were unavailable in the proper form and for this reason an intermediate material of plain carbon steel was selected with a material index of $2.0 \times 10^8 \text{ J}^2 / (\text{m}^4 - \text{K}^2 - \text{s})$. The selection of plain carbon steel serves a dual purpose as it was used in the guider mechanical property study.

Figure 4 - A comparison plot of the heat partition coefficients for the three selected materials for the guider thermal properties study.

The four materials selected were C11000-H2 copper, 1018 steel, 1045 steel, and commercially pure (CP) titanium (grade 2). A plot of the heat partition coefficients as a function of sliding velocity for copper, plain carbon steel, and titanium is shown in Fig.4. It is important to note that copper and titanium provide the upper and lower bounds, while steel falls in between as the intermediate material as predicted by the material index M_1 .

4. Experimental Results

A set of eight experiments were conducted. The slider material was held constant as 6061-T6 aluminum for all tests. Five tests were conducted using a C11000-H2 copper guider, and one test each using 1018 steel, 1045 steel, and CP titanium guider materials. A comparison of the test results from the guider thermal property study is shown in Fig. 5. Contact pressure varied from test to test and this is reflected in the distribution of data. Since the effect of mechanical properties on normalized wear rates in the melt lubrication region are negligible and the pressure effects can be removed by plotting the normalized wear rate as a function of $\sigma^{1/4}v$, the influence of the guider thermal properties can be isolated as shown in Fig. 6. A distinct reordering of the guider materials is apparent. The predicted ordering of the three guider materials, using material index, $M_1 = \rho \cdot c \cdot K$, is titanium, steel, and copper. As titanium has the least favorable thermal properties of the three materials tested, meaning that of the heat generated at the contact interface, a lesser portion of the heat is partitioned into the guider and a greater portion is partitioned into the slider, creating the conditions necessary to develop a melt lubrication film at a lower transition condition. Accordingly, the same reasoning is applied to the steel and copper guider tests. However, an ordering of titanium, copper, and steel in Fig. 6 indicates that the material index M_1 is not applicable under the sliding conditions leading up to the severe plastic deformation and melt lubrication regions.

Figure 5 - Normalized wear rates as a function of velocity for three different guider materials in the melt lubrication region. The data from the five copper guider tests are represented by the red triangles, the two steel tests are represented by the black diamonds and the single titanium test is represented by the blue squares.

Figure 6 - Normalized wear rate dependence on $\sigma^{1/4}v$ for three different guider materials in the melt lubrication region.

An explanation for the reordering can be made by comparing the dwell time, which is the time that a point on the guider stays in contact with the sliding heat source, to the diffusion time, which is the time it takes for the heat to penetrate into the bulk material [21]. The dwell time is defined as

$$\tau_d = \frac{2l}{v} \quad (9)$$

where $2l$, is the slider length, and v , is the slider velocity. Furthermore, the diffusion time is defined as

$$\tau_h = \frac{z^2}{\chi} \quad (10)$$

where z is the diffusion depth, and χ , is the thermal diffusivity. The ratio of the diffusion time to the dwell time is as follows

$$\Phi = \frac{\tau_h}{\tau_d} = \frac{v \cdot z^2}{2l \cdot \chi} \quad (11)$$

Equation 11 represents the ratio of time required for heat to diffuse into the bulk material to the available dwell time of the heat source. A Φ value less than one indicates that a sufficient amount of time is available for bulk diffusion to occur resulting in steady state heat transfer conditions, whereas a ratio greater than one results in transient heat transfer conditions. For the values of $2l = 3.18$ mm, $v = 1,000$ m/s, $\chi = 1.13 \times 10^{-4}$ m² / s (thermal diffusivity of copper), and $z = l = 1.59$ mm, a Φ value of 7,000 is calculated, indicating that the conditions are representative of transient heat transfer. For this reason a simple transient conduction problem in which a small

Figure 7 - Diagram of the lumped capacitance approach to analyzing the guider thermal properties.

volume of guider material at the surface experiences a sudden change in surface temperature is considered. This approach is similar to that of quenching a hot metal. The concept is depicted in Fig. 7. Based on the large calculated Φ value, it is assumed that there is inadequate time for heat to diffuse into the bulk material, such that a small volume of material near the surface acts as a heat sink. The temperature of this volume is assumed to be spatially uniform and the temperature gradients within the volume are negligible. Utilizing this assumption a lumped capacitance approach is taken and an energy balance is performed [20],

$$\dot{E}_{storage} = \alpha \cdot \dot{E}_{gen} \quad (12)$$

where $\dot{E}_{gen}$, is rate of heat generated at the contact interface, α the portion of that heat partitioned into the guider, and $\dot{E}_{storage}$ is the energy storage rate of the volume of guider material near the surface. The rate of energy storage can be rewritten as

$$\dot{E}_{storage} = \rho \cdot c \cdot V \cdot \frac{\Delta T}{\tau_d} \quad (13)$$

where ρ is the density, c is the specific heat, V is the volume of guider material, ΔT is the rise in temperature and τ_d is the guider dwell time. It is assumed that the volume is fixed in size and relatively thin.

The ratio of the energy storage rate to the total rate of energy dissipation $\dot{E}_{gen}$ is the definition for the heat partition coefficient and is represented in the following form

$$\alpha = \frac{\dot{E}_{storage}}{\dot{E}_{gen}} \quad (14)$$

Substituting in Equation 13 into 14 and rearranging the terms

$$\alpha = \rho \cdot c \cdot \frac{V \cdot \Delta T}{\tau_d \cdot \dot{E}_{gen}} \quad (15)$$

Equation 15 can be used to better understand the effects of guider material properties on heat partitioning at the slider-guider interface. This leads to a material index in the form of the volumetric thermal mass,

$$M_2 = \rho \cdot c \quad (16)$$

A guider material with a large value of M_2 will partition more heat into itself, consequently decreasing the heat partitioned into the slider, resulting in an increase in the transition condition.

The volumetric thermal mass values for the guider materials tested, C11000-H2 copper, plain carbon steel (both 1018 and 1045 steels were essentially the same), and CP titanium are provided in Table 3. These material properties were used to adjust the experimental data such that the data for all eight experiments “collapsed” onto a single line, removing the effects of guider thermal properties on normalized wear rates. It was found that the copper and steel material properties in Table 3 adjusted the associated experimental data well, but those for CP titanium did not. The material properties for CP titanium were replaced by those of titanium dioxide [16] as the bar was formed by a hot extrusion process and cooled in open air, which resulted in a significant titanium dioxide scale on the guider. Using the titanium dioxide material properties instead of CP titanium adjusted the experimental data appropriately as it “collapsed” the data to the copper and steel data. The same oxide layer effects on the material properties for the copper and steel guiders were insignificant as the bars were cold drawn resulting in a relatively thin oxide scale and for this reason the bulk properties of these materials were appropriate.

Table 3 – Guider thermal properties of materials tested.

Material	ρ (kg/m ³)	c (J/kg-K)	M_2 (MJ/m ³ -K)	β
CP Ti (Grade 2)	4510	540	2.4	1.41
Titanium Dioxide	4010	690	2.8	1.24
Copper	8890	385	3.4	1.00
Plain Carbon Steel	7850	485	3.8	0.90

A normalized volumetric thermal mass term β is introduced as

$$\beta = \frac{(\rho \cdot c)_{copper}}{(\rho \cdot c)_x} \quad (17)$$

The volume of guider material that is available to store energy as described in Equation 15 is a combination of volumetric thermal mass and guider volume. The volume of guider material available to store the energy generated at the contact interface is dependent on the real area of contact, which is sensitive to contact pressure. For this reason the normalized volumetric thermal mass is incorporated into the pressure term of the normalized wear rate equation for a turbulent melt film [9],

$$\tilde{W} = \Psi \cdot (\beta \cdot \sigma)^{\frac{1}{4}} \cdot v + b \quad (18)$$

where Ψ is the melt lubrication proportionality constant or slope and b is the y-intercept. Replotting of the normalized wear rate data for the eight experiments as a function of $(\beta \cdot \sigma)^{1/4} \cdot v$ collapses the data onto a single line as shown in Fig. 8. The experimental data supports the use of volumetric thermal mass as the guider material metric when operating in the melt lubrication region. This suggests that the effects of thermal conductivity on the heat partition coefficient are secondary in nature, as the exposure time is on the order of a microsecond, making heat diffusion into the bulk of the guider material negligible.

Figure 8 - Normalized wear rate dependence on $(\beta \cdot \sigma)^{1/4} v$ for three different guider materials in the melt lubrication region.

5. Discussion

For tribological systems that operate at high sliding speeds and high contact pressures, greater than 100 MPa, it is ideal to operate in the plasticity – dominated wear region as the normalized wear rates are relatively low when compared to the severe plastic deformation and melt lubrication regions. The transition conditions from the severe plastic deformation to the melt lubrication are influenced by the thermal properties of the guider. For a tribomaterial pairing of a 6061-T6 aluminum slider with CP titanium, C11000-H2 copper, and steel guiders, the transition conditions ($\sigma^{1/4} \cdot v$) are 3100, 3300 and 3400 MPa^{1/4} m/s and their associated volumetric thermal masses ($\rho \cdot c$) are 2.8, 3.4 and 3.8 MJ / (m³ – K), respectively. The results show that a higher volumetric thermal mass results in a higher transition condition. However, the overall impact of the different guider volumetric thermal masses tested on the transition condition is relatively small, within approximately 6% of the baseline C11000-H2 copper.

While both the guider mechanical and thermal properties have a lesser impact on the transition conditions at high sliding speeds, they are still important to consider at lower sliding speeds. In traditional wear theory normalized wear rates are proportional to the contact load and material hardness of the softer material, assuming plastic contacts. For this reason a significantly harder guider material would be ideal at lower velocities, but not necessary at higher velocities where the slider has undergone thermal softening. Once the type of wear has shifted to the melt lubrication region, the slider and guider surfaces are fully separated by a melt film. Additionally, the sensitivity of the heat partition coefficients to guider thermal properties at lower sliding speeds (<100 m/s) is more significant.

The results presented in this study provide insight into how the properties of the guider material influence the response of the slider under high sliding speeds and high contact

pressures. While the impact of guider mechanical and thermal properties is less significant, as they relate to the wear of the slider, they are important when durability is a consideration. For practical engineering applications the guider is often subjected to repetitive use unlike the slider, which more often than not is designed for single use. In these instances it is essential that the guider is durable for performance and economic viability. Degradation of the guider needs to be considered when selecting a robust tribomaterial pairing. Some of the more common degradation mechanisms under high sliding speeds and high contact pressures are high velocity gouging, erosion and fracture. Therefore, for high sliding speeds and high contact pressure applications, the selection of the guider material is decided primarily by the properties that control durability [22].

6. Conclusions

An electromagnetic tribometer technique capable of generating high sliding speeds and high contact pressures was used to study melt lubrication of a 6061-T6 aluminum slider on a C11000-H2 copper, 1018 steel, 1045 steel and CP titanium guiders, which provided insight into the effects of guider material properties on slider wear under extreme sliding conditions.

- The slider normalized wear rates are insensitive to the guider hardness in the melt lubrication wear region as the slider has undergone thermal softening due to a bulk temperature rise as the slider interface approaches the melting point of the 6061-T6 aluminum.
- The transition from severe plastic deformation to melt lubrication wear is sensitive to the guider volumetric thermal mass ($\rho \cdot c$) such that a guider with a higher volumetric thermal mass results in a higher transition value than one with a lower volumetric thermal mass.

- The guider thermal properties have a small impact on the transition conditions, approximately $\pm 6\%$ of the baseline C11000-H2 copper and a negligible impact on normalized wear rates in the melt lubrication region for the materials tested.
- When selecting materials for a durable guider, the focus should be placed on degradation mechanisms at lower sliding speeds leading up to the melt lubrication region as the mechanical properties (hardness) and thermal properties (density and specific heat) have shown to have little effect on slider wear in the melt lubrication regime.

The consequence of operating in the melt lubrication region is significantly higher normalized wear rates than those in plasticity – dominated wear regime. The overall impact of guider material properties on the transition condition is small and the shift from the high normalized wear rate region to a low one can be addressed through the slider material properties and operating conditions if minimizing component wear is the primary objective.

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