Wear at High Sliding Speeds and High Contact Pressures

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Abstract - Metal on metal wear at high sliding speeds and high contact pressures results in the melting of one or both of the sliding solid bodies due to heat generated at the contact interface. Understanding the influence of sliding speeds and contact pressures on normalized wear rates is important in developing predictive models for designing more efficient and effective engineering system components. Typical engineering applications subjected to extreme sliding conditions include ultrahigh speed machining, rocket sleds, large caliber cannon, and electromagnetic launchers. Sliding speeds on the order of 1,000 m/s and contact pressures in excess of 100 MPa are common in these applications and difficult to replicate in a laboratory environment. A unique electromagnetic tribometer based on a minor caliber electromagnetic launcher has been designed and implemented to characterize wear deposition of a 6061-T6 aluminum pin (slider) on a UNS C11000-H2 copper flat (guider) at sliding speeds from 0 – 1,200 m/s and contact pressures from 100 – 225 MPa. Optical microscopy and 3D profilometry were used to investigate and quantify slider wear. Three distinct wear regions were observed. Test results provided evidence that the aluminum slider contact interface was molten and experimental wear data showed a dependence on both pressure and velocity. Comparisons between melt lubrication theory and experimental data provide insight into the nature of the contact interface under the sliding conditions tested.

Index Terms – Wear, Aluminum, Copper, High Velocity, High Contact Pressure, Melt Lubrication

Nomenclature

A_n	Nominal contact area (mm ²)	ρ	Mass density (kg / m ³)
c	Specific heat capacity (J / kg · K)	σ	Contact pressure (MPa)
δ	Geometric factor	T_m	Melting point (°C)
G	Geometric constant (m ^{-1/2})	T_o	Initial temperature (°C)
μ	Dynamic (absolute) viscosity (Pa·s)	v	Sliding speed (m/s)
Γ	Material property constant (Pa ^{-3/4})	v_c	Critical velocity (m/s)
λ	Turbulent viscosity constant (Pa · s ² / m)	$\bar{V}$	Volumetric wear (mm ³)
L	Latent heat of fusion (kJ / kg)	$\bar{W}$	Normalized wear rate (mm/mm)
l	Slider half length (mm)	x	Distance slid (mm)
Ψ	Proportionality constant (s / m · MPa ^{1/4})		

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1. Introduction

Metal on metal wear at high sliding speeds and high contact pressures can result in the melting of one or both of the sliding solid bodies due to heat generated at the contact interface. Typical engineering applications subjected to these extreme conditions include ultrahigh speed machining [1], rocket sleds [2], large caliber cannon [3], and electromagnetic launchers [4]. The interaction of the moving solid body (slider) and stationary solid body (guider) may result in wear of one or both components which is of critical importance to the performance and durability of these systems. Operating conditions with sliding speeds on the order of 100 – 1,000 m/s and contact pressures in excess of 100 MPa are common and difficult to replicate in a laboratory environment.

Characterization of slider wear under these high sliding speeds and high contact pressures is important to designing more efficient and robust engineering systems. Wear mechanisms and rates under these conditions are 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 and wear rates for a range of operating conditions. 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, which provides lubrication resulting in a low coefficient of friction [6], to melt lubrication, which is characteristic of large scale melting, such that the entire slider interface is molten and a hydrodynamic film capable of supporting the contact load is formed. Using conventional tribometers, melt lubrication is typically only observed with metals of lesser thermal capability (i.e., lower melting temperature) than steel [7]. Under melt

lubrication the dominant heat dissipation mechanism is viscous in nature and wear rates tend to be rather large due to the ease of expulsion of the liquid metal from the contacting interface. The maps also suggest the possibility of seizure if contact pressure is extreme, though there is no experimental evidence of seizure at these high sliding speeds. Using the same methodology, a wear mechanism map for Al alloys has also been generated [8]. The wear mechanisms of Al alloys at high sliding speeds and high contact pressures are also not well established due to the challenge of attaining these operating conditions with conventional tribometers.

A unique electromagnetic tribometer based on a minor caliber electromagnetic launcher (EML) [9] has been designed and implemented to characterize wear deposition in the melt lubrication wear region of a 6061-T6 aluminum slider on a UNS C11000-H2 copper guider. A set of experiments was designed to explore the effects of velocity and contact pressure on slider wear. Peak sliding speeds of 1,200 m/s and contact pressures from 100 – 225 MPa were achieved.

2. Experimental Methodology

2.1 Experimental Setup

The electromagnetic tribometer is derived from a specialized launch package developed by Stefani and Parker [10]. The minor caliber electromagnetic launcher (EML) at Georgia Tech provides the propulsive force necessary to generate the sliding speeds and contact pressures on the order of 1,000 m/s and 100 MPa. A schematic of the EML physics is shown in Fig. 1. A power supply involving several large capacitors stores electrical energy and when discharged generates a pulse of electrical current. The electrical current travels down one rail, passes through the armature and returns down the adjacent rail. The electrical current generates a

magnetic field that encircles the rails. The interaction of the magnetic field and electrical current produces a Lorentz force that accelerates the armature down the rails and out of the containment into a soft catch. The armature is the component of the launch package that completes the circuit between the rails with a preload.

Fig. 1. Schematic of an electromagnetic launcher (EML).

Modifications to the standard EML launch package and bore, shown in Fig. 2, were made to study mechanical wear with no electrical component at high sliding speeds and high contact pressures. The modifications include a milled channel down the center of each sidewall insulator. Each channel is sized to accommodate a 6.35 mm² bar, 1.56 m in length. Two bars, one embedded in each of the sidewall insulators are referred to as the guiders. The launch package is typically a monolithic armature, but has been modified to carry two 6061-T6 aluminum wedges. The launch package, as shown in Fig. 3, referred to from here on out as the tribo-slider is made

up of several components with a total mass of approximately 10 grams. The aft end of the tribo-slider is machined from a 6061-T6 aluminum plate and provides the propulsive force necessary to accelerate the tribo-slider to a peak sliding speed of 1,200 m/s. A 25 degree, from centerline, G-10 glass fiber composite ramp converts the inertia load of the wedge into a normal load on the guider, as shown in Fig. 4. Each wedge is machined from 6061-T6 aluminum bar stock has a 3.18 mm square contact area (10.1 mm^2), effectively termed the slider. The slider is designed such that the center of contact is geometrically positioned over the wedge center of mass as to provide a uniform load distribution at the contact interface. Prior to launch the wedges are supported and aligned by two nylon bore riders. Under high sliding speeds and high contact pressures the slider wears and deposits material onto the guider.

Fig. 2 - Cross-sectional view of the standard (left) and modified (right) EML bore.

Fig. 3 – Fully assembled tribo-slider (left) and half open view of a loaded tribo-slider and modified EML bore (right).

Fig. 4 - Overhead view of a tribo-slider and guiders.

A quasi-static analysis in the form of a free body diagram, as shown in Figure 5, is used to analyze the wedge-guider system. The guider normal load, G_N , guider shear load, G_S , wedge normal load, W_N , and wedge shear load, W_S , are the result of an inertia load, F_B and ramp angle, θ . Simplifying assumptions can be made at the wedge-ramp and slider-guider interfaces by assuming a low coefficient of kinetic friction at both interfaces. During operation, as the slider wears, a small relative motion, on the order of 1 m/s, occurs between the wedge and ramp. Published data has shown that the coefficient of kinetic friction of a glass fiber reinforced epoxy on aluminum at a sliding speed of 5.3 m/s and a contact load of 72 N to be 0.04 [11]. Similarly for the slider-guider interface at high sliding speeds the coefficient of kinetic friction has been shown to be on the order of 0.01. This estimation is based on a wide range of published data using different tribomaterial pairings and load conditions at high sliding speeds [5 - 7]. Using

Figure 5 – An inertia loaded wedge system used to generate contact pressures at the slider-guider interface.

these simplifying assumptions the following relationship is used to calculate the guider normal load

$$G_N = \frac{m_w a_c}{\tan \frac{\theta}{2}} \quad (1)$$

where m_w , is the mass of the wedge, a_c is the tribo-slider acceleration, and θ is the ramp angle. This form is consistent with the method employed by Stefani and Parker for a set of similar experiments in which they assume the wedge is allowed to move freely [10].

2.2 Experimental Procedure

During testing the total mass of the tribo-slider and the electrical current profile are held near constant. A peak electrical current of 280 kA is maintained for approximately 750 microseconds. Over this time the tribo-slider accelerates from rest to 1,200 m/s resulting in a near constant tribo-slider acceleration of approximately $1.60 \times 10^6 \text{ m/s}^2$ for a sliding distance of 0.45 meters. The tribo-slider contains a ramp upon which the two wedges slide freely. 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 [12-14] and Rogowski coils [15] are used to obtain the tribo-slider acceleration, velocity, and position as a function of time. Five tests of varying contact pressure between 100 – 225 MPa with a peak sliding speed of approximately 1,200 m/s for a tribo-material pairing of a 6061-T6 aluminum slider on a UNS C11000-H2 copper guider were conducted. The test conditions are summarized in Table 1.

Table 1 – Summary of test conditions to study the effects of pressure and velocity on slider wear.

Test No.	Slider Material	Guider Material	Contact Pressure (MPa)	Peak Velocity (m/s)
1	6061-T6	C110-H2	101	1210
2	6061-T6	C110-H2	122	1180
3	6061-T6	C110-H2	124	1210
4	6061-T6	C110-H2	130	1190
5	6061-T6	C110-H2	225	1180

At the start of each test the slider engages with the guider. Contact pressure is held near constant, while the sliding speed at the contact pressure increases with time and distance. The result is a different combination of pressure and velocity as a function of distance slid. The slider wears and deposits material on 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 (3.18 mm). The appearance and amount of slider deposition varies as a function of distance slid, which in turn is related to the operating parameters pressure and velocity. Two different techniques were used to analyze the deposition. The first is optical microscopy, which offers a qualitative assessment of the deposition and the second is 3D profilometry, which provides a quantitative assessment of the deposition.

After each test, the guiders were removed from the EML bore and prepared for analysis. The guiders were viewed at different locations 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 each guider specimen underwent a qualitative assessment the specimen was then prepared for 3D profilometry. The slider deposition on each guider was quantified using a Zygo NewView 6k scanning white light interferometer (non-contact optical profilometry). Discrete volumetric

deposition measurements at incremental locations along the length of each guider provide volumetric wear data as a function of distance slid, velocity, pressure and tribomaterial pairing. Prior to each scan the guider location of interest is marked into three different segments, a left, middle and right area. The middle area was masked using a steel fixture and the left and right areas were cleaned by “flaking” off the deposition followed by a sodium hydroxide swab to remove any residual aluminum, as sodium hydroxide reacts in a corrosive manner with aluminum. The removal of the deposition to the left and right of the middle area is necessary in order to properly characterize the guider surface roughness and any deformation that may have taken place due to contact with the slider. The MetroPro 8.1.5 software package that is part of the scanning white light interferometer system utilizes the left and right areas to define a plane from which to take a volume measurement in the middle area. Due to the size of the scan, 10 mm by 5 mm, it is necessary to use an application within the MetroPro 8.1.5 software called “stitch.app.” The stitch application takes several smaller scans and combines them to form a larger representative scan of the total area. An extended scan length option is necessary to capture the full range of depth. The combination of the large scan area coupled with the extended scan created a pixel-to-pixel resolution of 2.18 μm with a vertical resolution of 0.02 μm . Average deposition thickness, in the high velocity region, is on the order of 10 μm , making the error due to vertical resolution approximately 0.2% of the measurement.

2.3 Error Analysis

The data presented in the experimental results section does not include error bars for plotting clarity, as multiple sets of data are often plotted together. The error associated with both the contact pressure and velocity parameters, for a 95% confidence interval, is 7.6%. The primary source of error for these calculated values is due to curve fitting associated with the position

sensors used to obtain acceleration. Additionally, the error associated with the wear data measurements is 5-10%. The main source of error for this data is due to the guider surface topography. Guider material processing and deformation due to the slider – guider contact results in a surface roughness, $R_a \leq 1 \mu\text{m}$. The MetroPro 8.1.5 software takes a best fit plane of the left and right areas to average out the effects of the guider topography and to calculate the volume of material in the middle area. The slider deposition and guider topography are included in this calculation, which introduces error due to the statistical distribution of the guider topographical features (peaks and valleys). For a R_a 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%.

3. Experimental Results

3.1 Qualitative Analysis

A qualitative assessment was made for each test to correlate the changes in the type of wear, identified using optical microscopy, to operating parameters (pressure and velocity) and volumetric wear measurements using 3D non-contact profilometry. In general three wear regions with distinct differences presented themselves and were correlated to wear measurements and wear mechanisms for aluminum alloy wear maps [8]. The three correlated regions are plasticity-dominated wear, severe plastic deformation and melt lubrication. The plasticity-dominated wear region occurred at lower velocities, less than 800 m/s, while severe plastic deformation occurred at mid-range velocities, 800 to 1,000 m/s and melt lubrication at velocities greater than 1,000 m/s. The plasticity-dominated region is characteristic of wear rates that are proportional to the contact load [16, 17] in which the softer material is plastically deformed and sheared off as it adheres to the harder material. The severe plastic deformation region is representative of significant plastic flow / deformation as a result of thermal softening due to frictional heat

dissipation at the contact interface. Lastly, the melt lubrication region is characteristic of large scale melting and the formation of a melt film capable of supporting contact loads in a hydrodynamic manner.

An optical image of the plasticity-dominated wear region for a 6061-T6 aluminum slider on a UNS C11000-H2 copper guider at a contact pressure of 101 MPa and a sliding speed of 700 m/s is shown in Fig. 6. The reddish brown colored material is the UNS C11000-H2 copper guider, while the darker gray material is the deposited 6061-T6 aluminum. Visually the slider deposition in the plasticity-dominated wear region has a shiny appearance and is representative of uniformly smeared aluminum, leaving behind a track of material approximately equal to the width of the slider.

Figure 6 – An optical image of the plasticity-dominated wear region for a 6061-T6 aluminum slider on UNS C11000-H2 copper guider at a sliding speed of 700 m/s and a contact pressure of 101 MPa.

An optical image of the severe plastic deformation wear region for a 6061-T6 aluminum slider on a UNS C11000-H2 copper guider at a contact pressure of 101 MPa and a sliding speed of 930 m/s is shown in Fig. 7. The severe plastic deformation wear region deposition differs in appearance from the plasticity-dominated wear region. In general the deposition is representative of larger pieces of randomly distributed material with non-uniform coverage. Visually the deposition had a more matte finish rather than a shiny appearance. The change from plasticity-dominated wear to severe plastic deformation can be thought of as a change from localized heating at the asperity level to bulk interface heating. This rise in bulk temperature results in thermal softening and in turn large scale shearing / plastic deformation of the slider surface.

Figure 7 – An optical image of the severe plastic deformation wear region for a 6061-T6 aluminum slider on UNS C11000-H2 copper guider at a sliding speed of 930 m/s and a contact pressure of 101 MPa.

Lastly, an optical image of the melt lubrication wear region for a 6061-T6 aluminum slider on a UNS C11000-H2 guider at a contact pressure of 101 MPa and a sliding speed of 1,070 m/s

is shown in Fig. 8. The deposition in the melt lubrication wear region differs from both the plasticity-dominated and severe plastic deformation regions. In general the melt lubrication wear deposition is hemispherical in shape and more uniformly dispersed. Visually the deposition has a matte finish. The shift from severe plastic deformation to melt lubrication is the result of an increase in heat dissipation due to the large scale shearing / plastic deformation of the slider interface. Under these conditions the resultant heat generated is sufficient to melt the slider interface and to form a melt film capable of supporting the contact load.

Figure 8 – An optical image of the melt lubrication wear region for a 6061-T6 aluminum slider on UNS C11000-H2 copper guider at a sliding speed of 1,140 m/s and a contact pressure of 101 MPa.

3.2 Quantitative Analysis

A quantitative analysis was conducted and data from the five tests were compiled. Volumetric wear measurements of the deposited slider material on the guider were taken at different locations along the guider and correlated to operating parameters (pressure and

velocity). For comparison and analysis purposes the volumetric wear data was put into a rate form and normalized. The normalized wear rate is defined as

$$\tilde{W} = \frac{V}{A_n \cdot x} \quad (2)$$

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

The normalized volumetric wear rate for a 6061-T6 aluminum slider on a UNS C11000-H2 guider at a contact pressure of 101 MPa as a function of sliding speed is shown in Fig. 9. Three different regions, quantitatively, were identified and correlated to the qualitative results. The first region, plasticity-dominated wear, is representative of low normalized wear rates, less than 1.0×10^{-4} . In this region the volume of deposited slider material is characteristic of localized adhesion and is difficult to measure as it fell within the noise (peaks and valleys) of the guider surface roughness ($R_a \leq 1 \mu\text{m}$). For this reason only an upper bound could be placed on the normalized wear rates in this region. A second wear region, severe plastic deformation is demarcated by a sharp increase in the normalized wear rates followed by a steady decrease. The sharp increase is due to a bulk temperature rise at the slider interface, which results in thermal softening and large scale shearing / plastic deformation. The heat dissipated due to the large scale shearing / plastic deformation leads to the development of a partial melt film and is marked by a steady decrease in normalized wear rates until a full melt film is established. This shift from partial to full melt film is referred to as the critical velocity and represents the change from severe plastic deformation to melt lubrication. The development of a full melt film is characteristic of melt lubrication and the normalized wear rates steadily increased with velocity as viscous dissipation is the primary heating mechanism.

Figure 9 - Wear regions and normalized wear rates as a function of velocity for 6061-T6 aluminum on UNS C11000-H2 copper at 101 MPa.

A normalized wear rate plot for the melt lubrication region of a 6061-T6 aluminum slider on a UNS C11000-H2 copper guider at five different contact pressures is shown in Fig. 10. For plotting clarity only the data in the melt lubrication region is included. The critical velocity, v_c , at which the wear shifts from severe plastic deformation to melt lubrication is sensitive to pressure and is calculated from the intersection of the severe plastic deformation and melt lubrication linear fits, as shown in Figure 9. As the pressure increases, the critical velocity decreases. It was found that the shift to melt lubrication occurs when the product of the contact pressure raised to the $1/4$ power and sliding speed ($\sigma^{1/4}v$) equals $3,350 \text{ MPa}^{1/4} \text{ m/s}$ and is referred to as transition.

Figure 10 - Melt lubrication test data for a 6061-T6 aluminum slider on UNS C11000-H2 copper guider with varying contact pressure as a function of velocity.

4. Melt Lubrication Theory

Melt lubrication theory was used to interpret the experimental data into a more insightful form. A melt lubrication model for a fully melting slider and a viscous heat source was developed by Stiffler [18]. Stiffler utilized the Reynold's equation in conjunction with the heat equation to evaluate and predict slider melting rates. Several assumptions were made and they are

- 1) Molten metal lubricant is laminar and incompressible
- 2) Pressure, density and viscosity are constant across the film thickness
- 3) Molten metal film thickness is small relative to the slider geometry

4) Only the slider is melting

5) Quasi-steady state conditions are reached in the molten film

The normalized wear rate for a laminar melt lubrication film according to Stiffler is defined

$$\tilde{W} = \frac{\sigma^{\frac{1}{4}} \cdot (\mu v)^{\frac{1}{2}}}{l^{\frac{1}{2}} \cdot \delta^{\frac{1}{4}} \cdot \rho^{\frac{3}{4}} \cdot [L + c(T_m - T_o)]^{\frac{3}{4}}} \quad (3)$$

where σ is the nominal contact pressure, μ is the dynamic viscosity, v is the slider velocity, l is the slider length, δ is a geometric factor, ρ is the room temperature mass density, L is the latent heat of fusion, c is the specific heat, T_m is the melting point, and T_o is the initial temperature. The thermal properties are those of the melting slider. The geometric factor [17] is defined

$$\delta = 1 - \frac{192}{\pi^5 \cdot \zeta} \sum_{n=1,3,5}^{\infty} n^{-5} \tanh\left(\frac{n \cdot \pi \cdot \zeta}{2}\right) \quad (4)$$

where ζ is the aspect ratio of the slider contact area (length divided by the width).

Equation 3 suggests that the normalized wear rate is proportional to the contact pressure and sliding speed raised to the $\frac{1}{4}$ and $\frac{1}{2}$ powers, respectively. The data presented in Fig. 10 is re-plotted as a function of $\sigma^{1/4} v^{1/2}$ in Fig. 11. The results do not appear to agree well as a good correlation would “collapse” the data onto a single line. Further investigation into the melt lubrication model assumptions showed uncertainty in the assumption of laminar flow. Using the sliding conditions and material properties for molten aluminum, [19, 20] a Reynold’s Number of approximately 12,000 was calculated. Merrill and Stefani [21, 22] found the transition from

laminar to turbulent flow in journal bearings to be as low as 2,000. So, for the sliding conditions in the melt lubrication region the fluid film may be considered turbulent, which provides added complexity when analyzing the slider-guider contact interface.

Figure 11 - Melt lubrication test data for a 6061-T6 aluminum slider on UNS C11000-H2 copper guider as a function of $\sigma^{1/4} v^{1/2}$.

Based on the results shown in Fig. 11 the effects of turbulence on the melt film viscosity are investigated. It was suggested by Kothmann and Stefani [23] and further investigated by Merrill and Stefani [22] that a higher effective viscosity, which includes a laminar viscosity term and a turbulent viscosity term, is necessary for better agreement between experimental data and melt lubrication theory. For this investigation the effective viscosity term is defined as follows

$$\mu_{effective} = \lambda \cdot v + \mu_{laminar} \quad (5)$$

where λ is the turbulent viscosity constant, v is velocity and $\mu_{laminar}$ is the laminar viscosity. For high velocities, the first term dominates and the effective viscosity term is reduced

$$\mu_{effective} = \lambda \cdot v \quad (6)$$

Substituting Equation 6 into 3 the normalized wear rate for a turbulent melt film is defined

$$\tilde{W} = \frac{\lambda^{\frac{1}{2}} \cdot \sigma^{\frac{1}{4}} \cdot v}{l^{\frac{1}{2}} \delta^{\frac{1}{4}} \rho^{\frac{3}{4}} [L + c(T_m - T_o)]^{\frac{3}{4}}} \quad (7)$$

It is important to note that the geometry terms, l and δ are constants for a fixed slider geometry. These terms can be represented by a single geometry constant,

$$G = \frac{1}{l^{\frac{1}{2}} \delta^{\frac{1}{4}}} \quad (8)$$

As the slider thermal terms, ρ , L , c , T_m , and T_o , are representative of the energy required to melt the slider material, these terms can be represented by a single thermal constant,

$$\Gamma = \frac{1}{\rho^{\frac{3}{4}}[L + c(T_m - T_o)]^{\frac{3}{4}}} \quad (9)$$

Combining Equations 7, 8, and 9 a simplified form for the normalized wear rate for a turbulent melt film is

$$\tilde{W} = \lambda^{\frac{1}{2}} \cdot G \cdot \Gamma \cdot \sigma^{\frac{1}{4}} \cdot v \quad (10)$$

When the data in Fig. 11 is re-plotted as a function of $\sigma^{1/4}v$, as shown in Figure 12, the lines of constant pressure “collapse” onto a single line and the slope of each line is now representative of the turbulent viscosity, geometry and thermal constants λ , G , and Γ , collectively referred to as the melt lubrication proportionality constant Ψ defined by

$$\Psi = \lambda^{\frac{1}{2}} \cdot G \cdot \Gamma \quad (11)$$

Substituting Equation 11 into 10

$$\tilde{W} = \Psi \cdot \sigma^{\frac{1}{4}} \cdot v \quad (12)$$

This simplified form is useful when analyzing the experimental data as the slope of each line is equal to the melt lubrication proportionality constant. The melt lubrication proportionality constant, determined through regression analysis using all the data in Fig. 12, was found to be $5.59 \times 10^{-6} \text{ s} / \text{m} \cdot \text{MPa}^{1/4}$.

Figure 12 - Melt lubrication test data for a 6061-T6 aluminum slider on UNS C11000-H2 copper guider as a function of $\sigma^{1/4}v$.

5. Discussion

Sliding speeds on the order of 1,000 m/s and contact pressures in excess of 100 MPa are not common and are difficult to replicate in a laboratory environment making the existing published experimental data rather limited. Safety concerns and limitations in test equipment make it difficult to replicate these extreme sliding conditions using traditional tribological test apparatuses. Modifications to the actual engineering system are often necessary to isolate and study extreme sliding contact parameters. This was the approach taken in this paper. A unique

electromagnetic tribometer was implemented using the minor caliber EML at Georgia Tech to investigate the wear type, rates and mechanisms that occur under extreme sliding conditions.

Wear mechanism maps [5, 8] have traditionally identified the type of wear under high sliding speeds for steel on steel as melt wear. Melt wear is representative of localized melting at the asperity level. The localized melting provides lubrication, which results in a low coefficient of friction and a relatively low normalized wear rates. It has been shown for lower melting point metals [7], such as Wood's Alloy and bismuth that a second type of melt wear exists in the form of melt lubrication. Melt lubrication differs in that the sliding conditions are sufficient for large scale melting to occur. The large scale melting results in a melt film that is hydrodynamic in nature. The combination of high sliding speeds and high contact pressures achieved in the inertia loaded wedge experiments were adequate to achieve melt lubrication for a 6061-T6 aluminum slider.

For most engineering systems it is advantageous to operate in a lower normalized wear rate region. For a 6061-T6 aluminum slider operating at high sliding speeds and high contact pressures the ideal region to operate in is the plasticity-dominated wear region. The shift from plasticity-dominated wear to severe plastic deformation / melt lubrication can be estimated by the transition condition, $\sigma^{1/4} \cdot v$. For a 6061-T6 aluminum slider on a UNS C11000-H2 copper guider the transition condition is equal to $3,350 \text{ MPa}^{1/4} \text{ m/s}$, which means a sliding contact with a high contact pressure results in a low critical velocity and a sliding contact with a low contact pressure results in a high critical velocity. In addition to the operating parameters, the transition condition is also affected by the slider material [7]. A slider with a higher melting point than 6061-T6 aluminum will result in a higher transition condition and a slider material with a lower melting point will consequently have a lower transition condition. When selecting a tribomaterial

pairing, more specifically a slider material, it may be beneficial to operate in a lower normalized wear rate region than that of melt lubrication. When operating conditions exceed the transition condition for a given slider – guider tribomaterial pairing, the transition condition can be increased by selecting a slider material with a higher melting point and by doing so the normalized wear rates may be reduced, resulting in improved component performance.

For engineering system components where operating in the melt lubrication region is unavoidable, the experimental results combined with melt lubrication theory discussed in this study provide insight into how normalized wear rates may be reduced. Utilization of melt lubrication theory with an effective viscosity term, which includes the effects of turbulence, has shown good agreement with experimental data.

6. Conclusions

Using a newly developed electromagnetic tribometer designed to generate high sliding speeds and contact pressures necessary to study melt lubrication wear, a study of a 6061-T6 aluminum slider on a UNS C11000-H2 copper guider shed new light on this extreme wear regime.

- The wear mechanism depends on the sliding speed under these extreme conditions. For a 6061-T6 aluminum slider under a contact pressure of 101 MPa, the plasticity-dominated wear region occurred at lower velocities, less than 800 m/s, the severe plastic deformation region characterized by thermal softening due to frictional dissipation at mid-range velocities, 800 to 1,000 m/s, and melt lubrication at velocities greater than 1,000 m/s.

- Experimental wear rates in the melt lubrication region were found to be proportional to contact pressure raised to the $\frac{1}{4}$ power times velocity, $\sigma^{1/4} \cdot v$, which correlated well to the melt lubrication theory established by Stiffler [18].
- A shift from severe plastic deformation to melt lubrication for a 6061-T6 aluminum slider, referred to as transition, occurred when the combination of contact pressure raised to the $\frac{1}{4}$ power times velocity, $\sigma^{1/4} \cdot v$, reached a value of $3,350 \text{ MPa}^{1/4} \cdot \text{m} / \text{s}$. The wear rate exhibited a local minimum at this transition.
- Experimental data coupled with theory identified the primary heat dissipation mechanism in the melt lubrication region as viscous and turbulent in nature.
- Operating in the melt lubrication region results in significantly higher wear rates than those in the localized melt wear and plasticity – dominated wear regimes.

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